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MILITARY HANDBOOK

GUIDELINES FOR SAFE DESIGN OF POLYPHASE ELECTRICAL SYSTEMS

AMSC/NA

AREA SAFT

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DEPARTMENT OF DEFENSE
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Guidelines for Safe Design of Polyphase Electrical Systems

1. This standardization handbook was developed by the Field Safety Activity of the US Army Materiel Command with the assistance of other organizations within the Department of the Army.
2. This document supplements department manuals, directives, military standards, etc., and provides information on the design of safe polyphase electrical systems.
3. Beneficial comments (recommendations, additions, deletions) and any pertinent data that may be of use in improving this document should be addressed to Director, US Army AMC Field Safety Activity, ATTN: AMXOS-SE, Charlestown, IN 47111-9669, by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

FOREWORD

The primary purpose of this handbook is to improve the safety of polyphase electrical systems and components by addressing the associated risks and hazards and by offering solutions for eliminating or reducing them. To facilitate its use, the handbook is divided into two major parts: (1) general safety considerations presented in Chapters 2 and 3 and (2) design safety for specific items of electrical equipment presented in Chapters 4 through 8. Furthermore, the chapters conform to the following standardized format to assist the reader: introduction, induced environment, hazards, design considerations, compatibility and interoperability, test criteria for design and item acceptance, and operational precautions. The handbook content, although broad, is sufficiently specific to satisfy the needs of the design engineer, safety manager, safety engineer, and equipment user.

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LIST OF ABBREVIATIONS AND ACRONYMS

AC = alternating current
ACSR = aluminum conductors steel reinforced
AISI = American Iron and Steel Institute
AMC = US Army Materiel Command
AMCP = US Army Materiel Command Pamphlet
ANSI = American National Standards Institute
AR = Army Regulation
ASME = American Society of Mechanical Engineers
ASTM = American Society for Testing and Materials
AWG = American Wire Gage
BIL = basic insulation level
Cl_2 = chlorine
CO = carbon monoxide
CO_2 = carbon dioxide
DC = direct current
DoD = Department of Defense
DS2 = Decontaminating Solution No. 2
EGSA = Electrical Generating Systems Association
EMI = electromagnetic interference
EMP = electromagnetic pulse
EPA = Environmental Protection Agency
EPRI = Electric Power Research Institute
EPS = emergency power supply
FARS = Federal Accident Reporting System
FEP = fluorinated ethylene propylene
FET = field effect transistor
FL = fuel level
FM = field manual
GFCI = ground fault circuit interrupter
GFI = ground fault interrupter
GFP = ground fault protection
GND = ground
GPH = gallons per hour
H_2 = hydrogen
HCl = hydrochloric acid
HCN = hydrogen cyanide
He = helium
H_2O = water
H_2S = hydrogen sulfide
ICAO = International Civil Aviation Organization
IEC = International Electrotechnical Commission
IEEE = Institute of Electrical and Electronics Engineers
IR = infrared
ISO = International Organization for Standardization
KOH = potassium hydroxide
MIL-STD = military standard
NATO = North Atlantic Treaty Organization
NBC = nuclear, biological, and chemical
NEC = National Electrical Code
NEMA = National Electrical Manufacturers Association
NESC = National Electrical Safety Code
NFPA = National Fire Protection Association
NO = nitrous oxide
NO_2 = nitric oxide
N_2O_4 = nitrous tetroxide
O_3 = ozone
OD = outside diameter
OL = overload
OP = oil pressure
OS = overspeed
OSHA = Occupational Safety and Health Administration
OV = overvoltage
PCB = polychlorinated biphenyl
ppb = parts per billion
ppm = parts per million
PSIL = preferred speech interference level
RFI = radio frequency interference
rms = root mean square
ROWPU = Reverse Osmosis Water Purification Unit
RP = reverse power
SBR = styrene-butadiene rubber
SC = short circuit
SCR = silicon-controlled rectifiers
SF_6 = sulfur hexafluorine
SO_2 = sulfur dioxide
SO_3 = sulfur trioxide
STB = supertropical bleach
TB = technical bulletin
TFE = polytetrafluoroethylene
TCUL = tap change under load
UF = under frequency
UL = Underwriters Laboratories
UPS = uninterruptible power supply
UV = ultraviolent
Vac = volts, alternating current
VAR = volt-amperes reactive
VLSI = very large scale integration
VOM = volt-ohm-milliammeter
W = electrical wire, e.g., 2W or 3W
WT = water temperature
ϕ = electrical phase
1ϕ-2W = one phase, two wire
1ϕ-3W = one phase, three wire (split phase)
3ϕ-4W = three phase, four wire

CHAPTER 1

INTRODUCTION

This handbook was prepared to identify and discuss those design aspects of polyphase systems that impact the safety of personnel and equipment. In this introductory chapter the scope of the handbook is defined in terms of the equipment covered—i.e., electrical systems that generate, distribute, and use polyphase electrical power—and in terms of the type of information included, i.e., only those design issues that affect safety are discussed. Definitions and descriptions of the components and configurations of systems are included to illustrate types of equipment and to introduce the terminology used for those systems. Finally, the organization of the handbook is described and examples illustrating suggested application of it are given.

1-0 LIST OF SYMBOLS

n = number of phases, dimensionless
V_{ab} = voltage between adjacent lines ordered according to phase, V
V_{an} = voltage between any line and neutral, V

1-1 PURPOSE

The purpose of this handbook is to provide technical guidance for those aspects of the design of polyphase (two or more phases) electrical systems and components that affect the safety of personnel and equipment. Design information is given for features that, if designed properly, will minimize the risk of an accident. Technical features that affect system performance, efficiency, or convenience are not discussed unless these features affect the safety of personnel or equipment.

This handbook is intended to fill the gap between reference texts on system safety and texts on electrical system engineering but is not intended as a replacement for either. It supplements system safety manuals by providing technical information specific to electrical system safety. This information includes identification of hazards in electrical systems and precautionary measures that eliminate the hazards or reduce the risk associated with them. This handbook also augments technical power system handbooks by providing a discussion of safety-related design considerations for power systems. The power system designer can use this handbook to flag system considerations that must be taken into account in the design and can find technical guidance on the appropriate method of implementing the required design features.

1-2 SCOPE

1-2.1 SYSTEMS COVERED IN THIS HANDBOOK

Covered in this handbook are polyphase electrical systems used by the US Army that either may be powered continuously by an engine-driven-generator set or powered by a backup engine-driven-generator set, which supplies power when the primary supply is disabled. The typical polyphase system used by the Army has certain characteristics:

1. Alternating current (AC)
2. Power capacity up to 750 kVA
3. Polyphase—usually 3 phases
4. Line voltages of 120, 240, 2200, or 2400 Vac between any phase and ground (208, 416, 3800, or 4160 Vac between phases)
5. Tactical systems or backup systems used for strategic equipment, e.g., communication facilities, or hospitals.

This handbook covers electrical system components and interconnections from the power source through the distribution system to those end-items that are connected directly to three-phase systems. The power sources covered are primarily the engine-driven-generator set including the prime mover (internal combustion engine or turbine) and the generators driven by them. In addition, the interface with permanent utility systems is discussed along with transfer switching apparatus to provide information pertinent to those systems that use engine-driven-generator sets as a backup power system. Also discussed are the safety aspects of those end-items that are connected directly to the polyphase system. These components include large motors, strip heaters, and communications equipment. The transformers that convert the polyphase power to one or more single-phase circuits are also discussed as an end-item. Not discussed as end-items are the wiring or loads associated with the single-phase circuits connected to the transformer secondary.

1-2.2 TECHNICAL DATA INCLUDED IN HANDBOOK

As stated in the par. 1-1, the purpose of this handbook is to provide technical guidance for the design of polyphase systems and components that affects the safety of personnel and equipment. For this reason only design features that affect safety are discussed in this handbook.

Those features that affect only system performance and do not impact safety are not discussed since they are covered extensively in the numerous design handbooks on electrical power systems.

MIL-STD-882 (Ref. 1) requires that hazards, especially those involving catastrophic or critical risks, shall be reduced through design selection or reduced by appropriate warning devices.

If the hazard cannot be eliminated or the risk cannot be reduced with warning devices, operational procedures and personnel training must be used to minimize the hazard. Therefore, system operation and maintenance manuals must discuss the proper procedures for safe operation of the system, and operators and maintenance personnel must be trained in those procedures. For this reason operation and maintenance procedures that have safety implications are discussed as well. Procedures discussed are those that have an inherent hazard to personnel at the time the procedure is performed and those procedures that, if improperly performed, may precipitate unsafe conditions that remain after the procedure has been completed. The intent is not to include detailed procedures in this handbook but rather to describe practices that must be incorporated in procedures and the rationale behind them.

1-3 DESCRIPTION OF POLYPHASE SYSTEMS

1-3.1 DEFINITION OF POLYPHASE SYSTEMS

Electric power consisting of alternating voltages and currents is transmitted from one location to another using one of the system configurations shown in Fig. 1-1. In these diagrams, transformers are used to illustrate a possible driving source for each configuration, and only the secondary connections of the transformers are shown. The grounding points shown represent commonly encountered grounding schemes. Other schemes are used, and grounding considerations are discussed in par. 3-3.3.The three configurations shown are described in the following paragraphs:

1. *Single-Phase*. The simplest of an AC electrical distribution system, the single-phase—shown in Fig. 1-1(A)—consists of a single wire to supply power to the load and a return wire (usually grounded at the generator or primary transformer) to complete the circuit. This configuration is designated by 1ϕ-2W, which means one phase, two wire. ϕ is the symbol for phase.*

2. *Split-Phase*. In a split-phase system—shown in Fig. 1-1(B)—power is supplied from two equal voltage sources (two windings on a transformer) connected to a common neutral, which is usually grounded. The two sources have equal voltage outputs, which are opposite in the polarity (180-deg phase difference). The split-phase system will deliver a specified power more efficiently than a single-phase system if the load is divided between the two lines. This increase in efficiency is due to a reduction in losses in the common return line arising from the partial or total cancellation of the out-of-phase return currents from each of the loads. Split-phase systems are designated as 1ϕ-3W for one phase, three wire.

3. *Polyphase System*. The term "polyphase" means many phases and was most popular around the turn of the century when phase networks were considered in limitless dimensions. However, this very quickly gave way to three-phase systems based on efficiency and practicality. The term "polyphase" receives rather limited use in modern technical literature. The term is used in this handbook as a matter of thoroughness since the safety considerations would apply to networks of more than three phases and to help clarify the meaning of this infrequently used term. In a polyphase system—shown in Fig. 1-1(C)—power is delivered to a load over three or more lines with or without a common return. The voltage on the lines is the same with respect to a common neutral. However, the phase of the voltage on any line is different from the phase of each of the other lines. For the most common three-phase configuration, the phase on one line differs by 120 deg from each of the other two.

Polyphase systems have certain characteristics that differentiate them from single-phase systems:

1. Voltages are present that have a phase relationship other than 0 deg (in phase) or 180 deg (out of phase).

2. At any instant, some voltage is present on at least two lines of a polyphase system, and power is being delivered to the load continuously. In the single- or split-phase systems the voltage on all lines simultaneously diminishes to zero during the polarity reversal, which occurs twice during each cycle of the line frequency.

3. When the lines are ordered in the sequence of their phase, the voltage between adjacent lines and the voltage between the first and last lines are equal. Also the voltage among all lines and the common neutral are equal.

The relationship between the line-to-line and the line-to-neutral voltages is

$$V_{ab} = V_{an}\{2[1 - \cos\left(\frac{360}{n}\right)]\}^{1/2},\ \text{V} \qquad (1\text{-}1)$$

where

V_{ab} = voltage between adjacent lines ordered according to phase, V
V_{an} = voltage between any line and neutral, V
n = number of phases, dimensionless.

For the most common system, three-phase, Eq. 1-1 becomes

$$V_{ab} = 1.732\,V_{an},\ \text{V}. \qquad (1\text{-}2)$$

*The wire count indicated by the notation "1ϕ-2W" does not include the ground connector; consequently, a 3-conductor cable will be required to supply power in a 1ϕ-2W system. The same is true whenever designating wiring, i.e., include the ground wire as part of the wire count. For example, configurations such as 3ϕ-3W and 3ϕ-4W require 4- and 5-conductor cable, respectively.

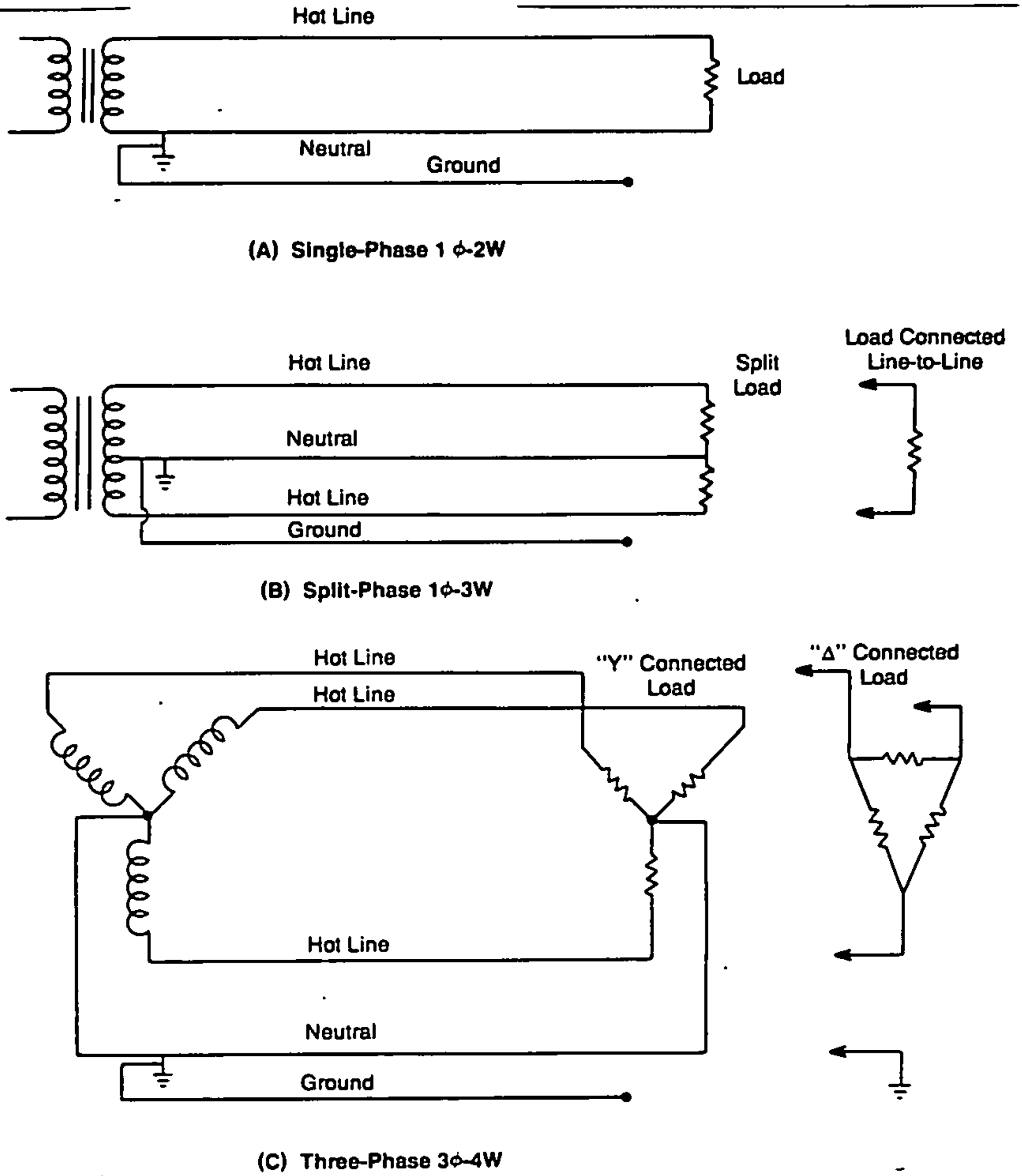


Figure 1-1. Representative Connections for Single-Phase, Split-Phase, and Three-Phase Systems

1-3.1.1 *System Components*

A diagram of a power system of the type generally used by the Army in the field is shown in Fig. 1-2. The system shown in this figure incorporates many of the components that can be used in polyphase electrical systems centered around engine-driven-generator sets. Fig. 1-2 is included to illustrate the typical interconnection of the components to be discussed in this handbook and the function of those components in the system. However, when configured properly, the components may be used for other applications as well. (For example, switchgear, used in this configuration for selecting the source of power, may also be used for isolating circuits for maintenance or controlling the power to large loads.) The various components shown are discussed in the paragraphs that follow.

1-3.1.1.1 Engine-Driven-Generator Set

The engine-driven-generator set consists of an internal combustion or turbine engine whose rotating shaft output is used to drive an alternator or generator to produce electricity. In this handbook only those systems that generate three-phase power are discussed, although there are single-phase units with output capacities as low as 500 W that are available in the Army inventory.

1-3.1.1.2 Distribution System

The distribution system is an encompassing term for the collection of cabling and components, which transport the electrical power from the source or point of generation to the ultimate load. Distribution systems are sometimes differentiated by the level of voltage they conduct within a system. Distribution of power is usually more efficient at higher voltages because of the lower current and consequent lower line losses. However, since the line ultimately must feed end-items requiring lower voltages, the distribution system is sometimes divided into two sections: a primary distribution system that distributes the power over significant distances to transformers located near the end-items to be powered by the

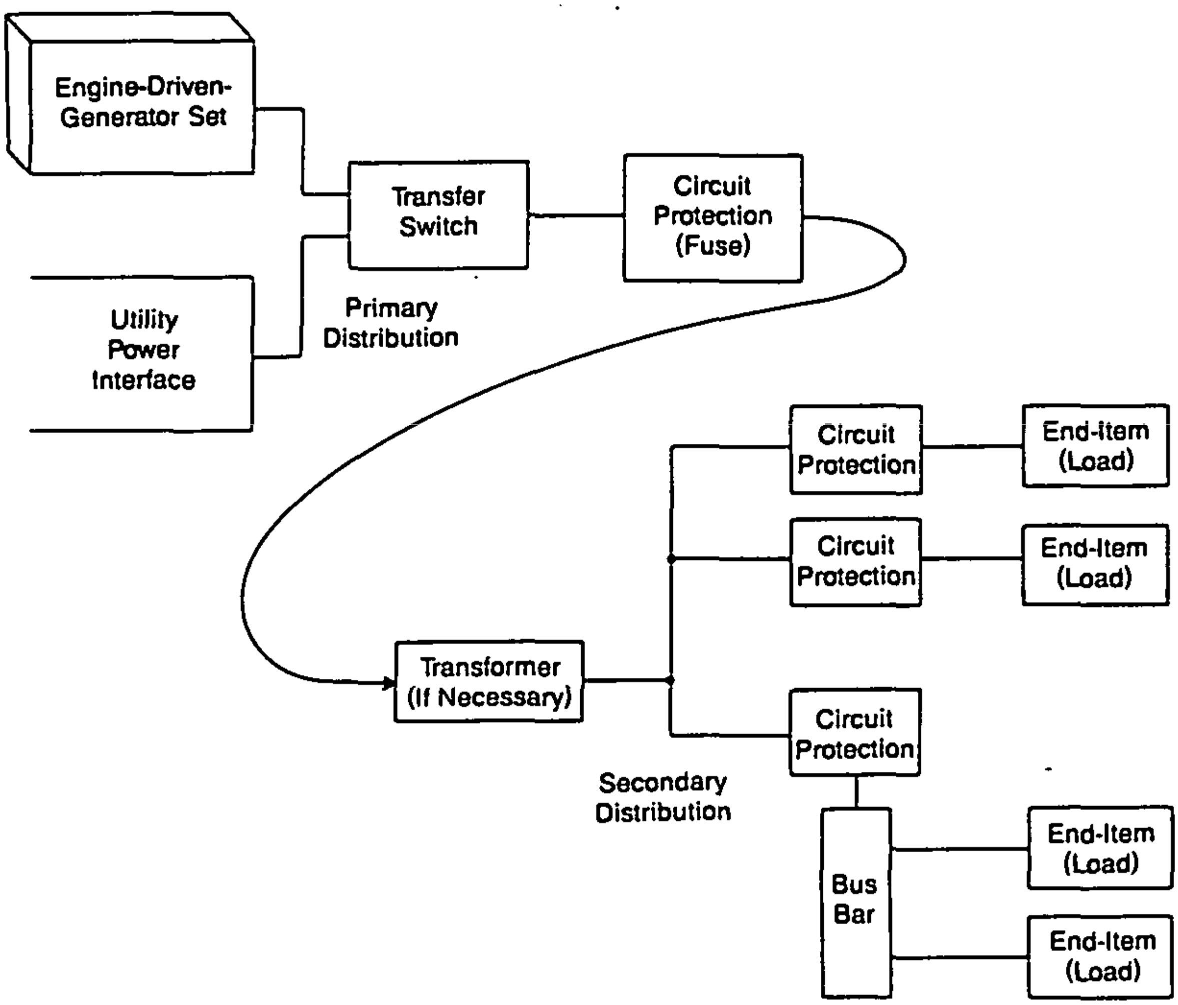


Figure 1-2. Electric Power Generation and Transmission System

system and a secondary distribution system that distributes the low voltage power from the transformer to nearby loads. A discussion of the components that may be used in the distribution system follows.

1-3.1.1.2.1 Transmission Lines

Transmission lines are the cabling that connects the power source to the loads located some distance away. Transmission lines may be buried, mounted on poles (aerial), or laid along the surface of the ground.

1-3.1.1.2.2 Bus Bars

Bus bars are a set of rigid conductors used within enclosures to distribute power to various components or mounted in raceways to distribute power within buildings. Bus bar distribution systems are usually configured so that external connections are easily made by bolting, clamping, or otherwise attaching conductors or connecting devices to the bus bars. Therefore, bus bars are commonly used in high-current distribution systems confined to small areas or in distribution systems that must be modified frequently to accommodate changes in loads or configurations.

1-3.1.1.2.3 Distribution Transformers

Distribution transformers are used to transform the voltage level of the distribution network to a higher or lower voltage. The transformer may be used to transform the generator output to the high voltage for transmission with minimal losses and back to low voltage for consumption at the load.

1-3.1.1.2.4 Switching Systems

Switching components used in polyphase systems perform the same function as switches in any system, i.e., the convenient making or breaking of the continuity of a conductor path. In polyphase systems various types of switchgear are used for the following purposes:

1. Disconnection of sections of transmission lines for maintenance
2. Isolation of sections of transmission line to remove ground faults (conductor shorted to ground) and to allow restoration of power to remainder of system
3. Removal of power from end-items or systems
4. Switching between sources of power.

Switchgear is used in a wide variety of forms within polyphase systems. Some of these forms include high-capacity switching systems capable of operating under full-load conditions and light-duty switches used to reconfigure a distribution system that must be operated when little or no load current is flowing. Also included in the definition of switchgear are the automatic switches with powered controls that are used for circuit protection or for extinguishing arcs.

1-3.1.1.2.5 Protective Devices

Protective devices used in distribution systems include devices that prevent excessive current in conductors, e.g., fuses or circuit breakers, or interrupt power during over- or undervoltage conditions. Fuses and circuit breakers typically are used where power enters an electrical cable and are sized to prevent current flow greater than that which can flow safely through the cable. Circuit breakers may also be used with voltage sensing (instead of current sensing) to interrupt power to a critical load when voltage rises (or falls) to levels that could cause damage or with current imbalance sensing to remove hazardous voltages when small leakage currents are detected (ground fault circuit interrupters (GFCI)). Finally, a crowbar configuration may be used to trip overcurrent devices by inducing a line-to-ground fault when an unsafe condition is detected.

1-3.1.1.3 End-Items

In this handbook, end-items refer to pieces of equipment that are powered from a polyphase source, which usually implies those loads that require more than one kW of power. Common end-items include large motors, heaters, high-powered communication equipment, industrial apparatus—e.g., welding and metalworking equipment—and X-ray equipment.

1-3.1.2 System Configurations

Presented in this paragraph are the various means of classifying polyphase systems according to system topology, capacity, and application. These classifications are presented to define the terminology used both in industry and throughout this handbook.

1-3.1.2.1 System Topology

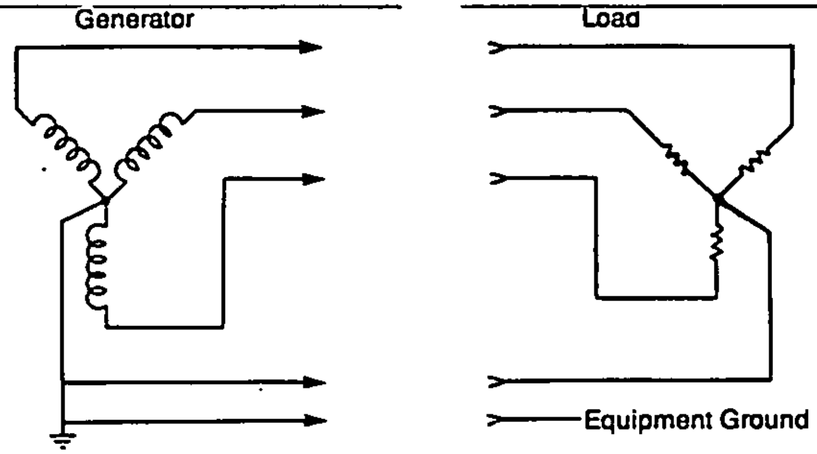
The usual configurations used for polyphase systems are shown in Fig. 1-3 along with the terminology used to identify the various lines used. The wye or "Y" configuration shown in Fig. 1-3(A) is the most common configuration for a power source because the grounded neutral insures that the voltage with respect to ground of each line is the same and, therefore, the maximum voltage to ground is the lowest achievable. The delta or "Δ" configuration shown in Fig. 1-3(B) is commonly used for loads in which the voltage relationship between the lines and ground are established elsewhere, e.g., at the source. Other configurations are sometimes used, such as the delta with one line grounded as shown in Fig. 1-3(C). This configuration has two lines with a voltage with respect to ground, which is 1.732 times the line-to-neutral voltage of the wye configuration.

Electrical systems powered by engine-driven-generator sets used by the Army in the field are generally single or split phase for power levels below 3kW. Systems powered by larger generators are usually three-phase, four-wire systems but may be three-wire systems if only delta-connected loads are used.

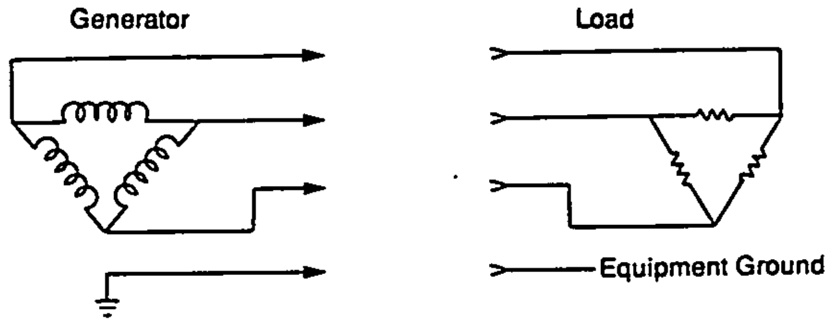
1-3.1.2.2 Electrical Parameters

The electrical systems are also classified according to the parameters that describe the power that can be supplied by them. These electrical parameters include

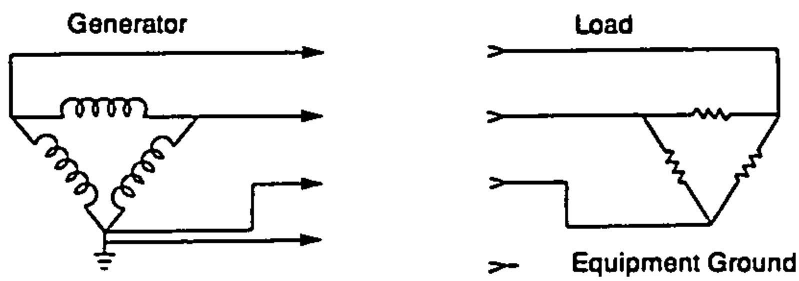
1. *Voltage*. The voltage may be either line-to-line or line-to-ground.



(A) Wye or "Y" Configuration



(B) Delta or "Δ" Configuration



(C) Grounded Leg Configuration

Figure 1-3. Common Three-Phase Configurations

2. *Current, maximum.* This is the maximum current that can be delivered by the system.

3. *Power, maximum.* This is the maximum power that can be delivered by the system, determined by the voltage and current.

4. *Frequency.* The frequency that is associated with the sinusoidal line voltage and current.

An engine-driven-generator set powered electrical system used by the Army generally operates at line-to-neutral voltages of 120 V (208 V line-to-line) with an operating frequency of 60 Hz. Systems powered by high-capacity generators (750 kW) may operate at 2400 V line-to-neutral (4160 V line-to-line) using transformers to convert these voltage levels to the 120-V or 208-V levels required by typical loads. The power capacity (and therefore current) depends on the generators, which range in capacity from 1.5 kW up to 750 kW, used to power the system.

1-3.1.2.3 Standby vs Primary Power Systems

Polyphase systems are also classified by their reliability requirements. The source of power for polyphase systems is usually the commercial utility system, which in the United States has few outages per year. If no power outages can be tolerated, the primary system is augmented by a backup system that supplies power to critical loads when the primary system fails. These systems are characterized by the following four parameters (Ref. 2):

1. *Type.* This parameter—also called "tolerance duration of power failure"—refers to the maximum duration of a power outage that can be tolerated, which, in the case of a backup system, refers to the allowable time between the onset of a power outage and the time the backup system must begin to supply power.

2. *Class.* Class, also called "recommended auxiliary supply time", is the maximum length of time the backup power source must continuously supply power.

3. *Category.* This parameter refers to the nature of the backup power source. Category A sources are those capable of beginning operation immediately, e.g., battery-powered or inertial systems, whereas Category B systems are engine-powered units that require a certain period of time to begin operation.

4. *Level.* Level is the relative importance of maintaining power. Level 1 systems are those systems where loss of power would result in loss of life or serious injury; therefore, an immediate standby is required. In Level 2 systems the consequences of loss of power are intermediate, but the use of a standby system is still legally required. In a Level 3 system the loss of power would not jeopardize the life or health of personnel, but an uninterrupted supply of power is required because of economic or convenience reasons.

Army systems may operate with a primary generator or with a "hot", "warm", or "cold" standby generator. A "hot" standby is operating and providing power to a dummy load, a "warm" engine-driven-generator set is one that employs auxiliary heating devices to maintain elevated engine temperatures so the engine may be started quickly, and a "cold" standby is a generator that must be started to replace the primary generator on-line.

1-3.2 EQUIPMENT POWERED BY POLYPHASE SYSTEMS

1-3.2.1 Introduction

Equipment may be powered from a three-phase power source either because the equipment itself justifies the installation of a three-phase power source or because the equipment is operated from a three-phase source installed to operate another power source located nearby. The features of three-phase power that justify its use with certain types of equipment include

1. *Efficient Power Transmission.* Lines losses are less with polyphase power than with single-phase power sources.

2. *Continuous Supply of Power.* Although power from a single-phase supply diminishes to zero at least twice during each power line cycle, the total power from all lines of a balanced three-phase system does not change with time. (Imbalanced loads will introduce a cyclic variation in the power delivered.)

3. *Efficient Motor Operation.* Motors operated from polyphase power draw lower starting currents and run more efficiently than similarly constructed motors powered by a single-phase supply.

Equipment that is operated from polyphase systems typically has one or more of the following characteristics, which allow it to use advantageously the features of three-phase power:

1. *High-Power Loads.* Three-phase power is usually used where the savings from increased efficiency offset the cost of the additional complexity of the generating and distribution system. The savings realized are proportional to the power consumed by the load. Consequently, three-phase loads are usually those that draw high power.

2. *Physically Large Electrical Equipment.* Polyphase equipment, because of its high-power capability, tends to be large. Also the large multiwire interconnections necessary for polyphase power do not encourage its use on small hand-held equipment.

3. *Groups of Equipment.* Equipment, typically not operated from a polyphase source, can be grouped together with other equipment to form a system that is powered by a polyphase system.

The subparagraphs that follow identify typical equipment used by the Army that is powered by polyphase systems. This list is not a comprehensive one of all three-phase equipment but simply provides examples of the more common applications.

1-3.2.2 Radars

Developments in radar technology have made possible the replacement of the large, rotating antenna structure with a stationary, electronically steerable antenna array, which eliminates the large motors in the radars. Also, advances in the state of the art of electronics have reduced the power requirements for performing various signal-processing functions on the radar return signal. However, the increase in system complexity has lead to the addition of large amounts of ancillary equipment for generation of signals, received signal detection, and target tracking, all of which has increased the size and power requirements of the radar facility. An example of a modern radar facility fielded by the Army is the PATRIOT missile system. This system employs a 150-kW generator mounted on a truck to power the radar and weapons control system and a second 60-kW unit for the command and relay groups.

An example of a smaller radar facility is that used with the HAWK guided missile system. This system is housed with multichannel communication facilities in a shelter that also serves as a platoon command post. Power requirements for the complete shelter are 12.5 to 24 kW (depending on the amount of equipment that is operating) and 400 Hz.

1-3.2.3 Communication Equipment

Although high-power radios and complex communication systems can be powered directly from polyphase power, the more common use of polyphase power for tactical communication applications is the powering of shelters that contain multiple single-phase loads distributed among the phases. Alternatively, polyphase sources of the appropriate capacity can be used to supply power to multiple equipment shelters, which are collocated to form a communication facility. Examples of communication equipment or systems that are powered by three-phase generators include

1. AN/TSC-58, Tactical Satellite Communication System, which uses a 10-kW generator
2. AN/TTC-38, Tactical Telephone Communication System, used at division headquarters and corps level, is powered by a 30-kW generator.
3. AN/TYC-39, Automatic Message Switch, is used for secure automatic switching of data and narrative information at corps and theater army nodes. This system is powered by a 60-kW generator.
4. AN/MSC-46, Satellite Communication Terminal, is currently being developed. A 100-kW generator powers the total system, supplying single-phase power to most of the internal subsystems and three-phase power to the microwave power amplifier.

1-3.2.4 Welding Equipment

Welding equipment in use in the Army typically is designed to operate from a wide variety of power sources—either from its own internal engine, from a single-phase source, or from one phase of a polyphase source. Electric-powered welding equipment likely to be included in fieldable mobile repair shops, used for maintenance and light construction, typically requires 12 kW from a single-phase source. Usually larger units are powered from built-in diesel engines.

1-3.2.5 Medical Equipment

Sterilizers and X-ray machines are the most commonly encountered electrically operated items found in Army field hospitals. Examples of the sterilizers include the Sterilizer, Surgical Instrument and Dressing, Field, Electrical and Fuel Operated (FSN 6530-00-926-2151) and the Sterilizer, Surgical Instrument and Dressing, Dual Chamber, referred to as the "piggyback" unit (FSN 6530-00-027-5260). Either of these sterilizers may be configured to operate from either single-phase or three-phase power and draws 9 kW in each case. (With the appropriate attachment, either sterilizer may be operated from fuel also.) This equipment is designed to be compatible with most available sources of power, including generator- and utility-supplied power in the United States and abroad.

The Military Radiographic and Fluoroscopic X ray (FSN 6525-01-192-1884) is used in Army field hospitals. This unit also can be powered from a single-phase (220V) system or from two phases of a three-phase system (208V); it draws approximately 45 kW in each case.

1-3.2.6 Other Equipment

Equipment powered by polyphase systems is not limited to the items listed in the preceding paragraphs. There are a number of special purpose, field-deployable systems whose power requirements are sufficient to justify the use of a polyphase power source, frequently that supplied by built-in engine-driven-generator sets. One system is the Reverse Osmosis Water Purification Unit (ROWPU), which decontaminates water by pumping it under high pressure through tubes containing a special spiral-wound membrane. A 600-GPH (gallons per hour) unit, which uses a 30-kW polyphase generator for supplying power to the large electric-motor-driven pumps, is currently in use by the Army and Marine Corps. Larger units with capacities of 3000 GPH, which will require greater quantities of power, are being developed.

1-4 HANDBOOK OVERVIEW

1-4.1 HANDBOOK ORGANIZATION

The seven subsequent chapters of this handbook can be divided into two major groups. In the first group, general considerations for safety in electrical equipment are discussed. In the second group, design safety considerations for specific items of electrical equipment are addressed.

The first group of chapters, covering general considerations for safety in electrical equipment, consists of Chapters 2 and 3. Safety considerations appropriate for, but not unique to, specific electrical equipment are discussed in Chapter 2, "General Safety Considerations". Topics included in this chapter are risk assessment, hazard limits (maximum surface temperatures, exposed voltages, etc.) and sources of hazard information specific to electrical equipment.

Chapter 3, "System Design", describes general design considerations for the electrical system as a whole and considerations common to all parts of the system. Discussed in this chapter are characteristics of the environment that affect the operation of electrical equipment and typical environments in which the equipment is expected to operate. Also discussed are system considerations that apply to all components in the system; such topics as system grounding and material selection are included.

The group of chapters that treats the safety-related design factors for specific polyphase electrical system components comprises the largest portion of this handbook. Chapters in this group describe problems associated with specific components, e.g., distribution system components, (such as transformers, switchgear, and transmission lines), end-items, and portable and permanently installed test and measurement equipment.

The design information for electrical components is presented in a uniform manner throughout this handbook. Hazards, design features necessary to minimize those hazards, and operational considerations are discussed for each component. The discussion of the design information for each component is organized into subparagraphs with the title and content of each subparagraph as follows:

1. *Introduction*. This topic defines the component and describes those components that are typically found in polyphase systems of the capacity that could be powered by engine-driven-generator sets (up to 750 kVA).

2. *Induced Environment*. The alteration of the environment made by the component that could affect the operation of the component or other equipment located nearby is described. Subtopics, such as heating and presence of high voltage, are presented.

3. *Hazards*. In this subparagraph safety hazards that are introduced by the equipment both in normal operation and in the event of component failure are discussed. Example hazards include electrocution during normal operation and fire or explosion resulting from overcurrents, which can occur in the event of component failure.

4. *Design Considerations*. Technical information concerning proper design of electrical equipment to minimize associated hazards is presented.

5. *Compatibility and Interoperability*. A discussion of the compatibility and interoperability issues associated with the component and other components in the system is presented. Two units are compatible when their features and characteristics allow each unit to be used as a direct replacement for the other. Two units are interoperable when they can be operated satisfactorily in the same system simultaneously. Features and characteristics of electrical components that affect or determine compatibility and interoperability are discussed under this heading. Hazards introduced when dissimilar units are used in the same or similar systems are discussed, including those problems that arise from the direct electrical interconnection of incompatible electrical components and the potential problems that arise from incompatible or noninteroperable components in the same supply inventory. Examples of problems introduced for the latter reason include (1) hazard due to improper connection of a replacement component that was connected improperly because of different labeling or configuration and (2) hazards introduced because of inadvertent use of supplies or replacement parts intended for a similar but incompatible component in the same inventory.

6. *Test Criteria for Design and Item Acceptance*. This subparagraph provides a list of performance parameters that should be verified through acceptance testing to prevent or detect hazards that could be introduced through component failure or improper design. The nature of the test is briefly discussed along with the reasons for the importance of it.

7. *Operational Precautions*. The procedures that must be specified in training programs and operating manuals and the rationale for their importance are discussed. The intent of this discussion is not to describe the procedures but to state considerations that should be covered in published procedures.

1-4.2 HOW TO USE THIS HANDBOOK

The stated objective of this handbook is to provide technical guidance for those aspects of electrical system and component design that affect the safety of personnel and equipment. Since only those design issues that impact safety are addressed, this handbook should not be considered a complete handbook on polyphase electrical systems, but instead it is intended to supplement the numerous handbooks available on the subject of power generation and transmission systems. The intended applications for this handbook are described by type of user, i.e.,

1. *Design Engineer*. When designing equipment for polyphase electrical systems for military applications, the design engineer should refer twice to the chapter or paragraph pertaining to the equipment being designed. The first reference should be prior to initiating the design, or at least prior to completing the design, to identify those design factors that affect safety. The second check should be after the design is completed to determine whether all safety considerations are covered adequately and properly. This process should begin as early as possible to insure the physical configuration, material selection, and component selection are chosen properly for safe operation. Most of the material included in this handbook is appropriate for the design engineer since the purpose of this handbook is to discuss safety-related design issues.

2. *Safety Manager*. Persons responsible for the safety of personnel using electrical generation and distribution equipment should use the description of hazards associated with electrical equipment to identify critical or hazardous areas in electrical systems.

3. *Safety Engineer*. Topics under the specific item of equipment, such as design considerations, will be of interest to the safety engineer because they provide information on features that should be incorporated into the systems to enhance overall safety. This information can be used as the basis of a checklist to insure that equipment designs include adequate and appropriate provisions for safety and that modifications do not defeat existing safety features.

In addition, safety engineers and other engineers charged with engineering the safety into military equipment may find the material in Chapter 2 applicable to the assessment of the safety of electrical equipment. Material in this chapter provides information specific to electrical systems and can augment the system safety information found in safety handbooks and MIL-STD-882.

4. *Equipment User*. The user of equipment will profit from the information found in the chapter or paragraph that discusses the design features and the operational procedures specific to the item of equipment or component of interest. This information will provide insight into the purpose of the design features and installation procedures. With this understanding the user will be less likely to negate inadvertently safety provisions of the design, either through inappropriate field-expedient repair of the

unit or improper installation. This understanding will make the user more cognizant of design and operational factors that affect the safety of personnel and equipment during operation of electrical equipment.

REFERENCES

1. MIL-STD-882B, *System Safety Program Requirements*, 30 March 1984.
2. G. Stromme, "Multiple Levels and Classifications of Emergency Electrical Power Systems", Conference Record for IEEE Industrial and Power System Technical Conference, Houston, TX, 1980, pp. 27-30.

CHAPTER 2

GENERAL SAFETY CONSIDERATIONS

Discussed in this chapter are those safety-related considerations that must be addressed during the development of electrical equipment, primarily in establishing those equipment requirements that impact safety or in assessing the safety of the system. MIL-STD-882 provides guidance on the management of a safety program conducted during equipment development and provides, among other topics, a risk assessment procedure. The information in this chapter supplements MIL-STD-882 by providing information that is unique to electrical systems. Considerations important for assessing the risk associated with electrical apparatus are discussed along with guidance for determining acceptable risk for those systems. Also discussed are hazards that are common to various items in polyphase electrical systems—e.g., electrical shock, noise, fire, and extreme temperatures—and the restrictions placed on equipment to assure that no unnecessary hazards are introduced. Finally, sources of safety information are identified. These sources include standards and specifications for safety programs, and safety considerations for equipment design as well as data bases containing electrical accident information.

2-0 LIST OF SYMBOLS

a_d = vibration expressed as linear displacement, peak-to-peak or rms corresponding to the manner in which a_v is specified, m

a_v = vibration expressed as acceleration, peak-to-peak or rms, m/s²

a_{xg} = rms acceleration in x-direction (see Fig. 2-5), g

a_{xm} = rms acceleration in x-direction (see Fig. 2-5), m/s²

a_{yg} = rms acceleration in y-direction (see Fig. 2-5), g

a_{ym} = rms acceleration in y-direction (see Fig. 2-5), m/s²

a_{zg} = rms acceleration in z-direction (see Fig. 2-4), g

a_{zm} = rms acceleration in z-direction (see Fig. 2-4), m/s²

f = frequency, Hz

I = current, mA or A

t = time, s

2-1 INTRODUCTION

General issues that are not specific to a particular item of equipment are discussed in this chapter. Safety topics—such as risk assessment, sources of safety information, and general requirements for hazard reduction—which pertain to all electrical components are discussed. Safety considerations that are specific to the design of electrical hardware are discussed elsewhere in this handbook. Chapter 3 focuses on safety considerations in electrical system design, and the remaining chapters focus on safety considerations in the design of different components.

2-2 RISK ASSESSMENT

Risk assessment is defined by MIL-STD-882 (Ref. 1) as the determination of the level of risk, either in relative or absolute terms, due to one or more specified hazards. The purposes of risk assessments are to identify hazards that require the most attention and to enable management to make intelligent decisions about the level of attention required for reducing the hazard. Risk is specified in terms of two factors—the severity of consequences from the hazard and the likelihood of occurrence of the hazard.

Usually a hazard is introduced by an unintentional redirection of energy. In an electrical system the effects of such a hazard can be far-reaching due to the large amount of potential energy associated with electrical systems and to the extensive area over which energy is distributed. The consequences of an accident in an electrical system may be catastrophic, and personnel located a considerable distance from the original fault can be affected by the hazard.

Assessment of risk begins with the determination of the hazards and the nature of their impact. To determine risk related to electrical apparatus, the consequences of an identified hazard are assessed by one of several methods—a technical review of the operation of the system, a review of "lessons learned" from data bases recording accidents on similar equipment, or by following prescribed safety measures given in published electrical safety texts (Refs. 2 and 3). Par. 2-4 identifies sources of information that may be used to identify hazards.

2-2.1 HAZARD SEVERITY

Several techniques are available for the determination of hazard severity. In one technique the severity is expressed by the amount of monetary loss likely to be incurred if the hazard causes an accident. Although this method permits precise assessment of loss, certain incalculable losses, such as loss of life or permanent bodily injury, are difficult to express in monetary terms.

To quantify the severity of a given hazard, it is often sufficient to specify the effect in terms of the four categories specified in MIL-STD-882 (Ref. 1). These four categories and their designations are

1. Catastrophic (Category I)—results in death or system loss
2. Critical (Category II)—severe injury or illness
3. Marginal (Category III)—minor injury or illness, minor system damage
4. Negligible (Category IV)—insignificant injury, illness, or damage.

Severity of electrical hazards may be determined from the same sources for the identification of hazards in the preceding paragraph. The techniques are as follows:

1. From the hazards identified, find examples of similar occurrences in lessons-learned data bases, safety handbooks, or literature in which the effects of hazards are discussed. From the description, determine the degree of severity by comparing the effects of the hazards with the definitions of the categories given in MIL-STD-882.
2. For each hazard, determine the consequences of it by an analysis or review of the hazard mechanism, and determine the degree of severity by comparing the effect with the definition of each category given in MIL-STD-882. (Electrical safety textbooks generally describe, or at least enumerate, the hazard mechanisms.)

Potential accident scenarios in the proposed application may differ from cases documented in texts, handbooks, and data bases because of the variability in circumstances surrounding each possible accident. Consequently, existing information on accident severity from these sources may or may not be appropriate for the situation being analyzed. In all cases, sound engineering judgment and a logical analysis must be applied to ascertain the reasonable hazard consequence prior to determining the appropriate severity category.

The severity of a hazard is generally considered to be the "worst case" or most severe consequence, which is a direct result of the hazard. However, a more accurate assessment of hazard severity would include intangible and indirect effects of the hazard. Intangible effects include adverse publicity and lower morale, which could result from an accident. Indirect effects include lost productive time and a decrease in staff effectiveness because of incapacitation of trained key personnel. Typically, the intangible and indirect effects are not included because of the difficulty of accurately quantifying the losses associated with these effects. The consideration of the intangible or indirect effects is usually limited to applying judgment as to whether the intangible or indirect effects warrant the elevation of the risk severity classification to the next higher level. Note that if the indirect consequence has a low conditional probability of occurrence (probability that the indirect event will occur given that an accident has resulted from the hazard) but has a severity that is much greater than the direct consequence of the hazard alone, then the assessment of risk should be considered for two cases—i.e., one in which the indirect consequence does not occur and one in which it does. The cases will have different severities and different probabilities of occurrence. Since the purpose of risk assessment is to rank hazards in terms of significance, consideration of both cases will allow the case that is most significant to determine the relative necessity for corrective action.

Equipment to be used in a tactical environment provides an example of where indirect consequences of a hazard may lead to far more severe consequences. An accident from the hazard may lead to incapacitation of critical troops or equipment, which reduces the fighting effectiveness; this may result in numerous troops being subjected to hostile action. Stated another way, if the reliability of critical military systems including both personnel and equipment can be materially reduced by hazards, then any assessment of the severity of the hazard must be adjusted accordingly. The assessment of hazard severity must be based on a careful analysis of the consequences of a particular hazard occurring when the system is operated in a battlefield environment. This assessment includes an analysis of the extent of damage or injury that would be likely due to increased vulnerability to enemy action. These considerations might well necessitate the addition of a fifth severity category, "multiple incapacitating injuries or casualties". (Hazards identified in this category would be the most significant and should therefore be reduced through design modifications.)

2-2.2 HAZARD PROBABILITY

The probability of the occurrence of a hazard may be stated quantitatively or qualitatively. Quantitative statements of probability usually consist of the probability of the hazard occurring within the lifetime of the system; within a specified period, i.e., one year; within a specified period of operation, i.e., per hour of operation; or for a certain number of operations. For electrical equipment that is operated continuously, the probability of the occurrence usually is expressed appropriately in terms of the probability of occurrence over the life of the system. In some cases, the occurrence of an accident depends on the simultaneous occurrence of two or more conditions. In these cases the probability of the occurrence of an accident may be determined by fault tree analysis, which determines quantitatively the combination of individual event probabilities. Quantitative techniques for determining hazard probability are described in numerous system safety texts, including Refs. 4 and 5.

Hazard probability, like hazard severity, also may be determined according to qualitative classifications. Qualitative determinations of hazard probability are more easily performed than are quantitative determinations. MIL-STD-882 recommends probability be specified qualitatively according to the following categories:

1. Frequent—likely to occur frequently (defined as "A" frequency in MIL-STD-882)
2. Probable—occurs several times over the life of the equipment (defined as "B" frequency)
3. Occasional—likely to occur sometime in the life of an item (defined as "C" frequency)
4. Remote—unlikely to occur but possible (defined as "D" frequency)
5. Improbable—unlikely to occur but not impossible (defined as "E" frequency).

A more complete discussion of these qualitative probability classifications is given in MIL-STD-882.

The probability of occurrence of a hazard that depends on the occurrence of multiple events—whose individual probabilities are specified by qualitative classifications—may be determined by a procedure described in Ref. 6. In this technique, judiciously chosen probability values are assigned to each classification. This assignment permits the use of a conventional fault tree analysis to calculate a quantitative probability for the combination. Finally, a quantitative probability classification is obtained from the quantitative calculations by reference to a set of defined ranges.

For electrical systems the probability of a fault may be determined by standard fault tree analysis techniques by using reliability data specified for electrical components and specified probabilities of human error found in handbooks such as Ref. 7. If data are not specified for a specific component or system, the failure rate data for a similar component or system may be used by taking into account differences that might influence the probability.

2-2.3 RISK ACCEPTANCE CRITERIA

Although zero risk is the goal for all systems, it will seldom be achieved because it may be obtained only at the sacrifice of performance objectives or at great expense. Therefore, systems will always have some finite probability that a specified hazard will occur. Obviously, the greater the severity of the hazard, the lower this probability must be. The level of acceptable risk may be determined hypothetically on the basis of economics by considering the probable losses from hazards along with the cost of measures to prevent them and the cost of reduced performance attributed to those measures. The collection of data necessary for those calculations would be tedious and would probably require numerous assumptions during the course of the analysis. Instead, the assessment of the acceptable risk is frequently made by management based upon recommendations of safety personnel who are knowledgeable of systems similar to the one under development and who are familiar with the relative frequency of accidents on those systems.

No detectable risk should be accepted without an attempt to reduce it by the process that follows. First, the hazard should be reduced by equipment design to reduce hazard probability and/or severity. Second, if it is not possible to reduce the hazard without jeopardizing performance requirements, warning devices to detect the presence of unsafe conditions should be incorporated into the design. Next, warning labels should be affixed to equipment to warn personnel of potential hazards. Finally, if the hazard cannot be reduced by any other means, training programs should be used to educate all personnel about safety measures to avoid the hazard.

Even when all safety measures have been incorporated, some risks still remain. Fig. 2-1 illustrates the two types of risk assessment matrices given in MIL-STD-882 and identifies regions of acceptable and unacceptable risk. Also identified are regions in which risk is conditionally acceptable. Note that the definitions of acceptable risk shown in Fig. 2-1 are only examples. Other factors to be considered in determination of acceptable risk include the consequences of safety measures, the performance value of equipment, and monetary considerations.

2-3 DEFINITION OF HAZARD LIMITS

2-3.1 ELECTRICAL SHOCK

Electrical shock is a potential hazard associated with electrical apparatus. Consequences of electrical shock include

1. Potential damage to the body caused by the flow of electric current through it
2. Injury that may be produced by the involuntary muscular contractions that occur when the current flows through nerve and muscle tissue
3. Burns at the locations where the current enters or leaves the body or along the current path.

Electric shock directly affects the body by interfering with the normal mechanisms of muscle control by the nervous system. The most significant effects are the disruption of breathing, the disruption of heart action, and the "hold-on" effect. If the muscles that control the diaphragm are paralyzed by the current flow, the subject may suffocate unless the circuit is broken quickly and proper breathing is restored either by natural means or by artificial respiration. The more common cause of death from electrocution is the initiation of ventricular fibrillation in the heart. In this condition the normal control mechanism of heart muscles by nerves is rendered inoperative, and the various muscles contract randomly, or quiver, which prevents the vital pumping action of the heart. The "hold-on" effect is the involuntary gripping of an energized conductor by the victim, who, although conscious, cannot release the grip. This incapacity to break the circuit prolongs the current flow, which enhances the effect on the victim and increases the likelihood of fatal suffocation or ventricular fibrillation. Table 2-1 gives the effects of various levels of electrical current flow on the body.

The risk of electrocution is dependent on three factors, namely,

1. Path of current
2. Frequency and level of current
3. Duration of current flow.

These factors are discussed in the paragraphs that follow.

The path of current flow through the body during electrical shock is determined by points of contact with the electrical source. Shock occurring when hands or arms contact a voltage source and the feet are grounded, e.g., standing on damp earth, generally is serious because

Frequency of Occurrence	Hazard Categories			
	I Catastrophic	II Critical	III Marginal	IV Negligible
A — Frequent	1A	2A	3A	4A
B — Probable	1B	2B	3B	4B
C — Occasional	1C	2C	3C	4C
D — Remote	1D	2D	3D	4D
E — Improbable	1E	2E	3E	4E

Frequency of Occurrence	Hazard Categories			
	I Catastrophic	II Critical	III Marginal	IV Negligible
A — Frequent	1	3	7	13
B — Probable	2	5	9	16
C — Occasional	4	6	11	18
D — Remote	8	10	14	19
E — Improbable	12	15	17	20

KEY

- Unacceptable
- Undesirable (Managing Activity Decision Required)
- Acceptable With Review by Managing Activity
- Acceptable Without Review

Figure 2-1. Example Risk Assessment Matrices Showing Regions of Acceptable, Conditionally Acceptable, and Unacceptable Risk (Ref. 1)

TABLE 2-1
EFFECTS OF ELECTRIC CURRENT ON HUMANS (Ref. 2)

Effect	Current, mA					
	Direct		Alternating			
			60 Hz		10,000 Hz	
	Men	Women	Men	Women	Men	Women
Slight sensation on hand	1	0.6	0.4	0.3	7	5
Perception threshold	5.2	3.5	1.1	0.7	12	8
Shock—not painful, muscular control not lost	9	6	1.8	1.2	17	11
Shock—painful, muscular control not lost	69	41	9	6	55	37
Shock—painful, let-go threshold	76	51	16	10.5	75	60
Shock—painful and severe, muscular contractions, breathing difficult	90	60	23	15	94	63
Shock—possible ventricular fibrillation effect from 3-s shocks	500	500	100	100		
Short shocks having duration t, s			$165/\sqrt{t}$	$165/\sqrt{t}$		
High-voltage surges	50*	50*	13.6*	13.6*		

*Energy in W·s or J

Note that as low as 30 V can be considered dangerous. (See par. 8, TB 385-4.)

the current path travels through the trunk of the body where the life-sustaining organs are located.

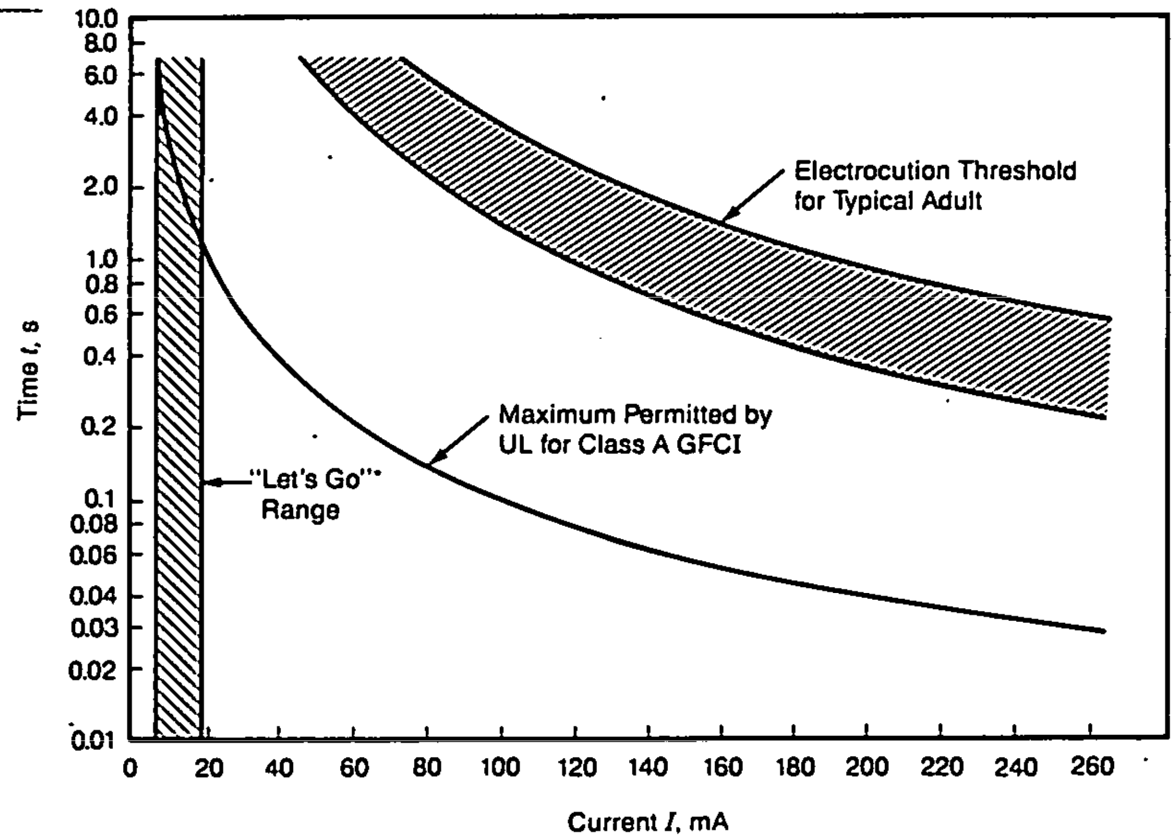
The level of current flow is dependent on conductor voltages, the resistance of the body between points of contact, and the effective resistance at the points of contact. High-voltage sources pose the greatest threat of injury from electrical shock. However, low-voltage sources, such as 117 Vac or less, can be very hazardous when the contact area is large (which reduces resistance), when the skin is moist or damp at the point of contact, or when the outer layers of the epidermis are penetrated. For the last reason, it is most important that exposed conductors be configured so that inadvertent penetration of the skin is impossible.

The frequency of the current also affects the severity of injury from electrical shock. Unfortunately, the frequency (50-60 Hz) normally used for power is likely to induce ventricular fibrillation. Electrocution is more likely at normal power frequencies than it is at DC frequencies or at frequencies above 100 Hz. Currents at high frequencies usually do not induce electrocution because of the "skin effect", i.e., a high-frequency effect in which current flow is confined to surfaces ("skin") of imperfect conductors. However, severe skin burns may be incurred from electrical shock from high-frequency currents.

The probability of electrocution increases with duration of current flow through the body. The graph in Fig. 2-2 illustrates relationships between currents at which electrocution is probable and durations of current flow for 60-Hz power (Refs. 3, 8, and 9).

2-3.2 NOISE

Exposure to excessive noise may result in either a temporary or permanent loss of hearing. Permanent loss is caused by irreversible damage to the corti—the organ of the inner ear that senses sound waves, determines their spectral content, and passes the information to the brain through the auditory nerves. An early symptom of hearing loss is a diminished sensitivity to high frequencies, usually first noted by difficulty in understanding speech in a noisy environment. Other symptoms include tinnitus (a ringing sensation), muffled hearing, and a sensation of fullness in the ears. These early symptoms of hearing damage may progress to a total loss of hearing.



UL = Underwriter's Laboratories
GFCI = Ground Fault Circuit Interrupter

*"Let Go" range is the range of current that produces a painful electrical shock but does not inhibit muscular control, hence the victim can consciously release his grip on energized conductors.

Figure 2-2. Current Sufficient to Cause Electrocution vs Time for 60-Hz Power (Ref. 8)

Noise that can lead to hearing damage is divided into two categories, i.e., steady state and impulse noise. Steady state noise corresponds to a tone or combination of tones that, although not necessarily constant in frequency or amplitude, remains at a steady, elevated level for a long period of time. The parameters describing steady state noise are amplitude and frequency spectral content. In contrast, impulse noise is a noise pulse of short duration or burst, which rises above a tolerable background level of noise. Impulse noise is characterized by peak amplitude and duration.

The hazard due to noise exposure increases with noise level and exposure period. Maximum or recommended exposure levels are specified in three ways, i.e.,

1. Hearing damage-risk criteria that specify the relationship between noise exposure—described in amplitude, duration, and spectral characteristics—and the probability of temporary or permanent hearing loss. These criteria serve as the basis for standards that set limits for noise exposure or generation.

2. Hearing conservation criteria define noise exposure limits for personnel and specify hearing conservation programs. These criteria are specified in TB-MED-501 (Ref. 10) and MIL-STD-1472 (Ref. 11).

3. Material design standards provide specific noise limits for equipment to conform with standards for noise environmental exposure given by criteria in Item 1 with allowances made for hearing protection and necessity for personal communication. For the Army, equipment requirements are specified in MIL-STD-1474 (Ref. 12).

Fig. 2-3 from Ref. 10 illustrates the relation between the risk associated with intensity of steady state noise exposure and duration. For noise levels below 80 dBA, the risk of hearing damage is negligible even for long-term exposures. At 84 dBA, exposure for up to 8 h produces negligible risk. Noise intensities above 116 dBA for even short periods produce a risk Category IIB*, which means that a critical injury—e.g., severe noise-induced, sensory-neural hearing loss; severe occupational illness; or major property damage—probably will occur because of the noise exposure. Short-term exposure, < 2.2 min. to noise levels between 84 and 116 dBA produces an intermediate risk Category IIIC, which implies that an injury of marginal significance may occur in time, e.g., a mild high-frequency hearing loss with no communication handicap. Examples of noise produced at this level include lawnmowers with a noise level at the operator's position in the range of 80 to 90 dB and chain saws at a range of 100 to 125 dB.

The risks associated with impulse and ultrasonic noise are also specified in TB-MED-501. Impulse noises exceeding 140 dBP, which are typical of small arms fire, are categorized as a risk Category IIB. Table 2-2 gives levels of ultrasonic noise, which, if lasting 8 h or longer, produce a risk Category IIB.

Lower limits may be prescribed for situations in which adequate or safe performance of tasks requires that the operator hear and respond to sounds that could be masked by noise levels below the threshold for significant risk. Both MIL-STD-1472 (Ref. 11) and MIL-STD-1474 (Ref. 12) define maximum recommended sound levels for specific areas such as general work spaces, areas in which frequent telephone use is required, and extremely quiet areas. Table 2-3 summarizes the limits for occupied areas as specified in MIL-STD-1474.

Typically, acoustical noise limits for equipment are specified for noise levels at the normal operator position, either within the equipment for vehicles or adjacent to it for power hand tools. For some equipment, additional requirements are imposed on the maximum level of acoustical noise that can be emitted into the surrounding environment. This noise, referred to as exterior noise, should be limited to prevent adverse effects on personnel who must work near the equipment for long periods or whose presence in the area is coincidental and who, therefore, would not be expected to wear ear protection. Limits for exterior noise with reference to measurement procedures are given in MIL-STD-1474 for motor vehicles,

*Risk definitions such as IIB, IIIC, etc., are the concatenation of a Roman numeral indicating hazard severity with a letter indicating hazard frequency. Definitions of the various symbols are given in pars. 2-2.1 and 2-2.2.

TABLE 2-2
ULTRASONIC NOISE THRESHOLDS FOR A RISK CATEGORY IIIB AFTER 8-h EXPOSURE (Ref. 10)

One-Third Octave Band Center Frequency, kHz	Level of Noise in One-Third Octave Band, dB
10	80
12.5	80
16.	80
20.	105
25.	110
31.5	115
40.	115

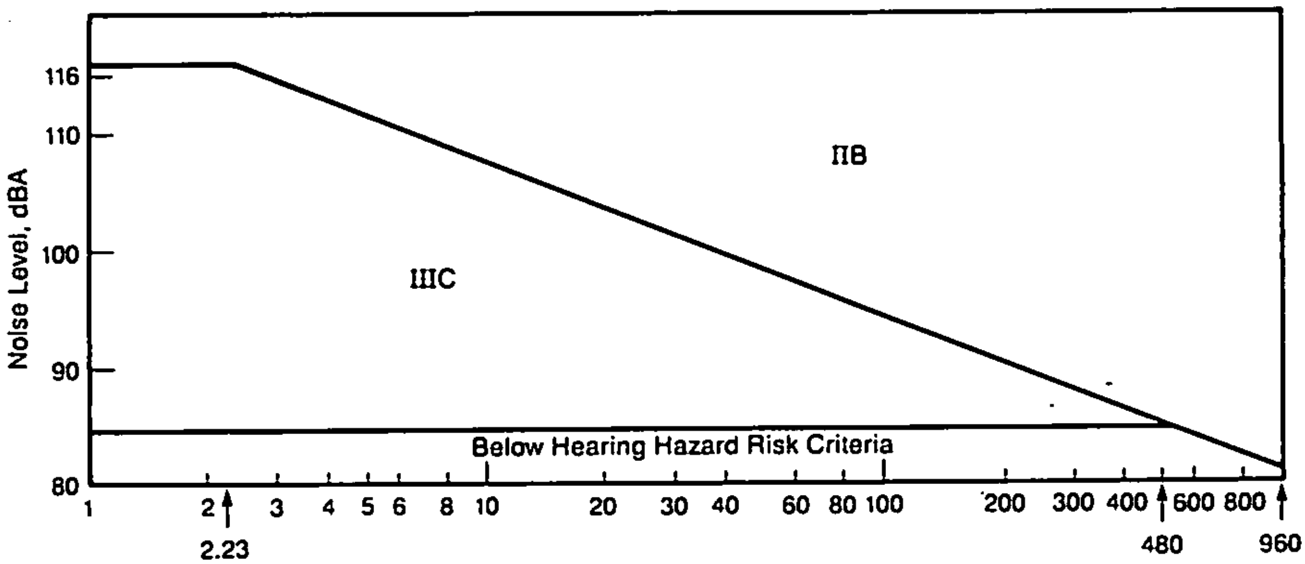


Figure 2-3. Risk Assessment Codes for Noise Amplitude and Deviation (Ref. 10)

TABLE 2-3
STEADY STATE NOISE LIMITS FOR PERSONNEL-OCCUPIED AREAS (Ref. 12)

Octave Band Center Frequency, Hz	Category[a] A[b]	B[b]	C[b]	D[b]	E[c]	F[c]
63	130 dB	121 dB	111 dB	106 dB		
125	119	111	101	96		
250	110	103	94	89		
500	106	102	88	83		
1000	105	100	85	80		
2000	112	100	84	79		
4000	110	100	84	79		
8000	110	100	86	81		
dBA Criteria	108	100	90	<85	75	65
Alternate PSIL-4 Criteria[d]					67	57

NOTES:

[a] Definitions of categories are

(Note that Categories, A, B, C, and D are based primarily on hearing conservation priorities, whereas the remaining categories are based primarily on communication requirements).

Category A. No direct person-to-person voice communication required. Maximum design limit. Hearing protection required.

Category B. System requirement for electrically aided communication via attenuating helmet or headset. Noise levels are hazardous to unprotected ears.

Category C. No frequent, direct person-to-person voice communication required. Occasional shouted communication may be possible at a distance of 0.3 m (1 ft). Hearing protection required.

Category D. No frequent, direct person-to-person voice communication required. Occasional shouted communication may be possible at a distance of 0.6 m (2 ft). Levels in excess of Category D require hearing protection.

Category E. Occasional telephone or radio use or occasional communication at distances up to 1.5 m (5 ft) required. (For mobile or transportable systems).

Category F. Frequent telephone or radio use or frequent, direct communication at distances up to 1.5 m (5 ft) required. (For mobile or transportable systems).

[b] In those cases where the mission profile for the equipment being developed exceeds 8 h of operation in each 24 h, the limits specified in Categories A, B, C, and D shall be reduced sufficiently to allow for an exposure for longer than 8 h, as approved by the procuring activity in conjunction with the Surgeon General's Office, HQDA, DASG-PSP, Washington, DC 20314.

[c] Criteria in Categories E and F are defined by either the sound level in dBA or the preferred speech interference level (PSIL-4). The dBA sound level is the desired requirement. Where it is not possible to meet the specified dBA level, the corresponding PSIL-4 level requirements shall be met.

[d] PSIL-4—Preferred Speech Interference Level—A message of effectiveness of noise in making speech. It is the arithmetic mean in dB of sound pressure levels in the four active bands with the center frequencies of 500, 1000, 2000, and 4000 Hz.

construction equipment, and mobile generating sets. The specific levels quoted range from 76 to 85 dBA at distances of 7 or 15.2 m (23 or 50 ft.)

2-3.3 TEMPERATURE

2-3.3.1 High Temperature (Burns)

Tissue burns are produced from the heating of the skin either by direct contact with a hot material or by absorption of radiant energy, e.g., common sunburn. Burns are classified into three degrees of severity, i.e.,

1. *First-Degree Burns.* The first-degree burn is the least severe. It is characterized by a redness of the skin accompanied by pain in the area of the burn.
2. *Second-Degree Burns.* The second-degree burn is more severe than the first-degree burn and is characterized by the presence of blisters, often containing fluid. Second-degree burns are more painful than first-degree burns, especially if the blister opens, because the separation of skin layers results in exposure of nerve endings.
3. *Third-Degree Burns.* The most severe burns are classified as third-degree burns and are characterized by significant damage to the skin and underlying tissue. Third-degree burns may be identified by a white, light grey, brown, or black appearance of the skin where the color depends on the severity of the burn and the source (contact with fluid, flame, or heated surface).

The severity of a burn depends on several factors including

1. The temperature at the surface of the contact
2. The duration of contact
3. The thermal coupling between the heated surface and the tissue in contact with it.

Table 2-4 lists effects on skin in contact with heated surfaces under different conditions.

TABLE 2-4
EFFECTS ON SKIN FROM CONTACT WITH HEATED SURFACES
(Adapted from Refs. 13 and 14)

Temperature, °C	(°F)	Sensation or Effect
100	(212)	Second-degree burn on 15-s contact
82	(180)	Second-degree burn on 30-s contact
71	(160)	Second-degree burn on 60-s contact
60	(140)	Pain; tissue damage
49	(120)	Pain; "burning heat"
33	(91)	Warm sensation

Table 2-4 indicates that burn hazard is not significant when the temperature of the contacted surface is below 49°C (120°F). For this reason, MIL-STD-1472 (Ref. 11) requires that exposed equipment surfaces that must be handled must be kept below 49°C (120°F), and surfaces that are subject to inadvertent contact must be kept below 60°C (140°F).

2-3.3.2 Low Temperature (Ref. 13)

Skin contact with low-temperature surfaces may result in burn-like injury to the tissue. Typically, frostbite is induced by brief contact with severely cold temperatures or prolonged contact with a moderately cold environment. (Temperatures do not have to be below freezing.) In severe cases the tissue actually freezes and dies. If the circulatory vessels are affected, gangrene may result from impaired circulation in the vicinity.

The probability of frostbite increases with decreasing temperature and with increasing thermal conductivity between cold material and skin, e.g., immersion in a cold liquid. In air or liquids the cooling effect that produces frostbite is accelerated by motion of the cooling medium. A 16.1-km/h (10-mph) wind in ambient air at −6°C (21°F) produces a cooling effect equivalent to still air at −15°C (5°F). This effect, called the windchill effect, does not induce the freezing of tissue when the air temperature is above freezing, but it does reduce the exposure time that can be tolerated when the ambient temperature is below freezing.

However, it is not necessary for the ambient temperature to be below freezing for damage to occur. Frostbite may be induced even when the temperature is near but slightly above freezing. Also the exposure to cold temperatures may reduce circulation and thereby cause numbness or chilblains, which are characterized by itching and swelling. Long-term exposure at even higher temperatures, up to 12°C (54°F), can produce symptoms of trench foot, or immersion foot. In this ailment, the legs become cold, pale, and numb; this is followed by swelling and redness. Damage to nerves may occur, and a loss of feeling may last for weeks after the return to ambient temperature.

2-3.4 FIRE

Fire is an exothermic oxidation-reduction reaction, which is self-sustaining until either of the reactants is consumed. From the safety perspective fire produces several important effects: (1) heat, possibly intense; (2) gases produced by partial or complete combustion of the burning material; and (3) the consumption of the fuel.

The most obvious hazard due to fire is the destruction of property—e.g., damage due to total or partial consumption, melting, baking, and smoke. However, the primary hazards to human life are the emitted smoke and gases because these hazards are the principal causes of death from fire.

Fire or combustion can take place when three ingredients are present—i.e., a fuel, an oxidizer, and an ignition source. For fire to be initiated and sustained requires that the fuel and oxidizer exist in suitable proportions; have the proper contact area; and a physical shape that allows sustained combustion, e.g., the fuel must not have a shape that conducts heat away from the site of combustion faster than the rate at which the heat is generated.

Numerous materials—solids, liquids, or gases—may be used as fuel. Typically, only fuels that are easily ignitable are burned intentionally for the generation of heat or mechanical energy. The suitability of a material for use as a fuel or the suitability of a material for use where fire retardant characteristics are desired may be determined by examining the temperatures at which combustion is initiated or sustained and the concentration of oxygen necessary to sustain combustion. The flammability characteristics of materials are usually specified in one or more of the following terms:

1. *Flash Point.* The minimum temperature at which a liquid will give off combustible vapors at a rate that is sufficient to produce a concentration of the vapor in the adjacent atmosphere that can be ignited
2. *Fire Point.* The lowest temperature at which a liquid will give off vapor at a rate sufficient to maintain combustion
3. *Ignition Temperature.* The minimum temperature at which a flammable material will begin burning because of its own heat in the absence of spark, flame, or other local ignition source
4. *Lower Flammability Limit.* The percentage of fuel in air at one atmosphere that will ignite and burn
5. *Oxygen Index.* The lowest oxygen concentration that will support the combustion of a given material.

Table 2-5 lists combustion characteristics of various materials, including solids, liquids, and gases that are used in, or found near, electrical apparatus.

Fire must be initiated by a source of energy sufficient to raise the temperature of some portion of the fuel to a temperature above the ignition temperature. Typical ignition sources are

1. Open flame from candles, gas pilot lights, etc.
2. Electrical or mechanical sparks, including those produced by static discharge and arcing of electrical circuits or welding equipment and those from grinding or colliding hard material
3. Heated surfaces produced by hot gases, electrical resistance, or friction between moving parts
4. Spontaneous ignition caused by heat buildup of fuel constituents to the point at which heat is sufficient to ignite the bulk of the material
5. Chemical reaction in which two reactive components produce energy sufficient to ignite the surrounding material
6. Adiabatic compression of gases
7. Radiation, especially concentrated solar radiation or intense radiation from a high-energy source such as a laser
8. Catalytic action that makes possible, or accelerates, exothermic reactions that give off heat sufficient to ignite adjacent materials.

As mentioned previously, the form of the fuel has a significant effect on its combustion properties. If a material that is ignited easily is ground into a fine dust, it will

TABLE 2-5
IGNITION TEMPERATURES OF COMMON MATERIALS (Refs. 15 and 16)

Material	Temperature °C	Temperature °F
Absorbent Cotton	228 to 230	442 to 446
Acetate	246	475
Acetone	538	1000
Acetylene	305	581
Acrylic	293	560
Benzene (Benzol)	857 to 982	1575 to 1800
Butane	466	871
Carbon Monoxide	609	1128
Carbon Soot	186	366
Cellophane	242	468
Cellulose Acetate	475	887
Cellulose Nitrate	141	285
Cellulose Triacetate, Fiber	540	1004
Coal	316	600
Cotton Batting	266	511
Cotton Sheeting	240	464
Creosote	336	637
Ethane	510	950
Ethanol	371	700
Ethyl Alcohol	423	793
Ethylene	490	914
Fuel Oil #1	254	490
Fuel Oil #2	257	494
Fuel Oil #3	259	498
Fuel Oil #4	263	505
Fuel Oil #6	407	765
Gasoline	280 to 456 (depending on octane)	536 to 853
Gasoline, Aviation Grade		
100-130 Grade	440	824
115-145 Grade	471	880
Hay	172	342
Hydrogen	400	752
Isopropyl Alcohol (Rubbing)	456	852
Jute Fiber	193	379
Kerosene	123	254
Leather	212	414
Linseed Oil, Liquid	343	650
Linseed Oil, Oxidized	462	864
Magnesium	507	945
Match Heads	163	325
Methane	537	999
Methyl Alcohol	470	878
Natural Gas	482 to 632	900 to 1170
Newspaper	418	785
Nylon	424	795
Nylon 6	485	905
Nylon 6/6, Fiber	532	990
Nylon 6/10	458	856
Octane	231	448

(cont'd on next page)

TABLE 2-5 (cont'd)

Material	Temperature	
	°C	°F
Paint	462	864
Paper	449 to 499	840 to 930
Paraffin Propane	493 to 604	920 to 1120
Paraffin Wax	225	437
Phenolic	571 to 580	1060 to 1076
Polycarbonate	499	930
Polyester	432 to 488	810 to 910
Polyether	416	780
Polyethylene	349	660
Polypropylene	402	756
Polypropylene, Fiber	570	1058
Polystyrene, Beads	491	915
Polystyrene, High Impact, Flame-Retardant	423	793
Polystyrene, High Impact, High Rubber	478	892
Polystyrene, Medium Impact, Low Rubber	468	874
Polytetrafluoroethylene	529 to 531	984 to 987
Polyurethane Rigid Foam	416	780
Polyvinyl Chloride (Clothing, Upholstery, etc.)	416	780
Polyvinyl Chloride-Acetate	446 to 557	835 to 1035
Polyvinyl Chloride, Semirigid, 105-C Appliance Compound	425	797
Polyvinyl Chloride	533	992
Propane	466	871
Rayon, Oiled Viscose	248	478
Rayon, Unoiled Viscose	234	453
Silicon	550 to 564	1022 to 1047
Sulphur	232	450
Shellac	432	810
Styrene	490	914
Turpentine	253	488
Varnish	462	864
Woods	208 to 261	406 to 502
Wood Fiberboard	218 to 229	424 to 444
Xylene-(M)	530	986
Xylene-(O)	496	924
Xylene-(P)	530	986

ignite more easily for two reasons. The surface area for the reaction with oxygen to take place is greater, and the mass of individual particles is smaller, which allows faster heating to combustion temperatures.

Note that materials used as fuels for internal combustion engines are necessarily flammable. The presence of volatile fuels, with their low flash points, greatly increases the risk of fire. Contributing factors are the ignition system of the engine and hot exhaust gases, fuel spillage during engine refueling, fuel leaks from ruptured or corroded fuel tanks and lines, and escaping fuel vapors from improperly vented tanks. If the escaping fuel, or its vapor, contacts any of the sources of ignition, the fuel supply may be ignited and explode and result in injury to personnel or in a larger fire that consumes nearby materials.

2-3.5 VIBRATION (Ref. 11)

Rotating objects that are imbalanced, vehicles traveling over roads that are not smooth, and vibrating tools may all set up vibrations that are transmitted to personnel. Such vibrations may be transmitted through handles grasped by the individuals or through seats. The degree of vibration may be specified in several different ways.

In many cases the displacement of the vibrating object is specified as a peak-to-peak or rms displacement. In other cases, the vibration is expressed in terms of the acceleration expressed in meters per second squared or number of g (acceleration due to gravity). The two measurements may be related at any frequency f by

$$a_x = 39.478 f^2 a_d, \text{ m/s}^2 \qquad (2\text{-}1)$$

where

a_s = vibration expressed as acceleration, peak-to-peak or rms, m/s^2

a_d = vibration expressed as linear displacement, peak-to-peak or rms corresponding to the manner in which a_s is specified, m

f = frequency, Hz.

Vibration of the whole body (not including the effects on hearing perceived as noise) exhibits various effects on personnel for both short-term and long-term exposures. Short-term exposure to low frequency vibration may produce discomfort and frustration by interfering with the individual's coordination, especially in the performance of delicate manual tasks. The effects of vibration will vary widely across individuals and depend on the nature of tasks being performed, the conditioning of the individual to a vibrating environment, and the individual's tolerance of vibration. Long-term exposure to low frequency vibration, < 1 Hz, produces the symptoms of motion sickness including nausea, fatigue, and dizziness. Again, the duration of exposure necessary to produce these symptoms depends on the frequency of the vibration and the tolerance (natural and conditioned) of the individual. Fig. 2-4 is a graph representing the amount of vibration necessary to induce motion sickness for different durations of time (from 0.5 to 8 h) over a range of frequencies (0.05 to 1 Hz). For higher frequencies commonly encountered in moving vehicles, the vibration should be kept below the levels specified in Fig. 2-5 to maintain the individual's proficiency to perform tasks associated with operating the vehicle. However, performance of tasks requiring fine detail work would require maintenance of vibration at significantly lower levels. For the comfort of the individual, vibration should be reduced below 32% of the values shown in Fig. 2-5, but where safety of the individual is the only concern, the level of vibration should not exceed twice the values shown in the figure.

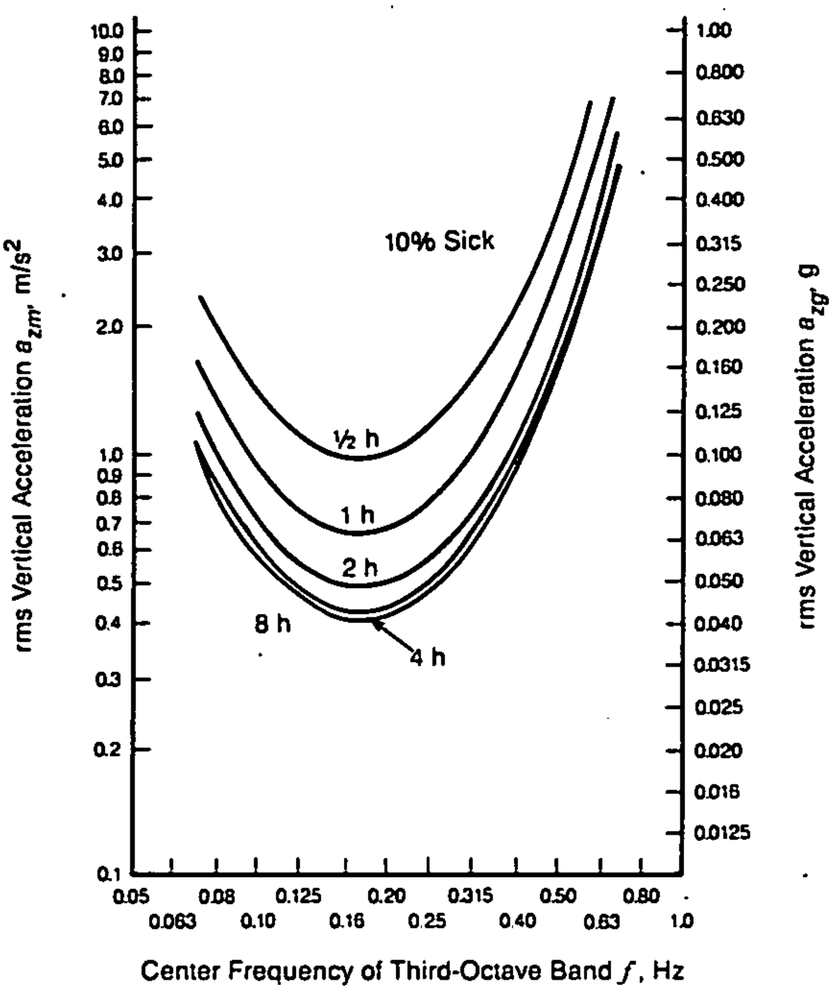
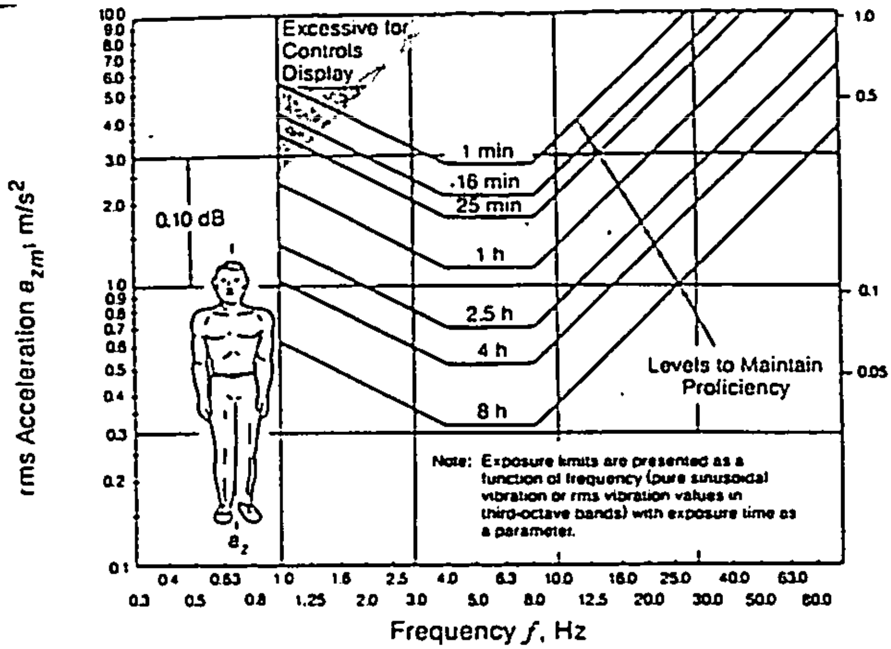
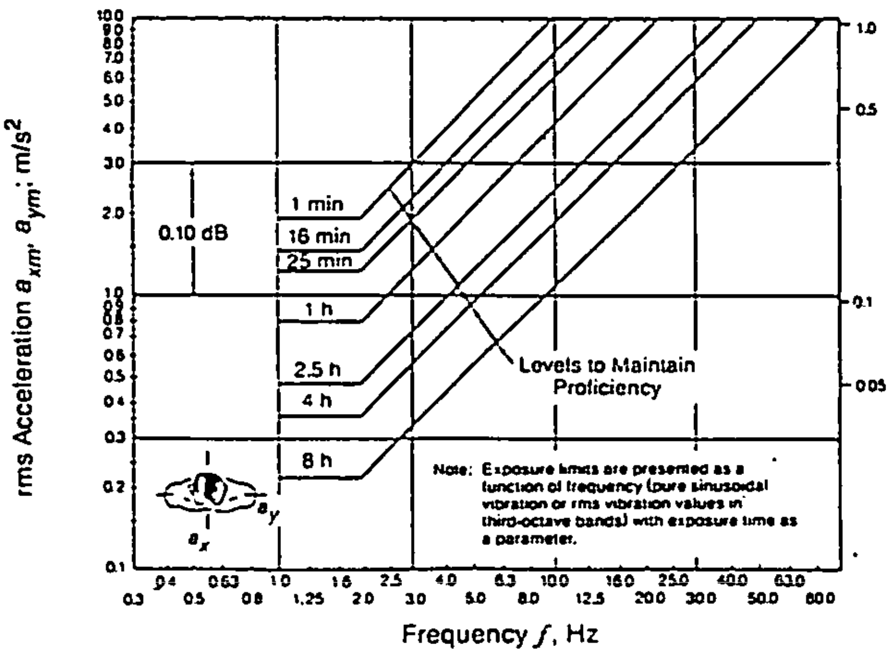


Figure 2-4. Level of Low-Frequency Vibration Sufficient to Produce Motion Sickness in 10% of Population (Ref. 11)



(A) Limits for Longitudinal Body Vibration



(B) Limits for Transverse Body Vibration

Figure 2-5. Maximum Design Limits for Vibration in Equipment Specified by MIL-STD-1472C (Ref. 11)

A secondary safety-related effect of vibration is the degradation of mechanical structures and assemblies over time due to vibration. Metal fatigue and loosening of fasteners can result from vibration, thereby directly endangering equipment or personnel or indirectly endangering human lives or health in cases where persons are dependent on the equipment or affected personnel.

Additional information on effects of whole-body vibration may be found in Refs. 17 through 19.

2-3.6 TOXIC FUMES

Toxic fumes are any gases whose presence causes injury to exposed personnel. Toxic gases may cause injury through several mechanisms including irritation or burning of the skin and eyes, irritation of the lungs or respiratory tract, interference with the absorption of oxygen into the bloodstream, or internal poisoning from absorption of toxic material through the lungs or skin into the bloodstream. Sources of toxic fumes from normal operation of electrical equipment include exhausts and evaporating fuel from engines. However, other emissions may be produced during electrically caused fires or by intense component heating due to overload conditions. Common toxic emissions are listed and described in the following paragraphs:

1. *Carbon Monoxide (CO).* CO is a product of incomplete combustion and is usually found in the exhaust from internal combustion engines such as those used with engine-driven-generator sets. CO poisons by combining with the hemoglobin in the blood and thus negates the oxygen-carrying capability of the affected cells. Relatively low concentrations can induce death: 1.28% by volume will be fatal in 1-3 min, 0.64 % in 10-15 min, and 0.32% in 30-60 min. Any concentration over 0.05% is considered dangerous (Ref. 13).

2. *Carbon Dioxide (CO_2).* CO_2, normally comprising about 0.03% of the atmosphere by volume, can affect respiration when the concentration is above 2%. However, concentrations of 5% may be tolerated for a duration of 1 h without permanent effects. Concentrations of 10% can cause death if breathed longer than a few minutes.

3. *Hydrogen Chloride (HCl).* HCl when dissolved in water forms hydrochloric acid, a very caustic substance. HCl is produced during the burning of a commonly used plastic wire insulation material, polyvinyl chloride.

4. *Hydrogen Sulfide (H_2S).* H_2S is produced during incomplete combustion of materials containing sulfur such as rubber used as an insulation material. Its presence may be detected easily by the familiar rotten egg smell usually associated with burning sulfur. In strong concentrations, however, hydrogen sulfide desensitizes the sense of smell rapidly. As a consequence, exposed personnel may be unaware of the continuing presence of even hazardous concentrations. Concentrations of 400-700 parts per million (ppm) may be fatal in 30-60 min.

5. *Sulfur Dioxide (SO_2).* SO_2 is produced during the complete combustion of fuels containing sulfur and is more toxic than H_2S. Only 150-ppm concentration is required to induce death in 30-60 min. SO_2 is extremely irritating because it dissolves in moisture to form sulfurous acid. Fortunately, the irritation makes it extremely difficult to withstand lethal concentrations of this gas.

6. *Oxides of Nitrogen.* The oxides of nitrogen include nitrous oxide (NO), nitric oxide (NO_2), and nitrogen tetroxide (N_2O_4). These gases are produced by combustion of wood products and high-temperature combustion of fuels used in internal combustion engines. Exposures of 100 ppm for 30 min may be fatal.

Limits for combustion product concentrations are specified in MIL-HDBK-759 (Ref. 20).

2-3.7 OPERATION IN HAZARDOUS ATMOSPHERES

Hazardous atmospheres are those atmospheres in which the presence of a mechanism that is normally harmless in air can cause an accident. The most common hazardous atmosphere is one with an extremely explosive mixture of gases or airborne particulates that can be ignited easily. Operation of conventional equipment with switch contacts, sliding brushes on a commutator, or static charges can provide the right condition for gases in the atmosphere to be ignited and, thereby, produce an explosion.

The National Electrical Code (Ref. 21) divides hazardous atmospheres into three classes. This classification is based on the type of hazardous material present and is further subdivided into two divisions based on the degree or severity of the hazard. The classes are listed as follows:

1. *Class I.* Atmospheres containing a combustible mixture of gases
2. *Class II.* Atmospheres containing a combustible dust
3. *Class III.* Atmospheres containing airborne fibers or other combustibles.

Within each class, two subclassifications or divisions are defined. Division I describes those situations where the condition, i.e., the combustible mixture, is expected to exist either continuously or intermittently under normal operating conditions. Division II, in contrast, describes situations in which the hazardous condition exists only in abnormal circumstances, such as equipment failure or operator error. Further classification within each division is based on the flammability characteristics of materials present in the atmosphere.

Equipment intended for use in hazardous atmospheres is designed to (1) minimize the occurrence of heated sources or electrical arcs and (2) confine any combustion or explosion to a small area to prevent ignition of the total environment. Components, such as relays or switches, containing exposed contacts and motors that use brushes cannot be used in hazardous atmospheres because the electrical arcs could initiate a fire or explosion. In cases requiring use of components that could ignite the explosive atmosphere, such components must be mounted in an "explosion-proof" enclosure. This enclosure is designed to confine an explosion to a small area and to release the combustion products slowly through small openings so that they are cooled to a safe temperature through expansion.

2-4 SOURCES OF HAZARD INFORMATION

Information for hazard or risk assessment is available from several sources in industry and Government. Available information includes accident data, failure-rate data, and standards and recommended practices for construction and installation of equipment. The accident data and failure-rate data provide information that is directly applicable to risk assessment—i.e., the identification of hazards and their severity and the probability of their occurrence. Frequently the standards and recommended practices also will provide indirectly information on hazards by specifying measures to prevent accidents due to the hazard. In many cases the nature of significant hazards may be inferred from these specifications.

The subparagraphs that follow describe organizations that provide this information. Addresses and type of information available are included in these descriptions.

2-4.1 INDUSTRIAL EXPERIENCE

Industrial organizations providing safety information include the following types of organizations:

1. Professional societies
2. Standardization organizations
3. Association of manufacturers
4. Insurance companies.

Specific examples of these organizations are listed in the subparagraphs that follow.

2-4.1.1 Institute of Electrical and Electronics Engineers (IEEE)

The IEEE, the major professional society for electrical engineers, publishes a series of standards and recommended practice documents concerning all facets of electrical engineering. Included in this series is information about power system design, including both safety and performance aspects. IEEE also publishes a manual of reliability data for electrical components, which is useful for estimating the probability of occurrence of hazards due to component failure (Ref. 22). An index of IEEE standards may be obtained from

IEEE Service Center
445 Hoes Lane
Piscataway, NJ 08854.

2-4.1.2 American National Standards Institute (ANSI)

ANSI is a nongovernmental institute founded to coordinate the development of voluntary standards for use by US industries and consumers, and to represent the United States in those organizations that perform a similar function at the international level. Standards submitted by various sponsoring organizations—e.g., IEEE and National Electrical Manufacturers Association (NEMA)—are reviewed to minimize redundancy across standards and to insure that they are responsive to needs. ANSI also serves as a clearinghouse for these revised standards, as well as for standards developed by other countries and approved by international standardization organizations—such as the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC). ANSI standards are available for many topic areas including structural and mechanical fabrication, materials production, and electrical and electronic design practices. A catalog of safety standards is available from

American National Standards Institute, Inc.
1430 Broadway
New York, NY 10018.

Standards pertinent to safety of electrical devices and wiring, fire protection, occupational safety, and other safety practices are identified in this catalog.

2-4.1.3 National Fire Protection Association (NFPA)

The NFPA maintains a collection of standards whose sole purpose is the prevention of fire or the minimization of damage from fire in a variety of situations. Standards are available that cover combustion properties of specific materials, specific structures, and problems unique to specific industries. Most pertinent to the subjects in this handbook are the two most popular NFPA standards: the National Electrical Code (Ref. 21) and the Fire Protection Handbook (Ref. 16). Requests for information concerning NFPA publications may be addressed to

National Fire Protection Association
Batterymarch Park
Quincy, MA 02269.

2-4.1.4 Electrical Generating Systems Association (EGSA)

The EGSA is an association of manufacturers of electrical generators and equipment used in electrical generating systems. Publications by this association address two separate areas, marketing and engineering. In the engineering area EGSA publishes performance specifications for engine-driven-generator sets, instrumentation and control systems incorporated into the engine-driven-generator sets, and switching systems for use with standby engine-driven-generator sets. Information regarding EGSA publications may be obtained by writing to

Electrical Generating Systems Association
P.O. Box 9257
Coral Springs, FL 33065.

2-4.1.5 National Electrical Manufacturers Association (NEMA)

NEMA is a trade association for the manufacturers of products used in the generation, transmission, distribution, control, and end use of electricity. Its publications include standards covering the design, and general publications describing topics associated with the application, of electrical equipment. Of special interest are those standards that discuss design, material selection, installation and testing for motors, switchgear, uninterruptible power supplies, industrial batteries, and control devices. An index of publications, published semiannually, may be obtained from

National Electrical Manufacturers Association
2101 L Street, NW
Washington, DC 20037.

2-4.1.6 Underwriters Laboratories (UL)

The UL is an independent testing laboratory that performs two functions for the electrical industry. The first function is the development of standards for the electrical industry that govern characteristics of electrical components used in electrical apparatus, such as wiring and power connectors. The second function is the testing of components and the publication of an "approved" list of components that satisfy the test criteria. Information concerning UL publications may be obtained from

Underwriters Laboratories, Inc.
333 Pfingsten Rd.
Northbrook, IL 60062.

2-4.1.7 Insurance Organizations

Insurance organizations have an economic interest in the minimization of accidents that result in losses for insured companies. Hence certain organizations are sponsored by companies within the insurance industry for the purpose of specifying safe procedures, developing standards, testing components, and investigating accidents. One example is the Factory Mutual Engineering Corporation, a part of the Factory Mutual System of insurance companies. This organization publishes information on the proper design and installation of equipment in an attempt to minimize losses due to accidents, especially those due to fire. A significant portion of a comprehensive handbook published by the Factory Mutual Engineering Corporation discusses electrical fires, their causes, and preventive measures (Ref. 23). Another useful publication is *Loss Prevention Data* (Ref. 24), a collection of sheets maintained in a set of eight loose-leaf binders. This collection covers a variety of industrial safety topics with a specific section on electrical safety.

A catalog of available information may be obtained from

Training Resource Center for Loss Central Management
Factory Mutual Engineering Corporation
1151 Boston-Providence Turnpike
P.O. Box 9102
Norwood, MA 02062.

2-4.1.8 Electric Power Research Institute (EPRI)

EPRI is a relatively new organization (founded in 1972) formed by the electric utility companies. This organization's purpose is to plan and manage a national research program covering topics that benefit the electric power industry. EPRI supports research in the development of new technology in all phases of the power generation and distribution process, with particular emphasis on safety, economy, efficiency, reliability, and the environment. Most technical efforts are performed under contract by universities, research institutes, manufacturers of electrical apparatus, or individual utilities. A final report describing the research and results is produced for every study, and multiple reports summarizing various phases are usually produced.

Areas of research within EPRI are best summarized by the names of divisions that comprise it, namely,

1. Advanced Power Systems
2. Electrical Systems
3. Energy Analysis and Environment
4. Energy Management and Utilization
5. Nuclear Power.

Information on available reports or current programs may be obtained by writing

Technical Information Center
EPRI
3412 Hillside Drive
Palo Alto, CA 94303.

2-4.1.9 Equipment Manufacturers

Equipment manufacturers publish information on the proper application of their products, in which they stress operational procedures for maximizing reliable service and safe operation. Publications range from simple, printed instruction sheets to comprehensive texts covering the design rationale, installation procedures, and operating instructions. Such information may be obtained from any reputable manufacturer of the product of interest.

2-4.2 INTERNATIONAL EXPERIENCE

International standardization is becoming more important as electrical equipment trade between countries increases. From the military perspective, standardization at the international level is especially important to design equipment for use in all North Atlantic Treaty Organization (NATO) countries. A set of international, voluntary standards is being developed by two international organizations that coordinate the activities of the standards organizations in various countries.* A description of these international organizations follows.

2-4.2.1 International Electrotechnical Commission (IEC)

The IEC is the principal organization responsible for management of the international, voluntary standardization program for electrical and electronic engineering. The IEC was founded in 1906 and is presently composed of 42 national committees representing 80% of the population of the world. Liaison is maintained with approximately 200 other organizations, both governmental and

*In the United States, this coordinating organization is ANSI.

private. Information available from IEC consists of standards covering components of electronic and electrical systems, motors and appliances, materials for insulators and conductors, electrical tests, and instrumentation. Standards that are directly applicable to subjects discussed in this handbook include generators and motors, safety requirements for equipment, installation of equipment in various situations (e.g., grounding), and components used for power switching and distribution. Standards published by the IEC are printed both in French and English on facing pages in the same document and may be obtained in the United States through ANSI:

American National Standards Institute, Inc.
1430 North Broadway
New York, NY 10018.

A catalog of publications, published twice a year, is also available through ANSI for a nominal charge.

2-4.2.2 International Organization for Standardization (ISO)

ISO, founded by the United Nations in 1947, coordinates the development of standards covering subjects not covered by IEC. These two organizations, although separate, coordinate their activities and have headquarters at the same location. The distinction among the subject areas covered by each organization has been made less clear by technical advances that have broadened significantly the number of disciplines involved in the electronics and electrical industries. Therefore, even closer cooperation between these two organizations is expected in the future.

2-4.2.3 Other Standardization Organizations

Most countries in the world have governmental or private organizations that manage the development of both voluntary and mandatory standards in their own country. Some of the organizations more frequently encountered, and their English abbreviations, are (Ref. 25)

AS	Standards Association of Australia
B.S.	British Standards Institution
CSA	Canadian Standards Association
DIN	Deutscher Normenausschuss (West Germany)
DS	Dansk Standardiseringsrad (Denmark)
DTD	Ministry of Technology (Great Britain)
IS	Indian Standards Association
JIS	Japanese Standards Association
MNC	Metallnormcentralen (Sweden)
NBN	Institut Belge de Normalisation (Belgium)
NF	Association Francaise de Normalisation (France)
NZSS	Standards Association of New Zealand
ONORM	Osterreichischer Normenausschuss (Austria)
SABS	South African Bureau of Standards
SIS	Sveriges Standardiseringskommission (Sweden)
Wbl	Verein Deutscher Eisenhuttenleute (Germany; Stahl-Eisen-Werkstoffblatt)
UNI	Ente Nazionale Italiano di Unificazione (Italy)
V	Nederlands Normalisatie-Instituut (Netherlands)
VSM	Normenburo des Vereins Schweizerischer Maschinenindustrieller (Switzerland).

2-4.3 GOVERNMENT EXPERIENCE

2-4.3.1 Department of Defense (DoD)

Safety and hazard information available from agencies in the DoD include accident data, handbooks covering appropriate design and application information for equipment, and standards and specifications that govern the construction of equipment.

2-4.3.1.1 Data Bases for Accidents Involving Military Personnel

The United States Army, Air Force, and Navy/Marines all maintain data bases describing accidents involving military personnel and civilian personnel working for the military. Information contained in these data bases includes date and nature of the accident, number and name of persons involved, extent of damage to personnel and materiel, and cause of accident. All data bases are computerized, which allows selective retrieval of records based upon specified criteria. Data may be requested from any service by personnel in service, contractors, or Government civilian employees. However, the amount of data that may be released is governed by the privacy act and any classification that may be applied to the data or parts of it. Information may be requested in writing from the following organizations:

1. Army: Commander
   US Army Safety Center
   Fort Rucker, AL 36362

2. Air Force: Air Force Inspection and Safety Center
   AFISC/SER
   Norton Air Force Base, CA 92409

3. Navy/Marines: Commander, Naval Safety Center
   Code 14, Naval Air Station
   Norfolk, VA 23511-5796.

2-4.3.1.2 Military Standards and Specifications

Military standards and specifications are written for the procurement of equipment that is suitable for the intended application and that meets performance and maintenance requirements. Since one of the typical performance requirements is that equipment must be capable of being operated safely by the personnel who will use it, the general performance specifications or standards that cover a class of equipment, or group of equipment items, typically specify requirements for incorporating safety features. In addition, there are specific standards that describe procedures, such as grounding and management of safety programs, to be performed specifically for safety.

2-4.3.1.3 Military Handbooks

The military produces numerous handbooks including the military handbook series, field manuals (FM-), and the US Army Materiel Command (AMC) Engineering Design Handbook series (AMCP 706-). These handbooks describe conventions, operating or installation procedures, and other topics with general application. Safety-related considerations pertinent to this handbook topic are incorporated in many of these handbooks.

2-4.3.2 Occupational Safety and Health Administration (OSHA)

OSHA was formed by Congress in 1970 and placed under the Department of Labor. It was formed for the purposes that follow:

1. To develop standards or promulgate the adoption of codes or standards developed by voluntary standards associations
2. To conduct inspections to insure compliance
3. To maintain statistics of all "disabling, serious, or significant injuries or illnesses, whether or not involving loss of time from work other than minor injuries requiring first-aid treatment" (Ref. 26).

To accomplish these goals, OSHA coordinates accident recordkeeping at the state level for participating states and tabulates summaries of accident information for the country. In addition, OSHA is required by law to monitor safety of federal employees and to keep adequate records of all occupational accidents and illnesses for evaluation and for development of appropriate corrective action. Summary data are maintained with the Federal Accident Reporting System (FARS) to track accident trends in the entire federal Government (including DoD). Results are summarized in an annual report.

2-5 APPLICABLE DOCUMENTS

Listed in pars. 2-5.1 through 2-5.4 are documents related to safety aspects of polyphase systems. Topics covered by the documents are management of safety programs and requirements for safe design for general application and for specific components. Note that although many documents are listed, the list is not complete. This is especially true for military standards and commercial standards because there are a large number of standards that cover specialized topics. In these cases only representative documents have been cited.

2-5.1 MILITARY STANDARDS AND SPECIFICATIONS

2-5.1.1 General Safety Considerations, Documents

MIL-HDBK-764(MI), *Safety Engineering Design Guide for Army Materiel*
AR-380-30, *Reporting of Critical Intelligence Information*
AR-380-40, *Policy for Safeguarding and Controlling COMSEC Information*
EM 385-1-1, *US Army Corps of Engineers Safety and Health Requirements Manual*
MIL-STD-721, *Definitions of Effectiveness Terms for Reliability, Maintainability, Human Factors, and Safety*
MIL-STD-882, *System Safety Program Requirements*
MIL-STD-1472, *Human Engineering Design Criteria for Military Systems, Equipment, and Facilities*
MIL-STD-1474, *Noise Limits for Army Materiel*
TB-MED-501, *Hearing Conservation.*

2-5.1.2 Documents on Safety for Electrical Systems

MIL-STD-1857, *Grounding, Bonding, and Shielding Design Practices*
MIL-STD-454, *Standard General Requirements for Electronic Equipment*
AR-385-30, *Safety Color Code Markings and Signs.*

2-5.1.3 Engine-Driven-Generator Set Standards and Specifications

MIL-STD-178, *Definition Applicable to Speed-Governing of Electric Generator Set*
MIL-STD-633, *Mobile Electric Power Engine Generator Standard Family Characteristics Data Sheet*
MIL-STD-705, *Generator Sets, Engine-Driven, Methods of Tests and Instructions*
MIL-STD-882, *System Safety Program Requirements*
MIL-HDBK-705, *Generator Sets, Electrical, Measurements and Instrumentations*
FM-21-30, *Electric Power Generators in the Field*
MIL-G-38195, *Generator Set, Gas Turbine Engine, 60-Kilowatt, 400-Hertz, General Purpose*
MIL-G-52732, *Generator Sets, Gasoline Engine Driven, 0.5-Kilowatt thru 10-Kilowatt, 60-Hertz and 28-Volt Direct Current, Type I (Tactical), Class 2 (Utility), General Specification for*
MIL-G-52884, *Generator Sets, Diesel Engine Driven, 15- thru 200-Kilowatt, 50-, 60-, and 400-Hertz, (Tactical), General Specification for*
MIL-G-82058, *Generator Set, Diesel Engine, 750-Kilowatt, 50/60-Hertz, Prime, Utility.*

2-5.1.4 Documents Describing Distribution of Electric Power

MIL-B-5087, *Bonding, Electrical, and Lightning Protection for Aerospace Systems*

MIL-HDBK-419, *Grounding, Bonding, and Shielding for Electronic Equipments & Facilities, Volumes 1 & 2*

MIL-STD-13100, *Shipboard Bonding, Grounding, and Other Techniques for Electromagnetic Compatibility and Safety.*

2-5.1.5 Documents Describing Electrical Components

MIL-STD-1360, *Fuse, Fuseholders, and Associated Hardware, Selection and Use of*

MIL-STD-1498, *Circuit Breakers, Selection and Use of*

MIL-C-2212, *Controller, Electric Motor AC or DC, and Associated Switching Devices*

MIL-F-5373, *Fuseholder, Block-Type, Aircraft*

MIL-C-7079, *Circuit Breaker, Non-Trip-Free, General Specification for*

MIL-A-9094, *Arrester, Lightning, General Specification for Design of*

MIL-T-15108, *Transformers, Power, Step Down, Single Phase, 1 kVA Approximate Minimum Rating, Dry Type, Naval Shipboard*

MIL-F-15160, *Fuse, Instrument, Power, and Telephone*

MIL-T-17221, *Transformers, Power, Distribution, Single Phase, 400-Hertz, Insulation System Class 220 deg C, Dry Air Cooler, Naval Shipboard Use*

MIL-F-19207, *Fuseholder, Extractor Post-Type, Blown Fuse Indicating and Nonindicating, General Specification for*

MIL-F-21346, *Fuseholder, Block and Shroud Type, and Associated Fuse Clips, General Specifications for*

MIL-I-23264, *Insulator, Standoff, Style 01, 02, 03, 04, and 06*

MIL-C-23280, *Cabinet, Electrical Equipment CY-2675*

MIL-F-23419, *Fuse, Instrument-Type, General Specification for*

MIL-P-23928, *Panel, Electrical, Power Distribution and Manual Transfer, Circuit Breaker Type*

MIL-I-23972, *Insulator Assemblies, Rack, Secondary*

MIL-E-24142, *Enclosure for Electrical Fittings and Fixtures, General Specification for*

MIL-P-29183, *Panelboard, Power Distribution, Portable, Weatherproof, General Specification for*

MIL-C-39019, *Circuit Breakers, Magnetic, Low-Power, Sealed, Trip Free, General Specification for*

MIL-C-55629, *Circuit Breaker, Magnetic, Unsealed or Panel Seal, Trip Free, General Specification for*

MIL-R-55223, *Regulator, Voltage CN-514()/GRC*

MIL-D-55456, *Distribution Box, J-1077(()U, Distribution Box, J-2317(()U*

MIL-P-81653, *Power Controller, Solid-State, General Specification for*

MIL-C-81883, *Control Group, Electric Power OK-XXX (V), A General Specification for*

MIL-T-82402, *Transformer, Dry-Type, Power Distribution, Step Up and Step Down Service, 1000 kVA and Below*

MIL-C-83383, *Circuit Breaker, Remote Control, Thermal, Trip Free, General Specification for*

MIL-P-83825, *Panel Assy., Automatic Power Transfer for MB-TEEN and EMU Series Diesel Engine Generator Sets.*

2-5.1.6 Documents Describing Testing and Test Equipment

MIL-STD-1309, *Definitions of Terms for Test, Measurement, and Diagnostic Equipment*

MIL-D-82134, *Dummy Load, Electrical, 60/100-kW, 55/90-kVAR 3-Phase, 60/400-Hertz, AC.*

2-5.2 GOVERNMENT STANDARDS AND SPECIFICATIONS

2-5.2.1 Document on Safety for Electrical Systems

OSHA Safety and Health Standards 29CFR1910, *Subpart S, Electrical.*

2-5.2.2 Documents Describing Testing and Test Equipment

W-C-375, *Circuit Breaker, Molded Case, Branch Circuit, and Service*

W-T-631, *Transformer, Power Distribution*

W-F-870, *Fuseholder and Fuseclips (For Plug and Enclosed Cartridge Fuses)*

W-F-1726, *Fuse, Cartridge, Class H, General Specification*

W-F-1814, *Fuse, Cartridge, High Interrupting Capacity, General Specification.*

2-5.3 INTERNATIONAL SOURCES

The following documents are all published by the International Electrotechnical Commission (IEC).

2-5.3.1 Documents on Safety for Electrical Systems

IEC#479, *Effects of Current Passing Through the Human Body*

IEC#536, *Classification of Electrical and Electronic Equipment With Regard to Protection Against Electric Shock.*

2-5.3.2 Motor-Generator Standard and Specification

IEC#34, *Rotating Electrical Machines.*

2-5.3.3 Documents Describing Distribution of Electric Power

IEC#79, *Electrical Apparatus for Explosive Gas Atmospheres*
IEC#364, *Electrical Installations in Buildings*
IEC#621, *Electrical Installations for Outdoor Sites Under Heavy Conditions (Including Open-Cast Mines and Quarries)*
IEC#664, *Insulation Coordination Within Low-Voltage Systems Including Clearances and Creepage Distances for Equipment.*

2-5.3.4 Documents Describing Electrical Components

IEC#56, *High-Voltage Alternating-Current Circuit Breakers*
IEC#76, *Power Transformers*
IEC#99, *Lightning Arresters*
IEC#144, *Degrees of Protection of Enclosures for Low-Voltage Switchgear and Controlgear*
IEC#157, *Low-Voltage Switchgear and Controlgear*
IEC#158, *Low-Voltage Controlgear*
IEC#214, *On-Load Tap Changers*
IEC#241, *Fuses for Domestic and Similar Purposes*
IEC#269, *Low-Voltage Fuses*
IEC#282, *High-Voltage Fuses*
IEC#289, *Reactors*
IEC#298, *AC Metal-Enclosed Switchgear and Controlgear for Rated Voltages Above 1 kV and Up to and Including 72.5 kV*
IEC#354, *Loading Guide for Oil-Immersed Transformers*
IEC#420, *High-Voltage Alternating Current Fuse-Switch Combinations and Fuse-Circuit Breaker Combinations*
IEC#445, *Identification of Apparatus Terminals and General Rules for a Uniform System of Terminal Marking, Using an Alphanumeric Notation*
IEC#466, *High-Voltage Insulation-Enclosed Switchgear and Controlgear*
IEC#470, *High-Voltage Alternating Current Contactors*
IEC#518, *Dimensional Standardization of Terminals for High-Voltage Switchgear and Controlgear*
IEC#542, *Application Guide for On-Load Tap Changers*
IEC#606, *Application Guide for Power Transformers*
IEC#616, *Terminal and Tapping Markings for Power Transformers*
IEC#644, *Specification for High-Voltage Fuse-Links for Motor Circuit Applications*
IEC#742, *Isolating Transformers and Safety Isolating Transformers—Requirements.*

2-5.3.5 Documents Describing Testing and Test Equipment

IEC#267, *Guide to the Testing of Circuit Breakers With Respect to Out-of-Phase Switching*
IEC#348, *Safety Requirements for Electronic Measuring Apparatus*
IEC#414, *Safety Requirements for Indicating and Recording Electrical Measuring Instruments and Their Accessories*
IEC#695, *Fire Hazard Testing.*

2-5.4 COMMERCIAL SOURCES

2-5.4.1 General Safety Considerations, Document

ANSI C2, *National Electrical Safety Code.*

2-5.4.2 Documents on Safety for Electrical Systems

ANSI/NFPA 70, *National Electrical Code*
ANSI C2-1984, *National Electrical Safety Code.*

2-5.4.3 Motor-Generator Standards and Specifications

ANSI C50.30, IEEE Std 67, *Operation and Maintenance of Turbine-Generators*
ANSI/UL 674, *Electric Motors and Generators for Use in Hazardous Locations, Class I, Groups C and D, Class II, Groups E, F and G, Safety Standard for*
ANSI/IEEE Std 117, *Insulating Materials for AC Electrical Machinery*
IEEE Std 126, *Governing of Internal Combustion Engine-Generator Units*
ANSI/IEEE Std 275, *Thermal Evaluation of Insulation Systems for AC Electric Machinery Employing Form-Wound Preinsulated Stator Coils.*

2-5.4.4 Documents Describing Distribution of Electric Power

ANSI C33.27, *Electrical Outlet Boxes and Fittings for Use in Hazardous Locations*
ANSI C33.84, *Electrical Outlet Boxes and Fittings*
ANSI C33.85, *Power Outlets*
ANSI C33.91, *Electrical Rigid Nonmetallic Conduit*
ANSI C33.92, *Electrical Flexible Metal Conduit*
ANSI C62.1, *AC Power Circuits, Surge Arrester for*
ANSI C62.2, *Valve Type Lightning Arresters for AC Systems: Application*
ANSI C62.92, IEEE Std 143, *Ground Fault Neutralizers, Grounding of Synchronous Generator Systems, Neutral Grounding of Transmission Lines, Application*
ANSI C76.1, IEEE Std 21, *Outdoor Apparatus Bushings*
ANSI/IEEE Std 32, *Neutral Grounding Devices*
ANSI/IEEE Std 80, *Safety in AC Substation Grounding*
ANSI/IEEE Std 141, *Electric Power Distribution for Industrial Plants*
ANSI/IEEE Std 142, *Grounding of Industrial and Commercial Power Systems*

ANSI/IEEE Std 241, *Electric Power Systems in Commercial Buildings*
ANSI/IEEE Std 446, *Emergency and Standby Power Systems*
NEMA LA-1, *Surge Arresters*
NEMA PB 2, *Dead-Front Distribution Switchboards*
NEMA RN 1, *PVC Externally Coated Galvanized Rigid Steel Conduit and Electrical Metallic Tubing*
NEMA TC 2, *Electric Plastic Tubing, Conduit, and Fittings*
NEMA TC 3, *PVC Fittings for Use With Rigid PVC Conduit and Tubing*
ANSI/UL 96, *Components, Safety Standard for Lightning Protection*
ANSI/UL 467, *Grounding and Bonding Equipment, Safety Standard for*
ANSI/UL 486A, *Wire Connectors and Soldering Lugs for Use With Copper Conductors*
ANSI/UL 486B, *Wire Connectors for Aluminum Conductors*
ANSI/UL 498, *Attachment Plugs and Receptacles, Safety Standard for*
ANSI/UL 514B, *Fittings for Conduit and Outlet Boxes, Safety Standard for*
ANSI/UL 817, *Cord Sets and Power-Supply Cords, Safety Standard for*
ANSI/UL 1010, *Receptacle-Plug Combinations for Use in Hazardous Locations, Safety Standard for*
ANSI/UL 1053, *Ground-Fault Sensing and Relaying Equipment, Safety Standard for*
UL 6, *Electrical Rigid Metal Conduit*
UL 543, *Electrical Fiber Conduit*
UL 797, *Electrical Metal Tubing*
UL 891, *Electrical Dead-Front Switchboards*
UL 943, *Ground Fault Circuit Interrupters*
ANSI/NFPA 78, *Lightning Protection Code.*

2-5.4.5 Documents Describing Electrical Components

ANSI C17.076, *Pressurized Components of AC High-Voltage Circuit Breakers*
ANSI C33.10, *Fuseholders*
ANSI C33.26, IEEE Std 547, *Thermal Protectors for Electric Motors*
ANSI C33.42, *Fuses*
ANSI C37.078, IEEE Std 343, *External Insulation for Outdoor AC High-Voltage Circuit Breakers*
ANSI C37.13, IEEE Std 20, *Low-Voltage AC Power Circuit Breakers Used in Enclosures*
ANSI C37.19, *Low-Voltage AC Power Circuit Breakers and Switchgear Assemblies*
ANSI C37.24, IEEE Std 144, *Solar Radiation on Outdoor Metal-Clad Switchgear*
ANSI C37.27, IEEE Std 331, *Low-Voltage AC Nonintegrally Fused Power Circuit Breakers, Application for*
ANSI C37.29, IEEE Std 508, *Low-Voltage AC Power Circuit Protectors Used in Enclosures*
ANSI C37.30, IEEE Std 324, *High-Voltage Air Switches, Insulators, and Bus Supports*
ANSI C37.34, IEEE Std 326, *High-Voltage Air Switches*
ANSI C37.35, *High-Voltage Disconnecting Switches, Operation and Maintenance of*
ANSI C37.60, IEEE Std 437, *Automatic Circuit Reclosures for AC Systems*
ANSI C37.61, IEEE Std 321, *Automatic Circuit Reclosures, Application, Operation, and Maintenance*
ANSI C57.12.00, IEEE Std 462, *Distribution, Power and Regulating Transformers*
ANSI C89.2, *Dry-Type Transformers for General Applications*
ANSI C97.1, *Low-Voltage Cartridge Fuses*
IEEE Std 22A, *Interrupter Switches to Switch Capacitance Loads*
IEEE Std 76, *Transformer Askarel in Equipment, Acceptance and Maintenance*
IEEE Std 112A, *Polyphase Induction Motors and Generators*
IEEE Std 283, *Oil-Immersed Transformers Installation*
IEEE Std 345, *Thermal Evaluation of Oil-Immersed Distribution Transformers*
IEEE Std 387, *Diesel Generator Units Applied as Standby Power Supplies for Nuclear Power Generating Stations*
IEEE Std 484, *Installation Design and Installation of Large Lead Storage Batteries for Generating Stations and Substations*
UL 489, *Molded Case Circuit Breakers and Circuit Breaker Enclosures*
ANSI/UL 20, *Snap Switches, Safety Standard for General Use*
ANSI/UL 50, *Cabinets and Boxes, Safety Standard for*
ANSI/UL 98, *Enclosed and Dead-Front Switches, Safety Standard for*
ANSI/UL 198C, *High-Interrupting Capacity Fuses, Current-Limiting Types, Safety Standard for*
ANSI/UL 198H, *Class T Fuses, Safety Standard for*
ANSI/UL 347, *High-Voltage Industrial Control Equipment, Safety Standard for*
ANSI/UL 508, *Industrial Control Equipment, Safety Standard for*
ANSI/UL 698, *Industrial Control Equipment for Use in Hazardous Locations, Class I, Groups A, B, C, and D, and Class II, Groups E, F, and G, Safety Standard for*
ANSI/UL 823, *Electric Heaters for Use in Hazardous Locations, Class I, Groups, A, B, C, and D, and Class II, Groups E, F, and G, Safety Standard for*
ANSI/UL 869, *Service Equipment, Safety Standard for*

ANSI/UL 877, *Circuit Breakers and Circuit-Breaker Enclosures for Use in Hazardous Locations, Class I, Groups A, B, C, and D, and Class II, Groups E, F, and G, Safety Standard for*
ANSI/UL 977, *Fused Power Circuit Devices, Safety Standard for*
ANSI/UL 1008, *Automatic Transfer Switches, Safety Standard for*
ANSI/UL 1054, *Special-Use Switches, Safety Standard for*
ANSI/UL 1077, *Protectors for Use in Electrical Equipment, Safety Standard for Supplementary*
ANSI/UL 1097, *Double Insulation Systems for Use in Electrical Equipment, Safety Standard for*
ANSI/NFPA 496, *Purged Enclosures for Electrical Equipment in Hazardous Locations*
ANSI/NEMA 250, *Enclosures for Electrical Equipment (1000 volts maximum)*
NEMA AB 1, *Molded Case Circuit Breakers*
NEMA SG 2, *High-Voltage Fuses, Standard for*
NEMA SG 3, *Low-Voltage Power Circuit Breakers*
NEMA SG 5, *Power Switchgear Assemblies*
NEMA SG 6, *Power Switching Equipment*
NEMA SG 13, *Automatic Circuit Reclosures, Automatic Line Sectionalizers and Oil-Filled Capacitor Switches*
NEMA TR-P4, *Distribution Transformers, Underground Type*
NEMA TR 27, *Dry-Type Transformers, Commercial, Institutional, and Industrial.*

2-5.4.6 Documents Describing Testing and Test Equipment

ANSI C39.5, *Electrical and Electronic Measuring and Controlling Instrumentation, Safety Requirements for*
IEEE Std 118, *Electrical Measurements in Power Circuits.*

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4. S. W. Malasky, *System Safety, Technology and Application*, Garland STPM Press, New York, NY, 1982.
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CHAPTER 3

SYSTEM DESIGN

Discussed in this chapter are the safety-related topics for electrical systems that do not pertain to a single component but rather apply to the whole system. Included are requirements for electrical equipment based on environmental factors such as moisture, lightning, temperature, gases, particulates, solar radiation, and pressure. Brief descriptions of each factor include a definition and a range of typical values for natural environments. Concise descriptions are given for the four climates of the earth: hot-dry, hot-wet, temperate, and cold. Also equipment design considerations that impact the safe and reliable operation of electrical systems are discussed. The topics discussed are those that pertain to the configuration of the system—i.e., grounding; interface with permanent power system; or that apply to all components, e.g., material selection and arcing.

3-0 LIST OF SYMBOLS

d = depth in water, m (ft)
g = acceleration due to gravity, 9.8 m/s^2 (32 ft/s^2)
P_0 = barometric pressure at sea level, Pa (lb/in.^{2})
ρ = density of water, kg/m^3 (lb/ft^3)
λ = wavelength, m
Q_s = solar irradiance, W·m^{-2}·μm^{-1}

3-1 INTRODUCTION

To insure that an electrical system is capable of safe operation, it is necessary that

1. Components are carefully designed to eliminate hazards that could exist when the equipment is operated in its intended environment.
2. The components are constructed sufficiently rugged and environmentally resistant that additional hazards are not introduced by physical deterioration of the structure or materials.
3. System components are properly interconnected to prevent hazards that would be produced by inadvertent fault currents or application of hazardous voltages to exposed conductors that are expected to be at ground potential.

To design electrical components and systems that can be operated safely, the designer must be cognizant of several factors including typical hazards of electrical apparatus, the performance requirements for the equipment including the nature of the electrical interaction of it with other equipment, the environment in which the equipment is to be operated, and the effect of the environment on performance of the equipment. The purpose of this chapter is to provide a discussion of these factors as they pertain to the total electrical system or multiple components in the system. Toward this objective, two major subject areas are discussed. First, the physical environment, including typical ranges of environmental factors, in which electrical equipment will be used by the military, is described. Second, technical considerations including both those that apply to the design of components, e.g., material selection, and those that apply to interconnection of various components, e.g., grounding, are discussed. Component specific information is discussed in Chapters 4 through 8. Each of these chapters or major paragraphs within the chapters provides information concerning the design of the component that is the subject of that chapter or paragraph. This is in contrast to the information in Chapter 3, which describes considerations applicable to all components or to the interconnection of various components into a system.

3-2 ENVIRONMENT

3-2.1 CHARACTERISTICS OF THE ENVIRONMENT

The operation of electrical equipment (or for that matter any equipment) is affected by factors in the natural environment, such as temperature, humidity, atmospheric contaminants, and changes in these environmental factors induced by nearby personnel or equipment. Typical factors in the induced environment that differ from the natural environment are sound, vibration, temperature elevation, and radiation. The expected range of the natural and induced factors of the anticipated environment must be defined quantitatively to establish requirements for the design. The purpose of this paragraph is to discuss environmental factors that impact the operation of electrical equipment normally used in polyphase systems. For each environmental factor, the nature and effect of the factor are described and a range of typical values is given. These discussions are not intended to provide a complete description of the environment and its effects. More extensive discussions of environmental effects, both natural and induced, are given in other handbooks. (Refs. 1, 2, and 3). These handbooks provide information on the expected values for each factor across various conditions, measurement techniques for the factor, impact of the factor on personnel and equipment, and equipment tests to determine the effect of environmental extremes on performance or resistance to degradation.

3-2.1.1 Moisture

Moisture refers to the presence of a limited quantity of liquid-phase water. Liquid-phase water includes water as a liquid, an aerosol, or condensation on a surface. Sometimes the definition of liquid-phase water is expanded to include water vapor at high humidity levels. Water is always present in the atmosphere in concentrations ranging from 3% relative humidity in the desert environment to 100% humidity during precipitation in more temperate areas. Natural moisture may be found in several forms including falling rain, condensation on surfaces, fog, or simply accumulated water trapped in cavities or absorbed into material. At low temperatures moisture will freeze, which significantly changes its properties and effects on material.

The effects of moisture on materials and equipment are the same as the effects of water; they differ only in degree. Specific effects on electrical equipment are

1. *Decreased Surface- or Bulk-Resistivity of Insulating Materials.* Moisture containing dissolved salts even in minute concentrations may form a conductive path across surfaces of insulators or through porous materials, but pure water is a poor conductor and does not introduce significant conductive paths. However, contaminants—which are always present in the atmophere, on surfaces, or in materials—enter solution upon contact with water and thereby release ions that provide a conductive mechanism across surfaces or through porous materials.

2. *Dimensional Changes in Materials.* Absorption of moisture by hydroscopic materials frequently will cause swelling of fibers or will reduce the strength of the material such that its dimensions are susceptible to changes due to externally applied stresses.

3. *Increased Corrosion Rate.* Moisture provides the vehicle for the chemical combining of certain metals, e.g., iron, and oxygen and, when present, greatly increases the rate of metallic oxidation.

4. *Dissolving of Adhesives (or Cohesive Properties of Material).* Excessive moisture frequently will degrade the strength of adhesives or the cohesive strength of materials and will lead to structural failure unless moisture-resistant materials and fastening techniques are used.

5. *Deposits Left After Evaporation of Water.* Contaminants in water remain on surfaces after water evaporates. These residue contaminants are usually poor conductors but may increase the electrical resistance of electrical contacts or may interfere with the operation of high-tolerance mechanical assemblies. This type of water damage is most significant for equipment that is submerged inadvertently in water, e.g., due to flooding or to accidental submersion.

6. *Internal Mechanical Stress From Freezing Moisture.* Moisture entrapped in materials expands upon freezing and thereby causes rupture of cellular structure, delamination of layered materials, rupturing of cavities or pockets, or increased brittleness of normally pliable, cellular materials.

7. *Increased Loads From Accumulation of Frozen Precipitation.* Accumulation of snow on flat surfaces or frozen glaze on suspended objects significantly affects the weight of the structure and, in severe cases, may lead to its collapse. Accumulation of ice on suspended cables may significantly increase their diameter, and the increased wind loading may lead to tensile failure of the conductors or collapse of the supporting structure.

8. *Limitation on Mechanical Movement by Frozen Moisture.* Equipment that requires mechanical movement of components for operation may be disabled when coated with ice. The ice may either lock some movable components into one position or prevent a movable component from seating properly. For example, ice can lock a movable contact in an outdoor switchgear in one position or can bridge a contact and thereby prevent proper contact.

9. *Physical Damage From Frozen Precipitation.* Moisture in the form of large hail can cause significant damage to wood, shingles, or sheet metal structures as well as direct injury to personnel.

The major impact of moisture on safety is the introduction of unintended conductive paths in or around equipment either by conduction through the water in the components or by failure of mechanical supports that separate energized components. These paths can connect energized, internal components that are normally protected to exposed, conductive components that are not normally energized; thus personnel may be exposed to hazardous voltages with no warning or protection. Moisture-induced leakage paths to ground also can contribute to the hazard by reducing the resistance of the electrical circuit through a person to ground and thereby increase the current flow through the body upon contact with energized conductors. The failure of supports may be induced by moisture through corrosion of metal structures, erosion of soil around supports, or rotting of wooden poles.

Rates of rainfall span a wide range of values—from very light, i.e., almost negligible, does not wet completely exposed surfaces, to heavy, i.e., greater than 7.6 mm/h or 0.3 in./h. Normal intensities vary greatly with geographic location; the heaviest precipitations are found in the tropics, at the middle latitudes, over coastlines with onshore prevailing winds, and on the windward side of mountain ranges that are parallel with those coastlines. Average yearly rainfalls in the most humid regions are 2 m (80 in.) per year with the highest average rainfall, over 11.7 m/yr (460 in./yr), occurring in Mt. Waialeale, Kanai, Hawaii. Average annual rainfall for the United States is about 0.74 m (29 in.), with the highest average rainfall occurring along the Gulf of Mexico—1.45 m/yr (57 in./yr) in New Orleans. The annual average for European countries is between 0.5 and 0.8 m/yr (20 and 30 in./yr).

Rainwater is seldom pure. Dissolved CO_2 from the atmosphere makes the rainwater acidic and lowers the pH to 6.8-6.9. (7.0 is neutral.) Gaseous emissions—e.g., nitric oxide (NO_2), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S)—from industrialized areas and motor vehicles lower the pH to values between 6 and 2 and cause "acid rain" in areas downwind of urban areas. Data from the eastern United States show that 60 to 70% of the acidity in precipitation is due to sulfuric acid that presumably originates from stationary sources. The remaining 30 - 40% is nitric acid that usually originates from mobile sources (Ref. 4). An example of severe acid-rain condition is the highly acidic rain that falls shortly after the launching of a solid-fuel rocket. This rain is sufficiently acidic to etch paint on vehicles near the launch area.

Pure water is a reasonable insulator and has a conductivity of less than 0.01 μmho/m. However, dissolving reactive gases in water raises its conductivity. Rainwater samples collected during an EPA study in various rural and urban locations in the United States had conductivities ranging from 11 to 23,000 μmhos/m (Ref. 5). The conductivity of rainwater reaching a surface is greater than falling rain due to the dissolving of soluble material at the surface. The specific conductivity values for rain depend on specific surface materials and concentrations.

The primary negative effect of acid rain is the destruction of natural life—both vegetation and aquatic life in affected streams and lakes. Additionally, acid rain containing dissolved SO_2 induces rapid corrosion in unprotected ferrous metals. These effects are discussed in par. 3-2.1.4.3.

3-2.1.2 *Static Electricity and Lightning*

3-2.1.2.1 Lightning

Lightning is an electrostatic discharge between oppositely charged clouds or between charged clouds and ground. It is the latter situation that is potentially hazardous to personnel and electrical equipment and, consequently, is the situation described here. Positive charges induced in clouds by convective air currents induce negatively charged regions on the ground. The negative charges are concentrated on elevated structures, trees, and terrain features because of their closer proximity to the clouds. When the electrical field strength in the region between the cloud and the charged area of the ground approaches the level sufficient to ionize the air, a lightning stroke is formed which begins at the cloud. The stroke is developed as a series of steps, each step being 10 to 80 m (33 to 262 ft) long and extending from the lower tip of the preceding step toward the ground. As the progressing stroke nears the ground, the charge is concentrated on the ground under the stroke and raises the electric field strength in that region. When the stroke descends to 100 m (328 ft) above the earth, a leader forms between the ground and the descending stroke. This leader completes the ionized conductive path between the cloud and ground, and a current of about 100 A begins to flow. Next a rapidly moving return stroke follows the established path upward and carries a large amount of current, typically 10,000 to 30,000 A. The return stroke lasts until the charge is depleted from the ground near the point of impact, usually 50-100 ms. Additional charge is drawn into the area where the charge is depleted by the stroke from the surrounding area, and additional return strokes are generated until the charge differential in the area is neutralized. A typical lightning flash consists of 3 or 4 return strokes with durations of 1 ms and separated by 40 to 80 ms (Ref. 6).

When the lightning strike draws charge from a broad, horizontal region of the cloud, the flash may consist of one or more strokes having a longer duration, typically 150 ms but sometimes lasting 500 ms. Currents for these flashes are substantially lower than the current associated with the normal 1-ms return strokes, typically 38 to 130 A. However, the damage from the longer duration stroke may be greater.

Lightning occurs most frequently in locations where atmospheric conditions favor the development of large storms with strong convective currents. In the United States thunderstorms occur most frequently in central Florida (100 days per year) and in the Midwest (70 days per year). Areas that are most susceptible to lightning are elevated areas that protrude above surrounding terrain. Objects that are located near the base of, or between taller objects, are provided direct protection from lightning by the taller objects. To access the degree of protection afforded by taller objects, one source (Ref. 7) suggests visualizing an imaginary impenetrable sphere, 90 m (300 ft) in diameter, rolling across the terrain and riding over terrain features such as towers, trees, buildings, etc. Any object that the sphere may contact has a greater than 0.005 probability of being hit by a lightning stroke of 10 kA or greater. Objects that cannot be touched by the sphere because of neighboring taller objects are "protected" and have a probability of less than 0.005 of being struck. An interesting observation of this model is that apparatus mounted more than 45 m (150 ft) above the ground on the sides of towers is vulnerable to direct lightning strikes.

Physical damage or electrocution usually results from the voltage drop that is produced by the large current flow through materials having some resistance. Trees are splintered from the intense heat generated by lightning currents forced through the high-resistance tree trunk, although relatively little damage occurs to aluminum-skin aircraft that are struck by lightning.

Electrocution may occur from direct hits by a lightning stroke, but usually injury occurs because only a portion of the stroke current flows through the victim. Large voltage gradients are produced on the surface of the ground surrounding the point at which the lightning current enters the ground.

The difference in potential between a person's feet where they contact the ground is called "step-potential"; this is shown in Fig. 3-1. If a person is standing near the point where a lightning stroke enters the ground, where the potential gradient is high, the step-potential may be sufficient to cause electrocution or injury. Examples of injurious step-potentials produced by lightning are documented in Ref. 8. In one case, a soccer player was stunned by lightning striking a soccer goal; in another case, cows were killed by lightning striking a nearby fence post. In both cases the afflicted person or animal was not struck directly but shocked through induced step-potentials.

Touch-potential is the difference in potential between the ground on which a person is standing and an object within his reach. Hazardous touch-potentials can result if a person standing some distance away from the impact point of a lightning stroke touches a fence or pipe that is grounded near the impact point. This situation is depicted in Fig. 3-2. A similar hazard would result if a person standing near the point of impact were touching an object grounded at a remote point. Under similar conditions, touch-potentials can be much higher than step-potentials because the potential is generated by more widely separated ground-contact points; however, the severity is determined by many factors including the strength (current) of the lightning stroke, the ground resistance, and the contact resistance between the victim and the ground.

Damage to equipment and facilities from lightning may be incurred by voltages or currents associated with the strike. Voltages that can cause damage are induced by high electric fields immediately before the strike and the voltage drops in conductors that carry current from the lightning strike. These voltages may be coupled into electronic equipment through direct connection, capacitive coupling, or inductive coupling. The resultant transient voltages easily can produce dielectric breakdown in unprotected, sensitive, solid-state components and can damage conventional electrical components and electrical insulation. Damage from lightning currents includes shattering of poor conductors or nonconductors and almost instantaneous vaporization of small conductors (American Wire Gage (AWG) No. 14 or smaller wire) from short-duration lightning strokes. The currents associated with the longer duration, continuous strokes are more likely to initiate fires in materials adjacent to conductors because of the prolonged period of intense heat (Ref. 9).

Damage from lightning may be prevented by several measures. These include

1. Providing lightning rods connected to low-

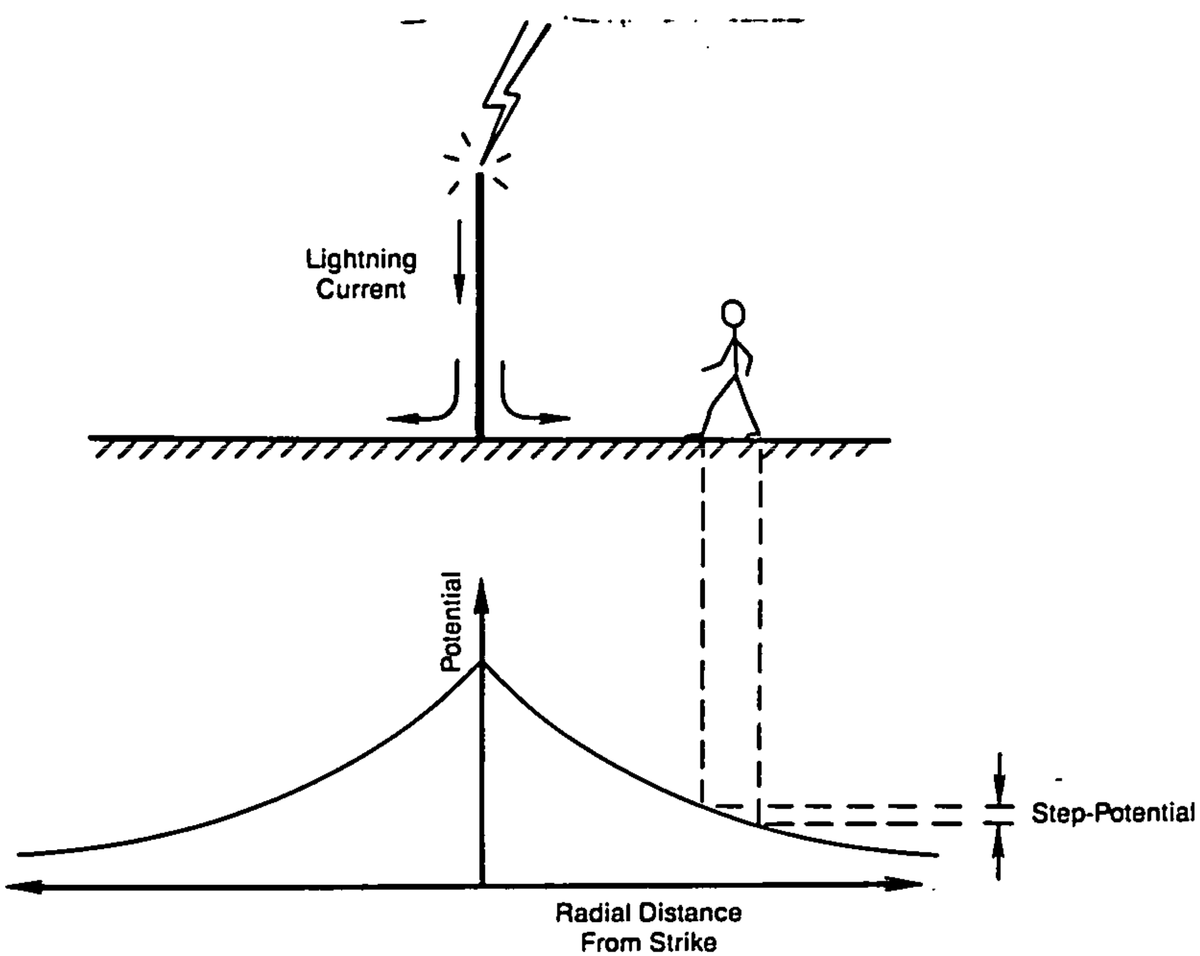


Figure 3-1. Elevated Potential of Ground in Vicinity of Lightning Strike Showing Development of Step-Potential

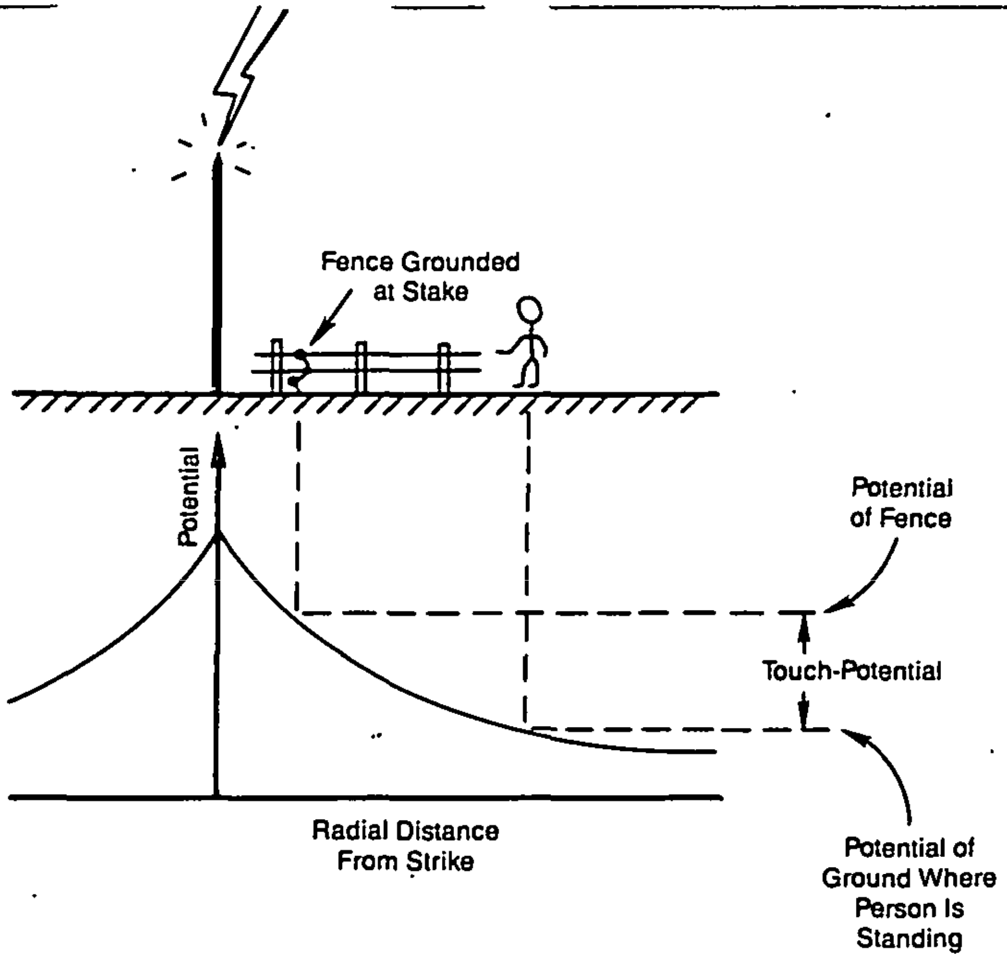


Figure 3-2. Development of Hazardous Touch-Potential on a Conducting Structure That Is Grounded Near Point of Lightning Strike

resistance grounding systems capable of sinking the stroke current without excessive voltage rise at or near the ground connection

2. Adding protective devices at input terminals of electrical apparatus to eliminate overvoltages and to bypass excessive current.

3-2.1.2.2 *Static Electricity*

Static electricity is the accumulation of charge on insulated objects and is usually produced by rubbing, rolling, or sliding contact between dissimilar materials. In comparison to lightning, the amount of charge present is limited and the energy available is not sufficient to cause directly the dramatic damage that often accompanies a lightning stroke. The principal hazard associated with static electricity is the initiation of fire from an electrostatic spark in an explosive atmosphere. Fuel-filling operations can be especially hazardous because both the mechanism for inducing a static charge and the flammable atmosphere are present. A static charge is developed by the flow of fuel out of hoses or metallic pipes. If one of the containers is made from an insulating material or if there is no electrical continuity between the tank being filled and the source, then charges may accumulate until an electrostatic discharge occurs. If a spark is produced at the tip of a hose used to fill a tank, fuel vapors may be ignited. Similar hazards exist for transferring dusts and solvents (Ref. 10).

Electrostatic energy produced by accumulation of charge is not sufficient to damage electromechanical equipment, transformers, etc., used in power distribution systems. However, solid-state electronic equipment is vulnerable unless safe discharge paths are built into the equipment. These paths include shunt resistors or zener diodes connected between sensitive inputs and ground. Static electricity generated in the process of packaging or unpacking of sensitive electronic components may be sufficient to cause damage.

Although some discomfort may be realized from it, an electrostatic shock seldom produces the harmful effects on the body that accompany electrical shock from a power source. Physical harm is more likely to occur from the involuntary or surprise reaction accompanying the unexpected shock, e.g., falls or dropping of heavy objects.

3-2.1.3 Temperature

The temperature of the environment around a piece of equipment usually impacts directly on the internal temperatures of the equipment. This impact affects operation of equipment in the following ways:

1. *Rate of Power Dissipation.* Colder temperatures increase the rate of power dissipation by means of convective cooling; warmer temperatures reduce the effectiveness of convective cooling.
2. *Rigidity of Materials.* Warmer temperatures may soften plastics and other low melting-point materials and thereby reduce the structural integrity of the equipment. Cold temperatures reduce flexibility and ductility of materials and increase the probability of fracture upon impact and breakage with applied stress. Cold temperatures also increase the viscosity of lubricants and increase the modulus of elasticity of materials.
3. *Material Dimensions.* Expansion of materials upon heating and contraction upon cooling can affect component tolerances; these changes, in extreme cases, cause deterioration in component fit, binding or looseness in bearings, and warping of bimetallic components.

The temperature of the natural environment on earth ranges from −88° to 58°C (−126° to 136°F), a span of 146 deg C (262 deg F). The temperature does not vary over the full range at any single location on earth, but it does vary over a 100-deg C (180-deg F) span at some locations. Actual temperatures at specific locations depend on a number of factors including the present and past solar insulation, winds, upwind environment, soil type, ground cover, presence of water, and altitude. The typical temperature range for arctic regions is −62° to 3°C (−80° to 38°F); for the African desert, −3° to 49°C (27° to 120°F); and for the Panamanian Jungle, 22° to 31°C (71° to 88°F) (Ref. 11). Temperature ranges for design of equipment for various ground applications are given in Table 3-1.

Temperatures in an enclosed area, such as an equipment shelter or cabinet, usually will be increased by heat generated from sources in the area and by radiant heat entering the enclosure through windows or being absorbed by external surfaces and conducted to the interior. The temperature in the interior depends on a number of factors including the rate at which heat is absorbed from external radiation, the amount of heat dissipation from other equipment in the shelter, external ambient temperature, the extent of thermal coupling between the inside and outside of the enclosure, the rate of air exchange between inside and outside, and whether or not environmental conditioning systems are used. Estimates of heat increase may be made by techniques discussed in texts on thermal design or heat transfer theory (Ref. 13). Examples of temperature extremes in enclosed areas are given in Table 3-2.

TABLE 3-1
DESIGN TEMPERATURE RANGES FOR VARIOUS APPLICATIONS (Refs. 11 and 12)

Classification	Temperature Range	
	°C	°F
Ground Level Building, Sheltered	−65 to 85	−85 to 185
Ground Level, Semisheltered in Black Boxes, Exposed to Natural Climatic Environments	−65 to 85	−85 to 185
Ground Level, Unsheltered and Exposed to Natural and Induced Environments	−65 to 85	−85 to 185
Ground Level, Semisheltered in Black Boxes, Exposed to Severe Natural and Induced Environments	−65 to 160	−85 to 320

TABLE 3-2
EXAMPLES OF TEMPERATURE EXTREMES IN ENCLOSED AREAS (Ref. 2)

Place	Temperature	
	°C	°F
Inside Tank	60	140
Inside Boxcar	67	153
Airplane Cockpit, Yuma, AZ	84	183
Airplane Cockpit, Edwards Air Force Base, CA	103	217
Typical Outdoor Enclosure in Sun, Intermediate Climate	60	140

3-2.1.4 Corrosive Gases and Aerosols

Many airborne gases and aerosols produced by industrial and natural sources are corrosive to metallic and nonmetallic materials. Discussed in this paragraph are some of the more common airborne corrosive agents that must be considered when designing equipment for use in unprotected environments. More detailed information on effects of corrosive gases and aerosols may be found in Refs. 2, 3, 14, and 15.

3-2.1.4.1 Salt Spray

Salts from oceans and landlocked lakes contain sodium, chloride, magnesium, and sulfate ions. In the atmosphere over and near the ocean, salts comprised of these ions are present in aqueous solution in fogs and sprays, and in the atmosphere as small solid particulates (aerosols). Concentrations of salt in atmospheres near the ocean are 1 to 10 $\mu g/m^3$ (originally specified as 10 to 100 lb/mi^3 in Ref. 2), varying greatly with meteorological conditions. Storms can increase concentrations of salt by an order of magnitude greater than these values. However, these concentrations decrease rapidly with increasing distance inland.

Salts combined with moisture increase corrosion by providing a highly conductive solution suitable for chemical, ion-exchange processes of corrosion. Also certain salts, when dissolved in water, form acidic or alkaline solutions that attack metals on contact. Salt also attacks nonmetals. Salt crystallization in concrete can break down the aggregate matrix and structurally weaken the concrete surface. Degradation of some paints and coatings is accelerated by salt spray. Deposits of salt on ceramic insulators can produce leakage paths leading to arc-over in high-voltage systems.

3-2.1.4.2 Ozone

Ozone (O_3) is gaseous oxygen with a molecular composition of three oxygen atoms instead of the usual two. It is a reactive oxidant produced by photochemical reactions in polluted air, intense ultraviolet radiation, and electrical discharge. Atmospheric concentrations typically range between 0 and 0.1 parts per million (ppm), with higher values found in the afternoon downwind of urban centers or other industrial complexes.

Ozone attacks elastomers by reacting with the surface to produce a brittle coating, which is easily cracked. Flexing of the elastomer breaks the coating, exposes new material, and causes propagation of the cracks to the interior of the material. Ozone also combines with dyes and surface pigments to cause fading due to bleaching. Ozone also oxidizes metals. However, the oxide coating for iron produced by ozone is protective and prevents further oxidation of the base metal provided the oxide is intact. In severe conditions, such as locations adjacent to ultraviolet sources or arcs, the high concentration of ozone will induce corrosion of metals beyond the surface coating.

3-2.1.4.3 Sulfur Compounds

Gaseous sulfur compounds found in the atmosphere include sulfur dioxide (SO_2), sulfur trioxide (SO_3), and hydrogen sulfide (H_2S). These compounds are by-products of the combustion of fuel containing sulfur. Sulfur dioxide and sulfur trioxide, when dissolved in water, react to form sulfurous acid and sulfuric acid, respectively. Both acids cause a breakdown in the protective oxide films that form on certain metals, such as aluminum. Hydrogen sulfide causes the familiar tarnishing of silver in humid atmospheres.

SO_2 is a necessary ingredient in the corrosion process of iron. Corrosion of iron or steel requires the presence of oxygen, water in liquid form (or at high humidity), and sulfuric acid. The sulfuric acid, produced by catalytic oxidation of SO_2 from the atmosphere with moisture on the metallic surface, attacks the base metal. Temperature affects the process only to the degree that it affects surface "wetness". Warm surfaces that are kept dry and surfaces in contact with frozen moisture do not corrode significantly (Ref. 16). Low concentrations of sulfur compounds are sufficient to enable corrosion processes to occur in the presence of moisture. Concentrations of only 0.025 ppm were sufficient to cause an 11% weight reduction in test panels with dimensions of 100 × 150 × 0.89 mm (4 × 6 × 0.035 in.) over a one-year period. Raising the concentration to only 0.12 ppm increased the weight loss to about 17% of the initial weight, which is an approximate increase of 50% (Ref. 3). Fortunately, ambient concentrations of sulfur compounds are low—background SO_2 values of 0.2 to 1 parts per billion (ppb) and background H_2S values of only 4.5 ppb. Higher concentrations may be found downwind of industrial plants that produce emissions from combustion.

3-2.1.4.4 Oxides of Nitrogen

Nitrous oxide (NO) and nitric oxide (NO_2) are gaseous compounds that are produced by fixation of atmospheric nitrogen during high-temperature combustion. Both are found in urban atmospheres at concentrations around 50 ppb. However, background levels are significantly lower—4 ppb for NO_2 and 2 ppb for NO over land—for locations between latitude 65 deg S and 65 deg N. Even lower concentrations are found outside this region. NO_2 is a corrosive oxidant but, at normal concentrations, does not contribute to material degradation as much as sulfur compounds and ozone do.

3-2.1.4.5 Susceptibility of Electrical Systems

The effect of corrosive gases and aerosols on electrical components may affect adversely electrical systems in several ways. Negative efforts include

1. Increased contact resistance due to tarnishing of silver by H_2S
2. Reduced strength of structural members in cases of moderate or severe corrosion
3. Reduced current capacity and increased resistance of corroded conductors due to reduction in conductor dimensions
4. Affected component fit and movement of rotating or sliding mechanical parts due to changes in dimensions and surface conditions caused by corrosion
5. Reduced surface resistance of insulating materials due to deposition of films.

Electrical components susceptible to gaseous or aerosol corrosion include high-voltage insulators, switchgear, and other outdoor equipment subject to structural damage. Susceptibility of these components can be minimized if proper corrosion control measures are implemented. Degree of damage from gaseous or aerosol corrosion is influenced by several environmental conditions, i.e.,

1. *Temperature*. Temperature directly affects corrosion reaction rates. More importantly, temperatures affect condensation of moisture on equipment, which more directly affects the corrosion process.

2. *Moisture or Humidity.* Typically, moisture is required for the corrosion process. In some forms, however, moisture may reduce corrosion, e.g., the cleansing effect of rain may remove corrosive films from material.

3. *Air Movement.* Winds disperse atmospheric pollutants and prevent the settlement of particulate matter.

4. *Presence of Voltage.* The presence of voltage on conductors can increase or decrease corrosion by affecting the natural galvanic action that causes corrosion where dissimilar metals are in contact.

3-2.1.5 Sand and Dust

Airborne particulate matter—sand and dust—is the most damaging environmental factor for military equipment. Sand and dust are defined as small, hard particles. Particles with diameters between 150 and 800 μm are defined as sand; dust particles have diameters less than 150 μm. Although damage from particles certainly can occur when the particles are mechanically introduced into mechanical or electrical apparatus, a greater concern is damage from the airborne particles because of the difficulty of preventing their entry into the equipment.

Sand and dust are comprised of minerals from the crust of the earth that are broken and ground into small particles by oceans, glaciers, and meteorological processes. The particles may become airborne through several mechanisms including vehicular traffic (especially fast moving or large ground vehicles and helicopters), meteorological conditions such as high winds and sand or dust storms, and industrial activity that yields particulate matter as an effluent. Sand—because of the large mass of the individual particles—tends to settle from the atmosphere quickly and, therefore, requires substantial aerodynamic force to remain airborne. Consequently, sand is found typically very near vehicular traffic and at low altitudes during storms. Smaller dust particles, i.e., $< 2\ \mu m$ $(0.08 \times 10^{-3}$ in.), have sufficiently low mass that even residual motions of apparently still air are sufficient to keep them airborne. However, these permanently airborne particles make up only a small portion of the typical dust concentration; usually less than 3% of the total mass are particles in this range. Most of the mass of a dust cloud is comprised of particles with diameters between 3 and 150 μm $(0.1 \times 10^{-3}$ and 5.9×10^{-3} in.). The distribution based on the number of particles is skewed toward the smaller diameters due to the reduced mass of the lower particles. Particles smaller then 3 μm $(0.1 \times 10^{-3}$ in.) make up 22% of the total number of particles in a typical dust cloud produced by tanks at Ft. Knox, KY (Ref. 17). The distribution of particle size is shown in Fig. 3-3.

The total concentration of dust particles is quite variable and depends on the meteorological conditions (especially wind and moisture), and the number, characteristics, and speed of vehicles stirring up the dust. Typical

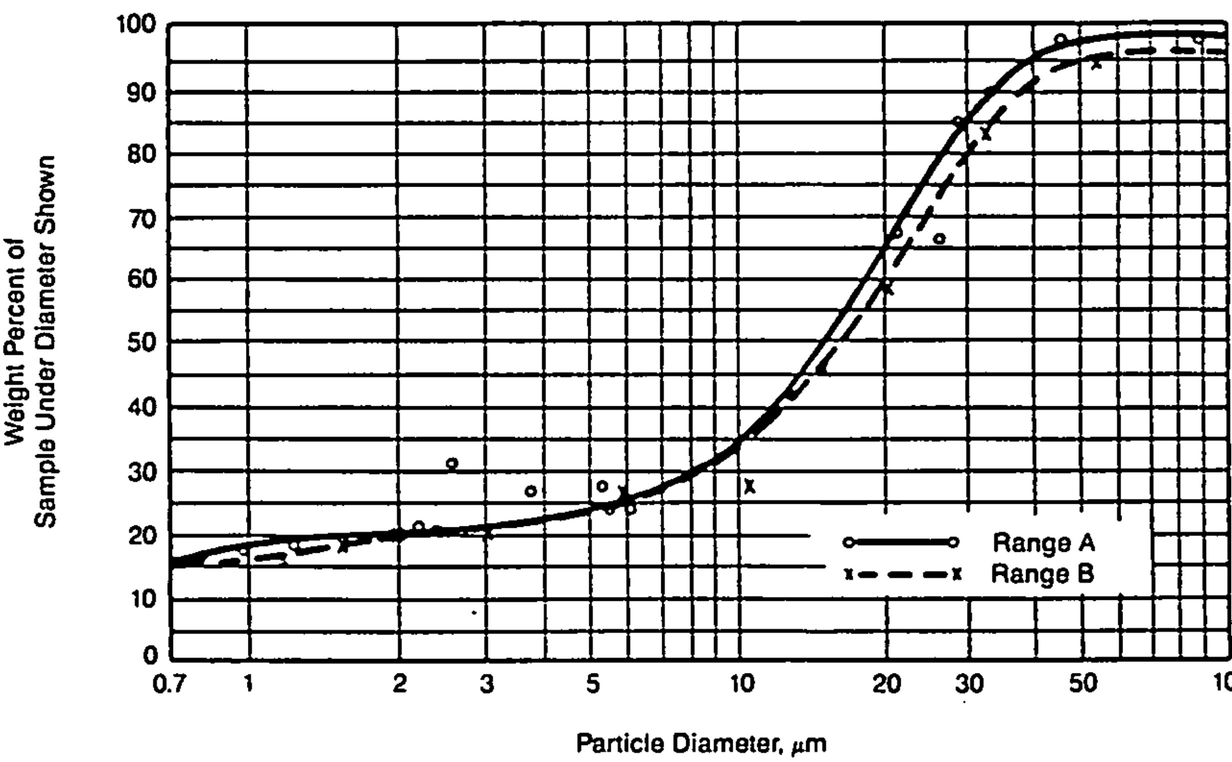


Figure 3-3. Particle Size Distributions of Dust Collected at Air Inlet of Army Tanks at Two Tank Ranges in Ft. Knox, KY (Percent Within Range) (Ref. 3)

background concentrations of dust for rural, metropolitan, and industrial environments are given in Table 3-3. Concentrations in the vicinity of vehicles are higher and reach 3.5 g/m^3 (originally specified as 100 mg/ft^3 in Ref. 3) in the vicinity of an M48 tank in the desert.

TABLE 3-3
DUST CONCENTRATIONS IN VARIOUS REGIONS (Refs. 3 and 18)

Region	Average Dust Concentration	
	μg/m^3	μg/ft^3*
Rural and suburban	46 to 113	1.3 to 3.2
Metropolitan	113 to 459	3.2 to 13.0
Industrial	459 to 1713	13.0 to 48.5

*Mixed units as originally presented in Ref. 3.

The effects of sand and dust on equipment are quite varied and depend upon the equipment involved, the type of particle, and how the particles come in contact with the equipment. Types of damage are

1. *Erosion.* Wind-borne sand can remove matter and thus ruin finished surfaces, remove paint, and in severe cases can deteriorate structural srength due to eroded structural supports. Moving parts, e.g., turbine blades and helicopter rotors, are especially vulnerable to sand erosion because of the substantial velocities at which the particles impact the surfaces.

2. *Abrasion.* Hard particles of sand falling in gears, on rotating shafts, or within other close-fitting, moving parts cause rapid wear to containing parts. The presence of lubricating oils or grease causes the sand to adhere to the surfaces longer and thereby increases the amount of damage from the sand.

3. *Corrosive Effects.* Although sand and dust usually are nonreactive and do not corrode materials directly, their long-term presence on surfaces may accelerate corrosion through absorption and retention of corrosive gases and moisture necessary for chemical reactions that produce corrosive acids.

4. *Electrical Arc-Over.* An accumulation of dust on high-voltage insulators provides a conductive path during high-humidity conditions. Moisture accumulating on the dust layer dissolves compounds that provide the ions necessary for conduction. In high-voltage applications, the conductive path may result in a sustained arc, which must be extinguished by removal of the applied voltage.

5. *Thermal Insulation.* The accumulation of dust on electrical apparatus provides an insulating layer, which reduces the heat dissipation capacity of the underlying components. Components vulnerable to heat include electronic motors, transformers, electronic equipment, and load resistors (load banks).

6. *Paint Contamination.* Dust that falls on paint while it is drying can provide a wicking path through the paint for corroding acids and thus negate the protection afforded by the paint.

7. *Limited Visibility.* Airborne sand and dust can limit visibility when concentrations are sufficiently high. Table 3-4 presents visibility limitation relative to concentrations of dust generated by moving vehicles. In most cases of limited visibility, the effect is temporary and does not jeopardize safety. However, when a critical operation that requires visual monitoring is being performed, an ill-timed dust cloud could create a serious hazard, e.g., when working around exposed energized conductors.

TABLE 3-4
VISIBILITY IN DUST (Refs. 3 and 19)

Dust Concentration		Visibility	
mg/m^3	mg/ft^3*	m	ft
4	0.1	no effect	no effect
7	0.2	no effect	no effect
8.16	0.231	15	50
8.30	0.235	15	50
30.7	0.87	3	10
85.1	2.41	3	10
89.3	2.5	0	0

*Mixed units as originally presented in Refs. 3 and 19.

8. *Electrical Insulation.* Most sand and dust particles are nonconducting. Settlement of particles on electrical relay or switch contacts may prevent electrical continuity between contacts and may cause faulty operation of equipment.

3-2.1.6 Solar Radiation

Radiation incident on the earth from the sun is primarily broadband radiation in the infrared, visible, and ultraviolet regions. Most of the energy (99.9%) lies in the spectrum between 100 nm and 100μm. The nominal intensity of solar radiation at the top of the atmosphere of the earth is 1.353 W/m^2. This intensity varies about 6% over a one-year period due to regular annual changes in the distance between the earth and sun. The spectrum of this radiation resembles that of a blackbody radiator with a temperature near 5900 K (10,620 R). This spectrum is illustrated by the solid black line on the plot in Fig. 3-4.

Only about 53% of the solar radiation incident on the earth reaches the ground. Of this amount, 31% is direct radiation and 22% is diffuse radiation. The remaining radiation incident on earth is reflected back into space by the atmosphere or is absorbed by clouds and atmospheric gases. The energy budget is described concisely in Table 3-5.

The solar radiation at high altitudes is the highest at the latitude corresponding to the solar declination at true

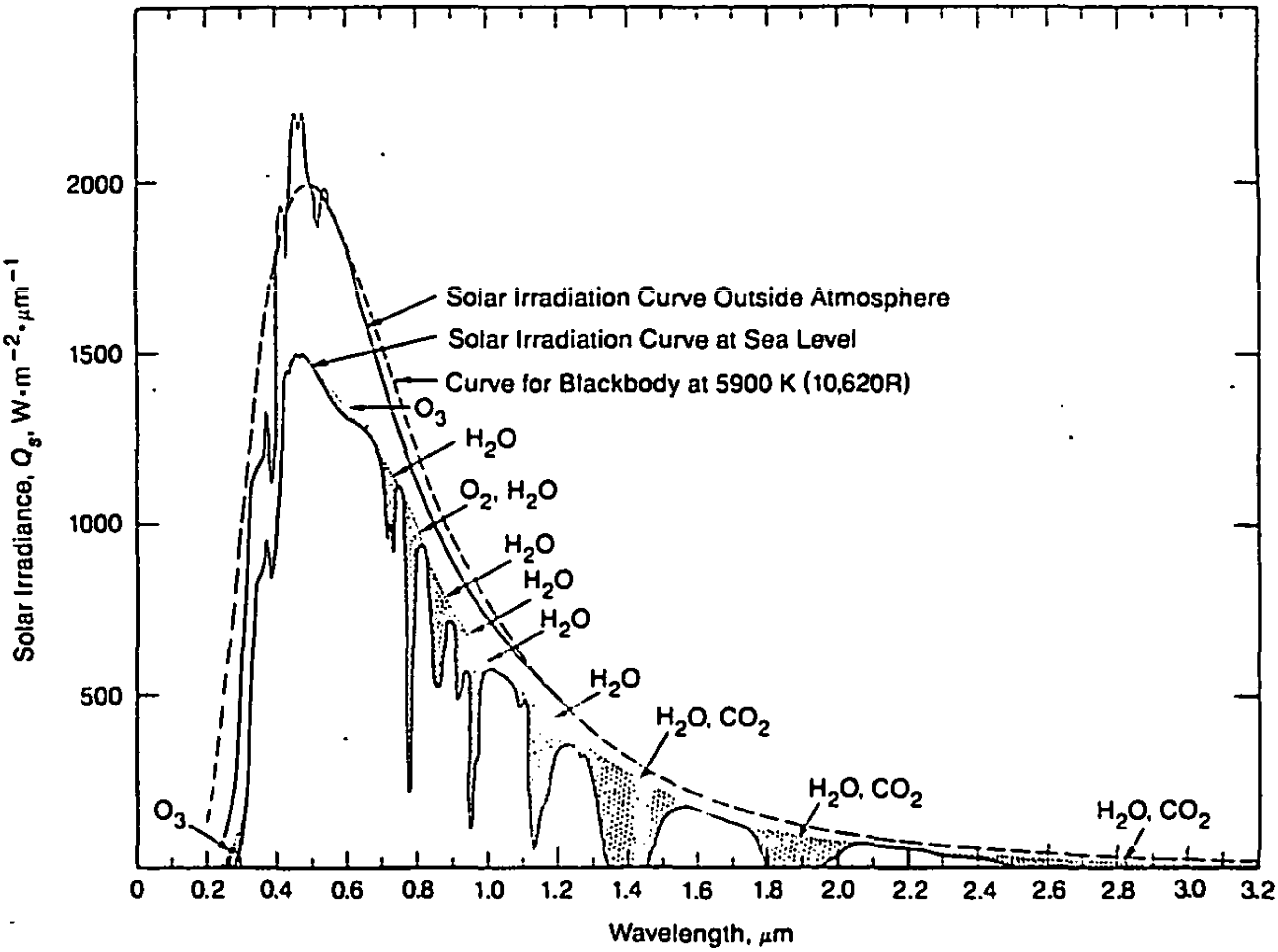


Figure 3-4. Spectral Distribution of Solar Energy With and Without Atmospheric Absorption (Refs. 2 and 20)

TABLE 3-5
DISPOSITION OF SOLAR ENERGY
(Refs. 2 and 21)

	Fraction of Total
Reflected or scattered back into space:	
By clouds	0.24
By air molecules, dust, water vapor	0.06
Absorbed:	
By clouds	0.03
By air molecules, dust, water vapor	0.14
Reaches earth:	
As diffuse sky radiation	0.22
As direct beam radiation	0.31
Total solar energy available at top of atmosphere	1.00

solar noon, i.e., the location on earth where the sun passes directly overhead. Nominal insulation values are dependent on the typical absorption of the atmosphere at that location and are determined by the composition of the atmosphere and the cloud cover. At times other than solar noon, solar insulation values are less than the peak value for two reasons. First, the sun is not incident perpendicular to a level plane at the surface of the earth, and second, radiation must travel along a longer path through the atmosphere of the earth. At other latitudes the diurnal peak solar insulation is also reduced because of the non-normal angle of incidence and the increased depth of the atmosphere. In addition, the cumulative quantity of insulation over a diurnal cycle in the winter hemisphere is reduced because of the shortened days.

The spectrum of solar radiation received at the ground is also shown in Fig. 3-4. The "gaps" in this spectrum correspond to selective absorption of certain regions of the spectrum by various atmospheric constituents, such as moisture, ozone, and CO_2. The peak value is quite variable depending on the meteorological and atmospheric conditions, the time of day, season of year, and location on earth. In the United States the daily mean values range between 240 and 390 W/m^2 (500 and 800 langleys/day) in the month of June.

Effects of solar radiation on material and equipment (and on the operation of the equipment) include photochemical degradation of materials, radiant heating, and common sunburn to workers. The photochemical degradation generally is bleaching, discoloration, or embrittlement of various materials due to long-term exposure to sunlight, especially to the ultraviolet radiation in sunlight. The tensile strength of fibers and textiles is reduced from exposure to sunlight directly from absorption of the radiation and indirectly from photochemically produced oxidants. Dyes used for textile coloring are bleached, and the base material is yellowed. Paper suffers similar degradation—embrittlement, weakening, and yellowing of the paper as well as bleaching of printing dyes. Many plastics—unless compounded for exposure to sunlight—also undergo discoloration, embrittlement, loss of strength, degraded electrical properties, and cracking due to ultraviolet-induced oxidation. Typical problems associated with the use of plastics in sunlight are darkening of the plastic material used for windows or viewing ports and embrittlement of insulation used on wire. Damage may be minimized either by selecting a plastic material that is inherently immune to sunlight-induced degradation or by adding compounds to the plastic that absorb the radiation and convert it to heat. Although most synthetic elastomers are resistant to sunlight, natural rubber and styrene-butadiene rubber (SBR) are subject to cracking, crazing, checking, and discoloration. Information on the selection of compounds for use where sunlight exposure is unavoidable is given in Refs. 2, 22, and 23.

3-2.1.7 Pressure

The pressure of the environment refers to the pressure exerted over the entire surface of an object by the weight of the atmosphere or water above it. The pressure produces a force that is constant over the surface and normal to the surface at every point. Hence the pressure affects only objects that have sealed volumes whose pressure may differ from the pressure of the environment. (Volumes that are not enclosed totally would be filled with air or water at a pressure equal to the outside and, consequently, would not experience any force due to differential pressure.) A representative pressure profile is described in Table 3-6. This table presents nominal atmospheric pressures for altitudes up to 16 km at 45 deg N latitude in both January and July. The difference in pressure values is brought about by differences in density due to seasonal temperature variations. Published data on other typical atmospheres can provide designers with expected pressure, temperature, and density data over a wide range of altitudes (see Refs. 24 and 25). Information about expected pressures for equipment at high elevations, such as in mountainous terrain, is pertinent to the design of power equipment.

The actual pressure changes daily based on current meteorological conditions, season of the year, and location on the earth. The pressure referenced to sea level

TABLE 3-6
PROPERTIES OF SUPPLEMENTAL REFERENCE ATMOSPHERES TO 16 km
(Refs. 2 and 20)

Geometric Altitude, km	Pressure Midlatitude 45 deg N			
	January		July	
	Pa	in. Hg	Pa	in. Hg
0	101.800	30.0615	101.350	29.9286
1	89.734	26.4984	90.220	26.6419
2	78.975	23.3213	80.159	23.6709
3	69.376	20.4867	71.043	20.9790
4	60.813	17.9581	62.806	18.5466
5	53.132	15.6899	55.362	16.3483
6	46.275	13.6650	48.663	14.3702
7	40.164	11.8604	42.640	12.5216
8	34.733	10.2566	37.235	10.9955
9	29.928	8.8377	32.402	9.5683
10	25.684	7.5895	28.090	8.2950
11	21.991	6.8939	24.255	7.1625
12	18.825	5.5590	20.858	6.1594
13	16.109	4.7570	17.857	5.2732
14	13.780	4.0692	15.251	4.5036
15	11.784	3.4798	13.025	3.8463
16	10.075	2.9751	11.125	3.2852

varies with a standard deviation of slightly over 2000 Pa (20 millibar (mb)) in the fall-winter-spring period over the region between the equator and 40 deg N latitude. Variation in the summer is somewhat less, with very small variations noted in the arctic region. Extremes in pressure occur during hurricanes, typhoons, and tornados. A low value of 87.7 kPa (25.90 in. Hg) was estimated for the eye of Typhoon Ida. High values in excess of 106 kPa (31.30 in. Hg) have been reported in high-pressure systems (Refs. 2 and 26).

Pressure increases with the depth underwater. The pressure P may be estimated by

$$P = \rho g d + P_0, \text{ Pa} \qquad (3\text{-}1)$$

where

ρ = density of water, kg/m^3
g = acceleration due to gravity, 9.8 m/s^2
d = depth in water, m
P_0 = barometic pressure at sea level, Pa.

In English units, the equation becomes

$$P = \frac{\rho d}{144} + P_0, \text{ lb/in}^2$$

where

ρ = density of water, lb/ft^3
d = depth in water, ft
P_0 = barometric pressure at sea level, lb/in^2.

The most important effects of decreased air density are reduced heat transfer, reduction in breakdown voltage, lower boiling temperatures of liquids, and increased ignition temperature of fuels. The pressure never changes radically under atmospheric conditions; therefore, most of these effects are not significant for equipment used at ground level. Only reductions in heat transfer and breakdown voltage are discussed further. For more information on effects due to changing pressure, see Ref. 2.

Reduction in heat transfer occurs as a result of an absence of a sufficient number of molecules transporting heat energy and is proportional to the reduction in pressure. Hence, for given air flow rates and temperatures (of both the air and the object being cooled), the rate of cooling is directly proportional to the absolute pressure.

The reduction in electrical breakdown at lower pressures is somewhat more complex. As the air density decreases with decreasing pressure, the breakdown voltage decreases until the effect of diminishing electron density from the rarefied gas becomes significant. Then the breakdown voltage increases until, at vacuum, the breakdown from gas conduction is no longer possible. The pressure-breakdown voltage relationship for gases is usually expressed graphically in Paschen's curves. Examples of Paschen's curves showing the breakdown voltage of five gases in uniform fields are shown in Fig. 3-5. Note that in Paschen's curves, the breakdown voltage is plotted against the pressure-spacing product because the electric field (voltage divided by spacing) sufficient to cause breakdown is dependent on the spacing. This effect is due to the greater number of free electrons that are present in the larger volume between more widely spaced electrodes. The curves shown in Fig. 3-5 are for uniform electric fields, i.e., the electric field in the volume between two large, flat plates. In practice, the voltage required to initiate breakdown will depend on geometry and will be lower because of the concentration of fields at corners or edges of electrodes.

3-2.2 NATURAL ENVIRONMENTS

Environments on the earth may be categorized into four climates—hot-wet, hot-dry, intermediate, and cold. Each of these climates may be described by a range of values for each of the environmental characteristics described in par. 3-2.1. Table 3-7 lists the climates and the more important characteristics of each. Each of the climates is discussed briefly in the four subparagraphs within this paragraph. The various climates are discussed in more detail in Ref. 1.

3-2.2.1 Hot-Wet Climates

The hot-wet climate, also referred to as the tropical climate, is typically found within 25 deg of the equator and covers all land areas except deserts. As the name implies, these areas are characterized by high temperatures, high humidities, and frequent precipitation—all of which provide an environment conducive to the growth of lush vegetation. Vegetation in established jungles consists of large trees whose tops join to produce a "canopy" that restricts the exchange of air from within the jungle with the air above it and shields the jungle floor from sunlight.

Temperatures in the hot-wet climates remain relatively high and constant throughout the year. Average temperatures for the warmer months in a typical tropic climate are usually 32°C (90°F) with cooler seasons only to 6 to 8 deg C (11 to 14 deg F) lower. Diurnal variations are reasonably large—3 to 14 deg C (5 to 25 deg F). Temperatures under the jungle canopy vary somewhat less. Daily minimum temperatures under the canopy are essentially the same as those in clear areas. However, at midday the temperature under the canopy is typically 4 deg C (7 deg F) lower than temperatures in the clearings.

The average solar radiation is greater than it is in most of the other climates. However, peak intensities are lower because of absorption by moisture in the atmosphere. The canopy forms a cap, which traps the atmosphere below it and prevents the passage of solar radiation to the ground below. The high humidity and the lack of sunlight keep the jungle floor moist and thereby promote growth of bacteria and fungi, which inhibit the growth of vegetation on the jungle floor.

There are several equipment design considerations unique to this environment. The rapid growth of vegetation may interfere with the structures and power lines; consequently, frequent brush clearing may be necessary. The high humidity promotes the growth of fungus on susceptible materials and may cause loss of strength in materials that tend to absorb moisture. Corrosion of

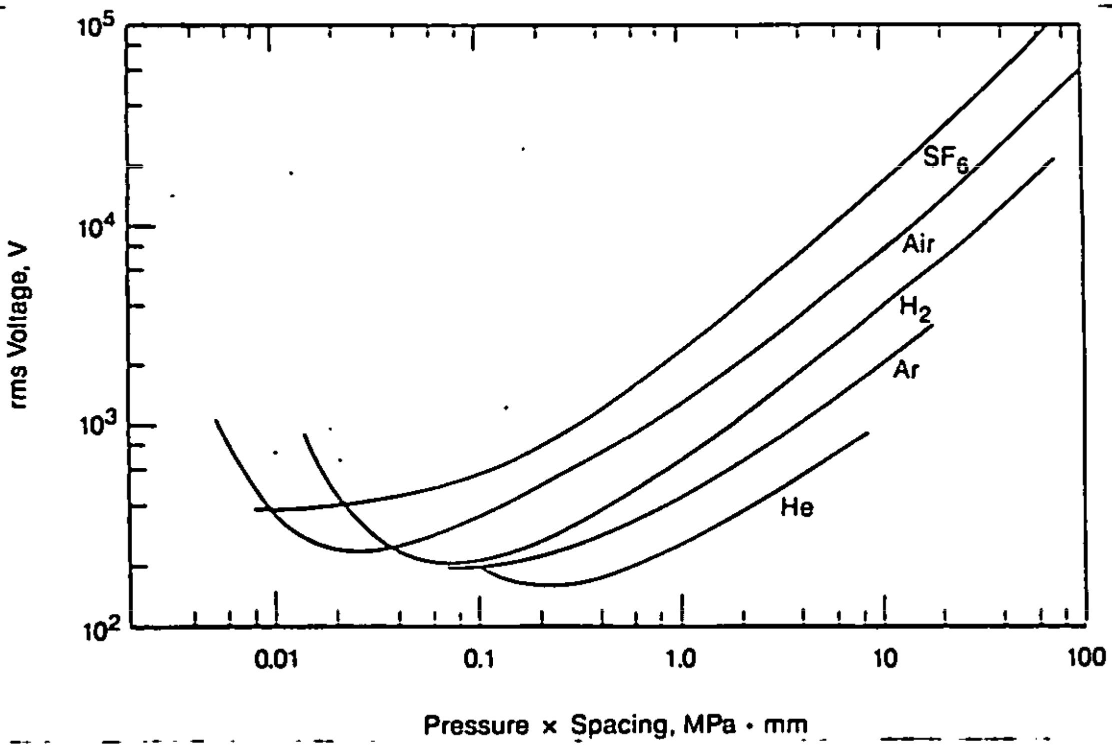


Figure 3-5. Pressure-Spacing Dependence of Dielectric Strength of Gases (Paschen's Curves) (Ref. 9)

metals is another effect of the high moisture; corrosion is worse in tropical areas near salt water, e.g., islands. The accumulation of moisture in soil impairs construction of firm foundations for buildings and can make wheeled or tracked vehicle travel difficult.

3-2.2.2 Hot-Dry Climates

Hot-dry climates are sometimes called desert climates, but the term is somewhat inaccurate because the desert may be a cold region as well. Hot-dry climates are found near the equator where the meteorological conditions and terrain produce high temperatures and low humidity. Desert regions are found in North Africa, West Pakistan, India, Arabian Peninsula near the Red Sea, the southwestern region of the United States, and Northern Mexico.

Typical characteristics of the hot-dry climate are hot days, wide diurnal temperature variations, low humidities, and intense solar radiation. Visibility is generally good except during windy conditions when blowing sand and dust obscure vision. The low humidity results in generally clear skies, which allow both a high inward energy flow during the daytime and a high outward flow at night, and thereby causes the rapid cooling of the desert areas during the evening. Temperatures in the desert frequently exceed 38°C (100°F) and in many cases have daily averages that exceed 38°C (100°F). Temperatures during cooler seasons are significantly lower.

Wind is typically 6 to 11 km/h (3.7 to 6.8 mph). However, high winds that blow sand to produce an abrasive and eroding atmosphere will sometimes occur. Another problem introduced by blowing sand is the accumulation of static on surfaces impacted by the sand. If appropriate discharge paths are not provided within electrical equipment, damage may be induced.

In addition to the damage from mechanical abrasion and electrostatic discharge, equipment is susceptible to overheating if operated in direct sunlight in this environment. Adequate cooling or shielding must be provided to prevent damage.

3-2.2.3 Intermediate Climate

Intermediate climate is the "other" climate, which includes all areas of the world that do not fall in the hot-wet, hot-dry, or cold climates. Intermediate climates are moderate in temperature and rainfall and, as such, generally do not set the requirements for equipment.

Temperatures in the intermediate climates range from −21° to 43°C (−5° to 110°F), although variations over this range typically will not be found in one location within one season.

Humidities are typically 20 to 100%—again, usually without transitions from one end of the range to the other at any given location within a season.

TABLE 3-7
SUMMARY OF DIURNAL EXTREMES OF TEMPERATURE, SOLAR RADIATION, AND RELATIVE HUMIDITY (Refs. 1 and 27)

Climate Category	Climatic Subcategory	Operational Conditions			Storage and Transit Conditions	
		Ambient Air Temperature, °C (°F)	Solar Radiation, W/m^2(cal·cm^{-2}·min^{-1})	Ambient Relative Humidity, %	Induced Air Temperature, °C (°F)	Induced Relative Humidity, %
Hot-Wet	1 Wet-Warm	Nearly Constant 24 (75)	Negligible	95 to 100	Nearly Constant 27 (80)	95 to 100
	2 Wet-Hot	26 to 35 (78 to 95)	0 to 1130 (0 to 1.62)	74 to 100	32 to 71 (90 to 160)	10 to 85
	3 Humid-Hot Coastal Desert	29 to 38 (85 to 100)	0 to 1130 (0 to 1.62)	63 to 90	32 to 71 (90 to 160)	10 to 85
Hot-Dry	4 Hot-Dry	32 to 52 (90 to 125)	0 to 1130 (0 to 1.62)	5 to 20	32 to 71 (90 to 160)	2 to 50
Inter-mediate	5 Intermediate Hot-Dry	21 to 43 (70 to 110)	0 to 1130 (0 to 1.62)	20 to 85	21 to 63 (70 to 145)	5 to 50
	6 Intermediate Cold	−21 to −32 (−5 to −25)	Negligible	Tending Toward Saturation	−23 to −34 (−10 to −30)	Tending Toward Saturation
Cold	7 Cold	−37 to −46 (−35 to −50)	Negligible	Tending Toward Saturation	−37 to −46 (−35 to −50)	Tending Toward Saturation
	8 Extreme Cold	−51 to −57 (−60 to −70)	Negligible	Tending Toward Saturation	−51 to −57 (−60 to −70)	Tending Toward Saturation

3-2.2.4 Cold Climates

Cold climates, often referred to as arctic climates, are characterized by temperatures that remain below freezing for periods sufficiently long to allow significant accumulation of frozen precipitation (usually snow). Cold climates are further subdivided into subclassifications of intermediate cold, cold, and extreme cold. These subclassifications are based on a 1% probability over a 6-h period of the occurrence of temperatures that do not exceed −25°, −50°, −70°C, respectively, (−13°, −58°, or −94°F). In extreme cold zones, melting does not occur for periods lasting 4 to 8 months.

Cold climates result from either a low level of solar insulation (typical of the polar regions) or a depression in air temperature from adiabatic expansion at high elevations. Consequently, the cold climates are found in both polar regions; on the Greenland ice dome; and in the mountainous areas in western North America, Europe, and Asia. Recorded mean temperatures for each of these regions are given in Table 3-8. Seasonal variation in temperature increases with increasing latitude, with the largest variations occurring at the poles.

Precipitation in cold climates occurs primarily in the form of snow, although the regions bordering intermediate climates may have freezing rain. Mountain ranges that lie perpendicularly to the inland flow of moist air from oceans receive substantial snowfall due to the cooling of air as it rises to pass over the mountains. Examples are the Himalayas, the Sierra Nevada, the Cascades, and the mountain ranges in Alaska. Typical annual snowfall for intermediate cold climates is 1 to 1.5 m (40 to 60 in.). However, annual accumulations are usually only 0.25 to 0.5 m (10 to 20 in.) because of the packing, melting, and refreezing of snow. Snowfall is somewhat less in extreme cold regions. However, the annual accumulation is about the same because of the lack of melting. Structures for use in these climates must be able to support the weight of snowfalls or be designed to shed the snow. Typical densities of newly fallen dry snow are 70 to 100 kg/m^3 (4.4 to 6.2 lb/ft^3) with higher densities of 450 kg/m^3 (28.1 lb/ft^3) for old, wet snow. Snow that has been compressed for a period of time can reach densities of 830 kg/m^3 (51.8 lb/ft^3).

TABLE 3-8
COMPARATIVE TEMPERATURES FOR COLD CLIMATIC CATEGORIES (Ref. 1)

Climatic Category	Station	Mean Temperature, °C (°F)		
		Coldest Month	Year	Annual Range
Lowland Regime				
Intermediate Cold	Peoria, IL	−4 (24)	11 (51)	11 (52)
	Bucharest, Romania	−3 (26)	11 (51)	9 (48)
	Peking, China	−4 (24)	12 (53)	13 (55)
Cold	Harbin, China	−19 (−2)	3 (38)	23 (74)
	Moose Factory, China	−20 (−4)	−1 (30)	19 (66)
Extremely Cold	Yakutsk, Siberia	−37 (−35)	−11 (12)	44 (112)
	Ft. Yukon, AK	−29 (−21)	−7 (20)	37 (99)
	Eureka, Canada	−39 (−38)	−19 (−3)	30 (86)
Highland Regime				
Intermediate Cold	Lake Moraine, CO 3050 m (10,000 ft)	−7 (20)	2 (36)	14 (57)
Extremely Cold	Camp Century, Greenland 1830 m (6000 ft) (1961)	−42 (−44)	−25 (−14)	24 (75)

Frozen moisture other than snowfall may accumulate. Ice may accumulate as a result of freezing rain (clear, glaze ice), deposition of frozen cloud or fog (rime), or deposition of condensation in still air equivalent to dew in temperate regions (hoarfrost). The negative effects of ice on equipment operation are clogged ventilation openings, restricted mechanical movement, exertion of pressure on opposite sides of crevices, and added weight to suspended structures.

Solar radiation in the cold environments ranges from near zero at the poles during winter to reasonably high average values during summer because of the increased daylight. The visible perception of solar radiation is increased by the highly reflective snow and ice surfaces. Visibility is reduced by the whiteout phenomenon, in which illumination of surfaces by sunlight diffused through cloud cover obscures the horizon line, surface features, and textures.

In cold regions the soil may be frozen year round and in some cases may melt on the surface but remain frozen underneath. In regions where melting does occur, some difficulty may be encountered in establishing foundations for structures because of the shifting of the soil that occurs between melting and freezing. Because of the poor electrical conductivity of ice, adequate ground or earth connections may be difficult in regions where frozen soil or accumulated snow is encountered.

3-2.3 BATTLEFIELD ENVIRONMENT

The nature of the battlefield environment depends on the effectiveness of the enemy whose objective is to make the environment as severe as possible. The specific environment of the battlefield may be described by the environmental factors of the climate of the location of the battlefield with the additional induced environmental factors due to the presence of active military forces. The extent of the induced factors is difficult to predict because they depend entirely on the level of, nature of, and proximity to military operations. A brief discussion of the induced environmental factors found on the battlefield follows.

3-2.3.1 Fragments and Projectiles

High-speed projectiles, including small arms fire, fragments from exploding artillery rounds, and debris scattered from mortar rounds pose many threats to electrical equipment. Possible damage includes physical penetration of the equipment, deformation of the structural members of machines, breakage of rigid insulation, and introduction of unintentional circuit paths by conductive debris.

3-2.3.2 Chemicals

Gaseous chemicals found in the battlefield environment include combustion products and nuclear, biological, and chemical (NBC) agents. Combustion products include those associated with artillery projectiles, small rockets and missiles, small arms fire, as well as the exhaust from diesel-powered vehicles. NBC materials include solid dusts, liquids (mists and rains), and gases. NBC materials are far more hazardous to personnel than to equipment. More significant are the effects of decontaminants, which are necessary to remove toxic residues from equipment. Decontamination agents are supertropical bleach (STB) and Decontaminating Solution No. 2 (DS2). STB is corrosive to metals and damaging to fabrics; DS2 is corrosive to aluminum, cadmium, tin, and zinc (Ref. 28).

3-2.3.3 Overpressure

Pressure waves created by artillery that impact flat surfaces may be sufficient to collapse enclosures or buildings onto equipment. In the nuclear battlefield, the problem is extreme. Major structural damage to buildings, vehicles, and utilities is induced by overpressures as small as 3.4 to 21 kPa (0.5 to 3 psi). Overpressures in excess of 21 kPa (3 psi) may be induced within a 6-km (19,700-ft) radius of a 100-kT nuclear blast.

3-2.3.4 Electromagnetic Pulse (EMP)

The EMP produced by nuclear detonation can disrupt the operation of most electronic systems unless specific protection is provided, e.g., shielding. EMPs at ground level on the order of 10 kV/m have been measured during high-altitude tests. In a 1961 test, the electric service in Hawaii was severely disturbed by a high-altitude nuclear test 1000 km (600 mi) away (Ref. 29).

3-2.3.5 Ionizing Radiation

Radiation is the direct product of battlefield nuclear events. Small levels, less than 500 rad, are sufficient to upset sensitive electronic components, such as very large scale integration (VLSI) circuits. Damage to microprocessors and memory devices would occur at levels below the levels that incapacitate personnel.

3-3 SYSTEM DESIGN CHOICES AND TECHNICAL CONSIDERATIONS

Certain design considerations that impact system safety apply to more than one type of power subsystem or affect the design of the entire system. These considerations include system control, material selection, and grounding. These and other considerations are discussed in this paragraph, but safety considerations that pertain specifically to one particular piece of equipment or subsystem are discussed in the chapter(s) describing that item.

3-3.1 SYSTEM CONTROL

The function of an electrical power system is to provide power at a nominally constant voltage to allow loads to draw the amount of current necessary to perform their function provided the capacity of the supply is not exceeded. Real-time control functions associated with power systems include control of the source voltage level and reconfiguration of the distribution system to isolate safely those sections that draw excessive current. These two central functions are described in the subparagraphs that follow.

3-3.1.1 Voltage Control

Voltage control in a power system is the maintenance of voltage within a reasonably constant range appropriate for loads connected to the system. Voltage fluctuations should be kept below 4 to 6% for isolated or infrequent events, below 3 to 4% for fluctuations occurring several times each hour, and below 1.5 to 2% for frequent fluctuations. Voltage regulation is typically performed at the generator by the control unit associated with the generator. However, line losses that vary with load current may cause voltage at remote points to fall below tolerable limits or to fluctuate excessively. When the relatively constant load currents are transmitted long distances, manually adjustable transformers may be used to boost the voltage to compensate for the voltage loss in the lines. However, if the expected line loss is significant and the load current is subject to wide variations, the compensated voltage out of the transformer may rise to unacceptable values when the load is reduced.

Voltage regulating transformers that change taps automatically to maintain a constant output voltage may be used to maintain the output voltage at a constant level. Three single-phase transformers may be used for the regulation of three-phase power. However, certain problems arise if the transformers are improperly connected—specifically from excessive third-harmonic levels, surge currents passing through the regulator, and fault currents. Table 3-9 lists possible connections of three single-phase transformer-regulators and indicates the relative safety of using each connection on both grounded neutral and ungrounded polyphase systems.

3-3.1.2 Configuration Control

Configuration control is the manual or automatic reconfiguration of an electrical distribution system to allow operation as nearly normal as possible when maintenance or repair of the system is being performed or when portions of the system are damaged. It also includes the incorporation of alternative sources of electric power into the system when the primary source fails. Configuration control for power systems is discussed in par. 3-3.2.

The capability for manual reconfiguration of the system may be incorporated by distributing power with a grid or loop configuration, with switches at various points to remove power from sections of the line for repair. If power may be fed to loads along more than one route, e.g., from two directions around a continuous loop, then when a fault occurs in a line, the defective section may be removed from the circuit without interruption of power. Such configurations are desirable because they provide more reliable service and eliminate the need for repair of lines that are energized. Reconfiguration of the network usually is performed when it is not energized, e.g., when power is removed because of a blown fuse or circuit breaker. Consequently, the switchgear used to isolate sections of lines may not be capable of interrupting load currents, and injury may result if such operation is attempted. Switchgear of this type should be opened a short distance, or "inched". If no significant arc is detected, the switch may then be completely opened safely.

A second example of reconfiguration is the use of automatic reclosers and sectionalizers. The recloser is similar to a circuit breaker that opens the line when a fault current is detected and then, after a fixed delay, closes. Short duration faults that are due to transient conditions such as arcs, lines which are blown together, and birds will clear with no further attention before the power is reapplied. In these cases power is restored with no necessary

TABLE 3-9
SAFE AND DANGEROUS CONNECTIONS OF THREE SINGLE-PHASE REGULATORS FOR THREE-PHASE REGULATION (Ref. 9)

Regulator Connection	System Connection	Effect* Third Harmonic	Effect* Line Surges	Effect* Line Ground	Conclusion
Grounded Y	Grounded	S	S1	S	S
Ungrounded Y	Grounded	D	S1	D	D
Delta	Grounded	S	S1	S2	S2
Grounded Y	Ungrounded	D	S1	D	D
Ungrounded Y	Ungrounded	D	S1	S	D
Delta	Ungrounded	S	S1	S	S

*S = safe
S1 = safe if suitable bypass series winding protection is supplied
S2 = conditionally safe—overexcitation of regulators may lead to failure if fault allowed to persist
D = dangerous

repair. Reclosers are usually used with sectionalizers or fuses to open the line in the event that the fault is "persistent" and does not clear when the power is interrupted. The sectionalizer is a switch that detects the pulses of fault current resulting from the cycling of the recloser. After a predetermined number of fault current cycles, the sectionalizer opens the circuit containing the fault while the recloser is open. If multiple sectionalizers are used on multiple lines from the recloser, only the line with fault is deenergized, and power is returned to the other lines for normal operation. Appropriately sized fuses also may be used in the place of the sectionalizers to isolate the line with the fault; the recloser can function to extinguish the resultant arc at the fuse.

3-3.2 INTERFACE TO PERMANENT POWER SYSTEMS

Local power sources are interconnected with a centralized power utility for one of two reasons. The first reason is to provide a more reliable local power supply through redundancy in power sources. The second is to reduce operating costs by using alternative energy sources for the generation of electricity and thereby reduce the amount of energy which must be purchased from the utility. Where increased reliability is the motivation for local electricity generation, a standby or an uninterruptable power system is used to provide electrical power when the primary supply is interrupted. Where the motivation is economy, generators may be connected in parallel with the utility power to provide power according to the capacity of the generators to reduce utility costs. Since the interconnection between the generators and the line are different in these two situations, they are discussed separately in the two paragraphs that follow.

3-3.2.1 Standby or Uninterruptible Power Supplies

In standby power systems, the alternative source must provide electrical power that is compatible with the power available from the utility. Compatibility specifically includes same voltage; same frequency; and same phase configuration, e.g., three-phase delta or three-phase wye. Alternative sources do not have to have the same capacity as the primary source because usually alternative power sources support only critical portions of the load and "shed" nonessential loads during power outages. Typical configurations for standby systems are shown in Fig. 3-6. Selection of an appropriate configuration is based on the classifications listed in par. 1-3.1.2.3, especially those classifications that specify the maximum duration of power outage that can be tolerated by the equipment to be protected. When short interruptions can be tolerated, the configuration shown in Fig. 3-6(A) may be used. In this configuration, power from the backup supply or generator is connected to desired loads through a transfer switch, a crucial piece of equipment for the safe operation of the system. When continuous power is required to operate sensitive or critical loads such as computers, an uninterruptible power supply (UPS), such as that shown in Fig. 3-6(B), is used. In this configuration critical loads are powered by a continuously operating generator that may be a mechanical generator or an electronic inverter. Energy input to the generator is derived from a source with some internal storage capability. For mechanical systems, stored energy is derived from the rotational inertia of flywheels. In inverter-based systems the energy is stored in electrical storage batteries. The operating time afforded by the energy storage capacity may vary significantly. The inertia of mechanical systems provides energy for a short period until an alternate energy source such as an engine can be brought on-line. Inverter-based systems may be connected to a bank of batteries that have sufficient capacity to operate the inverter for periods longer than expected power outages.

A critical safety concern in the backup system is the switching between sources of power. Some loads, such as lighting or resistance heating, may be switched from one supply to another regardless of electrical frequency or phase. Other loads, such as transformers and especially motors, are sensitive to abrupt changes in phase. When a motor at rest is connected, the current drawn is about six times the rated current listed on the nameplate. However, if a motor is switched instantaneously from one power source to another with the same frequency and voltage, the current drawn depends upon the discontinuity in phase. If the second source were in phase with the first, no change in motor current would be observed. However, if the voltage in the second source were 180 deg out of phase, currents in excess of the locked-rotor rating of the motor will be drawn, with possible resultant damage to interconnecting wiring and components and induction of harmful forces within the motor itself. If a delay is introduced between the time power is interrupted and reapplied, the effect can be reduced because the voltage generated in the motor decreases as the motor "spins down". If the motor stops, then the current drawn is six times the nameplate rating. If power is reapplied to the motor

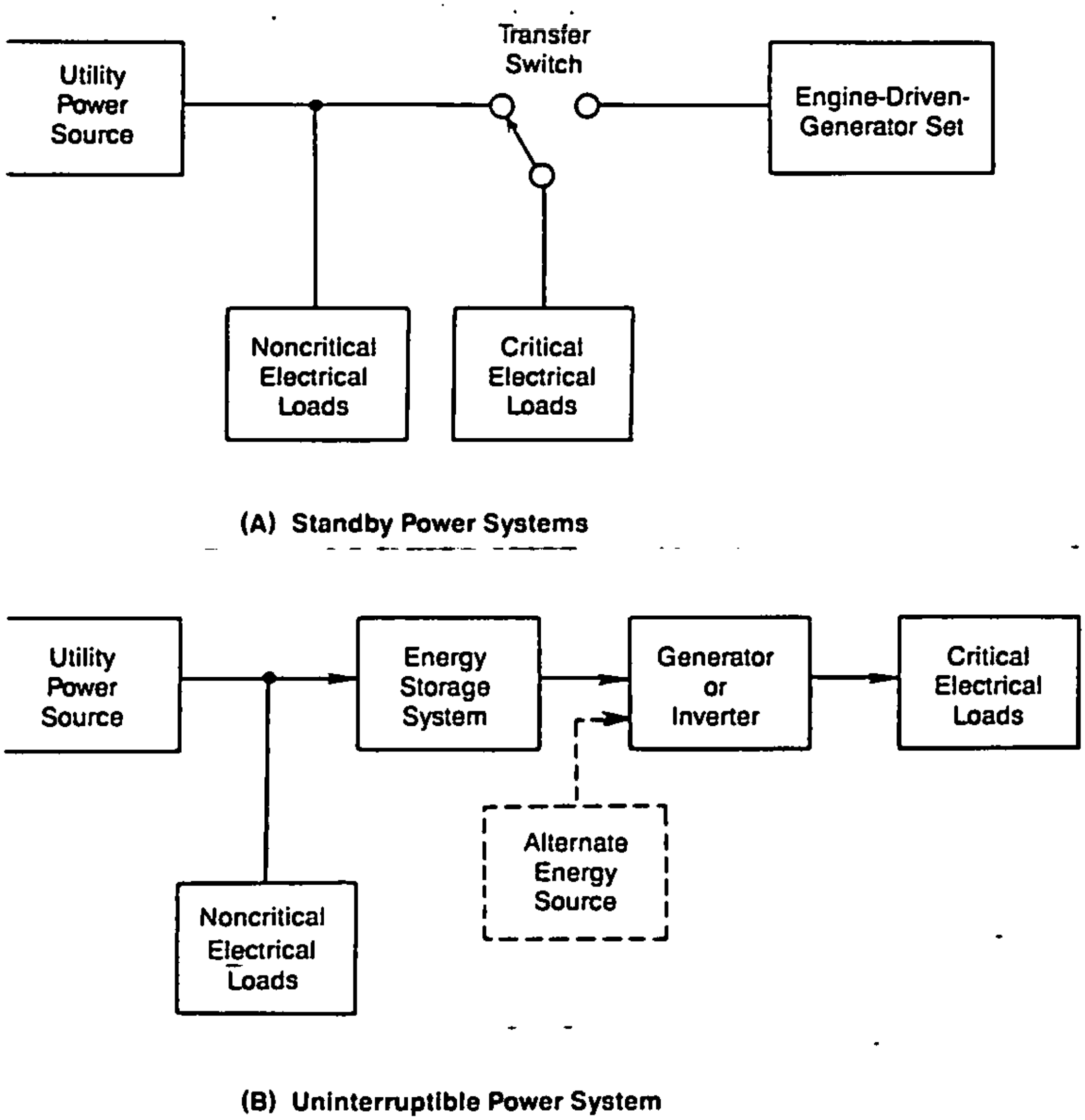


Figure 3-6. Power Systems for Standby Use

before it comes to rest, the current may be above or below this amount, depending on the relationship between the applied voltage and the voltage generated by the generator action of the motor as it spins. Since the phase relationship at the time power is reapplied is random, the current drawn will be greater than start-up currents some of the time and less at other times. The magnitude also is influenced by the length of the interruption. More extreme values occur with short interruptions followed by reapplication of power to the motor when it is rotating near operating speed.

Once a power failure is detected by a standby system, a period of at least 10 s is required to bring a diesel generator on-line (30 to 90 s for a turbine generator). This period is sufficient to allow motor armatures to come to rest so that the reapplication of power does not cause currents in excess of starting currents to be drawn. However, when power from the utility becomes available, and the transfer back to the utility is made quickly, high current surges may be produced. One method of preventing these damaging current surges is to build in a delay in the transfer switch to allow the motor to spin down to an acceptable speed. A minimum delay is 1.5 times the open-circuit time constant of the motor, i.e., the period required for voltages generated through the generator action of the spinning motor armature to decrease to 37% of the applied voltage value. Typical times of 1.5 to 2 s are usually acceptable for induction motors. Longer periods are required if power-factor correction capacitors are connected across motors or if synchronous motors are used (Ref. 30).

If a second interruption cannot be tolerated when the load is switched back to the utility, then phase-synchronized switching is necessary. This method uses a switching apparatus that monitors the phase of both the primary and backup supply and transfers the load when the self-generated motor voltage is in phase with the primary supply. This method requires some anticipation on the part of the transfer apparatus. The frequency of internally generated voltage in the motors is dependent on the shaft speed. Since motors differ in rate of spin according to motor characteristics and the load to which they are connected, the transfer must be made as quickly as possible to minimize differences in motor phase when more than one motor is on the circuit.

Uninterruptible power supplies, such as the configuration shown in Fig. 3-6(B), are used in applications where even short duration power interruptions cannot be tolerated, e.g., computer systems. In these systems power to critical loads is usually delivered directly from a motor-generator or inverter, which derives its power from the utility. When power from the utility fails, the source of energy is switched to an alternative source such as a diesel-powered generator for a mechanical system or batteries for a static-inverter-based system. Inertial energy in the rotating system is used to keep the generator rotating to provide electrical energy during the transition. In an alternative configuration, power to critical loads is delivered by a static inverter, which is powered from storage batteries continuously charged by utility power. If power is interrupted, the charging of batteries stops. However, batteries continue to deliver power until their capacity is used. Note that in either case the power delivered to the load is generated by the same generator in the primary and backup modes, so phase problems associated with load switching are eliminated.

If the standby system is to be operated in countries other than the United States, provision for operation at other voltage levels and line frequencies may be necessary. Utility system operation at 50 Hz is common in Europe and Asia, and nominal line-to-ground voltages of 100, 127, 220, and 240 V may be used in the place of the conventional 120 V that is used in the U.S. Connection devices are also different in most other countries. Power systems used in developing countries and small island countries frequently do not operate as reliably as power systems in the U.S. Consequently, operation of backup power systems may be a daily occurrence, and the equipment should be designed, installed, and maintained accordingly.

3-3.3 COGENERATION

Cogeneration is the operation of a power source, such as a generator, in parallel with the utility, e.g., an engine-driven-generator set or static inverter. Power generated by the generator in excess of the on-site load is fed back into the utility service in exchange for a reduction in utility charges. Considerations for the paralleling of a generator or inverter with the utility power source are similar to the considerations for paralleling two generators. First, the local generator or inverter must be compatible with the power from the utility, i.e., it must have the same output voltage, frequency, and configuration, e.g., three-phase wye or three-phase delta. In addition the control circuitry of the generator must be designed for parallel operation with a power bus that can accept or deliver a seemingly "infinite" current with minimal voltage variations. The control circuitry must be designed to provide positive feedback based on the measured power delivered to the utility. Computer-based control systems may be used to perform the following functions, which otherwise would be performed by individual systems:

1. Output current monitoring or control
2. Overcurrent protection (out or in)
3. Under- or overvoltage relay (to separate generator from utility when voltage from systems differs)
4. Frequency difference (separates generator or inverter from utility when bus frequency falls outside the acceptable range)
5. Synchronizer (controls frequency output of generator or inverter in order to match that of utility before the generator or inverter is brought on-line).

3-3.4 SYSTEM GROUNDING (Ref. 31)

Grounding of selected points in an electrical system is done to prevent damage or injury that results from higher-than-normal voltages on conductors, exposed or otherwise. Appropriate grounding accomplishes the following (Ref. 32):

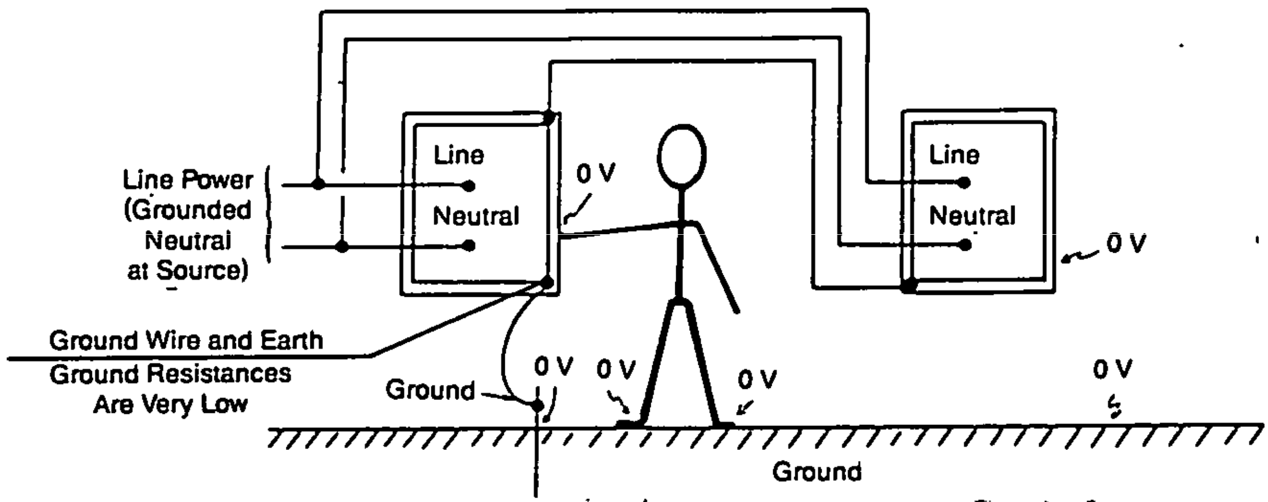
1. Prevents the buildup of hazardous voltages on electrical wiring from lightning, static electricity, switching surges, and contact with high-voltage systems.

2. Provides a safe path for fault currents. Appropriate grounding provides a relatively safe "short circuit" for ground faults that are unintentional contact between energized conductors and cabinets, structural members, or other conductors. The resulting high currents trip overcurrent protection devices and temporarily eliminate the hazard until the problem can be repaired permanently.

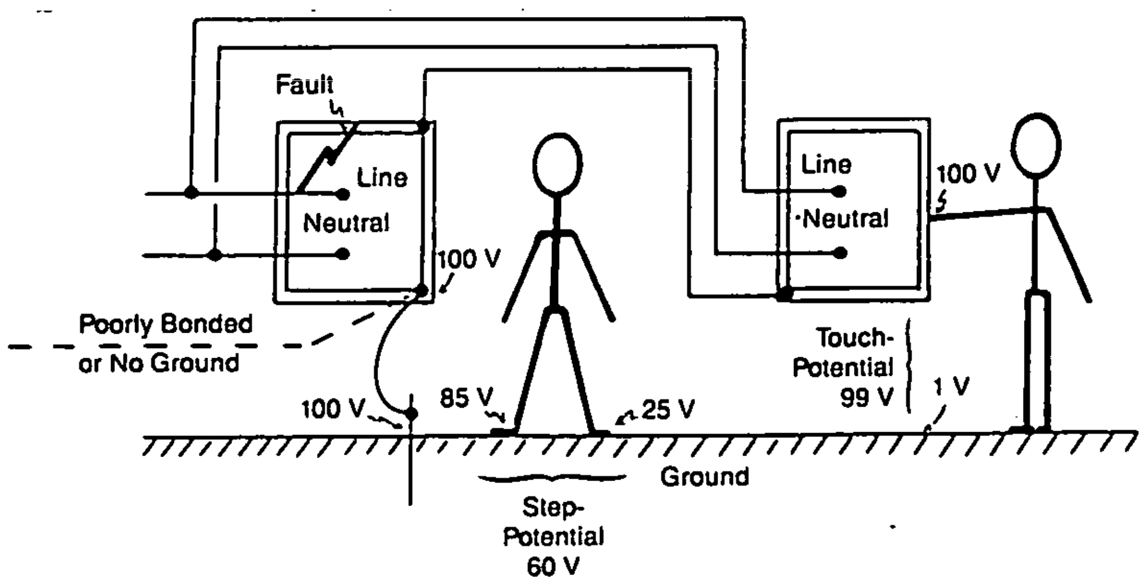
For these reasons, grounding of the electrical system is not designed in isolation from the rest of the system but rather must be coordinated with the overall system design for overcurrent protection and ground fault protection.

3-3.4.1 Ground Resistance

The usual purpose of a ground connection is to provide a connection to a hypothetical "mass of the earth" to insure that any exposed, electrically powered apparatus is at the same potential as ground. (See Fig. 3-7(A).) However, perfect connection to earth cannot be achieved



(A) Normal Configuration—Step- and Touch-Potentials Are Zero



(B) Fault Condition with High Resistance Ground Connection—Significant Step- and Touch-Potentials

Figure 3-7. Examples of Step- and Touch-Potentials because of the inherent resistance in the earth. Consequently, currents into the ground connection induce voltages at the point of connection due to the effective series resistance. These induced voltages can be hazardous when the current into the ground connection is large, such as the currents produced by lightning or by faults in high-voltage systems. The resultant hazard is manifest in two ways: (1) hazardous step-potentials and (2) hazardous touch-potentials. Step- and touch-potentials were defined and discussed in the context of lightning strikes in par. 3-2.1.2. Similarly, hazardous step- and touch-potentials may be developed by a fault between a high-voltage line and the ground. This situation is depicted in Fig. 3-7(B).

Hazardous step- and touch-potentials that may occur under fault conditions may be prevented by decreasing the resistance of the ground. This can be accomplished by using more or larger grounding electrodes, by chemically treating the soil, or by incorporating both measures. In critical cases an electrode network or ground mat is used to establish better contact with the ground and to minimize potential gradients in the area. Techniques for making the appropriate physical ground connections are discussed in par. 5-2.4.

3-3.4.2 Grounding Techniques for Polyphase Systems

Several techniques are available for grounding of polyphase systems, and the selection of the most appropriate one depends on power source(s), load, presence of ground fault circuit interrupters (GFCI), and potential hazards to be minimized. The most common techniques are

1. *Solid Grounding*. One conductor, usually the neutral of the three-phase wye system, is connected to ground through the lowest-resistance, practical ground connection. Advantages of this system are simplicity and lowest possible induced neutral voltage during faults. Disadvantages are high, possibly damaging, fault currents.

2. *Resistance Grounding*. The neutral is connected to ground through a resistance sufficient to limit the fault currents. Two approaches are used: (1) low-resistance grounding that limits the fault current to a safe value that is still high enough to trip overcurrent protection devices and (2) high-resistance grounding that allows only a small fault current to flow. High-resistance grounding allows the system to remain in operation when a fault condition exists. However, high-resistance grounding should be used only when the system is well maintained and detected problems, which do not prevent system operation, will be corrected instead of ignored. Resistance grounding is used only on three-phase, three-wire (delta) configurations because normal neutral current in a four-wire system would flow through the grounding resistance; this would introduce power loss and phase voltage imbalance. Also the National Electrical Code (Ref. 32) does not permit resistance grounding where line conductors are less than 150 V rms with respect to ground.

3-3.4.3 Grounding Considerations

3-3.4.3.1 Grounding at Utility Service Entrance

Appropriate ground connections for electrical systems that are connected to a utility service are shown in Fig. 3-8. The dashed lines in the diagram show the path of a possible fault current. Note that the ground connections insure that exposed equipment housings remain at ground potential when a fault occurs. However, the fault current does not flow into the ground, but rather it flows into low-resistance ground conductors. Consequently, these conductors should meet the following requirements:

1. Be permanent and continuous
2. Have ample capacity to conduct safely any ground-fault current likely to be imposed on them
3. Have impedance sufficiently low to limit the voltage to ground to a safe magnitude and to facilitate the operation of circuit protection devices.

The optional ground connections shown are necessary for preserving the safety of the system provided the ground conductors are present. The optional ground connections do provide some redundancy in the event of damage to the equipment-grounding conductor but should never be used in place of it.

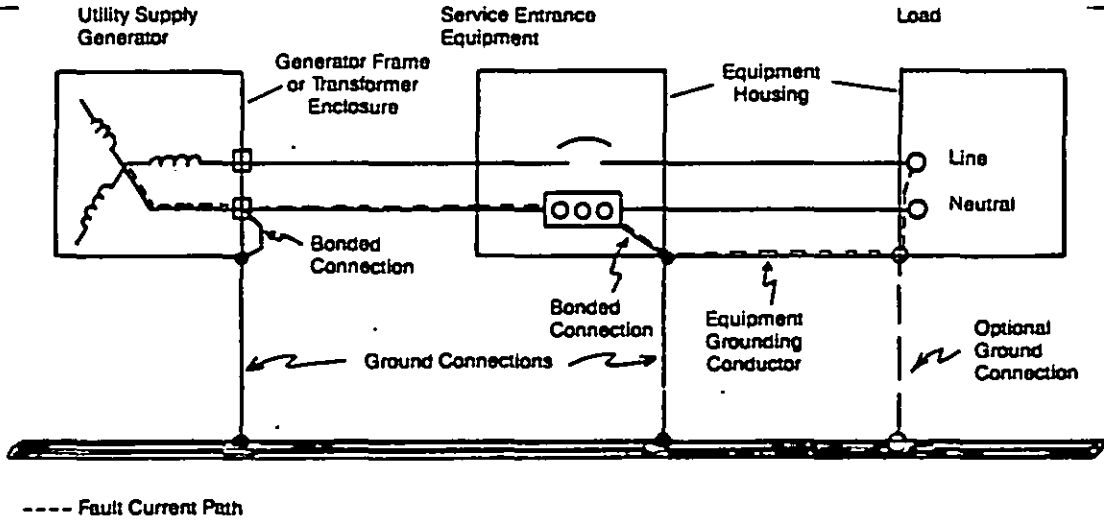
3-3.4.3.2 Grounding of Local Generators

A recommended grounding scheme for local generators is shown in Fig. 3-9. This configuration is similar to that of service-supplied configuration except that only one ground connection is required because of the proximity of the generator and loads.

Typically generators do not generate perfect sine waves but generate a waveform with up to 10% harmonic distortion (Ref. 33). The third harmonic from all phases is in-phase and, therefore, additive in the neutral. Use of resistance grounding attenuates this harmonic without inducing loss at the fundamental line frequency provided the generator load is balanced. Resistance grounding is even more strongly recommended for generators that operate in parallel with a utility supply to protect the generator windings from excessive transient fault currents (Ref. 34).

Generators that serve as standby power systems should be grounded in the same manner as the utility, i.e., the neutral connection should be tied to a low-resistance ground electrode installed for the generator. In most cases the neutral of the generator also is connected to the neutral of the utility. However, if the generator is located remotely from the point of service entry such that a difference in ground potential exists between the generator ground and the service ground, it may be desirable to switch the neutral with a set of make-before-break contacts on the transfer switch used to change service.

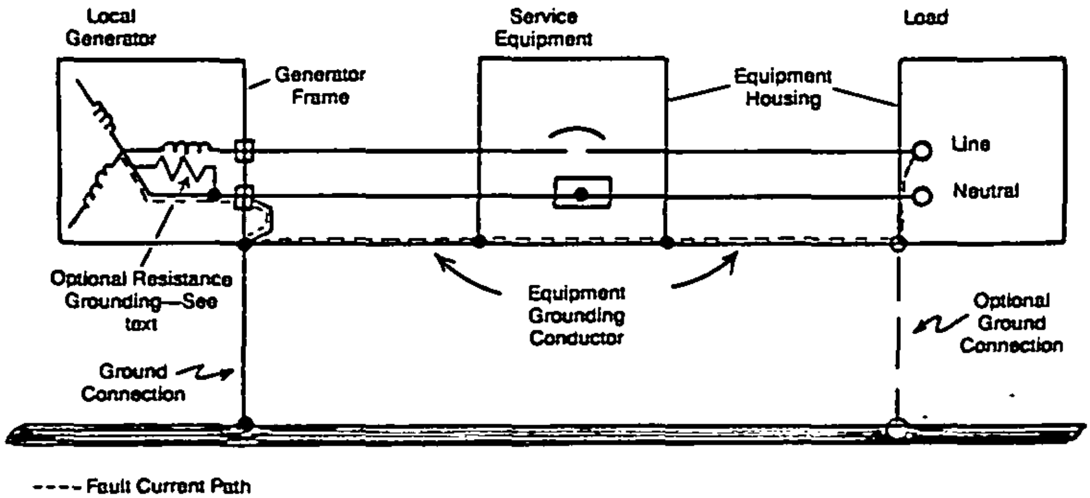
The grounding of generators that are used as standby power sources for systems with ground fault interruption must be designed carefully to insure that ground paths are not introduced that bypass the GFCI circuitry. An appropriate grounding configuration for the grounding of a



Note: Article 550 of the NEC (Ref. 32) requires that the neutral conductor of mobile home power wiring shall not be grounded to the frame of the structure or to the equipment ground wiring within the structure. The metallic frame of the structure and all exposed metallic surfaces must be grounded through an equipment ground conductor in the cable supplying power to the structure. (This does not preclude additional grounding through grounding electrodes.) The service entrance equipment—usually consisting of a disconnect switch, an overcurrent protective device, and connector for the power cable—is mounted near the mobile home but not on it. Army shelters are *also wired in accordance with this article. However, they typically share common service equipment* when the shelters are located in close proximity and are powered from the same source.

MIL-STD-1587 requires that the neutral conductor of a grounded power system be connected to ground at only one point within the immediate equipment area.

Figure 3-8. Grounding Configuration for a Single-Source Service Supplied System



Note: Use of the optional ground connection at the load does not eliminate the requirement for a dedicated equipment grounding connector. See notes on Fig. 3-8.

Figure 3-9. Grounding Configuration for System Powered Solely by Local Generator

three-phase, utility-powered system, which includes a generator for standby power, is shown in Fig 3-10. Information on additional configurations is given in Ref. 35.

Generators that are operated in parallel with utility should not be solidly grounded because significant, imbalanced currents may flow. Consequently, the neutral of the generator should be resistance grounded. If desired, the resistor may be shorted to provide solid grounding when utility service is disconnected (Ref. 34).

3-3.4.3.3 Separation of System Grounds

The high-voltage system associated with a transformer should not be grounded together with the low-voltage system associated with the secondary. If the two systems share a common ground, then large fault transient voltages, which are possible with the high-voltage primary system, may be induced in the ground connection for the secondary system. This situation is shown in Fig. 3-11(A). Fig. 3-11(B) illustrates the appropriate method of separating the grounds to prevent the occurrence of this hazard.

3-3.4.3.4 Grounding of Delta Configurations

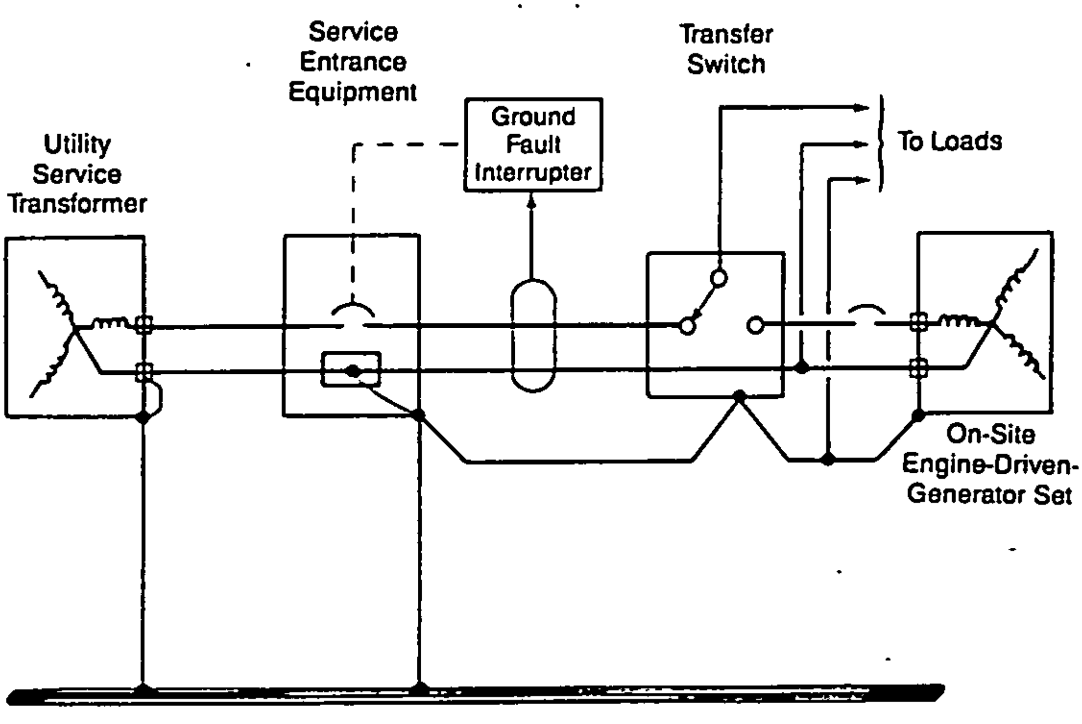
Grounding one phase of a three-phase source as shown in Fig. 3-12(A) is sometimes done for reasons of ease of installation and economy. However, this configuration is not recommended because the line-to-ground voltage is 73.2% higher in comparison to the wye-driven configuration shown in Fig. 3-12(B). In the latter configuration, a converted wye-voltage source is used to maintain all three phases of the delta-connected loads at an equal voltage aboveground. If a wye-connected source is not available, then a grounding transformer may be used with a delta-connected power source to generate a ground connection point.

A polyphase grounding transformer is a multiwinding transformer that generates a neutral potential from the three phase voltages. (The neutral potential in this context is the potential of the center or neutral connection of the source if the phase voltages were generated by a wye-connected source.) Grounding of this neutral connection as shown in Fig. 3-12(C) maintains the three phases at equal voltages (magnitude) with respect to ground.

3-3.5 SYSTEM LOAD CONSIDERATIONS

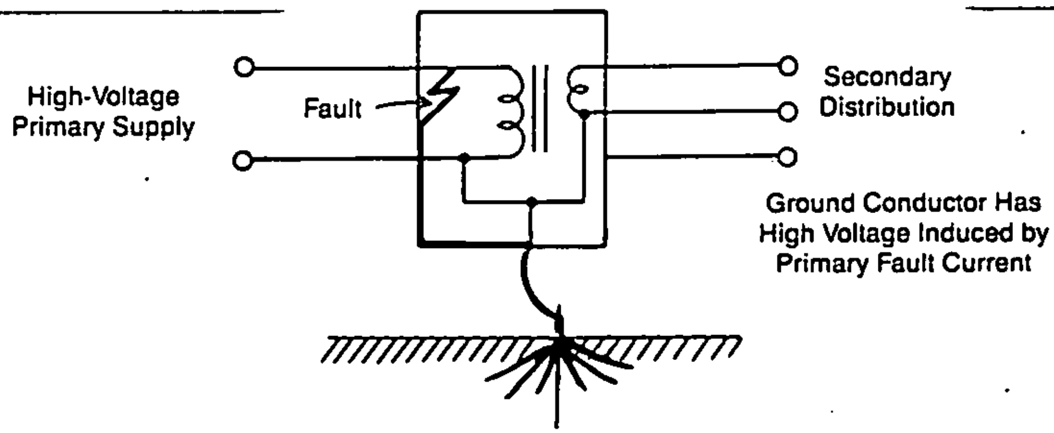
3-3.5.1 Matching Power System to Load

When the source of electrical power is a fixed, commercial utility, the consideration of compatibility between loads and source is simply one of compatible configuration—three-phase wye or delta, or single-phase—and adequate capacity. Because the increase in cost of additional capacity at the time of installation is not great, the usual practice is to make conservative estimates of required capacity to allow for errors in the estimates or for future expansion. These conditions are not true for systems powered by engine-driven-generator sets since the initial cost of the

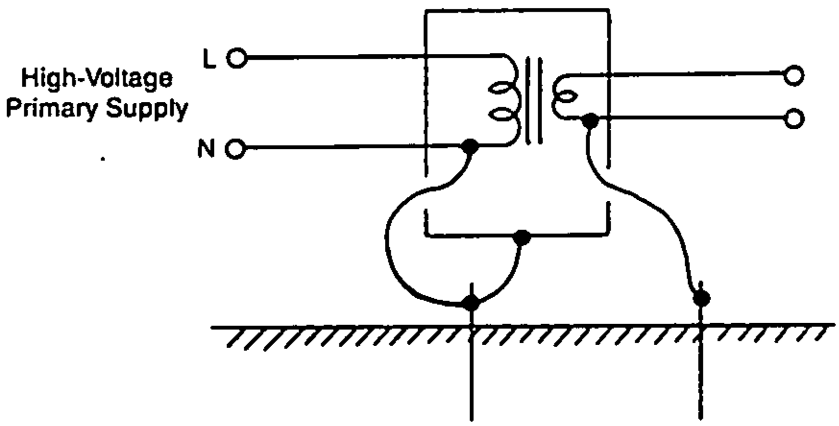


See notes on Figure 3-8.

Figure 3-10. Grounding Configuration of System Using On-Site Generation and Ground Fault Protection



(A) Dangerous Potential Induced in Secondary Ground by Primary Fault



(B) Grounding of Primary and Secondary Neutrals to Prevent Induction of High Voltage on Secondary Ground Conductor by Primary Fault

Figure 3-11. Proper Grounding of Distribution Transformers

system is high and increases in direct proportion to the generating capacity. Also, engine life is reduced by operation at either minimum or maximum load; optimum life generally can be obtained with loads in the 50 to 90% range (Ref. 36). Therefore, for these systems, the power source must be matched more closely to the electrical loads it supplies.

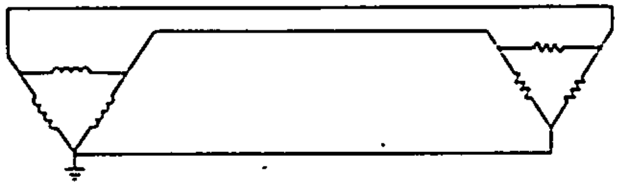
There are three objectives to be achieved by proper matching of the source to the load, i.e.,

1. Reliable system operation—i.e., minimal chance of system shutdown due to component failure in the engine-driven-generator set

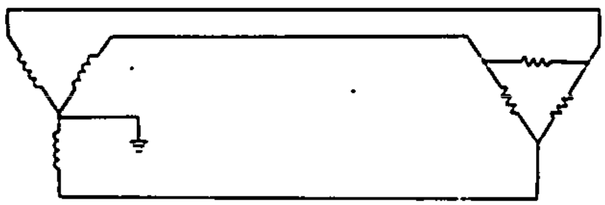
2. Acceptable quality of the power produced—i.e., voltage regulation, frequency regulation, and waveform

3. Reduced initial cost.

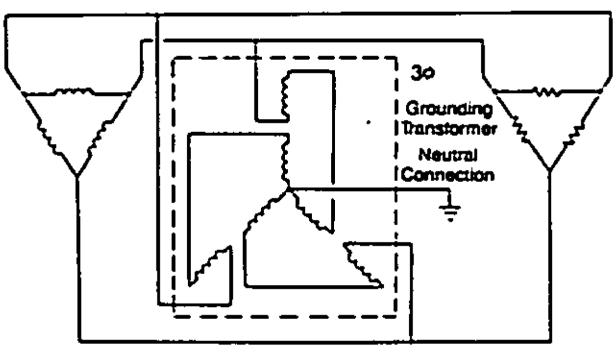
Matching the engine-driven-generator set to the load consists of defining the power requirements of the load and selecting or designing a generator that will deliver that power. Estimates of power should be realistic with some allowance for expansion. Typical estimates are usually biased high because the designer adds the power requirements of all the devices to be operated to determine the "worst-case" power requirements. Generators selected to satisfy those requirements will probably operate at a fraction of their capacity most of the time. To make realistic estimates, loads that will not be operated simultaneously should be identified, e.g., equipment used in either summer or winter but not both and equipment used in



(A) 3φ-3W Delta System with One Phase Grounded



(B) 3φ-3W Delta System Driven by Wye-Connected Source to Provide Ground Point



(C) Use of Grounding Transformer to Produce Grounding Point

Figure 3-12. Grounding of Delta Configuration

either daytime or nighttime. Only the larger load should be used in the estimation. Another typical error that causes overestimation is the overlooking of the duty cycle of equipment that is not operated continuously. Note, however, that allowances must be made for the possibility that all cycling loads could operate simultaneously—an occurrence that also reduces the diversity of the load and therefore the value for expected variability in the estimated load profile (Ref. 37). Decreasing diversity decreases the required maximum capacity and increases the probability that the actual load will remain in the desired operating power output range of the generator. In cases where high-diversity load combinations are anticipated, provisions may be incorporated in the power distribution system to sequence operation of significant items to reduce diversity. Also controls for motors may be staged so that motor-starting currents (typically six times the running current) are not drawn simultaneously.

If widely diversified loads are unavoidable, addition of fixed electrical loads to the system can meet the manufacturer's minimum design load for the generator during periods of light generator loads. One procedure for increasing loading is to operate certain equipment, such as electronics or heaters, to provide an acceptable load on the engine-driven-generator set. Alternatively, load banks consisting of power-dissipating resistors may be used to provide the minimum recommended load. A more desirable solution is to design the system with two generators so that when an operation is anticipated at a level that can be accommodated by one generator, the other may be switched off until power demand again warrants its use.

Another problem, which arises when small loads are connected to a system having larger capacity, is the reduction in effectiveness of fault current protection. Properly designed systems include overcurrent protection that trips upon detection of currents in excess of wiring or source capacity. This device protects the wiring from overcurrent damage and quickly deenergizes circuits containing a fault to eliminate any hazards that are produced by the fault condition. If a small load is connected to a high-capacity source without additional overcurrent protection sized for the load, internal faults may cause fault currents that are not sufficient to trip overcurrent protection devices. These fault currents, although not sufficient to cause damage to the source, may cause damage to the load and could be accompanied by a hazard resulting from the fault, e.g., hazardous voltage on an exposed conductor, that persists because of the ineffectiveness of overcurrent protection.

3-3.5.2 Load Allocation

Load allocation is the partitioning of electrical loads among electrical sources to achieve maximum use of generating capacity. The most common objective of load allocation is to balance the load between phases of a three-phase system. Three-phase systems that power only three-phase loads—e.g., motors and three-phase, transformer-powered equipment—are inherently balanced provided the loads are operating as designed. However, when single-phase loads are connected to a three-phase system, the system usually will become unbalanced, i.e., the current delivered by the individual phases will be different. Unbalanced operation of a three-phase generator is undesirable because the three stator coils are not operating at the same capacity. Since there is a limit to the power that may be delivered by each phase of a generator, unbalanced operation implies that at least one and probably two of the phases are operating significantly below capacity and overall output capacity of the generator is reduced.

Unbalanced loads are also hazardous to the generator and to certain types of loads. Three-phase motors require that voltages be balanced within 1% for operation at the rated capacity. With imbalances in source voltage of 5%, the motor must be derated 25% (Ref. 38). The amount of voltage imbalance caused by current imbalance depends on the droop characteristics of the generator. These characteristics vary among generator models; therefore, the requirements for balancing current loads to achieve acceptable motor operation are difficult to specify quantitatively. In general, however, it is sufficient to say that power drawn from the different phases of the generator should be balanced as closely as possible, especially when three-phase motors are driven by the generator.

Load allocation may also apply to the assignment of loads among multiple generators, which might be done to keep generators operating within acceptable load ranges as discussed in par. 3-3.5.1. Considerations in allocating loads among generators relate to the shedding of nonessential loads when power capacity is reduced either when switchover from utility power to generators occurs or when one generator becomes inoperative in a multiple-generator configuration. Similarly, essential loads, such as life-sustaining equipment in hospitals, must be supplied through switching the equipment to any available source of power in the system to provide maximum power-system reliability for that equipment.

3-3.6 GROUND FAULT PROTECTION

Ground fault protection (GFP) generally consists of equipment that disconnects power upon detection of undesirable current to ground. The components used to accomplish this may be referred to as GFP, ground fault interrupter (GFI), or ground fault circuit interrupter (GFCI). The advantage of ground fault protection is that only very small ground fault currents are necessary to trip the protective device, whereas the alternative requires fault currents in excess of circuit capacity before the overcurrent devices break the circuit.

GFP devices work on the principle that the new current summed over all conductors supplying an electrical load must be zero. Stated simply for single-phase loads, the current out to the load on the "hot" line should be exactly the same as the return current on the neutral—a condition that is necessarily true provided no alternative return paths exist. However, if a fault exists between the "hot" line and ground (not the neutral), the fault current causes a difference between currents in the "hot" wire and the neutral. This difference may be detected by a current transformer placed around the pair of wires. The sensitivity of this system may be set sufficiently high for single-circuit systems so that the circuit will be interrupted upon the detection of fault currents below levels sufficient to injure personnel. The same principle may be applicable to three-phase systems. Here the net current is sensed in the three phases and neutral by a current transformer surrounding the four wires.

GFP may be used for protection of personnel or for the protection of equipment. For the latter application the National Electrical Code (NEC) (Ref. 32) requires ground fault protection on three-phase feeder systems with a phase-to-phase voltage between 150 and 600 V and current capacities greater than 1000 A. For these applications, appropriately sized overcurrent protection equipment will pass sufficient current to sustain arcs capable of doing significant damage to the service equipment over a period of time.

When GFP is used in a system, care must be exercised so that the neutral is not grounded on the load side of the current-sensing transformer; this will cause the ground fault protection device to trip under any load above the ground fault setting. Systems with capacity for local generation of electricity, i.e., standby or cogeneration systems, must be designed carefully so that the grounding of the generator does not interfere with the GFP by providing an alternative grounding path for the neutral at any location that bypasses the current sensor. A suggested grounding configuration for these systems is given in Fig. 3-10.

3-3.7 MATERIAL SELECTION

As for any item of equipment, the materials from which it is to be fabricated must be selected on the basis of environmental and functional requirements dictated by the intended application for the piece of equipment. Improperly selected materials may be the cause of premature equipment failure either due to failure of the component made from the material or incompatibility with other components in the unit. The characteristics listed in Table 3-10 are considerations for material selection. Not all of these characteristics are significant considerations for every type of material or for every application.

Tables 3-11 through 3-14 (Refs. 9, 39, 40, and 41) give specific characteristics of metals, thermoplastics, thermosetting plastics, and ceramics. These tables are included to provide a general background of the properties of common materials used in electrical apparatus. More detail on properties of materials is found in Refs. 41 and 42.

Materials should be selected to satisfy requirements of the application. There are some common guidelines, however, for all applications of power systems in tactical environments. These guidelines are discussed in the paragraphs that follow.

Materials that may give off hazardous gases or particulates should be avoided, especially if they are to be used in confined spaces. For example, asbestos, a known carcinogen and formerly very popular as a high-temperature electrical and thermal insulator, should not be used in any application where nonhazardous high-temperature materials can be substituted. Asbestos fibers can be released to the atmosphere if the material is used where it could be abraided, handled, cut, or flexed. Similarly, materials that produce toxic chemicals when burned should not be used in applications where they may burn in an enclosed environment, e.g., polyvinyl chloride, when burned, releases hydrogen chloride gas and for that reason is not used in aircraft applications (Ref. 43). Fluorinated plastics are commonly used for electrical insulation in high-temperature applications, i.e., above 250°C or 480°F. Some formulations of fluorinated plastics release toxic gases including hydrogen fluoride upon combustion or thermal decomposition at temperatures well above the operating range, i.e., near 400°C (750°F). Therefore, these materials should not be used in unventilated spaces where fault conditions could produce temperatures that

**TABLE 3-10
MATERIAL SELECTION
CHARACTERISTICS**

- Mechanical Strength
  - Tensile Strength
  - Impact Strength
  - Hardness, Toughness, or Ductility
  - Abrasion Resistance
  - Flex Life
- Elasticity
- Maximum Elongation
- Moisture Absorption
- Temperature Characteristics
  - Melting Temperature
  - Softening Temperature
  - Ignition Temperature
  - Low-Temperature Characteristics
- Electrical Characteristics
  - Conductivity or Bulk Resistance
  - Dielectric Strength
  - Dielectric Constant
  - Loss Dissipation Factor
- Corrosion Resistance (and Compatibility With Other Materials)
- Corona Resistance
- Arc Resistance
- Radiation Resistance
- Chemical Resistance
  - Fungous Resistance
  - Bacteria Resistance
  - Solvent Resistance
- Ultraviolet (UV) Resistance
- Fabrication Capabilities
  - Applicable Fastening Techniques (welding, adhesives, soldering, brazing)
  - Forming Techniques (machine, casting, etc.)
  - Field Repairability

greatly exceed the ratings of the material. Even ordinary materials may produce toxic combustion products when burned in enclosed areas. For example, carbon monoxide is a common product of incomplete combustion, and hydrogen cyanide (HCN) is produced by combustion of wool, silk, polyacrylonitryl, nylon, polyurethane, and paper.

Materials that are to be used in tactical situations should be resistant to hazards of the battlefield, which potentially includes radiation. Not only should insulation materials be as resistant as possible, but all materials should be capable of being washed with decontaminating solutions heated to temperatures of 120°C (250°F).

Since military equipment may be used in any location in the world, susceptibility to corrosion is an important consideration. Specific materials that are resistant to corrosion should be selected. Equally important however is the combination of materials. Combinations should be selected to prevent the introduction of corrosion into components that might weaken or cause premature failure in other critical components. Table 3-15 lists the common metals used in equipment in order of electronegativity. Wherever possible, when two or more materials are fastened together, selected materials should be those that are located close together on this table to reduce the probability of galvanic corrosion. If not close together in the table, the joined parts should have a protective coating.

3-3.8 PHYSICAL CONFIGURATION

As in material selection, design of the physical configuration—the enclosure, supports, and the arrangement of components—must satisfy the requirements of the application and protect personnel from hazards associated with the equipment. Many of the considerations for the configuration design of safe equipment are specific to the item of equipment. Those equipment-specific considerations for equipment in this handbook are discussed in the chapter or paragraph pertaining to the item of equipment.

A major consideration in the design of all electrical equipment is the thermal design. Almost all electrical components generate heat and have a maximum temperature that they can tolerate. Therefore, the housing must provide cooling of the equipment while protecting it from other environmental factors. For some equipment natural convection through a ventilated enclosure is satisfactory. Such enclosures typically have louvers or overhangs to prevent the entry of falling precipitation. However, additional protection may be necessary for equipment that is sensitive to humidity or dirt. Equipment that has high-voltage conductors, electrical windings, or exposed moving parts that could be affected by moisture, sand, or dust should be mounted in sealed enclosures with provision for heat removal through a thermally conductive path or by circulating coolant through external cooling fins. This construction also is appropriate for preventing the accumulation of thermally insulating dirt on electrical components, a circumstance that could lead to higher operating temperatures and shortened equipment life. Vulnerable components may be mounted in sealed, oil-filled containers having an inert, smooth outer surface, which may be routinely cleaned or, more commonly, will be cleaned naturally by precipitation or wind.

A complicating requirement for thermal design of tactical equipment is the necessity to suppress the infrared signature of the equipment. Heat-generating equipment, especially engine-driven-generator sets, must be cooled with large volumes of air to meet requirements of low surface temperatures and exit air temperatures. This requirement, coupled with the requirement for a low-noise signature, has led to the development of new designs for tactical engine-driven-generator sets that incorporate baffled airflow for cooling and exhaust gas dilution and sound-deadened insulation for noise suppression.

An advantage of the self-heating characteristic of electrical equipment is that moisture will not accumulate within the equipment, even in humid environments, provided the equipment is operated continuously at a level that maintains the temperature above ambient. However,

TABLE 3-11
PROPERTIES OF COMMON METALS (Ref. 39)

Metal	Density mass kg/m³	Density weight* lb/in.³	Melting Point °C	Melting Point °F	Electrical Resistivity at 20°C (68°F) μΩ-cm	Tensile Strenth MPa	Tensile Strenth kpsi	Corrosion Resistance
Gray Iron, Cast	7200	0.26			50-200	186-228 172-207 138-165	27-33 25-30 20-24	Resistant to strong sulfuric acid, cold concentrated phosphoric, and nitric acids. Attacked by dilute sulfuric, phosphoric, and nitric acids. Resistant to sodium hydroxide, soda ash, and ammonia.
Malleable Iron, Cast	7170-7280	0.259-0.263			32.0	345-359	50-52	Resistant to atmospheric corrosion in rural, industrial, and marine atmospheres and fresh and salt waters.
Wrought Iron, Hot-Rolled	7695	0.278	1510	2750		331	48	Current improved wrought iron has at least 25% greater corrosion resistance than former grade.
Low-Carbon Steel	7835	0.283	1510-1524	2750-2775	14.3			Rusted by oxygen and water at room temperature: rate of attack increases sharply as pH goes above 4 and decreases below a pH of 8. Dilute salt solutions increase corrosion rate. Attacked by acids in general, but satisfactorily resistant to alkalis at normal temperature. Corrosion rate in ordinary rusting not appreciably affected by carbon or alloy content or by cold working.
Hot-Rolled						448	65	
Cold-Worked						538	78	
Medium-Carbon Steel	7835	0.283	1480-1510	2700-2750	19			Same as low-carbon steel.
Hot-Rolled						627	91	
Cold-Worked						689	100	
Hard and Tempered						779	113	
High-Carbon Steel	7835	0.283			18			Rusts when brought into contact with moisture and air at room temperature; rates not appreciably affected by carbon content. If salts are present, corrosion rate is increased. Attacked readily by acids, but resistant to alkalis at room temperature.
Annealed						724	105	
Hot-Rolled						800	116	
Hard and Tempered						1103	160	
Martensitic Stainless Steel	7750	0.28	1480-1530	2700-2790	70			Good resistance to weather and water; also good resistance to some chemicals.
Annealed						793-827	115-120	
Hard and Tempered						827-1379	120-200	

*Weight density in lb/in. as originally specified in Ref. 39.

(cont'd on next page)

TABLE 3-11 (cont'd)

Metal	Density mass kg/m³	Density weight* lb/in.³	Melting Point °C	Melting Point °F	Electrical Resistivity at 20°C (68°F) μΩ·cm	Tensile Strength MPa	Tensile Strength kpsi	Corrosion Resistance
Aluminum Alloy, Wrought (1100)	2710	0.098	643-657	1190-1215				High resistance to rural, industrial, and marine atmospheres. Good resistance to most neutral or nearly neutral fresh waters, sea water, organic acids, and anhydrides; alcohols, aldehydes; esters; ketones; oils; gasoline; greases, waxes, and other petroleum derivatives; ammonia and ammonium compounds; nitric acid above 82%; essential oils; amides; nitro paraffins; coal-tar derivatives. Hydrogen peroxide; and many neutral aqueous inorganic salt solutions.
Annealed					2.92	90	13	
Half-Hard					—	124	18	
Hard					3.02	165	24	
Aluminum Alloy, Wrought	2710	0.098	582-649	1080-1200				High resistance to rural atmospheres, good resistance to industrial and marine atmospheres. Degree and nature of attack in other environments are greatly influenced by heat treatment.
Annealed					3.8	124	18	
Heat-Treated (6061)					—	241 310	35(T4) 45(T6)	
Electrolytic Tough-Pitch Copper	8885-8940	0.321-0.323	1064-1083	1949-1981	1.71			Generally good resistance to industrial, rural, and marine atmospheres, also to gasolines, fuel oils, and lacquers. Generally poor resistance to ammonia, ferric and ammonium compounds, and cyanides. Good resistance to weak acids and bases; some resistance to strong acids and bases.
Annealed						221-241	32-35	
Hard						345-379	50-55	
Beryllium Copper	8195-8250	0.296-0.298	871-982	1600-1800				Same as electrolytic tough-pitch copper.
Annealed					4.82	414-552	60-80	
Hard					5.82	1138-1276	165-185	
Yellow Brass	8470	0.306	904-932	1660-1710	6.4			Generally good resistance to industrial, rural, and marine atmospheres; also gasolines, fuel oils, and lacquers. Poor resistance to ammonia, ferric and ammonium compounds, and cyanides. Susceptible to dezincification and stress corrosion cracking. Some resistance to weak acids and bases. Poor resistance to strong acids and bases and to soft and high-salinity water.
Annealed						317-345	46-50	
Hard						510-758	74-110	

*Weight density in lb/in. as originally specified in Ref. 39.

(cont'd on next page)

TABLE 3-11 (cont'd)

Metal	Density mass kg/m³	Density weight* lb/in.³	Melting Point °C	Melting Point °F	Electrical Resistivity at 20°C (68°F) μΩ·cm	Tensile Strength MPa	Tensile Strength kpsi	Corrosion Resistance
Nickel Silver, Wrought	8690	0.314	999-1037	1830-1900	8			Attacked rapidly by oxidizing acids. Resistant to sodium and potassium hydroxide but attacked rapidly by ammonium hydroxide and moist ammonia. Good resistance to rural and marine atmospheres and to fresh and salt waters. Subject to stress corrosion.
Annealed						359-421	52-61	
Hard						586	85	
Phosphor Bronze, 8% (Grade C)	8800	0.318	882-1027	1620-1880	13			Generally good resistance to atmosphere, water, salt water, and salt solutions. Some resistance to alkaline solutions and inorganic acids. Poor resistance to organic acids, cyanides, and ferric and ammonium compounds.
Half-Hard						524-724	76-105	
Spring						772	112	
Common Lead, Soft	11,350				124	18		Resistant to sulfuric, sulfurous, phosphoric, and chromic acids. Attacked by acetic, formic, and nitric acids. Resistant to atmosphere, and fresh and salt waters.
Nickel Alloy, Wrought	8720	0.315	1299-1349	2370-2460	48.2			Good resistance to flowing salt water, dilute acids, hydrochloric, hydrofluoric, sulfuric, phosphoric, and most organic acids and strong caustic soda. Not resistant to strongly oxidizing solutions such as nitric acid and ferric chloride.
Annealed						483-586	70-85	
Spring						689-965	100-140	
Nickel Alloy, Cast, As Cast	8640	0.312	1316-1343	2400-2450	53.2	448-621	65-90	Same as nickel alloy.
Gold	19,320	0.698	1063	1945	2.35			Does not oxidize when heated in air. Resists alkalis, salts, and most acids. Not attacked by oxygen or sulfur. Rapidly attacked by chlorine and bromine.
Annealed						131	19	
Cold-Worked						221	32	
As Cast						124	18	
Silver	10,490	0.379	961	1761	1.59			Does not oxidize when heated in air. Resists most dilute mineral acids and alkalis. Attacked rapidly by nitric and hot sulfuric acids. Attacked rapidly by sulfur-bearing gases.
Annealed						152	22	
Cold-Worked						372	54	
						103	15	
Grade A Tin	7310	0.264	232	449	11.5			Resists distilled sea and soft tap water. Attacked by strong acids, alkalis, and acid salts. Oxygen in solution accelerates rate of attack.
Annealed Sheet						15.2	2.2	
Cold-Rolled Sheet						19.3	2.8	
As Cast						14.5	2.1	

*Weight density in lb/in.³ as originally specified in Ref. 39.

(cont'd on next page)

TABLE 3-11 (cont'd)

Metal	Density mass kg/m³	Density weight* lb/in.³	Melting Point °C	Melting Point °F	Electrical Resistivity at 20°C (68°F) μΩ·cm	Tensile Strength MPa	Tensile Strength kpsi	Corrosion Resistance
Commercial Rolled Zinc	7140	0.258	419	786				Excellent resistance to both metropolitan and rural atmospheric corrosion, also hot soapy water, printing inks, trichloroethylene, carbon tetrachloride, dry illuminating gas, and moisture- and acid-free hydrocarbons. Fair resistance to pure ethyl and methyl alcohols, glycerine, water, and petroleum products. Poor resistance to steam, spray insecticides, animal oils, strong acids, bases, and mixtures of glycerine or alcohol and water.
Hot-Rolled					6.06	145-172	21-25	
Cold-Rolled					6.10	152-200	22-29	
Zinc Alloy, Cast								
Die-Cast	6645	0.24	386	727	6.54	328	47.6	
Tungsten, Cold-Worked	19,375	0.70	3400	6152	5.48	483-2068	70-300	Resists most acids and alkalis to 100°C (212°F), attacked by nitric-hydrofluoric mixture at room temperature, and by aqua regia at 100°C (212°F).

*Weight density in lb/in. as originally specified in Ref. 39.

when equipment must be operated on an intermittent basis or must be stored for long periods, then provisions must be made to protect it from effects of moisture, i.e., fungous growth and insulation breakdown. Appropriate material selection is necessary to minimize this problem. Sealed construction and potting of critical electronic components are possible alternatives to minimize problems due to moisture accumulation.

Tactical equipment that is subject to NBC exposure must be constructed to facilitate decontamination. Equipment subject to decontamination should be constructed so that all surfaces that are open to the atmosphere are accessible for cleaning and can withstand the solutions used. Where possible, exposed surfaces should be smooth and have minimal cavities, crevices, and dead spaces where radioactive debris may accumulate. Where cavities are necessary, access plates or removable covers should be provided along with drain holes to allow removal of decontaminating solutions. Complex assemblies may be designed for decontamination by making them easy to disassemble for cleaning or incorporating seals, gaskets, or other means to exclude both NBC agents or decontaminating solutions from internal components (Ref. 46). The process for nuclear decontamination, like the process for chemical or biological decontamination, consists of washing the equipment with a solution designed to remove any residue of the toxic agent. For chemical and biological agents, the decontamination agent may also neutralize or detoxify the residue.

3-3.9 ARCING (Refs. 47 and 48)

An arc is produced by the conduction of an electric current through an ionized column of gas whose ionization is maintained by the current through it. Significant voltage gradients are required to initiate an arc produced either by the narrow spacing of electrical conductors which are at different potentials—such as switch contacts at the moment they are opened—or by overvoltages that are produced by lightning-induced transients on lines with insufficient insulator spacings to accommodate them. Once the arc is initiated, it will be maintained provided there is a sufficient voltage gradient to maintain current through the arc and provided there are sufficient ions present in the arc channel to support conduction. The energy released by the current through the high-resistance channel maintains a high temperature within the arc and thereby maintains the high degree of ionization necessary to maintain the arc. However, the high temperatures can be quite damaging to nearby equipment and can cause the initiation of fires, melting of material, and the unintentional welding together of components. Also the sudden heating of air associated with large arcs produces large transient pressures that can damage or destroy enclosures that house the arcing apparatus. Arcs generate intense visible and ultraviolet light, which can cause temporary eye damage to nearby personnel. Ozone is a gaseous product of arcing in the atmosphere, and hydrogen is produced when arcs occur in oil-filled apparatus.

TABLE 3-12
ELECTRICAL PROPERTIES OF THERMOPLASTICS (Ref. 40)

Material	Volume Resistivity, Ω·cm	Dielectric Constant at 60 Hz, dimensionless	Dielectric Strength*		Dissipation Factor at 60 Hz, dimensionless	Arc Resistance,** s
			V/mm	V/mil		
Acetal	10^{14}	3.7-3.8	19,700	500	0.004-0.005	129
ABS	10^{15}-10^{17}	2.6-3.5	11,800-17,700	300-450	0.003-0.007	45-90
Acrylic	$>10^{14}$	3.3-3.9	15,700	400	0.04-0.05	(no tracking)
Acrylic, High-Impact	10^{16}-10^{17}	3.5-3.7	17,700-18,900	450-480	0.04-0.05	(no tracking)
Cellulose Acetate	10^{10}-10^{12}	3.2-7.5	11,400-23,600	290-600	0.01-0.10	50-130
Cellulose Acetate Butyrate	10^{10}-10^{12}	3.2-6.4	9800-15,700	250-400	0.01-0.04	50-150
Cellulose Propionate	10^{12}-10^{16}	3.3-4.2	11,800-17,700	300-450	0.01-0.05	170-190
Ethyl Vinyl Acetate	1.5×10^{8}	3.16	20,700	525	0.003	50-150
Chlorotrifluoroethylene	10^{18}	2.65	17,700	450	0.015	>360
Fluorinated Ethylene Propylene (FEP)	$>10^{18}$	2.1	19,700	500	0.0002	>165
Polytetrafluoroethylene (TFE)	$>10^{18}$	2.1	15,700	400	<0.0001	(no tracking)
Nylon 6	10^{14}-10^{15}	6.1	11,800-15,700	300-400	0.4-0.6	140
Nylon 6/6	10^{14}-10^{15}	3.6-4.0	11,800-15,700	300-400	0.014	140
Nylon 6/10	10^{14}-10^{15}	4.0-7.6	11,800-15,700	300-400	0.04-0.05	140
Polyallomer	$>10^{16}$	2.3	19,700-40,000	500-1000	0.0001-0.0005	
Polycarbonate	6.1×10^{15}	2.97	16,100	410	0.0001-0.0005	10-120
Polyethylene, Low-Density	10^{15}-10^{18}	2.28	17,700-40,000	450-1000	0.006	100-200
Polyethylene, Medium-Density	10^{15}-10^{18}	2.3	17,700-40,000	450-1000	0.0001-0.0005	100-200
Polyethylene, High-Density	6×10^{15}-10^{18}	2.3	17,700-40,000	450-1000	0.003-0.002	100-200
Polyethylene, High-Molecular Weight	$>10^{16}$	2.3-2.6	19,700-28,000	500-710	0.0003	100-200
Polyimide	10^{16}-10^{17}	3.5	15,700	400	0.002-0.003	230
Polypropylene	10^{15}-10^{17}	2.1-2.7	17,700-25,600	450-650	0.0007-0.005	36-136
Polystyrene	10^{17}-10^{21}	2.5-2.65	19,700-27,600	500-700	0.0001-0.0005	60-100
Polystyrene, High-Impact	10^{10}-10^{17}	2.5-3.5	19,700	500	0.003-0.005	60-90
Polyurethane	2×10^{11}	6.8	33,500-40,000	850-1000	0.276	100-150
Polyvinyl Chloride (Flexible)	10^{11}-10^{15}	5.9	11,800-40,000	300-1000	0.08-0.15	50-100
Polyvinyl Chloride (Rigid)	10^{12}-10^{16}	3.4	16,700-40,900	425-1040	0.01-0.02	50-100
Polyvinyl Dichloride (Rigid)	10^{15}	3.08	47,000-61,000	1200-1550	0.018-0.0208	50-100
Styrene Acrylonitrile (SAN)	10^{15}	2.8-3	15,700-19,700	400-500	0.006-0.008	100-150
Ionomer	$>10^{16}$	2.4-2.5	40,000	1000	0.001	100
Polymethylpentene	$>10^{16}$	2.12	27,600	700	0.001	100-200
Polyaryl Sulfone	3.2×10^{16}	3.94	13,800-15,700	350-400	0.003	67
Thermoplastic Polyester	4×10^{16}	3.3	23,200	590	0.002	190
Polyphenylene Sulfide	10^{16}	3.1	23,430	595	0.0004	75-150
Polyphenylene Oxide	10^{17}	2.58	15,700-19,700	400-500	0.00035	75
Polysulfone	5×10^{16}	2.82	16,700	425	0.008-0.0056	122
Polyethersulfone	10^{17}-10^{18}	3.5	15,700	400	0.001	100-200

*Short time, for 3.18 mm (1/8 in.) thickness.
**According to ASTM D495 (Ref. 44).

TABLE 3-13
ELECTRICAL PROPERTIES OF THERMOSETTING PLASTICS (Ref. 40)

Material	Property: Electrical Resistivity, Ω·cm	Dielectric Constant at 60 Hz, dimensionless	Dielectric Strength at 60 Hz, V/mm	Dielectric Strength at 60 Hz, V/mil	Dissipation Factor at 60 Hz, dimensionless	Arc Resistance,* s
Alkyd (Mineral-Filled)	10^{13}-10^{15}	5.1-7.5	13,800-17,700	350-450	0.009-0.06	75-190
Alkyd (Glass-Filled)	10^{15}	5.7	13,800	350	0.01	180
Diallyl Phthalate (Mineral-Filled)	$>10^{13}$	5.2	15,600-16,500	395-420	0.03-0.06	140-190
Diallyl Phthalate (Glass-Filled)	10^{13}-10^{15}	4.3	15,600-17,700	395-450	0.01-0.05	125-180
Epoxy (Mineral-Filled)	$>10^{14}$	3.5-5.0	11,800-15,700	300-400	0.01	150-190
Epoxy (Glass-Filled)	$>10^{14}$	3.5-5.0	11,800-15,700	300-400	0.01	120-180
Melamine (Cellulose-Filled)	—	6.2-7.8	13,800-15,700	350-400	0.019-0.033	95-135
Melamine (Glass-Filled)	2×10^{11}	9.7-11.1	6700-11,800	170-300	0.014-0.023	180
Phenolic (Wood-Flour-Filled)	10^{9}-10^{13}	5.0-13.0	7900-15,700	200-400	0.05-0.3	(tracks)
Phenolic (Glass-Filled)	7×10^{12}	7.1	5500-15,700	140-400	0.05	to 190
Polyester (Glass-Filled)	10^{12}-10^{16}	5.3-7.3	13,600-16,500	345-420	0.011-0.041	120-240
Silicone (Mineral-Filled)	10^{14}	3.5-3.6	7900-15,700	200-400	0.004-0.005	250-420
Silicone (Glass-Filled)	10^{10}-10^{14}	3.3-5.2	7900-15,700	200-400	0.004-0.03	150-250
Urea (Cellulose-Filled)	10^{12}-10^{13}	7.0-9.5	11,800-15,700	300-400	0.035-0.043	80-150

*According to ASTM D495 (Ref. 44).

TABLE 3-14
PROPERTIES OF CERAMICS AND GLASS USED FOR ELECTRICAL INSULATION (Refs. 9 and 41)

	Maximum Operating Temperature, °C	°F	Tensile Strength, MPa	psi	Dielectric Strength, V/mm	V/mil	Resistivity at 25°C (77°F) Ω·cm	Application
Ceramics								
High-Voltage Porcelain	980	1800	21-34	3000-5000	9800-16,000	250-400	10^{12}-10^{14}	Power line insulators
Steatite	980-1095	1800-2000	55-69	8000-10,000	8000-13,800	200-350	10^{13}-10^{15}	High-frequency insulators, electrical appliance insulation
Low-Voltage Porcelain	925	1700	11-17	1600-2500	1600-4000	40-100	10^{12}-10^{14}	Switch bases, wire holders, lamp bases
Glass								
Fused Silica	1050	1920	35-62	5000-9000*	—	—	10^{14}-10^{17}	High-temperature insulation
Borosilicate (Pyrex®)	435	815	41-69	6000-10,000	—	—	10^{13}	Line insulators

*Modulus of rupture—breaking strength measured by bending.

TABLE 3-15
GALVANIC SERIES (Ref. 45)

Less Noble (Anodic)

+	Magnesium Magnesium Alloys
	Zinc
	Aluminum 1100
	Cadmium
	Aluminum 2024-T4
	Steel or Iron Cast Iron
Electric current flows from + to −.	Chromium Iron (Active)
	Ni-Resist
	Type 304 Stainless (Active) Type 316 Stainless (Active)
No serious corrosion will result if fasteners are selected from alloys in the same group (or from groups below) as parts to be fastened.	Lead Tin Solders Lead Tin
	Nickel (Active) Inconel
	Brasses Copper Bronzes Copper-Nickel Alloys Monel
	Silver Solder
	Nickel (Passive) Inconel (Passive)
	Chromium-Iron (Passive)
	Type 304 Stainless (Passive) Type 316 Stainless (Passive)
	Silver
	Titanium
−	Graphite Gold Platinum

More Noble (Cathodic)

Not all arcs are damaging. Arcing almost certainly will occur with the opening of a switch on a high-voltage line, and the switches designed for that application include features to extinguish the arc before damage can occur. Arcs may be extinguished by two mechanisms—i.e., (1) lengthening the current path so that the energy supplied to the arc is no longer sufficient to sustain the degree of ionization required to support conduction and (2) by cooling the conductive channel of the arc either by a gas stream or by deflecting the arc onto plates. Lengthening of the current path is performed by rapid separation of switch contacts or by designing the geometry of the switch so that the electrostatic forces on the arc cause it to bow out by taking a curved path whose radius increases with time. Cooling of the arc channel is performed with jets of compressed gas, which blow through the arc and mix cool gas in the arc to dilute it. Also arc chutes are incorporated into high-voltage switches to extinguish the arc by cooling and segmenting it with insulating barriers. Arc chutes are insulating cylinders with parallel plates perpendicular to the arc. The arc is deflected onto the edges of the plates, which tend to cool the arc channel upon contact as well as lengthen it as it deforms around the contour of the plates.

The design of arc suppression for high-voltage switchgear takes into account the cyclic reversal of the alternating current, which, for 60-Hz systems, causes current to fall to zero 120 times each second. It takes less voltage to strike or restrike an arc than it does to sustain one. Therefore, switchgear is designed to eliminate conditions conducive to arcing as quickly as possible so that, when the arc is extinguished naturally because of the current-zero, it cannot restrike on the next half cycle and thereby take advantage of the naturally occurring current zero to quench the arc. For situations where the current does not fall to zero periodically, the arc will be sustained more easily and, therefore, will last longer. This is especially true where electrode spacing is sufficient to prevent restriking of an arc once extinguished but will sustain an established arc. Since the energy (and damage) due to the arc are proportional to the duration, the damage due to these arcs may be more severe. This phenomenon will occur during arcing with direct current sources or polyphase sources where the phases are located sufficiently close that the arcs among all the phases pass through a common region that is continuously ionized because of the continuous presence of current. This situation should be avoided by appropriate separation of phases of three-phase systems such that, if arcs do occur, they will be from a single-phase-to-ground or phase-to-phase and never involve all three phases simultaneously.

These design features may be incorporated where the generation of arcs is predictable, such as in switchgear. However, the extinguishing of unanticipated arcs is more difficult. These arcs may be produced by failure of structures that separate high-voltage conductors; by transient overvoltages; or by the occurrence of temporary conducting material between high-voltage conductors, e.g., flying birds or dropped tools. Generally, these arcs are extinguished by removing the voltage from the line with overcurrent protection devices or by use of reclosures, which remove the voltage for a period sufficient for the arc to extinguish and then automatically reconnect the voltage to resume service. Also ground-fault protection frequently is used to detect and interrupt currents from arcing but whose values fall below the levels that trip overcurrent protection devices.

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CHAPTER 4

ENGINE-DRIVEN-GENERATOR SET

For all power systems within the scope of this handbook, engine-driven-generator sets are either the primary power source, i.e., tactical or portable systems, or the backup power source, i.e., standby power systems. In this chapter safety aspects associated with engine-driven-generator sets are discussed. The effects of engine-driven-generator sets on the environment are discussed as well as the hazards they introduce. These environmental factors include the effects of exhaust, noise, high voltage, and elevated temperatures. Design features that should be incorporated to minimize hazards are presented and include the physical configuration of the system, safety controls and interlocks, labeling, and engine selection. Features that aid or prevent compatibility between generators are identified and discussed. Finally, safety procedures that should be specified in operating manuals are identified and discussed.

4-1 INTRODUCTION

4-1.1 DEFINITION OF ENGINE-DRIVEN-GENERATOR SET

An engine-driven-generator set is a self-contained power source consisting of a fuel-powered engine used to turn the armature of an electrical generator to produce electrical current. Components of engine-driven-generator sets are

1. *Engine or Prime Mover.* A gasoline, diesel, or turbine engine, which is used to supply mechanical energy to the generator
2. *Generator.* The electromechanical machine used to convert the mechanical energy in a rotating shaft to electrical energy
3. *Control and/or Monitoring System.* Sensors, indicators, and associated circuitry that are necessary to monitor operation of the engine-driven-generator set and to perform necessary control functions, which include frequency (engine speed) control, voltage regulation, and overcurrent protection
4. *Mounting Platform.* The housing and supports for the engine-driven-generator set. Platforms may be designed to be permanent, fixed installation, relocatable operation, i.e., skid mounted, or mobile, e.g., trailer or vehicle mounted.

Distinguishing features of engine-driven-generator sets include the type of engine used, i.e., gasoline, diesel, or turbine; the output winding configuration of the generator; and the means of field current excitation, e.g., direct excitation through brushes or brushless excitation. The configuration chosen for a specific application is determined by the required capacity of the engine-driven-generator set and the logistics necessary for its operation and maintenance. In the past gasoline engine-driven-generator sets have been used for applications requiring a generator having a capacity of 200 kW or less; diesel engine-driven generators have been used for larger capacities. Gas turbine generators are used for special applications including 400-Hz aircraft ground support and large 750-kW units. The desire to minimize the number of fuels has led to the replacement of gasoline generators with diesel units. Thus all tactical generators could be fueled from the same fuel pools already used for military vehicles. (Turbine generators may be fueled with diesel fuels as well as with a number of other fuels including aviation turbine fuels and, in an emergency, gasoline.)

4-1.2 EXAMPLE OF ENGINE-DRIVEN-GENERATOR SETS USED BY THE ARMY

To reduce the number of engine-driven-generator set models in the Army inventory, the Department of Defense (DoD) has standardized the use of 36 models to satisfy power requirements between 0.5 and 750 kVA. These models are identified and described in MIL-STD-633 (Ref. 1). Table 4-1 summarizes the engine-driven-generator sets listed in MIL-STD-633, including five discontinued models, which presently exist in inventories.

4-2 INDUCED ENVIRONMENT

The presence of an operating engine-driven-generator set will necessarily modify the environment because of the amount of energy released during the production of electricity and the resultant presence of potentially hazardous materials. Environmental factors specifically induced by operation of electrical generators are described in the paragraphs that follow.

4-2.1 ELEVATED TEMPERATURES (Ref. 2)

Only 20 to 30% of the usable energy value of fuel is converted to electricity. Most of the remaining energy is released from the engine in the form of heat, either

TABLE 4-1
ENGINE-DRIVEN-GENERATOR SETS SPECIFIED BY MIL-STD-633, SUMMARY OF CHARACTERISTICS (Ref. 1)

Designation	Capacity, kW	Voltage, V	Frequency, Hz	Prime Mover	Type
MEP-014A	0.5	120	60	Gasoline	Tactical
MEP-019A	0.5	120	400	Gasoline	Tactical
MEP-015A	1.5	120/240	60	Gasoline	Tactical
MEP-016A	3	120 240 120/208	60	Gasoline	Tactical
MEP-021A	3	120 240 120/208	400	Gasoline	Tactical
MEP-017A	5	120 240 120/208	60	Gasoline	Tactical
MEP-002A	5	120 240 120/208	60	Gasoline	Tactical
MEP-022A	5	120 240 120/208	400	Gasoline	Tactical
MEP-018A	10	120 240 120/208	60	Gasoline	Tactical
MEP-003A	10	120 240 120/208	60	Diesel	Tactical
MEP-412A[a]	10	120 240 120/208	60	Turbine	Tactical
MEP-023A	10	120 240 120/208	400	Gasoline	Tactical
MEP-112A	10	120 240 120/240	400	Diesel	Tactical
MEP-414A	15	120/208 240/416	50-60	Diesel	Tactical
MEP-103A	15	120/208 240/416	50-60	Diesel	Tactical

[a]Not type classified for Army use.

(cont'd on next page)

TABLE 4-1 (cont'd)

Designation	Capacity, kW	Voltage, V	Frequency, Hz	Prime Mover	Type
MEP-113A	15	120/208 240/416	400	Diesel	?
MEP-005A	30	120/208 240/416	50-60	Diesel	Tactical
MEP-104A	30	120/208 240/416	50-60	Diesel	Tactical
MEP-114A	30	120/208 240/416	400	Diesel	Tactical
MEP-006A	60	120/208 240/416	50-60	Diesel	Tactical
MEP-105A	60	120/208 240/416	50-60	Diesel	Tactical
MEP-115A	60	120/208 240/416	400	Diesel	Tactical
MEP-404A*	60	120/208 240/416	400	Turbine	Tactical
MEP-305A*	60	115/200 28vdc	400	Turbine	Tactical
MEP-357A*	72 21	115/200 28vdc	400	Diesel	Tactical
MEP-007B	100	120/208 240/416	50-60	Diesel	Tactical
MEP-116B	100	120/208 240/416	400	Diesel	Tactical
MEP-009B	200	120/208 240/416	50-60	Diesel	Tactical
MEP-011A	500	2400/4160 2200/3800	50-60	Diesel	Tactical
MEP-029	500	120/208 240/416	50-60	Diesel	Tactical
MEP-208A	750	2400/4160 2400	50-60	Diesel	Prime
MEP-409A	750	2400/4160 2400	50-60	Turbine	Prime

*Not type classified for Army use.

(cont'd on next page)

TABLE 4-1 (cont'd)

Designation	Capacity, kW	Voltage, V	Frequency, Hz	Prime Mover	Type
MEP-007A[b]	100	120/208 240/416	50-60	Diesel	Tactical
MEP-106A[b]	100	120/208 240/416	50-60	Diesel	Tactical
MEP-116A[b]	100	120/208 240/416	400	Diesel	Tactical
MEP-009[b]	200	120/208 240/416	50-60	Diesel	Tactical
MEP-108A[b]	200	120/208 240/416	50-60	Diesel	Tactical

[b]Exist in inventories but will not be procured in future.

radiated from the engine and generator or released from the exhaust in the form of hot gases. Sources of heat from the engine-driven-generator set are

1. *Engine Block.* During operation the temperature over most of the engine block is slightly above the coolant temperature for liquid-cooled engines or higher for air-cooled engines. Hottest areas are typically near the cylinder heads and the exhaust ports where temperatures may reach 540°C (1000°F). Approximately 15% of engine heat loss is dissipated directly from the block.

2. *Engine Coolant.* In liquid-cooled engines the coolant mixture is under pressure and may be heated to 90°C (195°F) under normal operating conditions and to higher temperatures when the cooling system malfunctions. The mixture is cooled with a radiator, which transfers the heat to the atmosphere. Surfaces of the radiator and the hoses leading to it may reach temperatures near those of the coolant, which are sufficiently hot to produce minor burns. Approximately 40% of the heat lost by the engine is rejected via the coolant.

3. *Exhaust System.* Exhaust gases for typical diesel engines have temperatures of about 650°C (1200°F) and account for approximately 45% of engine heat loss. These gases heat the interior of the components of the exhaust system to temperatures comparable to those in the engine. Exterior surfaces show slightly lower temperatures because of the cooling effect of the air.

4. *Electrical Generator.* Energy losses due to the resistance of conductors in the winding result in the heating of those conductors. The heat produced is equivalent to 4 to 6% of the output of the generator.

4-2.2 VIBRATION AND SOUND

Vibration of the engine may be transmitted through mountings to buildings and thereby may induce noise throughout the area or possibly may cause fatigue or loosening of fasteners. The pulsating nature of the exhaust of the engine produces high noise levels unless noise reduction mechanisms are incorporated. Typical diesel engine-driven-generator sets with minimum silencers produce noise levels of over 95 dBA 3.0 m (10 ft) from the point of discharge. These noise levels exceed the standard noise requirements specified in MIL-STD-1474 (Ref. 3). Silencers available from some manufacturers reduce this level to below 85 dBA (Ref. 2). Reduction of noise levels significantly below this level requires acoustic insulation of the motor to reduce mechanical noise associated with moving parts of the engine. New signature-suppressed generators currently under development by the Army use these techniques to achieve required inaudibility at a distance of 400 m (1300 ft), i.e., the noise level measured at 15 m (50 ft) is below 49 dBA at those frequencies to which the ear is most sensitive.

4-2.3 EXHAUST GASES

The emission of exhaust gases, especially in confined areas, affects the environment through the high temperature and pulsating pressure of the exhaust and through high concentrations of certain compounds in the gases. The temperature of the exhaust generally only affects materials near the point of exhaust discharge and the components of any exhaust system used to pipe the exhaust to another location. The effects of elevated temperatures associated with engine exhaust systems are discussed in par. 4-2.1, and noise considerations of exhaust systems are discussed in par. 4-2.2.

A more significant effect of exhaust is the presence of compounds in concentrations much higher than ambient. If the exhaust is trapped in confined areas, the resulting concentrations will be sufficient to affect personnel and materials. The exhaust products of internal combustion engines include the products of combustion as well as by-products of chemical reactions, induced by the heat of combustion, between atmospheric components. Combustion products include water vapor, carbon dioxide (CO_2), carbon monoxide (CO), sulfur dioxide (SO_2), and hydrocarbons. The most significant combustion by-products are the oxides of nitrogen resulting from the combination of atmospheric nitrogen and oxygen during high-temperature combustion. For gasoline engines, emissions are generally gaseous. Diesel engines produce particulate matter in the form of soot. Effects of these emissions include moisture effects (if temperatures and concentrations cause moisture condensation) and toxic effects on personnel. (See par. 4-3.7.) The solid carbon product, soot, from diesel engines is conductive and may introduce leakage paths across insulating surfaces on which soot accumulates. Sulfur oxides break down protective oxide films on materials that otherwise would be resistant to corrosion in unpolluted atmospheres.

4-2.4 HAZARDOUS VOLTAGES AND CURRENTS

Due to its intended function, an operating generator always has voltage present at the level being delivered to the load. Voltage is always present on windings, monitoring instrumentation, and interconnecting wiring. Voltage levels are the same as the rated output of the generator; available current flow is dependent on the configuration of the generator and may significantly exceed the continuous rated current output. The current available for short transients upon occurrence of a fault is determined by the dynamic characteristics of the control system of the generator—specifically, whether it maintains the rated voltage when the delivered current increases. Current available for longer periods is determined first by any overcurrent protection that is in the circuit and, second, by the thermal limitations of the windings of the generator.

4-2.5 PRESENCE OF FUELS

The presence of fuels associated with an engine-driven-generator set significantly impacts the environment because of the vapors associated with the fuels. The aromas associated with common fuels, gasoline, and diesel fuel are objectional, and some materials may be affected by strong concentrations of these vapors.

The greatest potential impact of vapors, however, is fire hazard due to the flammability of the vapors. One of the most significant flammability characteristics of a liquid fuel is the flash point, i.e., the temperature at which the liquid evaporates at a rate sufficient to produce an ignitable air-fuel mixture close to the surface of the fuel. Gasoline has an extremely low flash point of about −46°C (−50°F); the flash point of fuel oil is higher—above 43°C (110°F). The actual temperature necessary to initiate combustion is high for gasoline, between 280° and 456°C (536° and 853°F) depending on octane rating. The energy required may be very little if the combustion is initiated in a very localized area, i.e., as in that initiated by a small spark. Combustion only occurs if the percentage of gasoline in air is between 1.4 and 7.6%. The combustion temperature of fuel oil is lower—about 250° to 270°C (480° to 520°F).

4-3 HAZARDS

4-3.1 FIRE

Fire is one of the most significant hazards associated with the operation of engine-driven-generator sets because the key ingredients—i.e., fuel, air, and a source of ignition—necessary for the initiation and support of a fire are all present in the engine-driven-generator set. Specific factors that contribute to the fire hazard on the engine-driven-generator set are

1. Presence of a flammable liquid or gas fuel
2. Presence of hot gases and heated surfaces whose temperatures are above the ignition temperature of fuels and other combustible materials
3. Presence of electrical ignition systems, which generate sparks capable of igniting fuel-air mixtures (gasoline engines)
4. Presence of electrical systems, which, in the event of overload, can produce severe localized heating in generator coils.

The potential severity of the hazard depends on the installation and application of the engine-driven-generator set. In all cases, the occurrence of fire from burning fuel in the engine-driven-generator set may disable the generator and require major repair to replace all combustible materials or materials damaged by heat—e.g., plastics, low melting point metals, and electrical coils. Damage outside the generator may be even more catastrophic if the generator is located near combustible materials or in a confined area where the gases released from the fire would prove hazardous to personnel nearby.

The presence of a quantity of fuel having a significant heat of combustion implies that the engine could ignite materials that otherwise would be difficult to ignite and that the heat released from the fuel fire would be sufficient to damage nearby structural materials. The combustion of lubricants tends to be incomplete and releases CO, soot, and unburned hydrocarbons to the atmosphere. Lighter fuels, e.g., gasoline, tend to burn more completely.

The severity of the fire hazard associated with generators is also dependent on the application of the generator, i.e., the required reliability of the output of the generator. Since a fire will most likely remove the generator from service, the consequences of a power outage also contribute to the severity of the hazard. The effect of a power outage could range from inconsequential for noncritical loads to life threatening for an engine-driven-generator set used as standby power for a hospital facility.

4-3.2 BURNS (TO PERSONNEL)

The heated surfaces of the engine and generator cause tissue burns to personnel if touched during operation of the engine immediately after shut down of the system. The most severe burns can result from brief contact with the exhaust manifold, which may reach temperatures of 540°C (1000°F). The radiant heat given off by the manifold and exhaust system, however, provides an advance warning of the hot surface and thereby decreases the likelihood of inadvertent contact. More significant dangers are the possibility of burns from liquid coolants or lubricants that are under pressure in the engine. Normal water-cooled diesel engine water temperatures reach 80° to 95°C (180° to 200°F) or hotter. If these liquids are released either by operator error (opening the radiator cap while the engine is hot) or by malfunction, the liquid will be propelled some distance from the engine and possibly onto the skin of personnel where it will remain until the appropriate action can be taken to remove it. The prolonged period of contact and the high thermal conductivity of the contact tend to make these burns more severe than manifold-related burns.

Another factor that increases the probability of incidental contact with heated surfaces is unexpected temperature increases on surfaces that usually operate at safe temperatures, i.e., less than 60°C or 140°F. Loose connections, escaping exhaust, or an overload can create a situation in which these surfaces become hot. Examples of surfaces expected to remain cool are generator housings, junction boxes, and load-switching devices mounted on the generator. Since operating personnel expect these surfaces to be cool and routinely handle them during normal maintenance, inadvertent burns are likely during undetected malfunctions.

4-3.3 MECHANICAL HAZARDS

Engine-driven-generator sets are energy-conversion devices that use mechanical energy as an intermediate energy form. This energy, in the form of shafts usually rotating at 1800 rpm, is primarily found inside the engine and generator where it is safely shielded by the functional casings of the equipment. (Turbine engines operate at a much higher speed, but the internal speed-reduction gears reduce the speed of exposed shaft to lower speeds compatible with the generator.) The rotating components, however, are exposed at points where the energy must be coupled to the generator or to auxiliary components of the engine, i.e., fan or battery-charging alternator. At locations where rotating shafts are exposed, there exists the hazard of injury to personnel either by direct contact with the irregular surfaces on the rotating shaft or by inadvertent contact when loose clothing becomes entangled in the mechanical apparatus and draws the person into it. The hazard is not as great for smooth shafts as it is for shafts with couplings or pulleys with belts. Unfortunately, it is almost always necessary to use these devices between units to compensate for small misalignments or to couple multiple devices to a single shaft.

A second mechanical hazard associated with rotating machinery is due to the vibration induced by slight imbalances in the armature, periodic explosions of the fuel-air mixture, or reciprocating action of engine components. These vibrations, if not appropriately accounted for in the design, can cause problems both within the machine and in the structures in which the machine is housed. These problems include loosening of threaded fasteners, fatigue of metal components, and the generation of noise as mentioned in par. 4-2.2. Typically, the engine is mounted with vibration isolation mounts to contain the vibrating environment to the engine itself where suitable fasteners and materials are selected to withstand the vibration; otherwise, damage to the structure could occur during long-term operation. Connections to a properly mounted, vibrating engine are also a potential hazard because the flexing of the fuel, exhaust, and electrical connections to the engine may lead to premature failure unless preventive measures are taken. Failure in any of these connections may cause health hazards from release of flammable materials or poisonous gases or from the introduction of an electrical fault that, under certain conditions, could lead to the presence of high voltage on exposed conductors.

4-3.4 ELECTRICAL SHOCK

The presence of hazardous voltages in the generator portion of the engine-driven-generator set as discussed in par. 4-2.4 poses a hazard to personnel who service the generator. These voltages are normally exposed on terminal blocks, which are accessible for connection of the generator as well as for periodic inspection. Certain malfunctions may cause voltage to be on conductors that normally are not energized. These malfunctions include

1. Transfer switches that disconnect the neutral from service could allow voltage on the neutral connection to float to possibly hazardous levels unless the neutral is separately grounded.
2. Nondetection of faults between any conductor and an ungrounded conductor by overcurrent protection until inadvertent contact by personnel.

Usually, moisture increases the hazard of electrical shock by improving the ground connection in the path of the shock current. However, it also may provide leakage paths that energize conductors to which personnel are exposed. Moisture frequently collects in generator windings during periods of inactivity due to the absence of heat, which normally evaporates the moisture. Condensation on internal insulators of the generator could lead to internal faults or unintentional leakage between energized lines and control lines and thereby could cause damage to the generator.

4-3.5 ELECTRICAL FAILURES FROM IMPROPER CONNECTION

The improper or erroneous connection of polyphase systems can result in damage to equipment or injury to personnel. Such connections include application of voltage to exposed conductors that are expected to be at ground potential, application of voltage to grounded conductors, application of excess voltage to lines, or application of imbalanced voltage to balanced three-phase loads.

Omission of the ground connection on generator-load circuits allows the buildup of hazardous voltages between the system neutral and true ground potential. In many cases, the neutral and conductive enclosure are grounded together through a single connection to earth. If this connection is omitted in a polyphase generator-load system, the exposed enclosure typically rises to voltages dangerously above ground potential because of imbalance in the phase-to-ground leakage resistances.

Erroneous connection of power from a generator to a grounded line produces a low-resistance line-to-ground fault, and high currents will flow through the fault until overcurrent protection devices can open the circuit. If switchgear is used between the generator and the load, closing the switchgear onto the fault may result in an explosion that could damage the switchgear and/or nearby equipment.

Generators are typically made with two or more windings to deliver power to each phase. Connection of the windings in series provides higher voltage; connection of the windings in parallel provides higher current capacity. If the windings are connected in series when the parallel configuration is appropriate or if a wye connection on the generator is used when a delta is appropriate, the voltage out of the generator will be higher than intended. This excess voltage will damage motors, electronics, heaters, and most other electrical loads that are connected to the line.

In a three-phase system motors may be damaged if the phase loads are not balanced. Any erroneous connections that produce a voltage imbalance will lower the effective capacity of the three-phase motor and thereby shorten the expected life of the motor. In a system containing three equal, single-phase loads connected to the three lines, the balance would be upset if two or more of the loads were inadvertently connected to the same line.

Improper connection of generators that are paralleled with either a utility or a second generator is especially hazardous because the energy available for damage is more than that available from one generator alone. Misconnection of phases will cause high currents to flow through the generators once they are connected in parallel and possibly will damage the switchgear used to connect them to the line. Considerations for proper paralleling of generators are discussed in par. 4-5.5.

4-3.6 ACOUSTICAL NOISE—HEARING LOSS

The acoustical noise produced by engine-driven-generator sets discussed in par. 4-2.2 is sufficient for probable hearing loss for generator maintenance personnel and for personnel working near engine-driven-generator sets unless ear protection is worn or unless suitable noise-suppression design features for an engine-driven-generator set are employed. The degree of the hazard depends on the noise level of the engine-driven-generator set, the distance between the engine-driven-generator set and the personnel, and the daily period of exposure. For personnel working near the engine-driven-generator sets, the hazard may be eliminated by suitable exhaust silencers and does not exist in signature-suppressed generators that are operated with the acoustic-enclosure doors closed. However, the problem is most severe for operational and maintenance personnel who must work in close proximity to operating engine-driven-generator sets, frequently with the acoustic enclosure open to allow checking or adjusting generator components. These personnel will experience hearing damage unless ear protection devices are worn.

4-3.7 TOXIC EMISSIONS

CO emissions from internal combustion engines are a hazard to personnel in the plume of the engine exhaust or in areas where the exhaust may accumulate, e.g., rooms containing an engine-driven-generator set that has a leak in the exhaust plumbing. Other potentially hazardous materials emitted from internal combustion engines are nitrogen dioxide (NO_2) and aromatic hydrocarbons. The hydrocarbons are found primarily in the particulate emissions from diesel engines, and they have been shown to be mutagenic when they react with NO_2. The hazard is not great, however, because the hydrocarbons are tightly bound to the particulate matter and appear to be protected from chemical reaction by the particulate soot (Ref. 4).

4-4 DESIGN CONSIDERATIONS

4-4.1 PHYSICAL CONFIGURATION OF EQUIPMENT

Equipment should be constructed so that operators and maintenance personnel are not subjected to unnecessary hazards from exposure to moving parts, high voltage, or hot surfaces. Physical guarding of hazardous areas should be incorporated in the design of generators to reduce the hazard to an acceptable level. Proper wiring layout should be incorporated to prevent the development of hazardous conditions during the life of the equipment. Finally, tactical equipment must be designed so that decontamination may be accomplished readily. Provisions for implementing these concepts are discussed in the paragraphs that follow.

4-4.1.1 Principles of Guarding

Guarding is the enclosing of items with protective coverings to prevent unauthorized tampering with the equipment and to prevent inadvertent contact by, and injury to, personnel. Mechanical guards protect personnel from contacting moving parts, such as rotating shafts and belt-driven pulleys, and from possible local ruptures or explosions. Mechanical guards are frequently used with interlocks that prevent access to moving parts until the machine is at its "lowest mechanical state", i.e., energy sources are disconnected, internal movement is stopped, and stored energy is reduced to the lowest possible level. Thermal guards or shields are used to protect operators from inadvertent contact with heated surfaces by providing a protective, cooler surface between the hot surface and accessible areas. Finally, guards and nonbypassable interlocks are used to prevent contact with potentially lethal high voltages.

Guarding must be designed to prevent accidental contact with hazardous features of motor-driven-generator sets. To be effective, however, the guarding must not prevent normal inspection and preventive maintenance. Otherwise, the reliability of the equipment would be compromised and maintenance personnel, inconvenienced by the guards, would not replace the guards securely or would leave them off completely after performing maintenance. The most effective guards are those that are formed by configuring the equipment so that housings, supports, and or other essential structures serve also as protective guards. That is, the equipment is configured such that hazardous features are not exposed. Guards should be added when such configuration is not possible.

4-4.1.2 Protection From Moving Parts

Mechanical guards should be incorporated where necessary around rotating components that could cause injury through inadvertent contact or through entanglement with loose clothing. Components of an engine-driven-generator set that should be mechanically guarded include cooling fans, engine-to-generator coupling, belt-driven engine accessories, and the armature of the generator. Protective guards should be strong enough mechanically to stand up to abuse and should offer mechanical protection against intrusion throughout the life of the machine. Openings in the guards for ventilation, inspection, or access should be small enough to prevent penetration by fingers or clothing. The permissible size of these openings depends on the separation between the guard and the guarded components. Table 4-2 gives the largest recommended openings for guards as specified in ANSI/ASTM B15.1a (Ref. 5). Larger openings may be provided for access to lubrication fittings or for inspection of critical components. These openings, however, should have secure covers that are not easily removed by personnel not authorized to operate the equipment.

4-4.1.3 Protection From Heated Surfaces

Guards for heated surfaces consist of a plate or cover separated sufficiently from the hot surfaces such that it remains at a safe temperature. Thermal isolation is achieved by designing the guard to dissipate rapidly the thermal radiation of the hot surface or to provide sufficient separation or insulation to prevent heat from the hot surface reaching the protective guard. Frequently, guards for hot surfaces are made from perforated material that permits the free passage of air for convective cooling of the guard as well as the surface beneath.

Components of engine-driven-generator sets that should be guarded to prevent contact by personnel are the exhaust system and the engine block. The exhaust system includes both the manifold at the engine and the piping leading away from the engine. Most of the engine block is at temperatures that can cause burns and should be either enclosed, placed in an inaccessible location, or placarded to indicate the presence of hot surfaces.

4-4.1.4 Protection From High-Voltage Exposure

Energized conductors should be insulated or enclosed in a grounded, metal enclosure to prevent accidental contact. Protective material should be sufficiently strong to resist deformation from external stresses that could bring conductive material into contact with the energized conductors.

Moisture protection should be incorporated to prevent the development of moisture-induced leakage paths that could extend the electrical hazard outside of protected regions. Enclosures should be designed to prevent rain from falling or being blown into high-voltage apparatus containing uninsulated conductors, e.g., switchgear,

TABLE 4-2
MAXIMUM DIMENSION OF OPENINGS IN GUARDS FOR MECHANICAL TRANSMISSION APPARATUS (Ref. 5)

Separation Between Guard and Pulley, Gear, or Other Moving Mechanical Component mm (in.)	Largest Permissible Opening (Measured Across Smallest Dimension of Opening) mm (in.)
less than 31.8 (1.25)	6.35 (0.250)
31.8 (1.25) up to 63.5 (2.50)	9.52 (0.375)
63.5 (2.50) up to 88.9 (3.50)	12.70 (0.500)
88.9 (3.50) up to 139.7 (5.50)	15.88 (0.625)
139.7 (5.50) up to 165.1 (6.50)	19.05 (0.750)
165.1 (6.50) up to 190.5 (7.50)	22.22 (0.875)
190.5 (7.50) up to 311.2 (12.25)	31.75 (1.250)
311.2 (12.25) up to 387.4 (15.25)	38.10 (1.500)
387.4 (15.25) up to 444.5 (17.50)	41.28 (1.625)
444.5 (17.50) up to 762 (30.0)	53.98 (2.125)
762 (30.0) up to 1067 (42.0)	152.4 (6.00)

generators, and terminals. Where precipitation or condensation is unavoidable, insulators that have ribbed surfaces to increase the leakage path length should be used. Also all conductors located nearby should be grounded so that any leakage currents will be safely drained away.

4-4.2 FIRE CONTROL SYSTEMS

Fire control systems are systems that, upon detection of fire, take measures to contain or extinguish the fire by spraying or flooding the area or by containing the fire by automatically shutting off fuel supplies.

4-4.2.1 Extinguishing Systems

Extinguishing systems include both manual and automatic apparatus designed to extinguish fire by smothering or cooling the flames. The familiar fire extinguisher is an example of a manual system. To operate manual systems, personnel must position the extinguisher near the fire, activate it, and direct the flow of the extinguishing agent toward the flames. Automatic systems are permanently installed and configured so that, upon detection of fire, the areas most susceptible to, or most likely damaged by, fire are covered by the extinguishing agent. Manual and automatic systems may use the same extinguishing agents. Agents suitable for the combined liquid fuel and electrical fires likely to occur in engine-driven-generator sets are discussed in the paragraphs that follow.

4-4.2.1.1 Carbon Dioxide

CO_2, a nonflammable gas at normal temperatures and pressures, is nonpoisonous at concentrations below 9%. It acts to smother fire by displacing the oxygen necessary to support combustion or, if stored under pressure and cooled with rapid expansion upon expulsion, by producing a powdered dry ice, which rapidly cools the burning objects. Because of the low temperature of dry ice, CO_2 dry ice extinguishers should be used only on apparatus that can withstand sudden cold temperatures.

Available CO_2 extinguisher configurations include portable tanks, fixed tanks with long, flexible hoses, or central tanks connected to permanently installed nozzles. These extinguishers are appropriate for electrical or liquid fuel fires, and they should contain sufficient gas to fill completely the enclosed area in which they are to be used, plus an allowance for leakage. Extinguishers to be used in open areas should have a capacity sufficient to flood the surface with gas and/or solid mixture for 1 min. Sizing considerations are discussed in Ref. 6.

The effectiveness of CO_2 extinguishers is minimal for materials that contain their own oxidizing agents and superheated materials with sufficient heat retention to reignite after the CO_2 has dissipated. The hazards introduced by the use of CO_2 as an extinguishing agent include freezing of tissue upon exposure to the gaseous CO_2 and/or dry ice stream, suffocation in oxygen-deficient atmospheres (confined spaces), and reduced visibility during emergency exiting due to the dry ice "snow".

4-4.2.1.2 Halogenated Agents

Halogenated agents are hydrocarbons in which the hydrogen atoms are replaced by an element from the halogen series. Example halogens are listed in Table 4-3. Those containing fluorine are the most stable and least toxic. Chlorine and bromine atoms increase the ability of the halogenated agents to extinguish fires, but increased toxicity is a result.

Concern about the toxicity of halogenated agents that were developed before World War II led to the study of effects of halogenated agents and the identification of Halon 1301 and 1211 as safe fire-suppression agents. Both are gases at 23°C (74°F) but can be stored as liquids in pressure vessels. While some halogenated agents are corrosive, these are not and thereby permit their use around electrical apparatus without damage to the equipment.

Halogenated agents suppress fires by chemically reacting with the burning reactants. Total flooding of the area is not necessary to extinguish fires, and concentrations as low as 5 to 8% are sufficient. Human exposure to the following compounds should be kept below specified concentrations even for 15-min intervals—7% for Halon 1301 and 4% for Halon 1211. A greater hazard is the toxic materials that may be produced upon heating of these halogenated compounds to 482°C (900°F) or from contact with flame. Toxic compounds that may be produced at this temperature include hydrochloric acid (HCl) and chlorine gas (Cl_2).

Halogenated agents are used usually as part of a permanently installed system that totally floods the enclosed area. This system is used in conjunction with other systems to shut down ventilation systems and to warn personnel of the presence of halogens. These systems are installed on aircraft, vehicles, and engine-driven-generator sets. Such systems are suitable in conditions where

1. A clean agent is required.
2. Live electrical conductors are present.
3. Flammable gases are present.
4. Surface burning materials are present.
5. Valuable objects are to be protected.
6. Personnel are present.
7. Water is limited.

4-4.2.1.3 Dry Chemicals

Sodium bicarbonate, potassium bicarbonate, potassium chloride, urea-potassium bicarbonate, or monoammonium phosphate in powder form are sometimes used to extinguish fires. These materials extinguish fires by smothering, cooling, radiation shielding, and chemical reaction. They are most effective for liquids and surface burning materials. Since the materials are nonconductive, dry chemicals are especially suitable for engine-driven-generator set fires where electricity and fuel are both present. Water or other wetting extinguishing agents may be necessary to extinguish fires smoldering beneath the material surface. Powders are especially suitable for liquid fires and electrical fires.

TABLE 4-3
PROPERTIES OF COMMON HALOGENATED FIRE-EXTINGUISHING AGENTS (Ref. 6)

Agent	Chemical Formula	Halon No.	Type of Agent	Approx. Boiling Point, °C	Approx. Boiling Point, °F	Approx. Freezing Point, °C	Approx. Freezing Point, °F	Specific Gravity of Liquid at 20°C (68°F) (Water = 1)	Approx. Critical Temperature, °C	Approx. Critical Temperature, °F	Latent Heat of Vaporization, kJ/kg	Latent Heat of Vaporization, Btu/lb
Carbon tetrachloride	CCl_4	104	Liquid	77	170	−22	8	1.595	492	212		
Methyl bromide	CH_3Br	1001	Liquid	4	40	−93	135	1.73			259	112
Bromochloromethane	$BrCH_2Cl$	1011	Liquid	66	151	−88	124	1.93				
Dibromodifluoromethane	Br_2CF_2	1202	Liquid	24	76	−142	223	2.28	198	389	121	52
Bromochlorodifluoromethane	$BrCClF_2$	1211	Liquified Gas*	−4	25	−161	257	1.83	154	309	134	58
Bromotrifluoromethane	$BrCF_3$	1301	Liquified Gas	−58	72	−168	270	1.57	67	153	117	50
Dibromotetrafluoroethane	BrF_2CCBrF_2	2402	Liquid	47	117	−111	167	2.17			105	45

*May be kept as a liquid at reduced temperatures.

Dry chemical powders are not recommended for use in apparatus, e.g., electrical apparatus with open contacts, that will be damaged or contaminated by the presence of insulating particulate matter. Also, dry chemical powders should be used only in applications where transient protection is sufficient because the material, once applied and heated, loses its effectiveness.

Dry chemicals are used in fixed or portable fire-extinguishing systems in which the powder is dispersed by the flow of pressurized gas. The powder must be protected from temperatures in excess of 52°C (125°F) to prevent caking.

4-4.2.1.4 Foam Systems

Foam systems, which deliver a water and/or foaming agent mixture, are suitable for fires involving pooled liquid fuels because the foam floats on top of liquids and prevents oxygen from reaching the liquid. The foam must be applied at a high rate so that it will cool the fire and not be vaporized by it. Also viscous foams may be used to fill volumes and thereby eliminate convective air currents that fan flames. Foams are not especially suitable for engine-driven-generator sets because the foam solution is conductive and could introduce hazards when sprayed on electrical apparatus.

4-4.2.2 Configuration for Fire Control

Appropriate arrangement of the engine-driven-generator sets will minimize the potential damage to the unit in case of fire. Since the largest potential source of flammable material is the fuel, the fuel tanks should be located as far as possible from sources of ignition and away from locations where fires are likely to be initiated. Fuel-filling ports should *never* be located above exhaust or ignition system components because spillage or overflow of the heavier-than-air vapors during the refilling operation may be ignited. In fixed engine-driven-generator set installations, the fuel tanks should be located outside the structures and away from items subject to damage from fire; dikes or trays should be provided to contain fuel in the event of spillage. Except for fuel tanks that are integrated into the engine-driven-generator set, the fuel tank should be mounted below the engine and the fuel pumped up to it. This is necessary so that in the event of engine fire, the pumps may be shut off and gravity will not continue the flow of fuel to the engine. Automatic fuel-shutoff valves should be installed on lines to the engine so that if fire is detected, the fuel supply is shut off to allow the fire to be extinguished more easily. Where the tank is separated from the engine, plainly marked cutoff valves should be placed near the fuel tank or at other accessible locations where the fuel supply may be cut off.

4-4.3 SAFETY INTERLOCKS

4-4.3.1 Techniques for Safety Interlocks

Safety interlocks are mechanical or electrical devices that are configured to allow full operation of equipment when all protective systems are operational and to prevent operation when a hazardous condition exists, e.g., a panel is removed and high-voltage terminations or rotating shafts are exposed. Examples of interlocks are switch handles configured so that the enclosure housing cannot be opened unless the switch is in the off position and electrical switches that shut off power when access panels are removed.

Several mechanisms can be used to implement a safety interlock. Common ones are

1. Spring-loaded switches that open upon opening the enclosure panel or door
2. Installation of power through a panel-mounted socket that is disconnected from the equipment mounting plug when the panel is removed
3. Configuration of the equipment power-switch handle so that the switch must be in the off position before the equipment access door may be opened.

In certain cases, it may be necessary to provide a way to override the safety interlocks to observe equipment operation during maintenance. The addition of override switches that allow modified operation, e.g., slow speed, low power, is safer than no provision for observation because maintenance personnel may be inclined to invent "jury-rigged" mechanisms to override the interlocks.

4-4.3.2 Application of Interlocks to Engine-Driven-Generator Sets

Safety interlocks may be appropriate on engine-driven-generator sets to prevent exposure of operators and maintenance personnel to voltages associated with the generator. The most likely applications are switches to prevent operation of the engine-driven-generator set when the control panel is opened—exposing wiring to the indicators and controls—or when critical baffles are removed. Removal of critical baffles prevents the proper airflow for engine cooling.

Interlocks are not routinely used on engine-driven-generator sets. Rather, engine-driven-generator sets are typically installed such that unauthorized personnel do not have ready access to hazardous areas of the generator. Interlocks might prevent certain repairs or inspections necessary to assure continuous operation of the engine-driven-generator set. An interlock, because it would shut down the supply of power, could introduce a greater hazard than would exist without it. Likewise in tactical situations, it is usually critical to unit missions that the engine-driven-generator set remain operational continuously, and mechanisms that would shut it down during inspections would be unacceptable.

4-4.4 GENERATOR CONTROL AND PROTECTIVE SYSTEM

4-4.4.1 Functions of Control Systems

Control systems for engine-driven-generator sets must be designed to accomplish three functions, namely,

1. Regulate operation, e.g., automatic control of speed (frequency) and voltage, and manual control of voltage level and fuel source
2. Shut down equipment upon recognition of conditions that are unsafe for equipment or nearby personnel
3. Provide indications to operating personnel on status of equipment.

Control-system performance of these functions may be either totally mechanical, electronic, or a combination of mechanical and electronic. Electronic systems consist of sensors; analog or digital electronics to determine the desired corrective action based upon the acquired measurements; and solenoids, relays, or servomotors to effect the desired control. New technology allows the economical use of microprocessors, which permit the monitoring of additional parameters and implementation of more effective control algorithms. More sophisticated safety interlocks are possible with programmable digital controllers.

4-4.4.2 *Control-System Design Considerations*

Functional requirements for the controller are determined by the particular application. Voltage control and frequency control limits are determined by the equipment the engine-driven-generator set is required to operate, especially when the generator is to be operated in parallel with another generator or another power source. The most important requirements are voltage tolerance, frequency tolerance, and frequency-load relationship (droop characteristics). Manual controls on sets generally include voltage level (fine adjustment of nominal output voltage) and controls for connecting the generator-on-line in parallel with another power source.

Safety cutoff systems monitor engine operating parameters and, when unsafe conditions are noted, shut down the generator through the cutoff of the fuel supply (diesel engines) or by deactivation of the engine ignition system (gasoline engines). Parameters recommended by Ref. 7 for monitoring by safety cutoff systems are listed in Table 4-4 for systems that are both critical to life or health of personnel (Level 1) and those that are less critical (Level 2). Also, an electrical schematic is given in Fig. 4-1 (Ref. 8), which shows the wiring of a typical safety control system for a portable generator and indicates the parameters that, when out of limits, cause the engine-driven-generator set to be shut off. Note the emergency switch, sometimes called a "battle override" switch, that allows the generator to be operated under emergency conditions when one or more of the parameters is out of range or when a sensor malfunctions.

4-4.4.3 Other Protective Systems

Automatic fire control systems may be added to engine-driven-generator sets where additional protection is necessary for the generator and surrounding areas. These systems usually are added externally to the generator because the choice of an appropriate extinguishing agent and the capacity of the system are dependent on the environment of the engine-driven-generator set as well as on the unit itself. This is especially true for permanently installed engine-driven-generator sets mounted inside buildings where the fuel is stored somewhat remotely from the generator. Halogenated agents and CO_2 are suitable for engine-driven-generator set fires. High-capacity units, however, are required for generators installed inside buildings and surrounded by flammable materials. Under these conditions, automatic systems would be most effective with suitable heat or smoke detectors used to activate the extinguishing system. Sensors should be placed carefully so that normal exhaust and heat from the engine do not activate the protective system.

4-4.5 ACOUSTICAL QUIETING

To achieve the degree of noise suppression on diesel engines necessary to eliminate risk of hearing loss, it generally is sufficient to provide noise suppressors on the exhaust. Information on the design of silencers for reciprocating engine exhaust is given in Ref. 9. Commercially available exhaust silencers or mufflers reduce the sound of the exhaust noise below that of the combustion and mechanical noise radiating directly from the engine. For gasoline engines a proper cooling fan and intake design will minimize directly radiated noise; for diesel engines, these same noise sources should be corrected. Higher cylinder pressures and the more rapid pressure rise in diesel engines, however, cause greater noise emission due to transmission of the combustion wave through the engine block and the noise from mechanical sources such as piston slap. These noise sources can be reduced by proper mechanical design of the engine with features used on diesel passenger car engines, e.g., vibration dampers, stiffening ribs on the engine block, covers for noise-emitting surfaces, and acoustic isolators between external surfaces and the engine block (Refs. 10 and 11).

Gas turbines, which must be properly balanced for safe and reliable operation, generate less vibration than the reciprocating engines. The noise generated at the intake and exhaust has higher frequency components than a reciprocating engine. This noise may be easily silenced by proper baffleing of the intake and exhaust ports of the engine.

Further overall reduction of noise from either engine may be obtained by housing the engine in an acoustically insulated enclosure. (Acoustic insulation should be used on the inside of large surfaces to reduce sound transmitted through them.) Also the engine-driven-generator set should be mounted with vibration isolators to minimize transmission of mechanical noise to the outer surfaces of the housing. Provision also must be made to allow circulation of cooling air over the surface of the engine and through the cooling system radiator with appropriate baffles at the air intake and exhaust ports to minimize the transmission of noise through those openings.

4-4.6 TERMINAL DESIGN

Terminals for connection of an engine-driven-generator set to a distribution system should be designed to maintain a reliable connection and configured to minimize the probability of improper connection.

Terminals also should be designed to withstand vibration produced by engine-driven-generator sets without becoming loose. Vibration-resistant threaded nuts or locking washers should be used. In addition, the terminal should be designed to accommodate dimensional changes in the conductors or lugs used with it. Temperature cycling associated with changing ambient temperature.

TABLE 4-4
SAFETY INDICATORS AND SHUTDOWNS (Ref. 7)

Indicator Function (at Battery Voltage)	Level 1			Level 2		
	CV	S	RA	CV	S	RA
(a) Overcrank	X	X	X	X	X	0
(b) Low Water Temperature < 21°C (70°F)	X		X	X		0
(c) High Engine Temperature Prealarm	X		X	0		
(d) High Engine Temperature	X	X	X	X	X	0
(e) Low Lube Oil Pressure Prealarm	X		X	0		
(f) Low Lube Oil Pressure	X	X	X	X	X	0
(g) Overspeed	X	X	X	X	X	0
(h) Low Fuel Main Tank	X		X	0		0
(i) EPS Supplying Load	X			0		
(j) Control Switch Not in Auto Position	X		X	0		
(k) Battery Charges Malfunctioning	X			0		
(l) Low Voltage in Battery	X			0		
(m) Lamp Test	X			X		
(n) Contacts for Local and Remote Common Alarm	X		X	X		X
(o) Audible Alarm Silencing Switch			X			0
(p) Low Starting Air Pressure	X			0		
(q) Low Starting Hydraulic Pressure	X			0		
(r) Air Shutdown Damper When Used	X	X	X	X	X	0
(s) Remote Emergency Stop		X			X	

KEY:

CV = Control-panel-mounted visual indication
RA = Remote audible
S = Shutdown of EPS
X = Required
0 = Optional
EPS = Emergency power supply

ambient heating associated with the engine-driven-generator set, and, most importantly, resistive heating of the interconnection cause expansion of the conductors or lugs used with the terminal. The expansion causes deformation of the terminal, which may become permanent if the terminal design is not sufficiently elastic to accommodate the expansion. Cycling expansions can then loosen the connection further, which, in turn, increases the resistive temperature heating of the junction and accelerates the loosening process. The process is further accelerated if the terminal material has a temperature coefficient of expansion that differs significantly from that of the conductor or if the conductor is susceptible to deformation as is the case with aluminum wire sometimes used as a conductor.

Terminals should also have adequate separation between phase connections so that errant strands of a connected cable cannot contact the terminals, wiring associated with another phase, or the neutral. Terminals that are constructed to contain strands should be used in all cases. Split lugs with captive nuts are required for generators specified under MIL-STD-633. If crimped eyelet lugs are used, provision—e.g., barrier terminal strips with vibration-resistant fasteners—should be made to prevent the lugs from loosening and moving into contact with adjacent terminals.

Terminals should be clearly labeled for proper connection. Output connections for three-phase generators should be marked with the capital letter L with subscript 1 through 3 to indicate order of phase sequence, i.e., the order in which each line reaches its maximum voltage. A separate equipment ground connection should be located next to the output connections and marked "GND". The neutral connection is marked by the subscript 0, i.e., L_0. Separate windings in the generator may be connected to a terminal block called a changeover block so that the windings may be connected in different configurations to provide different output voltages and current capacities. The labeling of terminals should be uniform and consistent with standard practices to minimize the possibility of confusion when the generator is being configured. Fig. 4-2 (Ref. 12) illustrates the standard system for labeling terminals for generators with multiple windings for each phase. Fig. 4-3 illustrates the conventional positioning of terminals on the changeover block. Unless there is an overriding technical reason to use an alternative configuration, this configuration should be used to minimize the chance of misinterpretation of terminal connection and to allow the use of standardized reconfiguration blocks on a series of generators.

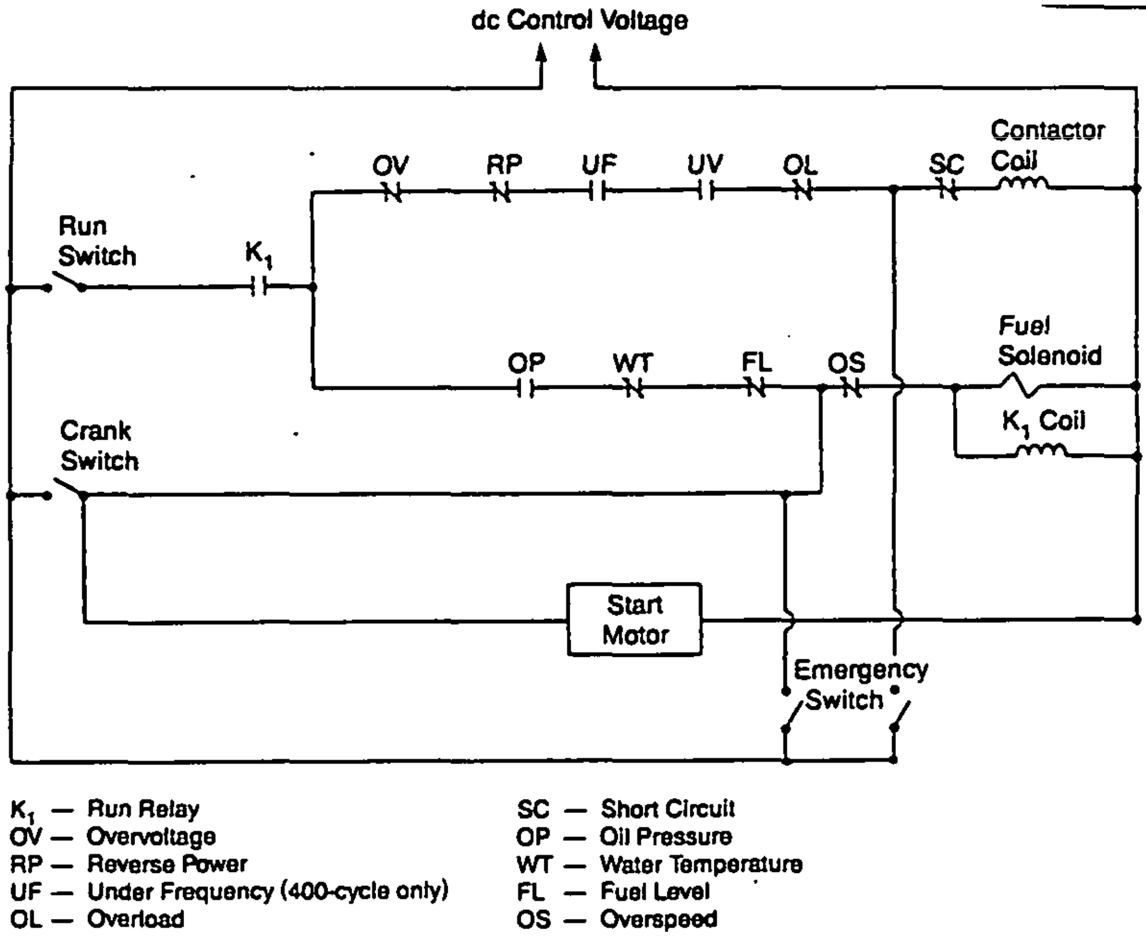


Figure 4-1. Wiring Diagram of a Typical Safety Control System for Portable Generator Sets (Ref. 8)

4-4.7 INSULATION MATERIAL SELECTION

The insulation system of a machine (generator or motor) is defined as the collection of all the insulation materials used in the machine including winding coatings, sleeving, insulating bushings, and rigid insulation used for terminal blocks and supports. Insulation systems are rated according to the allowable temperature rise of the machine in which they are used. The rating of a particular material is determined by the machine having the highest temperature classification in which the material has been successfully used. The actual temperature the material must withstand is affected by the application within the machine since the buildup of heat is not uniform throughout the machine. Furthermore, the allowable heat rise specified in governing specifications for machines will vary somewhat within each classification depending on the type of machine, its intended operation (e.g., continuous or intermittent operation), and the ambient temperatures (if above 40°C or 105°F). Nominal maximum temperature requirements for insulation materials used in these classifications are

1. Class A. 105°C (220°F)
2. Class B. 130°C (270°F)
3. Class F. 155°C (310°F)
4. Class H. 185°C (360°F).

Note that these temperatures are presented as a guide because the actual temperatures will depend on factors such as the use of the insulation within the machine and the stated type and/or use of the machine. The determination of the classification of a new insulation material is determined by comparison (through thermal testing) with materials that have traditionally been used successfully in machine insulation systems.

The selection of specific materials is made on the basis of experience with materials in generator applications, i.e., whether their classification has been supported by observation in use over a period of time, and testing of the materials to determine whether they retain the desired electrical and mechanical characteristics when operated at anticipated temperatures for long periods. Accelerated testing is performed at elevated temperatures assuming the 10-deg C rule, i.e., increasing the environmental

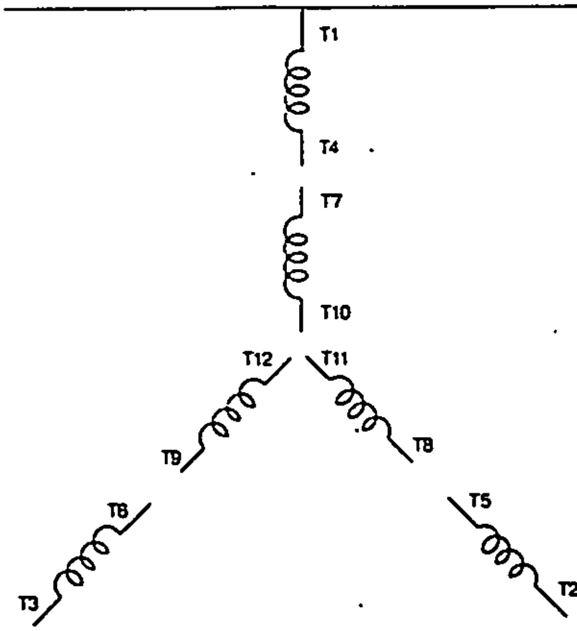


Figure 4-2. Terminal Marking of Generator With Multiple Windings per Phase (Ref. 12)

temperature by 10-deg C (18-deg F) shortens the expected life by one half provided the melting points or ignition temperatures of the insulation materials are not approached. Therefore, increasing the exposure temperature significantly above the operating temperature decreases the testing period necessary to determine the lifetime of the insulation. Examples of tests for generator winding insulations are given in Refs. 13 and 14. In these tests, coils in the same configuration to be used in the motors or actual motors are exposed to elevated temperatures under controlled environmental conditions and evaluated for deterioration in insulation performance.

Table 4-5 (Refs. 15 and 16) lists insulation materials, for various temperature classifications, used for windings and internal wiring in generators. When relatively soft insulations, such as rubbers or certain thermoplastics, are used, resistance to abrasion may be provided by an additional material covering, such as nylon, or by an outer braid of nylon, glass, or polyester.

Bushings for support or protection of wiring or live electrical components are generally made from phenolic, urea, cold-molded compositions, or other materials found through experience to be suitable for use in rotating machinery. Where high voltages are present, ceramic or glass insulators may be necessary; if used, provision should be made to protect these relatively brittle materials from fracture due to physical impact or thermal expansion. The insulator must also be configured so that expansion or warpage from overheating or moisture absorption does not introduce additional hazards of fire or electrical shock.

Characteristics of insulation materials are summarized in par. 3-3.7.

4-4.8 CURRENT CAPACITY

The continuous current-carrying capacity of an engine-driven-generator set usually is limited by the thermal limitations of the generator windings. The maximum temperature that the insulation can tolerate limits the amount of heat dissipation allowed in the windings and, in turn, limits the amount of current allowed to flow through the windings over a long period of time.

Limitations on transient currents, i.e., currents that flow for periods up to a few seconds, are more complex. The actual current that can flow upon sudden application of a load or fault depends on the voltage regulation circuitry, the inertia of the rotating components in the engine-driven-generator set, and the response time of the governor of the engine. Generators that rectify a portion of the generated AC power and feed the resultant DC through brushes to a rotating field coil have a fast response, but when severely overloaded, the voltage will collapse. Thus these generators are self-protected; however, the inherent current-limiting feature precludes the use of circuit breakers to isolate the portion of the load network containing the overload. Voltage regulation circuits that rely on inductive couplings to the armature typically require several cycles to boost voltage output to the original level after application of the load. Other techniques, such as optical coupling of control signals to the armature, allow much faster recovery to the nominal voltage output.

The sudden application of a load requires that the engine in the engine-driven-generator set supply more energy to the generator. This sudden mechanical load on the engine causes the speed to drop and lower the frequency and voltage of the generated electricity. If the rotational inertia of the generator is sufficiently large, the generator may "ride through" short transients in current consumption. If the engine has sufficient power, however, then the sudden application of loads in excess of the capacity of the engine-driven-generator set will stall or slow the motor and excessively reduce the output voltage and frequency to unacceptable levels.

Requirements for current capacity in an engine-driven-generator set are determined by calculating the maximum anticipated demand load, i.e., the maximum load that the generator is required to deliver, with consideration given to transient loads and power factors. The most common transient loads are motor-starting loads in which the motor current may be six times the normal rated current of the motor operating under load. In cases where motor-starting loads are supplied by the engine-driven-generator set, the engine-generator must have a voltage-current characteristic and transient current capacity such that when the motor is started, the output voltage remains at a level sufficient to

1. Start the motor
2. Maintain operation of other motors
3. Maintain operation of other equipment powered from the same engine-driven-generator set.

Another consideration in the specification of transient current requirements is overcurrent protection of the circuit. As mentioned earlier, static-excited generators are self-protected but usually do not have the capacity to deliver sufficient peak current to open circuit breakers.

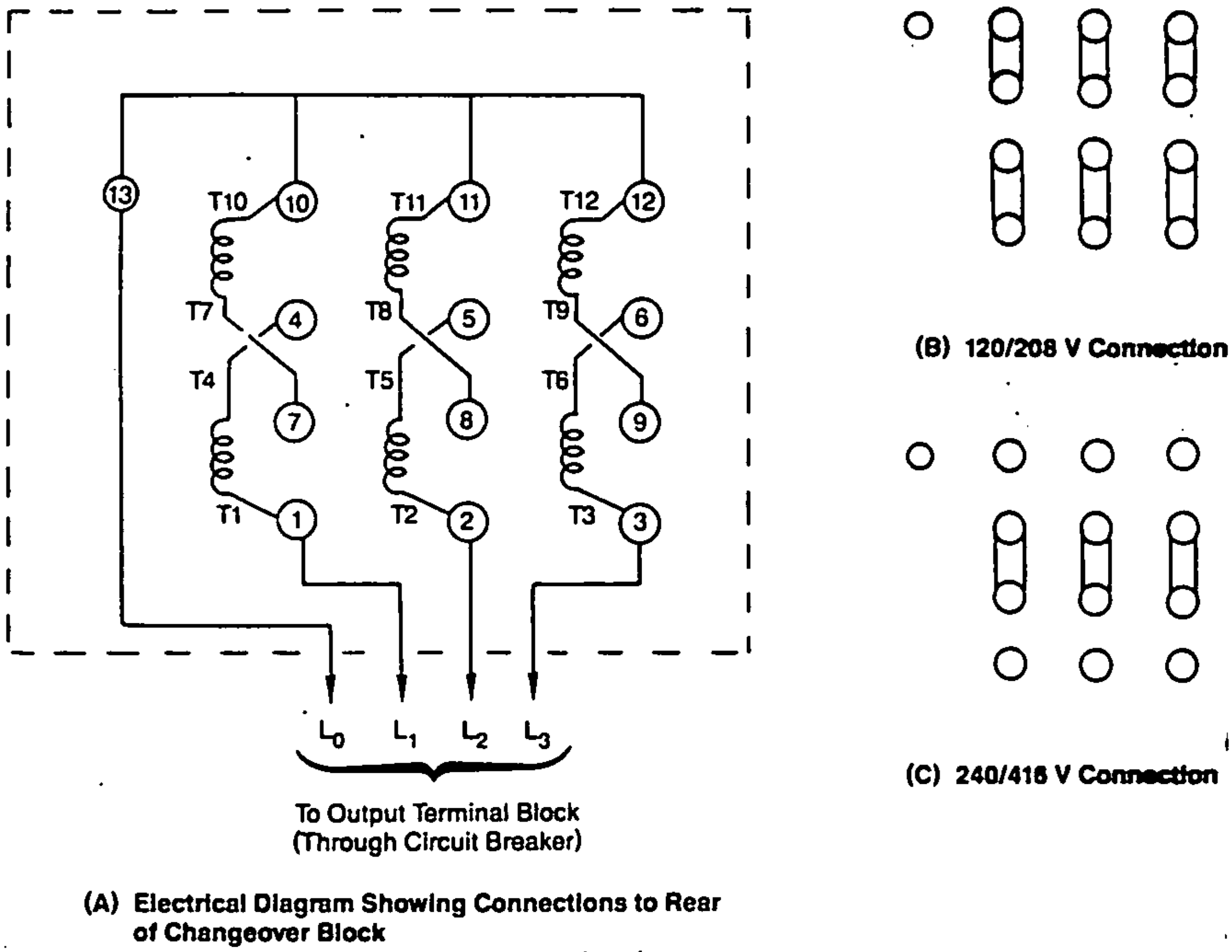


Figure 4-3. Changeover Block Used for DoD 120/208-240/416 V Engine-Driven-Generator Sets

Consequently, for applications where it is important that a single fault not disrupt operation of all loads connected to the generator, it is necessary for the engine-driven-generator set to have a current capacity sufficient to open overcurrent devices under fault conditions and to have voltage regulated at a level sufficiently high to force enough current through the fault to trip the circuit breaker.

4-4.9 EQUIPMENT MARKING

Labeling should be incorporated into the design of equipment to provide warnings about

1. Hazards that cannot be eliminated through appropriate design measures
2. Hazards that exist when the safety features are inoperative during normal maintenance or repair
3. Operational procedures that, if not performed properly, jeopardize the equipment and safety of personnel.

On engine-driven-generator sets, hazard warning signs or labels usually are required to warn of high temperatures and high voltages. Labels should be applied to removable protective panels or guards to warn of the hazardous conditions that exist upon removal. Labels should also be applied to the equipment near the hazard at locations where the label will not be covered or removed during normal maintenance or servicing of the equipment.

The colors and configurations of warning signs should conform to specifications given in Army Regulation (AR) 380-30 (Ref. 17) and American National Standards Institute (ANSI) Z.35.1-1972 (Ref. 18). In these standards, signs are classified according to the severity of the hazard. Classifications are

1. Class I. Warns of the possibility of irreversible damage or injury
2. Class II. Warns of the potential for severe damage or injury that is reversible

TABLE 4-5
TEMPERATURE GRADE OF INSULATION MATERIALS USED IN ENGINE-DRIVEN-GENERATOR SETS* (Refs. 15 and 16)

Temperature, °C	°F	Grade	Material
40	105	A	Enamels Polyamide-overcoated polyvinyl formal Polyamide Polyamide-overcoated acrylic Polyvinyl formal Wire insulation Polyvinyl chloride Polyvinyl chloride with nylon cover Polyethylene
55	130	B	Enamels Polyamide-overcoated polyurethane
70	155	F	Enamels Polyamide-overcoated terephthalate polyester coverings Glass and/or polyester fibers with phenolic bond Insulation Silicone
80 or greater	180	H	Wire insulation Polytetrafluoroethylene Silicone with glass and polyester covers

*Information is provided as a guide only. Actual temperature depends on compounding and should be verified by testing in a specific application.

3. Class III. Provides general safety information
4. Class IV. Provides fire-extinguishing or evacuation information
5. Class V. Warns of radiation hazards.

An example of a warning sign is shown in Fig. 4-4. The actual size of the sign is dependent on the length of the message and the distance at which it must be viewed to provide adequate warning. An approximate rule of thumb for determining the required letter size is that 11 to 12 m (35 to 40 ft) of viewing distance is attainable per 25 mm (1 in.) of letter height. Colors used on the signs, as indicated in Fig. 4-4, should conform to ANSI Z53.1 (Ref. 19). Warning or caution signs should not be affixed with adhesives. Signs should be affixed with mechanical fasteners and conform to MIL-P-514, Type III, Composition C, Grade A, Class 1, to withstand the ruggedness of military environments.

ANSI Z53.1 specifies colors to be used for marking physical hazards and safety features. The significance of specific colors according to this specification is given in Table 4-6. For engine-driven-generator sets red should be used for fire-extinguishing equipment, emergency cutoff switches, and fuel shutoff valves. Orange should be used around exposed rotating components and high-voltage conductors. First aid equipment should be marked with green.

Labeling should also be used to prevent accidents that could result from the improper operation of equipment. Placards showing the schematic of the generator windings along with the terminals and changeover blocks should be placed near the terminal block to aid in the proper connection of the engine-driven-generator set. Start-up and shutdown procedures should be described concisely on placards placed in protected areas, such as inner surfaces of doors. Critical procedures, such as fuel handling and generator paralleling, should be highlighted.

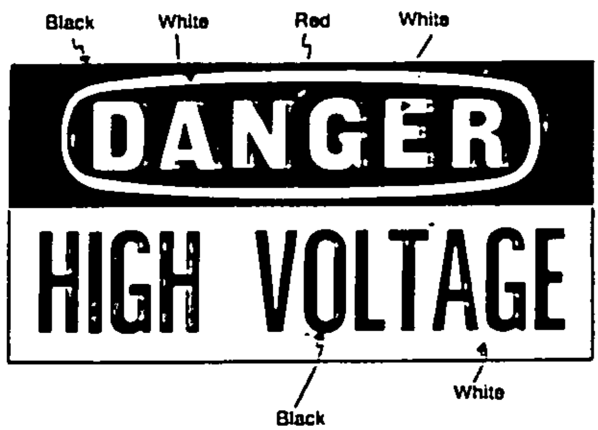


Figure 4-4. Standard Safety Sign per ANSI Z53.1 (Ref. 19)

TABLE 4-6
STANDARD COLORS FOR MARKING HAZARDS AND SAFETY EQUIPMENT
(Ref. 19)

Color	Significance
Red	Identifies fire protection equipment, danger, and shutoff controls of equipment
Orange	Identifies dangerous components of equipment, including inner surfaces of guards
Yellow	Marks potential hazards such as storage cabinets for flammable materials and physical features that could cause injury if bumped against or tripped over
Green	Marks safety equipment and information
Blue	Used for informational signs (other than safety-specific information)
Purple	Identifies radiation hazards

4-4.10 PROVISIONS FOR PARALLEL OPERATION

Parallel operation of an engine-driven-generator set with another source of electric power requires that the two power sources have the same frequency and voltage level. Furthermore, the engine-driven-generator set must have features that allow it to be synchronized to the other power sources, gracefully switched on-line, and operated in parallel so that the load is shared appropriately.

For operation in parallel two engine-driven-generator sets must have provisions for distributing the load equally between the generators and for minimizing the flow of current from one generator to the other. The current flow between the generators represents a flow of reactive power from one to the other. Although this power flow is not measurable as real power delivered by the generator, it does reduce the capacity of the pair of generators. Balancing the voltages generated by the generators minimizes the reactive power flow; however, changes in load current or power factor will usually introduce a voltage imbalance unless the pair of generators incorporates an active control system to synchronize the two outputs or the generators have certain matched characteristics.

Isynchronous generators (generators whose output frequency does not vary with the load) may be paralleled if a common control system is used to regulate the output voltage and frequency of both generators. The common control system may consist of components in both engine-driven-generator sets with control signals passed between them to synchronize them. For sets that employ this concept to be paralleled, the sets must be designed to interface with each other and are typically limited to units that are made by the same manufacturer.

When generators are to be paralleled with no electrical connection other than the outputs, the following characteristics of the generators must match:

1. Output voltage
2. Line frequency
3. Phase configuration (number of phases and angle of each)
4. Phase rotation
5. Speed regulation characteristics
6. Voltage regulation characteristics.

The final two items in this list are necessary for proper continuous sharing of the load under dynamic conditions. Generators to be paralleled must have a frequency droop characteristic of about 2 Hz, i.e., the output frequency should decrease about 2 Hz as the generator load is changed from near zero load to full load. This is required for continuous synchronization of paralleled generator speeds without "hunting" (instability of the generator speed and frequency of the power) and equal distribution of generator loading during load changes. The matched voltage regulation characteristic is necessary to prevent the flow of reactive power from one generator to the other. For generators to be paralleled, these six characteristics must be carefully matched or should have provisions for altering these characteristics through adjustments or tap selection in the control system of the generator (Ref. 2).

In addition to carefully designed compensation circuits, generators intended for parallel operation should incorporate certain features that permit graceful interconnections, i.e.,

1. Indicators (usually lights) to indicate differences in potential between the generators. Monitoring of these indicators allows the operator to connect generators in parallel at times when voltage differences between the two generators are at a minimum.
2. Switch or circuit breaker to isolate the generator from the line until the generator voltage and phase are matched to those of the line.
3. Power output meters for operator monitoring and/or adjustment of droop characteristics and a current meter for operator monitoring and/or adjustment of voltage-load characteristics.
4. Provision for adjustment of voltage level, voltage-load characteristic, and droop characteristic if the generator is to be paralleled with nonidentical generators.

4-4.11 ENGINE SELECTION

Selection among gasoline, diesel, and turbine engines for the engine-driven-generator set is based on application requirements for power, allowable weight, access for maintenance, environmental conditions, and fuel availability. The relative importance of each of these considerations also depends on the application. Fuel considerations affect the choice of engine from a safety perspective more than the other considerations and therefore are discussed separately in par. 4-4.12. The other considerations are similar in terms of operational hazards for gasoline and diesel engines and do not affect the safety of operation. Turbine engines operate on a different principle and turn at a much faster rate during operation. Proper mechanical design, however, will reduce any additional hazards from the high-speed components.

Usually, gasoline engines are most appropriate for small loads for which the additional weight of the diesel engine represents a handicap. Diesel engines are heavier but are more durable and do not require maintenance as frequently as gasoline engines. Diesel exhaust is cooler, nominally 540°C (1000°F) compared to 930°C (1700°F) for gasoline engines. Diesel engines generate more noise from sources other than exhaust when compared to gasoline engines; however, engine noise may be reduced by appropriate design when required. Gasoline engines generate more harmful emissions (NO_x and CO); diesel engines emit the more visible particulates and somewhat more objectional odors (Ref. 20). Although emissions are not important in tactical environments, generators are used in training exercises and other missions. Consequently, the goal should be a minimization of all pollutants. The choice between gasoline and diesel engines for engine-driven-generator sets for Army-wide applications generally will be diesel to minimize the number of fuels to be handled by the supply system.

In comparison to reciprocating engines, gas turbine engines are noisier and potentially more dangerous because of their higher rotational speed. For this reason, their use is usually justified only in applications in which their small size and low weight are required. However, gas turbine generators may sometimes be used in certain applications where the following features of gas turbine generators may be advantageous (Ref. 21):

1. Lower cost (for large capacity engine-driven-generator sets, e.g., 750 kW)
2. Faster starting (and lower power required for starting)
3. Easier to silence
4. Less vibration
5. Multifuel capability.

4-4.12 FUEL

Fuel considerations are among the most important aspects in the selection of an engine type for an engine-driven-generator set both in terms of the safety of fuel storage and the logistics of supplying fuel for all engines, vehicular as well as engine-driven-generator sets. Presently, engine-driven-generator sets are usually operated from gasoline or diesel fuel, although some multifuel engines will accept aviation fuels and kerosene. The Army has begun evaluating methanol-fueled engine-driven-generator sets, but this effort has been suspended because of the logistical problems of introducing another fuel into the supply system.

Gasoline is a volatile fuel and emits vapor sufficient to form a combustible air-gas mixture at almost all ambient temperatures. Consequently, its use as an engine fuel is not preferred due to the increased risk of fire associated with its high degree of flammability and the provisions that must be made for its safe storage and distribution.

Other disadvantages of gasoline are the deterioration of it due to the evaporation and the oxidation of more volatile compounds. The oxidized compounds produce a gummy substance, which can foul the carburetor and other components of the fuel system of the engine. Consequently, gasoline is not recommended for use in standby systems in which operation is infrequent or where the fuel must be stored for periods of six months or longer.

Diesel fuel is more easily stored because it is not as volatile as gasoline and does not deteriorate over long periods. It is more viscous, however, and may even jell at lower temperatures. In some low-temperature environments, diesel fuel may have to be heated in order to transfer it from one tank to another or from a tank to an engine. Also special provisions should be made in diesel engines to improve their cold starting performance, e.g., addition of fuel system heaters and glow plugs.

The logistical requirements of fuel distribution also impact the selection of engine types. Fuel should be readily available with no anticipated shortages throughout the expected period of equipment use. For engine-driven-generator sets used in permanent environments in the continental United States, both diesel fuel and gasoline are expected to remain in ample supply throughout the foreseeable future. Diesel fuel is preferred, however, for tactical equipment to eliminate the necessity of maintaining and distributing two fuel supplies since diesel fuel is used for vehicular engines.

An alternative for situations in which fuel supplies are uncertain is the multifuel engine. These diesel engines have combustion chambers designed for optimum air/fuel mixing and for minimization of heat loss during the compression of the air/fuel mixture. As a result, these engines may be fueled by diesel fuel, kerosene, or gasoline and thereby allow use of any available fuel.

4-5 COMPATIBILITY AND INTEROPERABILITY

Two engine-driven-generator sets are said to be compatible if either may serve as the replacement for the other or if they both may be operated independently in the same system. Compatibility implies that the generators produce the same type of power—e.g., 480 Vac, 3-phase, 4-wire—and can be powered from the same type of fuel. Thus, compatible generators may be operated with the same existing logistical supplies and power the same types of loads.

The requirement for engine-driven-generator sets to be interoperable is more stringent. Interoperability requires that two engine-driven-generator sets function together when both are connected simultaneously to the same system in such a manner that the output of one can affect the other, e.g., if the two engine-driven-generator sets are connected in parallel.

In this paragraph engine-driven-generator set characteristics that affect compatibility and interoperability are presented. Features of engine-driven-generator sets that aid or prevent compatibility are discussed. Finally, the interconnection of an engine-driven-generator set into an existing power distribution system is discussed.

4-5.1 CLASSIFICATION OF ENGINE-DRIVEN-GENERATOR SETS

Listed in Table 4-7 (Ref. 22) are the basic technical characteristics of engine-driven-generator sets that affect the compatibility or interoperability and that should be specified before selecting or designing an engine-driven-generator set for a specific application. MIL-STD-1332 defines three classifications based on the groupings of the most important of these characteristics. Two of the characteristics—mode (frequency) and type—are listed in the table. The third, class, describes the level of performance of the generator to include both its frequency regulation and voltage regulation characteristics. Class 1, or precise engine-driven-generator sets, provides clean, well-regulated power for critical applications in which excessive frequency and voltage variation cannot be tolerated. For less stringent, general-purpose applications, Class 2, or tactical generators, may be used. This class is further subdivided into Classes 2A through 2C: 2A is a substitute for commercial power, and Class 2C has minimal requirements for voltage and frequency regulation. Requirements for each classification are given in Table 4-8 (Ref. 22).

4-5.2 COMPATIBILITY BETWEEN CLASSES

The requirement for compatibility between engine-driven-generator sets implies that one unit should be able to be used in place of another. This requirement necessitates similar electrical characteristics and comparable use of logistical supplies, i.e., fuel, lubricants, and maintenance facilities. Specific requirements for electric compatibility are

1. Same output voltage levels
2. Same output configuration (or ability to be configured to the same output configuration)
3. Same power capacity if one unit is to be used as a replacement for another. A substituted smaller capacity unit could be overloaded, whereas an excessively larger unit might be operating below the desired 50% minimum loading.
4. The same or better voltage and frequency regulation characteristics, i.e., both units should be of the same class for complete compatibility. An engine-driven-generator set with a higher classification may be substituted for one with a lower classification.
5. The same type of prime mover—i.e., gasoline, diesel, or turbine engine.
6. Similar configurations to allow personnel already familiar with one unit to use the other without additional training or tools.

TABLE 4-7
OPERATING CHARACTERISTICS OF ENGINE-DRIVEN-GENERATOR SETS TO BE MATCHED FOR COMPATIBILITY OR INTEROPERABILITY (Ref. 22)

Characteristic of Engine-Driven-Generator Set	Characteristic That Must Be Matched for Compatibility	Interoperability
Voltage Level, e.g., 120V 1ϕ, 280V 3ϕ, 480V 3ϕ	X	X
Mode (Frequency) 50, 60, 400 Hz AC or DC	X	X
Phase Rotation	X	X
Frequency		
Adjustment range	A	X
Regulation, droop characteristics	A	X
Characteristics that are adjustable	P	P
Voltage		
Adjustment range	A	X
Regulation, droop characteristics	A	X
Characteristics that are adjustable	P	P
Engine Type (gasoline, diesel, or turbine)	A	X
Mounting (fixed pad, skid, or trailer)	A	A
Type—Tactical or Prime	X	—

KEY:

X = Characteristic that must be matched
A = Characteristic for which matching may be necessary in some applications
P = Feature required if generator is to replace a generator that is operated in parallel with another
— = Characteristic for which matching is unnecessary

TABLE 4-8
FREQUENCY AND VOLTAGE REGULATION REQUIREMENTS FOR CLASSIFICATIONS SPECIFIED IN MIL-STD-1332 (Ref. 22)

Characteristic Parameter	Precise Class 1	Utility Class 2A	Utility Class 2B	Utility Class 2C	Test Method MIL-STD-705
1. Voltage Characteristics					
a. Regulation, %	1	2	3	4	608.1
b. Steady State Stability (variation), bandwidth %					
(1) Short-term, 30 s	1	1	2	2	608.1
(2) Long-term, 4 h	2	2	4	4	608.2
c. Transient Performance					
(1) Application of rated load					
(a) Dip, %	15	20	20	30	619.2
(b) Recovery, s	0.5	3	3	3	619.2
(2) Rejection of rated load					
(a) Rise, %	15	30	30	30	619.2
(b) Recovery, s	0.5	3	3	3	619.2
(3) Application of simulated motor load (twice rated current)					
(a) Dip, %	30	N/A	40	N/A	619.1
(b) Recovery to 95% of rated voltage, s (Note 1)	0.7	N/A	5	N/A	619.1
d. Waveform (Note 2)					
(1) Maximum deviation factor, %	5	5	5	6	601.1
(2) Maximum individual harmonic, %	2	2	2	3	601.4
e. Voltage Unbalance With Unbalanced Load, % (Note 3)	5	5	5	5	620.2
f. Phase Balance Voltage, %	1	1	1	1	508.1
g. Voltage Adjustment Range, % min (Note 4)	−5 + 17	±10	−5 + 17 (Note 5)	−5 + 5	511.1
2. Frequency Characteristics					
a. Regulation, %	0-3 Adj'able	0-5 Adj'able	3	3	608.1
b. Steady State Stability (variation), bandwidth %					
(1) Short-term, 30 s	0.5	0.5	2	4	608.1
(2) Long-term, 4 h	1	1	3	4	608.2
c. Transient Performance					
(1) Application of rated load					
(a) Undershoot, %	4	4	4	4	608.1
(b) Recovery, s	2	4	4	4	608.1
(2) Rejection of rated load					
(a) Overshoot, %	4	4	4	5	608.1
(b) Recovery, s	2	4	4	6	608.1
d. Frequency Adjustment Range, % min (where required)	±3	±4	±3	±3	511.2

NOTES: 1. The voltage shall stabilize at or above this voltage. (Not applicable to all sets rated of 5 kW or smaller, or 500 kW and larger.)

2. Specified values are for three-phase output; for single phase, add additional 1%.

3. With generator set connected for three-phase output and supplying a single, line-to-line, unity power factor, load of 25% of rate current and with no other load on the set. (Not applicable for single-phase connections or sets.)

4. For Mode II sets, the upper voltage adjustment is +10% of the rated voltage. For Mode I sets operating at 50 Hz, the upper voltage adjustment may be limited to the nominal voltages appropriate for the generator—either 120/240 Vac or 2400/4160 Vac.

5. Values shown are for sets rated at 15 kW and above.

Interoperability requires that all the conditions for compatibility be met and that the following additional requirements be satisfied:

1. The engine-driven-generator sets must have matched voltage and frequency regulation characteristics.

2. Although engine-driven-generator sets of different capacities may be operated together, the control circuits must be capable of governing each independently so that the load is divided proportionally between the generators according to their individual capacities.

4-5.3 FEATURES CAUSING INCOMPATIBILITY

The absence of any of the features listed in par. 4-5.2 will cause the engine-driven-generator sets to be incompatible and/or noninteroperable. Typical engine-driven-generator set features that cause incompatibility include

1. Different voltage outputs
2. Different modes (frequency)
3. Different output configurations
4. Different prime movers.

4-5.4 FEATURES AIDING COMPATIBILITY

Features that aid compatibility include those features that increase the flexibility of the generator through provisions for adjustment or reconfiguration to allow use with, or replacement of, a variety of other units. Specific features that enhance the compatibility or interoperability of a given engine-driven-generator set are

1. Use of a reconnectable generator, i.e., a generator with multiple windings that can be connected in various configurations to produce single-phase, split-phase, or three-phase output power at one or two different voltage levels.

2. Use of an adjustable voltage and frequency regulation system that allows adjustment of both the nominal voltage and frequency of the output power and allows adjustment of the droop in voltage or frequency with increasing loads. (This feature is necessary for interoperability of generators that are not identical.)

3. Use of design features common with other units in the inventory to allow use of uniform operating procedures. An additional benefit of common components and features in several engine-driven-generator sets in the inventory is a reduction in the number of repair parts to be stocked and a reduction in the number of maintenance tools, manuals, and diagnostic equipment.

4. Use of multifuel engines in engine-driven-generator sets that can use a wide range of fuels.

4-5.5 INTEGRATION OF ENGINE-DRIVEN-GENERATOR SETS INTO BACKUP POWER SYSTEM

A common application of engine-driven-generator sets is to supply power to critical loads when the primary source of power is interrupted. Hence requirements for the engine-driven-generator set are determined both by the primary source of power and the loads that are to be kept operational by the standby generator.

The configuration of a typical backup power system is shown in Fig. 4-5. In this system power for all loads normally is supplied by a primary power source—usually power from a commercial utility but may be any source of continuous power. The engine-driven-generator set(s) shown in Fig. 4-5 supply power when the primary source is interrupted.

Control of the backup system is exercised by the transfer switch and the ancillary control circuitry of it.

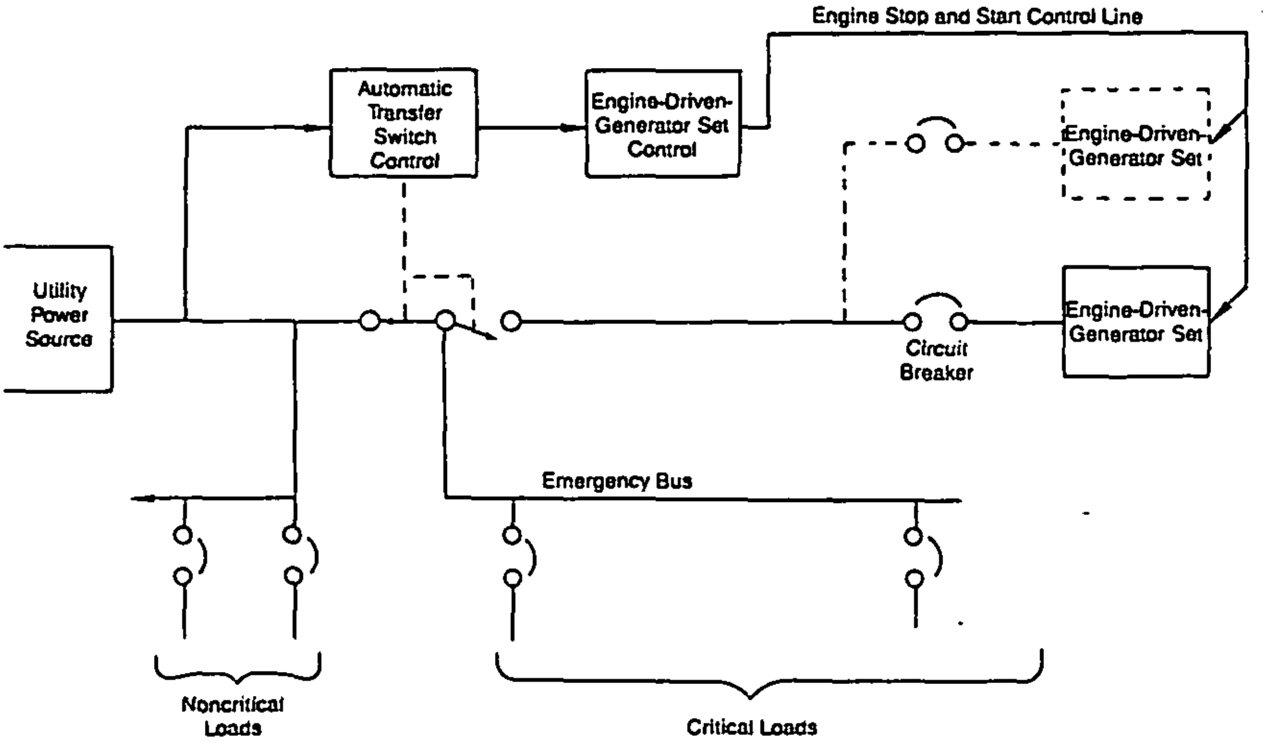


Figure 4-5. Typical Configuration of Backup Power System Using an Engine-Driven-Generator Set

These components perform the connection of the engine-driven-generator set to critical loads in place of the primary power source, time the switching operations so that motors do not draw excessive currents (see par. 3-3.2.1), and start and stop the engine-driven-generator set.

Typically, all loads are not connected to the backup power system because the cost of an engine-driven-generator set capable of supplying power to all loads may be excessive. Instead loads are partitioned into essential loads and nonessential loads. Essential loads—loads that, if disconnected, will result in damage, injury, or monetary loss—are connected to the center pole of the transfer switch so that when an interruption of the primary service occurs, they will be powered by the engine-driven-generator set (usually after a short delay). Nonessential loads—loads that can tolerate a power outage—are connected to the primary supply directly and the power to them will not be sustained in the event of a power outage.

The engine-driven-generator set used in a backup system must satisfy certain requirements imposed by the system to be protected, namely,

1. The engine-driven-generator set must start quickly and reliably upon demand. Starting equipment must operate completely from self-contained energy storage devices, usually batteries. (The batteries may be kept in the charged condition by power from the primary source; however, power will not be available from the primary source at the time the engine needs to be started.)

2. The engine-driven-generator set must be capable of intermittent operation with long periods of inactivity. Fuel supplies must not deteriorate. The carburetor system must not be fouled by evaporation of trace amounts of fuel that remain after the engine has stopped. In cold climates, provision may be necessary for heaters to maintain the engine (and fuel for diesel engines) at temperatures that permit easy starting.

3. Backup systems are usually installed in close proximity to the loads they are to protect. In many cases the engine-driven-generator set must be installed near, and sometimes in, inhabited areas and in these installations adequate noise suppression is essential. Either ventilation must be provided for engine cooling or an alternative for heat removal, such as a water-cooled heat exchanger, must be provided. The exhaust system must be designed for safe discharge of the hot exhaust with minimal danger of fire or accumulation of exhaust fumes in inhabited areas.

Typical installation considerations are illustrated in Fig. 4-6 (Ref. 23). Additional information—such as typical mounting, provisions for eliminating heat and exhaust gases from the engine, and reduction of noise—on permanent installation of engine-driven-generator sets may be obtained from the manufacturer of the engine-driven-generator set being used.

Several modifications may be made to the configuration of the backup system to relieve requirements on the engine-driven-generator set. Perhaps the most significant modification is the reduction of required generating capacity by load partitioning so that only essential loads are powered by the generator. Through the judicious selection of loads to be powered through an essential-load bus, a minimum capacity engine-driven-generator set can maintain power for necessary loads. Further reduction in capacity requirements may be obtained by sequencing motors so that large motors are not started simultaneously. If high-current, intermittently operating devices, such as heaters, are used, control circuits may be added to coordinate power distribution so that simultaneous operation of all units is prohibited and requirements for peak capacity of the engine-generator are reduced.

For load systems having a wide variability, multiple generators operating in parallel may allow the operation of engine-driven-generator sets near maximum capacity by operating one generator when the load is light and turning on the other generator only when power is needed to support additional loads. Note, however, that this approach is not useful for widely varying loads because engine-driven-generator sets should not be cycled on and off rapidly.

Integration of engine-driven-generator sets into the backup systems in foreign countries may be performed in the same manner as in the United States provided the engine-driven-generator set is compatible with local power. Interconnection of the generator into the system must be performed with care because the color conventions are different in various countries. Table 4-9 (Ref. 24) summarizes the color convention for wiring in the United States and in Europe.

4-6 TEST CRITERIA FOR DESIGN OR ITEM ACCEPTANCE

4-6.1 TESTS REQUIRED BY MILITARY STANDARDS

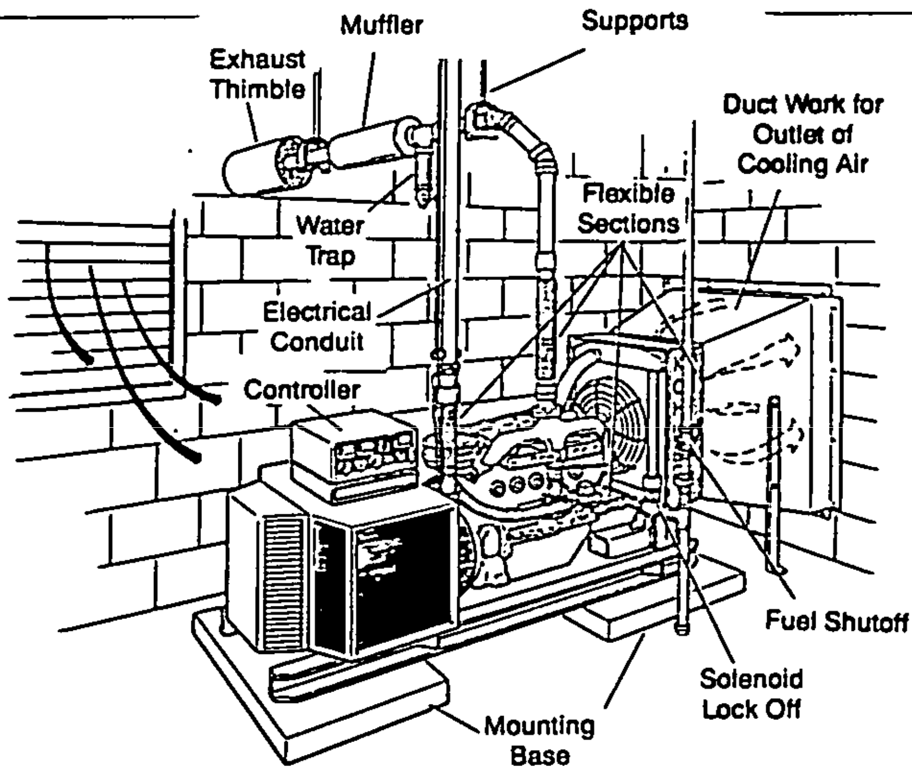
MIL-STD-705 (Ref. 25) defines approximately 105 separate tests that are used to evaluate performance, to verify operation, or to verify compliance with stated specifications of generating systems of engine-driven-generator sets and ancillary equipment. Additional information concerning procedures and test apparatus is given in Ref. 26. Individual tests are identified in the paragraphs that follow; however, the cited references should be consulted for a definition of the parameter being evaluated at the test port.

4-6.1.1 Insulation Tests

Insulation tests are performed to detect potential leakage paths, which could lead to development of high voltages on exposed conductors or short circuits, which could lead to overcurrent damage of generator windings. Insulation tests include

1. *Insulation Resistance Test.* This test measures insulation resistance between generator windings and the generator frame.

2. *High Potential Test.* High voltage is applied to windings, and breakdowns are noted. Voltage applied to output windings is 1000 V higher than twice the highest rated output voltage. For field coils, the voltage is usually ten times the peak field coil voltage.



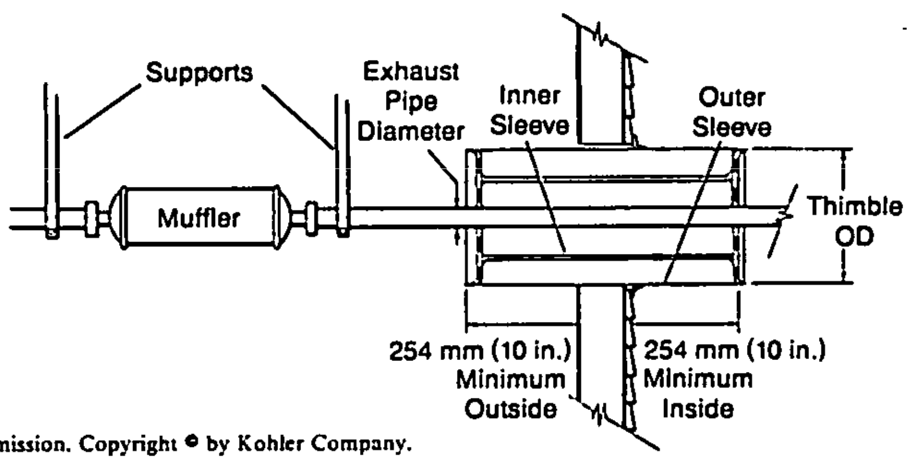


Figure 4-6. Typical Permanent Installation of an Engine-Driven-Generator Set (Ref. 23)

4-6.1.2 Electrical Characterization Tests

Electrical characterization tests are performed to verify that the generators will meet the requirements of the applications for which they are intended and to verify compatibility and interoperability between the generator under test and others of the same design. Characterization tests will also identify subtle manufacturing defects that could lead to inefficient operation, overheating, or premature failure. Characterization tests include

1. *Winding Resistance Test.* The resistance of individual windings is measured with a bridge or other instrument suitable for low-resistance measurements. Resistance information is useful for predicting heating under load of a generator.
2. *Open Circuit Saturation Curve Test.* While the generator is turning at the rated speed, voltage output with no-load is measured for various levels of externally supplied excitation. Voltage is plotted against excitation

TABLE 4-9. COLOR CODE FOR THREE-PHASE WIRING (Ref. 24)

USA		Europe	
Phase A	Black	Phase R or V	Black
Phase B	Blue or Black	Phase S or V	Brown
Phase C	Red or Black	Phase T or W	Black
Neutral	White or Gray	Neutral	Blue
Protective Ground	Green or Green w/Yellow Stripe	Protective Ground	Green/Yellow

to determine the break point (saturation point) at which the increasing excitation does not produce an increase in output voltage. The collected data are used in conjunction with data from other tests as a quality control check on quality of the iron and the length of air gap.

3. *Synchronous Impedance Curve Test.* With the generator output shorted through ammeters, field current is varied to produce short circuit currents from 0 to 150% of the capacity of the generator. The results are plotted to produce a curve called the short-circuit saturation curve. This information is used to design protective devices properly and to assure designers that the air gap, coils, and steel in the generator meet requirements.

4. *Zero Power Factor Saturation Curve Test.* With the generator delivering rated current into a variable load whose power factor is between 0.3 and 0.4, terminal voltages and field currents for various loadings are recorded. The plot of terminal voltage against field current is called the zero power factor saturation curve and is used in conjunction with other test data to predict field current of the generator for any load condition.

5. *Rated Load Current Saturation Curve Test.* With the generator delivering rated current into a variable load whose power factor is equal to the rating of the generator, the field current is varied to produce terminal voltages between 50 and 125% of the rated voltage. The field current and terminal voltage are recorded and plotted to produce the rated load current saturation curve. This curve is used along with other test data to predict field current of the generator for any load condition.

6. *Rotating Exciter Saturation Curve Test.* Slip rings are added to the rotating field generator to allow monitoring of the field current induced in the armature by the excitation winding. The field current is passed through a resistor equal in value to the armature field winding. While the generator is rotating, the excitation current and the resulting field current of the armature are recorded and plotted to produce the rotating exciter saturation curve. This curve is used to determine the suitability of an exciter for use in a generator.

7. *Summation of Losses Test.* This is a series of tests in which a generator is turned by a calibrated motor, and quantitative measurements of specific electrical losses and frictional losses are made. Frictional losses are indicated by the amount of power required of the prime mover to turn the generator, and electrical losses are measured by electrical measurements. The specific losses measured are bearing friction loss, brush friction loss, brush-contact resistance loss, open-circuit core loss, armature I^2R loss, field I^2R loss, stray-load loss, and exciter loss.

8. *Generator Power Input Test.* A complete generator is connected to a calibrated motor and a load, and the amount of input power required to operate the generator at rated capacity is measured. The results of this test are used to determine the size of the engine required to drive the generator.

9. *Brush Potential Curve Test.* While current is flowing into the armature through brushes, potential along one side of the brush is measured to determine the potential profile across the face of the brush. The resulting profile can be used to predict power losses attributable to resistance of the brush.

10. *Short-Circuit Ratio Test.* From a measurement made on the open circuit saturation curve and the synchronous impedance curve, the short circuit ratio is computed. This numeric value indicates the regulation and stability of the generators.

11. *Direct Axis Synchronous Reactance Test.* The direct axis synchronous reactance is determined by measurements made on the open circuit saturation curve and the synchronous impedance curve.

12. *Negative-Sequence Reactance and Impedance Test.* From measurements made on an externally excited polyphase generator with one phase shorted, the negative-sequence reactance and impedance are calculated. These two parameters are used to determine wye-connected generators under various load conditions.

13. *Zero-Sequence Reactance Test.* From measurements on a wye-connected generator with two phases connected to the neutral, the zero-sequence reactance is calculated. This parameter is used to determine the performance of three-phase, wye-connected generators under various load conditions.

14. *Quadrature-Axis Synchronous Reactance Test.* In this test the output of the generator is connected to an AC source that has the same frequency and voltage as the generator. The frequency of the generator is then changed slightly so that the two power sources alternately cancel and reinforce. During cancellation the current flow is determined by the quadrature-axis synchronous impedance; therefore, this impedance may be determined by inspection of an oscillographic recording of the voltage and current flow. The quadrature-axis impedance is used to predict the performance of the generator under various load conditions.

15. *Direct Axis Transient Reactance Test.* An independently excited generator is first operated with no load, and then the output is shorted by a switch. The resulting current flow and voltage are monitored with an oscilloscopic recorder (voltage and current for one phase on three-phase systems). The transient characteristics of the peak-to-peak current flow are analyzed graphically to determine the direct axis transient reactance. This parameter is used to measure the ability of the generator to withstand sudden load applications without the voltage dropping below acceptable levels, e.g., as in the evaluation of the starting capacity of the motor.

16. *Direct Axis Subtransient Reactance Test.* The direct axis subtransient reactance is determined by performing the transient reactance test and evaluating the transient performance of the recorded waveform immediately after the short circuit is applied. This parameter is used to determine the required interrupting capacity for generator overcurrent protective devices.

17. *Direct Axis Transient Reactance Test and Direct Axis Subtransient Reactance Test.* The data taken during the direct axis transient reactance test may be further analyzed graphically to determine these two parameters, whose values are used to predict performance of the generator under dynamic load conditions.

18. *Direct Axis Transient Open Circuit Time Constant Test.* The generator is operated with no load with the field energized from an external source. The field circuit is short-circuited, and the time decay of the output is measured on an oscillographic record of the terminal voltage. This parameter is used to predict the behavior of the generator under dynamic loading conditions.

19. *Short-Circuit Time Constant of Armature Winding.* From the oscillographic record obtained in the direct axis transient reactance test, the transient behavior of the centerline of the transient waveform is determined. This parameter is used in the design of protective devices for the generator and its load.

20. *Inherent Voltage Regulation Test.* With the field voltage of the generator supplied from an external source, the engine-driven-generator set is operated alternately with no-load and with full load to determine the characteristics of it in the absence of controllers. The voltage and frequency data are used in the design of voltage-regulation equipment for generators.

4-6.1.3 Controls and Instrumentation Tests

The controls and instrumentation tests verify that controls of the engine-driven-generator set perform their desired function reliably in a manner consistent with accepted practice for generators, that indicators accurately reflect the current status of the performance of the generator, and that automatic controllers and safety limit switches function properly. These tests include

1. *Start and Stop Test.* The measurement of the time required to start and stop the engine-driven-generator set. This test provides information about the response time for engine-driven-generator sets used in backup systems and the amount of time required to shut down the generator after development of a hazardous condition.

2. *Overspeed Protective Device Test.* The operation of overspeed protective components is verified by attempts to operate the engine-generator in an overspeed condition with the overspeed protective system connected.

3. *Phase Sequence Test.* With appropriate instrumentation, the phase of each terminal and power outlet on the generator is checked to insure that the electrical phase is consistent with the labeling.

4. *Phase Balance Test.* The output voltage on each phase is measured to determine the degree of imbalance.

5. *Circulating Current Test.* In a reconnectable generator coils are connected in parallel pairs for parallel operation. The generator is activated, and the current flow circulating in the loop formed by the paralleled coils is measured. Excess current in this loop leads to overheating of the generator and shortens service life.

6. *Rheostat Range Test.* While an engine-driven-generator set with a manual field rheostat is operating, the voltage level control is varied to determine the range of output voltages obtainable. This range determines the suitability of the generator to power nonstandard loads and its ability to compensate for changes in the inherent voltage regulation of the generator.

7. *Regulator Range Test.* The engine-driven-generator set is operated under varying load conditions to determine the degree of regulation, the voltage droop characteristics, and the range of nominal terminal voltages obtainable. These parameters are important in determining whether the generator can be paralleled and whether the generator may be used with nonstandard equipment that requires supply voltages somewhat different than the nominal standard values.

8. *Frequency Adjustment Range Test.* The engine-driven-generator set is operated with an appropriate load, and frequency adjustments are varied to determine the range of line frequencies obtainable. This information aids in the assessment of compatibility of the engine-driven-generator set with nonstandard loads and for parallel operation with other generators.

9. *Circuit Interrupter Test (Short Circuit or Overload).* With the engine-driven-generator set operating initially at a rated load, a short circuit or excess load to the output terminals is applied, and the resulting current and the time necessary to trip any overcurrent protective device are measured.

10. *Circuit Interrupter Test (Over- or Undervoltage).* The output of an engine-driven-generator set is connected to the overvoltage sensor through a switching network that is capable of changing the output from a normal to an overvoltage condition. The voltage level is switched, and the length of time necessary for the response is measured.

11. *Indicating Instrument Test.* The engine-driven-generator set is operated, and indications on internal instrumentation are compared with those on calibrated instruments connected to the engine-generator.

12. *Low Oil Pressure Protective Device Test.* By use of a cutoff valve, the oil pressure to the low oil pressure cutoff switch is reduced, and the time required before the engine is shutdown is measured.

13. *Overtemperature Protective Device Test.* Overheating of the engine is induced by blocking the flow of

cooling air across it. Temperature is monitored, and the temperature at which the overtemperature protective device stops operation of the engine is recorded.

14. *Low Fuel Protective Device Test.* The engine-driven-generator set is operated until the low fuel condition is detected, and the time until the engine is automatically shutdown is measured.

15. *Controls, Direction of Rotation.* The control orientation is inspected to ascertain that the direction of rotation is consistent with standard practice for military engine-driven-generator sets.

16. *Reverse Power Protective Device Test.* With two engine-driven-generator sets operating in parallel with a load, the frequency is reduced until the reverse voltage protective device trips and removes that engine-driven-generator set from the load. Load conditions are recorded to calculate the reverse power (power into the generator) necessary to operate the protective mechanism.

17. *Reverse Battery Polarity Test.* After a period of normal operation, the set is shutdown, the battery connections reversed, and an attempt is made to restart the engine. Then a visual inspection of damage is made.

18. *Paralleling Aid Device Test.* Two engine-driven-generator sets are connected in parallel while one is operating and the other is brought on-line by slowly bringing its voltage and/or frequency into a matched condition with the first. By use of external instrumentation, the actual phase and voltage differences are recorded at the time the paralleling aid closes the circuit interrupter on the second set.

4-6.1.4 Performance Tests

Performance tests measure the ability of the generator to deliver power with the quality and reliability desired for its intended application and determine the generator does operate safely. (Note that there is some overlap in the performance test and characterization test categories and that some tests described in one category provide data useful for both purposes.) These tests include

1. *Voltage Waveform Test.* The output waveform produced by an engine-driven-generator set is recorded, and the instantaneous difference between it and an ideal sine wave is measured. Alternatively, a spectrum analyzer can be used to determine the harmonic content of the voltage waveform.

2. *Voltage Modulation Test.* By use of a diode waveform clipping circuit, the cycle-to-cycle variation in peak height of the output voltage is measured by an oscillographic recorder.

3. *Frequency and Voltage Regulation, Stability and Transient Response Test.* The load connected to an engine-driven-generator set is switched between full load, no-load, and discrete intermediate values. By use of strip-chart recorders, the effect of load change on frequency and voltage—both overshoot (transient) phenomena and steady state response—is recorded and measured.

4. *Frequency and Voltage Stability Test.* An operating engine-driven-generator set is monitored with frequency- and voltage-monitoring instruments to determine the amount by which the frequency and voltage vary over long periods.

5. *Voltage and Frequency Droop Test.* Voltage and frequency droop characteristics of regulated engine-driven-generator sets are verified by measuring the terminal voltage and frequency for various loads between zero and full load.

6. *Inherent Voltage Droop Test.* The uncompensated reduction of terminal voltage with increasing load is measured. The resulting data are used to design an appropriate voltage regulation circuit.

7. *Voltage Dip for Low Power Factor Loads Test.* With an engine-driven-generator set operating, a load with a power factor of 0.4 or less suddenly is applied. The magnitude and duration of the voltage dip due to the increased load are observed.

8. *Voltage Dip and Rise for Rated Load Test.* On a normally operating engine-driven-generator set, the rated load is alternately applied and removed. The oscillographic record is examined for excessive voltage and current overshoot or undershoot on removal and application of the load, respectively.

9. *Voltage Unbalance With Unbalanced Load Test.* Loads are applied between one phase and ground, and voltages on all phases are recorded. The procedure is repeated with the load applied on each of the other phases. The voltage data for degree of unbalance between phases are examined. Similarly, a single load is applied between each pair of phases, and resultant voltages are recorded and examined for difference in amplitude.

10. *Unbalanced Load Heating Test.* An unbalanced load is connected to a three-phase generator, and then a balanced load is added until the current capacity of the generator is reached on one or more lines. The engine-driven-generator set is operated for a specified period, shutdown, and the temperature of the windings is measured to detect overheating conditions that could shorten the life of the generator.

11. *Short-Circuit Test.* Short circuits are applied to operating engine-driven-generator sets, followed by visual inspections for resultant damage.

12. *Parallel Operation Test.* Two (or more) engine-driven-generator sets are operated in parallel under various loads. Voltage, current, and power are measured by instrumentation to verify that the load is shared equally between the generators under all load conditions.

13. *Maximum Power Test.* Instrumentation recordings of data from temperature and pressure sensors on an operating engine-driven-generator set monitor the performance of the engine under variable load conditions. The load is increased until the maximum load that the generator set can provide without having the observed performance characteristics exceeding the specified performance characteristics is obtained.

14. *Commutation Test.* The generator is operated at full load, and the brushes are observed for excessive arcing. After completion of the test, the brushes are inspected for excessive wear or pitting.

15. *Shaft Current Test.* Voltages are applied between the shaft of a generator and the frame. Currents induced

by such voltages would flow through bearings and thereby cause damage or shortened life.

16. *DC Control Test.* After the engine-driven-generator set is operating, the batteries are removed and reconnected while output is monitored for perturbations caused by changes in the engine supply.

17. *Inclined Operation Test.* A check is made of leakage or changes in the cooling system, fuel, or lubrication system incapacities that are induced from operation of the engine-driven-generator set in positions other than level.

18. *Sound Level Test.* The noise level is measured, and observers note specific noises emitted by the engine-driven-generator sets operated in open areas.

19. *Fuel Consumption Test.* The engine-driven-generator set is operated for a specified period at a rated load, and the amount of fuel consumed is measured.

20. *Temperature Rise Test.* The engine-driven-generator set is operated for a prescribed period and then shutdown. Immediately after shutdown, temperatures of the coils and other internal components are measured.

21. *Endurance Test.* Performance checks, such as fuel consumption, frequency and waveform regulation, and maximum power, are run on the engine-driven-generator set. The engine-driven-generator set is then operated for a prescribed period under cyclic load conditions. Next, the performance tests are repeated, and the engine-driven-generator set is examined for signs of abnormal wear.

22. *Torsional Vibration Test.* A vibration-sensitive instrument is attached to the engine-generator shaft to detect and measure vibratory modes due to twisting of the shaft. These modes are not easily detected by visual inspection and can lead to premature failure of the rotating components.

23. *Overspeed Test.* An engine-driven-generator set (or a generator driven by a separate motor) is operated in an overspeed condition for a specified period to detect vibrations and/or other hazards that might appear under these conditions.

4-6.1.5 Environmental Tests

Environmental tests measure the ability of the generator to operate reliably under the range of environmental conditions encountered in a tactical environment. Environmental tests for engine-driven-generator sets include

1. *Starting and Operating Test.* The engine-driven-generator set—configured for low-temperature operation—is placed in a specified environment (usually low-temperature), and an attempt is made to start the engine. In a similar test, engine-driven-generator sets that are not winterized are tested for starting and operation in moderately cold environments.

2. *Standby Operation Test.* Engine-driven-generator sets that are equipped with equipment, e.g., heaters, to improve starting characteristics in cold weather are tested for their ability to start in arctic conditions.

3. *High-Temperature Test.* The engine-driven-generator set is operated in an environment at a specified temperature until the operating conditions of the unit have stabilized. The unit is then shutdown and the internal generator winding temperatures are measured to determine whether the temperature rise limit for the generator has been exceeded. The unit is also inspected for degradation due to overheating. The performance characteristics of other components and circuits also are determined.

4. *Humidity Test.* Insulation resistance, and voltage and frequency regulation of an engine-driven-generator set are measured. Then the unit is placed in an environmental test chamber, and the temperature and humidity are cycled according to a prescribed schedule. After completion of the exposure test, performance tests are repeated to detect degraded performance.

5. *Fungous Resistance Test.* The engine-driven-generator set is placed in a controlled chamber containing mold spores and is left for a specified period. At the end of the period, the engine-driven-generator set is removed and examined for presence of fungi.

6. *Rain Test.* The engine-driven-generator set is placed in a simulated rain and allowed to soak for a prescribed period. Then the unit is started and run for another prescribed period. At the completion of the exposure period, the unit is examined for water damage.

7. *Sand and Dust Test.* The engine-driven-generator set is exposed to sand and dust driven by airflow for a specified period and then tested for degraded engine or generator performance.

8. *Salt Fog Test.* The engine-driven-generator set is placed in a chamber containing an atomized salt water spray-induced fog. After completion of the exposure period, the unit is examined for excess corrosion.

9. *Altitude Operation Test.* The engine-driven-generator set is operated in an altitude simulation chamber at reduced pressure. Temperature measurements are made to determine whether the reduced cooling efficiency of the rarified atmosphere excessively affects the performance of the engine-driven-generator set.

10. *Storage Test (Extreme Cold).* The unit is placed in a cold chamber for a specified period. After removal, the unit is inspected, started, and tested to see whether performance was affected by the cold storage.

11. *Storage Test (Extreme Hot).* This test is the same as the cold storage test except that high temperatures are used.

12. *Vibration Test.* The unit is placed on a vibrating table for a specified period. After exposure, it is examined for damage due to the vibration.

13. *Drop Test.* Voltage and frequency regulation tests are performed on an engine-driven-generator set. Then the engine-driven-generator set is dropped onto a concrete base from a specified height and orientation. The unit is examined after impact, and the performance tests are repeated.

14. *Lifting and Towing Test.* The engine-driven-generator set is lifted by use of integral lifting eyes, and any tilt in the unit is measured after it is off the ground. The unit is then fastened to a fixed base, and eight times the force necessary for lifting is applied to the lifting eyes. Also a towing force equal to five times the weight is

applied to the towing eyes. The forces are relaxed, and the frame is examined for damage.

15. *Railroad Impact Test.* The engine-driven-generator set is mounted on an appropriate railroad car, and the car is impacted against others at a prescribed speed. The generator is then examined for damage.

16. *Forklift Handling Test.* The engine-driven-generator set is lifted with a forklift and transported over a prescribed course containing typical bumps. It is then examined for damage.

17. *Fuel Lift Test.* The engine-driven-generator set is started, and the fuel line is transferred to an auxiliary tank located a prescribed distance below the generator. The load is applied, and the operation is monitored for degraded performance.

18. *Winterization Test.* Heaters are tested for proper operation.

19. *Rectifier Test.* For generators containing rectifiers, peak reverse voltages are observed to ascertain whether the diode ratings are exceeded.

20. *Load Bank Test.* An engine-driven-generator set connected to a load bank is operated. The dissipation of the load bank is verified by external instrumentation.

4-6.2 OTHER RECOMMENDED TESTS FOR ENGINE-DRIVEN-GENERATOR SETS

Standards have been written that prescribe tests for the evaluation of performance of generators and engine-driven-generator sets (Refs. 27, 28, 29, 30, 31, and 32). Most of the tests described or specified by these documents are similar to the tests described by MIL-STD-705. One exception is the telephone influence factor test described in Ref. 27; this test measures the influence of the harmonics produced by an unloaded generator on telephone circuits.

4-7 OPERATIONAL PRECAUTIONS

Even though engine-driven-generator sets should be designed to reduce the potential for accidental injury, the hazard cannot be completely removed. Therefore, appropriate instructions for the proper application of the equipment must be provided in the form of operating, training, and maintenance manuals. These manuals must inform equipment users of the proper procedures for use of the equipment and must warn them of hazards associated with improper use.

The purpose of this paragraph is to identify the procedures that should be included in the manuals provided to users of the equipment. Detailed procedures are not described because they are machine specific and, therefore, are beyond the scope of this handbook. Included in this discussion are the rationales for procedures, the consequences of improper performance of procedures, and an identification of features that may be added to the equipment to facilitate the performance of the procedures. Emphasis is placed on procedures that impact the safe operation of the engine-driven-generator set, although other procedures are listed as well.

4-7.1 LOCATION AND INSTALLATION OF ENGINE-DRIVEN-GENERATOR SETS

4-7.1.1 Portable and Mobile (Including Tactical) Units

Site selection of portable and mobile generators should be made with the following considerations:

1. *Proximity to Load.* Placing the generator adjacent to the load reduces losses in lines that could cause unsatisfactory voltage regulation at the load.

2. *Access.* Clearance must be provided around the generator for performance of maintenance and repair functions. A configuration of the generator that permits all maintenance functions to be performed from one side of the unit increases the range of site possibilities. Also the placement of filling tubes, inspection points, etc., in accessible locations reduces the amount of clearance required around the unit and still provides convenient access for maintenance. Access to fuel tanks must be adequate for fuel trucks.

3. *Mounting.* An engine-driven-generator set must be placed on firm soil that will support it for the period it will be in place. Consideration must be given to likely weather conditions, e.g., rainfall and freezing temperatures, that affect the support provided by the ground.

4. *Fuel Supply.* Fuel tanks, when not mounted on the engine-driven-generator set, should be located away from sources of ignition and away from flammable materials to minimize the potential for damage to the tank and nearby structures. Fuel lines should be protected from personnel and vehicular traffic. Also fuel lines should not be exposed to sources of heat or sunlight in order to minimize the possibility of vapor lock.

Once the site is selected, it must be prepared for installation of the engine-driven-generator set. Specific steps that may be necessary are

1. *Footing.* If the soil is loose or likely to become soft when wet, then crushed rock, boards, or other material can be used to provide a solid footing for the engine-driven-generator set. The footing must be sufficiently level to satisfy the requirements imposed by the engine-driven-generator set. It must be capable of supporting the weight of the engine-driven-generator set and of withstanding the vibration associated with the operation of the engine-driven-generator set. Additional support may be required if long-term operation is anticipated.

2. *Shelter.* Shelter from precipitation should be provided for engine-driven-generator sets that do not have integral weatherproof shelters, and they should allow free circulation of air around the set for cooling and dissipation of exhaust. Adequate clearance should be provided between the engine-driven-generator set and flammable materials used in the shelter in order to reduce the hazard of fire. In tactical situations the shelter should be more substantial to protect the engine-driven-generator set from small arms fire and fragments. Examples of tactical shelters are given in Ref. 8.

3. *Drainage.* Drainage should be provided for fuel and lubricant spills to contain them, to keep the flammable materials away from sources of heat, and to dilute the

spilled liquid (with solid material) to minimize the possibility of fire. The addition of crushed rock or sand in a pit surrounding the engine-driven-generator set is recommended to contain spills.

4. *Exhaust*. Designers should insure that the exhaust is directed away from the fuel supplies and personnel to minimize the possibility of fire and carbon monoxide poisoning.

5. *Grounding Rods*. Appropriate grounding rods should be installed and connected to the engine-driven-generator set to minimize the possibility of electrocution. Grounding considerations are discussed in pars. 3-3.4 and 5-2.4.5.

4-7.1.2 Permanently Installed Engine-Driven-Generator Sets

Considerations for the installation of permanent generators are the same as those for mobile installations. except that for permanent installations supports must be more substantial and permanent in nature. Also in some cases, the engine-driven-generator set will be mounted in an enclosed area, and the following additional procedures must be observed:

1. *Exhaust Piping*. Selection of piping size and a silencer must be made in accordance with the manufacturer's recommendations to minimize the back pressure at the engine because excessive back pressure will degrade the performance of the engine.

2. *Fuel System*. Auxiliary tanks should be located outside of structures approximately at the same elevation as the engine-driven-generator set and at a location convenient for refilling. If the tank must be located higher than the engine-driven-generator set, provision must be made to prevent the flow of fuel into the engine, especially when the engine is not operating. In addition, a small tank on the engine will usually be necessary to facilitate quick starting for backup systems that are used only occasionally. If the engine-driven-generator set is used for emergency power in the event of a major catastrophe, a supply of fuel sufficient for a specified operational period may necessarily be stored with the generator to prevent severance of the unit from its fuel supply. Such installations, however, must conform to local codes, which frequently prohibit indoor storage of fuels, especially gasoline.

3. *Cooling*. Provision must be made for adequate cooling of engines located within structures. Cooling systems may use water cooling with a local water supply or with recirculated water cooled by a cooling tower, a conventional engine radiator located remotely from the engine, or airflow ducted through plenums over the engine-driven-generator set.

4-7.2 PREVENTIVE MAINTENANCE

Preventive maintenance procedures necessary for an engine-driven-generator set depend on many factors—i.e., the type of prime mover, its size and speed of rotation, and the operating conditions. Operator's and maintenance manuals must identify the preventive maintenance activities and give a recommended schedule for their performance. An example of a preventive maintenance schedule for a typical 1800-rpm gasoline engine is shown in Table 4-10. This table lists representative activities that should be performed on engines on a routine basis.

Preventive maintenance activities include lubrication of the equipment, routine replacement of limited-life components or materials, and inspection to detect situations that will, if uncorrected, limit the life or reduce performance of the generator. Proper record keeping is essential so that readings or measurements may be compared against previous values to detect engine degradation. (See the discussion of trend monitoring in par. 4-7.4.) The engine-driven-generator set should be designed to facilitate preventive maintenance procedures. If the

TABLE 4-10. TYPICAL MAINTENANCE SCHEDULE FOR 1800-rpm GASOLINE ENGINE-DRIVEN-GENERATOR SET (Ref. 21)

1. 25-h Interval (or four months, whichever occurs first):
   a. Adjust fan and alternator belt
   b. Add oil to oil cup for distributor housing
   c. Change oil in oil-type filter
2. 50-h Interval (or six months, whichever occurs first):
   a. Drain and refill crankcase
   b. Clean crankcase ventilation air cleaner
   c. Clean dry-type air filters
   d. Check transmission oil
   e. Check battery
   f. Clean external engine surface
   g. Perform 25-h service
3. 100-h Interval (or eight months, whichever occurs first):
   a. Replace oil filter element
   b. Check crankcase ventilator valve
   c. Clean crankcase inlet air cleaner
   d. Clean fuel filter
   e. Replace dry-type filter
   f. Perform 25- and 50-h services
4. 200-h Interval (or one year, whichever occurs first):
   a. Adjust distributor contact points
   b. Check spark plugs for fouling and proper gap
   c. Check timing
   d. Check carburetor adjustments
   e. Perform 100-, 50-, and 25-h services
5. 500-h Interval (or two years, whichever occurs first):
   a. Drain and refill transmission
   b. Replace crankcase ventilator valve
   c. Replace one-piece-type fuel filter
   d. Check valve-tappet clearance
   e. Check crankcase vacuum
   f. Check compression
   g. Perform 200-, 100-, 50-, and 25-h services

procedures are easily performed, they are more likely to be performed properly. Likewise, if points to be inspected are visible, the inspection will be more thorough. Equipment provisions that aid the preventive maintenance program include properly identified inspection and fluid checkpoints, sight glasses or transparent fluid containers that allow checking during operation, the grouping of all access points for maintenance on one side of the engine-driven-generator set (especially if unit is enclosed), easily readable instrumentation, and necessary tools kept with or attached to the engine-driven-generator set.

4-7.3 ROUTINE OPERATION

4-7.3.1 Start-Up

Procedures for start-up should begin with a check of the engine-driven-generator set equipment and installation to determine that the equipment is installed properly and, if operated previously, that no changes have occurred that would prevent normal, safe operation. These checks should include inspection of coolant levels, lubricant levels, condition of the battery, control positions (especially those that are not frequently used), and load connections (including changeover block or output selector switch). These checks are intended to prevent any inadvertent introduction of conditions that, if uncorrected, would result in an unsafe condition or an undetectable condition that could lead to a generator failure. The specified start-up procedure should include a procedure for starting the engine followed by specific observations to confirm normal operation. These checks include engine speed, oil pressure, and generator voltage. Once the engine is operating satisfactorily, the generator may be switched on-line as described in par. 4-7.4.

4-7.3.2 Operation

The procedure for routine operation consists of monitoring the operation to insure that no unsafe condition develops and the renewal of supplies, e.g., refueling and adding oil as required, necessary to sustain operation. The monitoring should consist of checks on operating parameters, such as oil pressure, temperature, and battery-charging circuits, for normal readings together with periodic logging as discussed in pars. 4-7.4.2 and 4-7.4.3. The instructions should also point out any special items to be inspected or observed.

Because of the fire hazard associated with refueling operations, special attention should be given to this topic in the operating instructions. If the generator is designed to permit refueling without stopping operation, warnings should be posted that specifically state the fire prevention procedures that must be followed. Such warnings include use of a clip lead to eliminate the possibility of static discharge between the gas delivery hose and fuel tank opening, and the requirement for the presence of fire-extinguishing equipment prior to refueling. If the fuel tank is located so that the generator may not be safely refueled while in operation, the operating manual should warn against that specific procedure and labels should be attached to the engine-driven-generator set to warn against that operation.

4-7.3.3 Engine Shutdown

Operating instructions should include the proper method of disabling the engine-driven-generator set—an operation that is typically accomplished by removing the load and then turning the battery switch or circuit breaker to its off position. The instructions should also specify a minimum period of operation for the engine, typically 15 min. If the generator is needed for shorter periods, the engine still should be operated for the minimum period to allow it to come to operating temperature, to remove condensation from the exhaust system, and to charge the battery fully.

4-7.4 ROUTINE TESTING AND MONITORING

Routine testing and monitoring are performed to detect any unsafe conditions or any conditions that require repair to eliminate or reduce unnecessary down-time. Testing and monitoring activities include those performed as a part of scheduled preventive maintenance or as a part of the normal operation of the equipment.

4-7.4.1 Monitoring of Electrical Performance

Electrical monitoring is performed on a routine basis as a part of normal operation to detect any conditions related to the engine-driven-generator set or the load that require corrective measures. Items to be monitored include

1. *Load Power.* The load must be kept less than the capacity of the generator. If the power becomes too high, nonessential loads must be removed.
2. *Unbalanced Loads.* In cases where individual single-phase loads are powered by an engine-driven-generator set, some degree of load unbalance will occur, especially if the loads are intermittent. If excessive unbalance persists, then the single-phase loads should be redistributed because the capacity of the generator is reduced by unbalanced operation.
3. *Frequency.* The nominal frequency should remain within the tolerance specified for the generator. If the nominal frequency is outside the range, appropriate adjustments should be attempted to bring it back within limits. If the frequency cannot be properly adjusted or if the frequency is unstable, repair or adjustment is required for the engine or the frequency control circuitry.
4. *Voltage.* Out-of-tolerance voltage at the generator may result from drastic change in the load or from problems in the voltage control system. When an out-of-tolerance voltage is noted, adjustment of the voltage should be attempted. If the control has to be readjusted to maintain the appropriate voltage level with changing load, adjustment or repair of the voltage droop circuitry is necessary.

4-7.4.2 Engine Monitoring

Like electrical monitoring, engine monitoring should be performed to detect symptoms that indicate the need for corrective action. Symptoms such as low oil pressure or high water temperature indicate a condition that may seriously damage the engine in a short period of time.

Therefore, the engine should be shutdown immediately when these conditions are noted. Other conditions that should be observed include battery-charging current or voltage, oil consumption, and fuel consumption. Changes in observed values from previously recorded values should be investigated because maintenance or repair may be required. Operating documentation should include the potential causes of the changes in these or other noted parameters.

4-7.4.3 Trend Monitoring

Trend monitoring is the ongoing observation and recording of performance indicators for either the generator or the engine with the goal of detecting symptoms of problems as early as possible through comparison of current values with previously recorded values.

A trend monitoring program consists of making periodic observations of important engine parameters and recording them in a log along with other data, e.g., electrical load on the generator, that may significantly affect them. The data should be taken under as nearly the same conditions as possible, e.g., with the engine stabilized at operating temperature and the generator delivering medium load. The data may be interpreted either by examining tabulated data or by plotting data to demonstrate abrupt changes in monitored data or, preferably, a trend in the data away from the previously recorded nominal values for the engine—a deviation that is the precursor to a more catastrophic change.

The incorporation of trend monitoring into the preventive maintenance program provides earlier detection of problems requiring corrective action so more time is available to schedule the necessary repair. In some cases effective trend monitoring programs have allowed the extension of regularly scheduled maintenance intervals for replacement of parts subject to wear by relying on the trend monitoring approach to detect, in advance, the need for replacement.

4-7.4.4 Engine-Driven-Generator Set Diagnostic Testing

Procedures should be provided for operators and maintenance personnel to perform tests to determine the condition of the engine-driven-generator set. Test procedures may be described by reference to MIL-STD-705 or by simplified descriptions of procedures that can be performed in the field. Examples of tests that provide information on the conditions of the engine-driven-generator set are

1. Voltage regulation
2. Frequency regulation
3. Maximum power test
4. Engine diagnostic tests:
   a. Gasoline engines:
      (1) Dwell and timing
      (2) Fuel consumption
      (3) Vibrational analysis
   b. Diesel engines:
      (1) Fuel consumption
      (2) Vibrational analysis.

Maintenance procedures should include criteria for these tests to include expected values for the equipment when new, tolerable values for operable equipment, and threshold values that indicate maintenance is necessary.

4-7.5 LOAD AND GENERATOR SWITCHING

The procedures for switching generators on- or off-line are fairly critical because the generator, a source of significant energy, is being connected to a load that could contain a fault or, if already energized, could be out of phase with the generator being connected. The large transfer of energy that would occur under either of these conditions could be hazardous to the generator, switchgear used to connect the generator to the line, equipment connected to the line, or to personnel operating the generator.

4-7.5.1 Bringing Generator On-Line

Procedures for bringing a generator on-line should begin with measures to insure that the anticipated load on the line is within the capacity of the generator, that the generator is connected properly to the line, and that the engine is operating. Once these conditions are satisfied, the procedure for bringing a generator on-line would be as follows:

1. If possible, open the circuit breakers on the load to be connected so that only a portion of the load will be energized. This reduces the probability of encountering a fault simply because of the smaller network being connected.
2. Adjust the voltage to the desired value for the load.
3. Adjust the frequency to the appropriate value. Isochronous generators should be set to the desired line frequency. Engine-driven-generator sets with droop-characteristic regulators should be set to a 2 to 3% higher frequency to allow for the slight reduction in frequency with increased load.
4. Close the switchgear or circuit breaker that connects the generator to the line. Immediately observe the voltage and current meters for indications of an overload, i.e., reduced voltage or excessive current. If problems are noted, open the circuit breaker.
5. Reconnect the remainder of the load while frequently checking the current or power indicators on the generator to make sure that an excessive load is not being connected.

4-7.5.2 Connecting a Second Generator in Parallel

Connecting a second generator in parallel with one that is already in operation must be performed carefully since large currents will be induced in the conductors between the generators if the generators are not in phase at the time they are connected. The procedure described here assumes that one generator is already running and connected to a load that is within its capacity and that the second generator is also running and the output terminals are connected to the same load. However, the output breaker is off and thereby isolates the second generator from the load. The ground terminals of both generators are connected together with a large wire (6 AWG or larger). The procedure follows:

1. Adjust the voltage of the second generator so the indicated voltage on it matches that of the loaded generator.

2. Adjust the frequency control so the two synchronizing lamps repeatedly grow bright and then dim together with a cycle of at least 3- to 5-s duration. If the lamp cycles alternate, i.e., one is on when the other is off, then the phase rotation or phase connections on one of the generators is incorrect and must be corrected before the generators can be paralleled. If the paralleling operation is attempted while the lamps are cycling at a faster rate, the chance of connecting the generators when they are in phase is reduced and damage is more likely.

3. When the synchronizing lamps become dark together, quickly throw the circuit breaker that connects the second generator on-line.

4. Observe the power delivered by both generators, and balance the power by increasing the speed of the one delivering the lesser power or by reducing the speed control of the one delivering the greater power.

5. If the speed is not correct, adjust the speed control on both generators to bring their speeds into tolerance while maintaining the power balance adjusted in Step 4.

6. Balance the current delivered by each generator, i.e., reduce the circulating current between the two generators, by adjusting the voltage controls on the two sets so that the currents delivered by the two sets are equal and the voltage is within the desired range.

7. Observe the current and power division with changing loads. If a proper balance is not maintained with changing loads, then the voltage and frequency droop characteristics must be adjusted.

4-7.5.3 Bringing a Second Generator On-Line Without Interruption

The procedure for bringing a second generator on-line without interruption of power to the load consists of connecting the second generator in parallel with the first as described in the preceding paragraph and then removing the first as described in the paragraph that follows.

4-7.5.4 Taking Generators Off-Line

Before a generator that is operating in parallel with another can be removed from service, the load on the combination must be reduced to the level that can be accommodated by the generator that is to remain in operation; otherwise, the remaining generator will be overloaded after the removal of the generator to be disabled. Once the load is reduced, the generator may be removed from service by opening the circuit breaker. The engine-driven-generator set should be allowed to cool by running with no-load for a short period before the engine is shut off.

Procedures should warn that once the generator is disconnected from parallel operation, hazardous voltages remain on the output terminals and certain locations inside the control panel. Also warnings should be placed on terminals to indicate that high voltages exist even though the generator is not operating.

The removal of a generator that is operating independently off-line is simply a matter of opening the circuit breaker to disconnect the load from the generator. After running a few minutes to cool down the engine, the disconnected generator may then be cut off.

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CHAPTER 5

DISTRIBUTION SYSTEM

This chapter discusses the various components that comprise the distribution system, including the conductors for power distribution, transformers, overcurrent protective devices, and special purpose conditioners. Switchgear, discussed more thoroughly in Chapter 6, is discussed briefly. Hazard, design, interoperability, compatibility, and operational considerations are included for each component.

5-0 LIST OF SYMBOLS

E = test voltage, V
E_{i-j} = test voltage measured between points i and j, V
E_{DC} = DC voltage of rectifier, V
E_{rms} = rms voltage to rectifier, V
I_{G-i} = current that flows when test voltage is applied between ground system being evaluated and ith test rod, A
I_{1-2} = current that flows when test voltage is applied between two test rods, A
R_G = resistance of ground system being evaluated, Ω
R_i = resistance associated with ith test rod, Ω

5-1 INTRODUCTION

Electrical distribution systems transform the voltage of the source or transmission system to the voltage level of the loads and deliver energy for the various loads at each installation or over a service.

The objective of the distribution system is to transfer electrical energy to various loads with minimal loss and maximum reliability. The equipment used for distribution of electricity may consist simply of a system of interconnections by which power from the source is distributed only to local loads. For larger scale systems transformers are used to boost voltage levels to improve transmission over long distances. Both systems include devices to protect the system and loads from damage due to overcurrents and/or faults.

5-1.1 DEFINITION OF A DISTRIBUTION SYSTEM

A distribution system is the network that interconnects the source(s) of electricity to loads. Included in the distribution system is the network of electrical conductors interconnected with control and protective equipment. This equipment includes components that protect the system from damage, that minimize the number of loads affected by failures, and that improve the efficiency of power transmission. The types of equipment and the function of each type in a distribution system follow:

1. *Transformers.* Used to alter the voltage level from that of the source to the level or levels required by the loads.
2. *Circuit Breakers, Fuses, Cutouts, Switches, and Disconnects.* Used to disconnect malfunctioning equipment, to control loads, and to permit maintenance and repair.
3. *Lightning Arrestors.* Used to protect the entire installation from surge voltages due to lightning or switching in the transmission system supplying the network.
4. *Overhead and Underground Conductors.* Used to deliver the energy from the source to the loads.
5. *Meters and Relays.* Used to monitor the operation of the network and operate switches and circuit breakers as required to minimize the extent of damage or area affected by an abnormal condition in the system.
6. *Instrument Transformers.* Required for metering but are also necessary to reduce large currents and voltages to magnitudes suitable for instrumentation.

5-1.2 TYPES OF DISTRIBUTION SYSTEMS

Distribution systems may be described by the voltage of the distributed power, the electrical topology of the network, and the physical configuration of the conductors. Specific descriptors include

1. *Voltage and Phase.* The electrical configuration of the polyphase power being distributed, including the voltage between phases (or phase to neutral), the number of phases, and phase connections (delta or wye)
2. *Primary or Secondary System.* In a distribution system that distributes power at a high voltage and then transforms it to a lower voltage for a local use, the primary system is the power distribution from the source to one or more transformers. The secondary distribution system is the network that distributes power from the low-voltage secondary to the loads. The secondary system may operate at the ultimate load voltage; however, in many cases additional voltage transformation is used to permit secondary distribution at higher voltages, e.g., 12 kV.

3. *System Topology.* The electrical connection arrangement. Most frequent configurations are loop, straight bus feeding multiple branch circuits, and tree structured in which the source feeds branch circuits, each of which, in turn, feeds multiple circuits.

4. *Permanent or Temporary.* The expected life of the distribution system application. Garrison and installations are permanent, whereas tactical and construction site systems are examples of temporary systems.

Distribution networks vary in scale from intrastate networks that tie together generating plants and users in regional areas to local systems that tie a single generator to a small number of loads. The systems to be emphasized in this handbook are those that can be fed by an engine-driven-generator set either as the sole source or as a backup source for a permanent utility. Where larger scale systems are described, the intention is to illustrate principles or considerations that usually are specific to large systems but can be scaled down for application to small systems as well.

The phase configuration of the distribution system is determined by the connection of generator or transformer windings that supply power to it. Typical configurations for a three-phase distribution include the wye (3ϕ-4W) and delta (3ϕ-3W) configurations. If a delta configuration is used, however, grounding transformers or a balanced wye-connected load should be used to maintain all phases at equal voltages with respect to ground. Although the wye configuration has the definite advantage of providing a convenient grounding mechanism, the delta transformer has the advantage of lower waveform distortion because a path is provided around the delta loop that prevents induced third harmonic currents from being applied to the load.

The transmission system supplying the large-scale distribution network has a high voltage, which is typically 66, 132, 220, 345, or 500 kV. This source voltage is reduced to the required load voltage by transformers. Two or more voltage reductions may be required, e.g., 132 to 34 to 12 kV and finally to load voltage. The first reduction, e.g., 34 kV, defines the distribution network voltage. The primary voltage is reduced again to load levels, e.g., 120/208 V, three-phase or 120/240 V single-phase. Source-to-primary voltage transformation may be accomplished by one three-phase transformer or by three single-phase transformers.

Distribution systems usually consist of a network of transmission lines installed aerially on poles or buried underground. Utility-fed systems having a 750-kVA capacity typically have primary voltages of 34.5 kVA. An intermediate voltage might be used if the loads are scattered over a wide area. For loads confined to a small area or within a single building, the secondary distribution would be made to the load voltage, e.g., 240, 480, or 600 V, three-phase. Systems served by engine-driven-generator sets usually cover a smaller area, and generally, high voltages are not necessary. Power for these systems may be distributed at the load voltage or at a moderately low primary voltage, e.g., 2400/4160 V, three-phase.

The simplest distribution system is a tree configuration fed from a single source. Other distribution networks, as shown in Fig. 5-1, are

1. A loop feeder connected to a single source
2. A loop feeder supplied by several sources
3. A low-voltage secondary network system.

The tree network is the least expensive installation but is also the least reliable. The single-source loop is

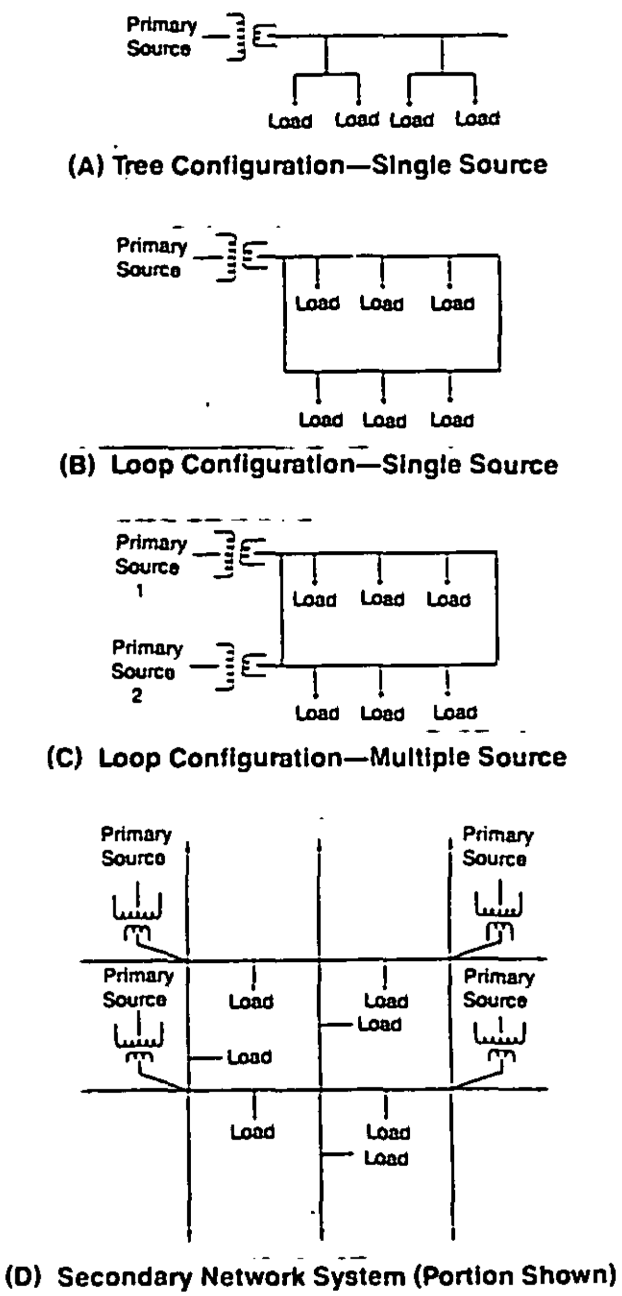


Figure 5-1. Distribution Network Configurations

more reliable than the tree network because fault detection and clearing can be implemented that interrupt only a small portion of the loads served by the distribution network. A loop-connected system with several transformers is even more reliable but requires an additional monetary investment in transformers. The most reliable distribution network is a low-voltage secondary network in which the low-voltage secondaries of distribution transformers are connected in parallel to a grid. and the primaries are fed from separate circuits from one or more sources (Ref. 1). The parallel connection of transformer secondaries provides a high degree of redundancy in routing power between sources and loads. Tolerance to faults in the secondary network is enhanced by sectionalizers, which isolate sections where faults have occurred. The appropriate selection of the distribution configuration is made by balancing cost and reliability factors.

The distribution system currently being developed for the Army for use in tactical situations is a secondary distribution system in which power is distributed at the load voltage (120 V/208 V). Portable distribution centers are used to provide circuit protection, switching capability, and connection of power cable to multiple power extension cables.

5-1.3 COMPONENTS USED IN DISTRIBUTION SYSTEMS

The equipment to be discussed in subsequent paragraphs of this chapter are

1. Distribution lines that transmit the energy from the source to the loads. (The term "transmission lines" is reserved for the transmission system network that is the source for the distribution system.)
2. Distribution transformers that modify the voltage in the network to the voltage required. Whether the transformer between the transmission system and the distribution primary is considered transmission or distribution equipment is a matter of preference. In this chapter it will be considered distribution equipment. Other distribution transformers reduce voltages as required. The voltage levels and the number of transformers are dictated by the requirements of the installation.
3. Power conditioners include a variety of devices such as capacitors for power-factor correction, voltage regulators, motor generators, and rectifiers.
4. Uninterruptible power supplies for critical loads
5. Switchgear
6. Metering and protective devices
7. Lightning arrestors.

5-2 TRANSMISSION AND DISTRIBUTION LINES AND BUS BARS

5-2.1 INTRODUCTION

The types of conductors used in the transmission or distribution lines of the network are

1. Uninsulated aerial conductors made of copper, aluminum, aluminum conductors steel reinforced (ACSR), and copper-weld (single conductors and stranded)
2. Insulated copper or aluminum single conductors, bundled and triplex cable (three-phase conductors intertwined)
3. Insulated cables either buried directly in soil or pulled through conduit
4. Insulated conductors laid on top of the ground for temporary service or for service to equipment moving across the ground (dragline equipment)
5. Cables used in underwater installations
6. Bus bars used for concentrated loads occupying limited space, e.g., inside manufacturing plants or repair shops.

5-2.2 INDUCED ENVIRONMENT

Environmental impact due to the installation of a distribution system takes several forms, namely,

1. The presence of high voltages on uninsulated conductors is an environmental consideration because of possible contact by cranes, oversize vehicles, or children's kites.
2. The electrical stress on solid insulation at or near the voltage gradient at which corona develops causes dendritic tracking in the solid insulation. Ultimately, discharges will develop on these paths and a permanent breakdown of the insulation will occur. Tracking will also occur over atmospheric-contaminated porcelain surfaces during foggy conditions. Arcing over the porcelain will usually result in only a temporary breakdown.
3. The overhead conductors and their supporting structures (poles) do not enhance the beauty of the landscape. Outdoor switch yards barricaded by cyclone fences can be equally offensive. Distribution facilities may be obtrusive due to the combined requirements for physical barriers to prevent access by unauthorized persons and for adequate space to permit maintenance and repair of equipment.

5-2.3 HAZARDS

Authorized personnel often must work in close proximity to uninsulated, current-carrying equipment in the maintenance, repair, and operation of high-voltage equipment. Great care must be exercised to achieve the maximum amount of safety during these activities. Suitable barriers should be provided to prevent exposure to arcing, e.g., from a switch that breaks the circuit in air. Equipment that contains oil, e.g., oil circuit breakers and transformers, must be located at least 7.6 m (25 ft) (horizontally) away from switchgear in indoor installations and 3 m (10 ft) away in outdoor installations. (See Items 172 and 180 B1 of the National Electrical Safety Code (Ref. 2).)

The intense heat of a power arc over a porcelain insulator following a lightning flashover can shatter the insulators, and the fractured porcelain could be a great hazard to personnel near the insulator.

Pollutants in the atmosphere can collect in the cracks (checks) that have developed in wooden poles. Under certain fog conditions, a very small leakage over 34-kV insulators, across crossarms, and down the pole can cause burning in the confined space of a crack in the wooden pole.

A line-to-ground fault can produce a hazardous condition. The step-voltage, i.e., the voltage on the surface of the earth between the feet of a person walking, during a ground fault can be lethal. A ground-fault current of 100 A is lethal for a normal stride at a distance of 5.7 m (20 ft) from the fault and at a distance of 18 m (60 ft) for faults of 1000 A. (See Ref. 3, p. 321.) Proximity to a ground rod during fault conditions is also dangerous because part of the fault current will divide among all grounded devices, e.g., ground rod and tower footing, and potentially will produce hazardous step-potentials in the vicinity of each one.

5-2.4 DESIGN CONSIDERATIONS

5-2.4.1 Installation

Overhead distribution conductors should have at least the minimum aboveground clearances specified in the National Electrical Safety Code (NESC) (Ref. 2, Table 232-1) for the particular ground surface condition—e.g., over railroad tracks 9 m (30 ft); 6.7 m (22 ft) over buildings, streets, and roadways. Further precautions to prevent cranes and other vehicles from contacting the lines are not required. Hanging barriers, however, should be placed across roadways frequently used by construction vehicles to warn operators of impending contact with the lines. The barriers should be placed at the same height as the lines and on either side at a distance from the line sufficient for the operator to stop the vehicle. Caution signs should be posted on towers and poles to warn against inadvertent contact by unauthorized personnel.

Adequate clearance must be provided between supply conductors and guy wires or other conductive supports to prevent ground faults through the guy wires because such ground faults, even though temporary, could produce hazardous step-potentials and/or disable the distribution system. For systems operating up to 8.7 kV, the NESC requires a clearance of 0.3 m (1 ft) for support conductors that run parallel with the line conductors or 0.15 m (0.5 ft) for others, such as guy wires. Additional clearance is appropriate for long guy wires or line conductors because of increased movement due to wind. (See Ref. 2, Table 235-6.)

Clearance should also be provided between line conductors and one side of the pole to allow personnel to climb poles to heights above the energized conductors. For lines operating up to 750 V, a horizontal clearance of 0.6 m (2 ft) is required by the NESC to allow space for workers to climb between the pole and energized conductors covered with suitable protective coverings that are rated for the voltage involved. Additional clearance must be provided at higher voltages—0.75 m (2.5 ft) at voltages up to 15 kV and 0.90 m (3 ft) at voltages up to 28 kV. Other distribution equipment, e.g., transformers and switchgear, should not be mounted in the climbing space.

Additional clearance considerations include clearance between parallel conductors for various operating voltages and spans between supports, clearance over buildings and signs, and clearance over waterways. These clearances are also specified in the NESC (Ref. 2).

Buried cable should be of the proper construction—i.e., conductors protected by a shield, sheath, or wrapped with a bare neutral conductor that is properly grounded. Warnings against digging either by hand or machine should be posted at locations where excavation is most likely. These warnings serve the dual purpose of protecting both the public and the equipment. Depth of cable burial should be 0.8 m (2.5 ft) for voltages up to 22 kV and 0.9 m (3 ft) for voltages up to 40 kV. The bottom of the ditch should be flat and well packed. Backfill should not contain sharp material that could damage the cable.

The installation procedures and sites for underwater cable installations (submarine crossings) should insure protection from damage due to tidal action or current flow. Underwater cable should not be located at possible anchoring sites for ships, and signs should be posted to warn of cable crossings. Cables used in underwater installations must be selected on the basis of serviceability in the particular environment.

Overhead installations over narrow valleys that may be on airplane flyways should have red sphere warning balls on the conductors or static wires.

5-2.4.2 Configuration

The network should be designed so that sections can be deenergized—either manually for repair or maintenance or automatically by operation of selected switching devices, fuses, cutouts, etc.—in such a way as to minimize the amount of equipment being deenergized. This cannot be a standardized design; it must be tailored to the particular installation and therefore requires considerable analysis and consideration.

5-2.4.3 Material Selection

Careful consideration should be given to the service in which the conductors will be used. In low-voltage, heavy-current installations, voltage drop should be minimized by the selection of a high-conductivity conductor. The final decision to use copper or ACSR must be made by considering the diameter of the conductors, their weight, and the span between supports.

In overhead lines operated at higher voltages, the tensile strength of the conductors is a more important consideration than conductivity. The tensile strength must take into account possible ice loading and crosswinds. The maximum loading of ice is 13 mm (0.5 in.) radial thickness and 200 Pa (4 lb/ft^2) of horizontal wind pressure at a temperature of -18°C (0°F). Higher loadings may be encountered in high-wind conditions typical of tornadoes or hurricanes.

Insulation in cables can be paper, rubber, cotton, thermoplastic, oil, or a combination of these. Once the solid insulation is punctured by voltage breakdown, the fault continues until complete destruction. Oil-filled cable can temporarily recover but will ultimately fail. Solid wrapping of a bus installation is subject to tracking caused by corona and local discharges, which also will induce insulation failure.

Bus bar support insulators are relatively failure proof except in areas of heavily contaminated atmospheres. Under certain fog or dew conditions, tracking and flashover can occur. String-type insulators and pin-type insulators are subject to the same difficulties as bus insulators but have the additional hazard of gunfire by hunters or military action.

In confined spaces, flammable materials—which could possibly result in the accumulation of smoke in the event of fire—should not be used. Materials, e.g., polyvinyl chloride, that produce toxic fumes upon burning should not be used.

5-2.4.4 Labeling

All conductor switches and other equipment in a switching center must be labeled as to voltage level and phase. Towers and poles of overhead lines should have warning signs that indicate the voltage of the lines. The location of the phases in an installation must be consistent and designated 1, 2, 3 from left to right, top to bottom, and front to back. The warning labels described in par. 4-4.9 should be placed wherever high voltage is exposed or could be exposed during normal maintenance activities.

5-2.4.5 Grounding and Bonding

Grounding conductors should be attached to machine cases and cabinets by brazing, welding, mechanical or compression connections, or ground clamps. Soldering may only be used with connections to the lead sheaths of cables. Fences and enclosures around electrical equipment shall be connected to an adequate ground by a copper connection of not less than a No. 8 American Wire Gage (AWG) conductor. If the fence posts are of a conducting material, the metal fence fabric should be electrically bonded to the posts. If the posts are nonconducting, e.g., wood, a suitable ground must be provided at frequent intervals.

Engine-driven-generator sets and loads may be grounded through the source connection with a conductor that has a greater current capacity than the phase conductor that would supply a fault current or the maximum current that could flow through it.

The most commonly used ground connection is the ground rod, i.e., a pipe or rod driven into the ground with a clamp attached to the protruding end for connection of a wire. The diameter of the rod is usually determined by the strength required to drive the rod to the depth necessary because the ground resistance obtained does not decrease rapidly with increasing rod diameter. Rods should be made from or coated with conductive, corrosion-resistant coatings to prevent the buildup of an insulating oxide layer on the surface of the ground rod. Longer rods generally provide lower resistance grounds because of the increased contact area and the penetration into deeper regions, which have lower soil resistance.

Lower ground resistance is obtained preferably by connecting additional ground rods in parallel, rather than by using chemical treatments to the soil, because chemical treatments may be corrosive to the ground rods and usually are not permanent.

Where convenient, buried conducting objects can be used as grounds. Burial of cylinders, pipes, or plate in trenches at a depth where soil remains moist and unfrozen should provide a low-resistance ground. Also conductors encased in concrete below grade, such as reinforcement bars in concrete foundations, may be used for grounding. For commercial substations where very low resistance must be obtained to prevent hazardous step-potentials in the event of large fault currents, a ground mat is used—a network of buried conductors supplemented by driven grounds. In environments where ground conductivity is especially poor, an artificial ground network should be constructed by connecting all units together with a safety ground capable of conducting fault currents. The integrity of this ground system is especially important in order to maintain all equipment enclosures in the system at the same potential. Attempts to pass fault currents through the earth would result in excessive induced voltages at ground terminals. Therefore, the ground network should be connected to earth by using conventional techniques such as ground rods and buried conductors. If possible, grounds should be located in areas where moisture would be available, i.e., as deep as possible in sand or ice. Pipes or other buried conductors should be used for ground connections to increase the probability of contact with conductive soil.

The conductivity of wet, organic soil is 100 times greater than that of moist soil and 1000 times greater than that of dry soil. The resistance of frozen soil is particularly high. After a grounding bus has been created, it should be tested to determine whether it is adequate for the intended purpose, especially if the earth is a low-conductivity soil. (See Ref. 3 and par. 5-2.6.4.)

A communication line closely coupled to a distribution line will have a voltage induced in it by magnetic induction. For safety reasons the communications line must be grounded at intervals to prevent voltages hazardous to personnel and communication equipment from occurring on the communication line, especially when heavy fault current is flowing in the distribution line. To prevent induced current in the communication line, however, only a single ground connection is necessary. Modifications of the communications line may be necessary to allow multiple grounding while minimizing the induced currents along the line. The techniques available for modifying the communication line include transformer couplings and fiber optics.

5-2.4.6 Overcurrent Detection Devices

Short circuits—phase to ground, phase to neutral, phase to phase, and three phase—where the fault resistance is low are easily detected by overcurrent relays or breaker trip coils. High-resistance faults in which the short-circuit current is within the normal load current range are difficult to detect early enough for appropriate action to be taken. Several early detection techniques are available, i.e.,

1. *Rapid Change in Current Load.* Because of the arcing nature of the high-resistance fault, there is a power flow that does not rise and fall in a smooth curve but rather has a jagged wave shape. This abnormal rate of rise in the power curve can be used to detect a fault.

2. *Noise on Electrical Line.* Noise on a circuit also can be used to detect a fault. Care must be used in making this determination because the connected load inherently may generate noise. For example, welders, dimmers for incandescent lamps, and fluorescent lamps all have harmonic currents.

3. *Ground Fault Interrupters.* Faults between a line and ground may be detected by differential relay schemes in which the currents entering and leaving a load (transformer or line) are compared within a protected region. Negative-sequence current filters can be used to detect single phase-to-ground or phase-to-phase fault currents.

Corrective action for overloads in a radial system is relatively simple. The fuse, switch, or circuit breaker—discussed in pars. 5-2.4.6.1 and 5-2.4.6.2—at the remote end of the line has the most sensitive setting and will react to a fault "downstream" before the devices closer to the source take action. In this manner, the corrective action minimizes the amount of load interrupted.

The protection of a loop-connected distribution system is more complicated since potential fault locations are fed by multiple paths. For maximum effectiveness overload devices must be placed at locations where power enters the loop. Sectionalizers must then be used to isolate a portion of the loop if a fault occurs.

5-2.4.6.1 Fuses

Low-voltage fuses generally contain a thin metal strip. Under overload or fault conditions, this strip melts, arcs, and then opens and removes power from the overloaded circuit. A time delay feature is provided by bonding two conductors together with a low-melting-point alloy. The conductors have a thermal mass sufficient to heat slowly under slight overloads. Thus a short delay occurs before the conductors separate and interrupt the current flow. Classes of low-voltage fuses are summarized in Table 5-1.

Current-limiting fuses are more sophisticated in design, i.e., they have multiple silver links that are surrounded by compacted quartz sand. The links contain numerous bridges that open rapidly upon fault conditions, and the resulting arcs are cooled by the sand. These fuses act rapidly, limiting, then interrupting, fault currents in milliseconds. The inherently high resistance of the fuse during the current-limiting process results in the introduction of large transient voltages into the supply feeding the fuse. These transients may damage unprotected equipment powered from the same line (Ref. 11).

Fuses for higher voltage systems include materials that vaporize from the heat of the arcing fuse link material. The fuse link is tension-spring loaded so that when the link separates from overheating, the two pieces are pulled apart and thereby elongate the arc. The arc heats and vaporizes the surrounding material, usually boric acid. The released gases and water vapor deionize and cool the arc and extinguish it in about one cycle (at 60 Hz). Upon interruption, gases are released with explosive forces that can damage enclosures when fuses are mounted inside. Mufflers or silencers are incorporated into some fuse designs to absorb the energy from expelled gases.

High-voltage fuses provide protection in the event of faults; however, they have limited effectiveness against overcurrent conditions. Therefore, their primary purpose is to protect equipment from damage, not to protect conductors.

The actual limiting current of the fuse is affected by ambient temperature. Fuses should not be installed where ambient heating will be excessive or, for high-voltage fuses, should not be installed where the vented gases could cause damage or injury. Likewise, fuse holders should be kept in good operating condition to maintain good electrical contact with the fuses because poor contact conditions will generate heat sufficient to cause fuses to fail or to blow at lower currents.

Selection of fuses must be based on the voltage of the circuit to be protected, the maximum continuous current allowed in the circuit, the maximum fault current to be interrupted, and the time required for activation. Fuse ratings for various branches and levels of a circuit should be coordinated so that service is interrupted only over a minimum portion of the system. For example, faults in branch circuits should blow fuses on that branch alone and should not affect fuses at points in the systems that feed the branch with the fault. Fuse capacity and time delay characteristics also must be chosen for compatibility with automatic reclosers. Information concerning fuse characteristics is given in Refs. 11 and 12; coordination considerations are described in Ref. 13.

5-2.4.6.2 Circuit Breakers

Circuit breakers are switches that are automatically activated by a thermal, magnetic, or combination thermal and magnetic mechanism that senses overcurrent conditions. Magnetic breakers may be designed so that the trip current is independent of temperature; however, thermal breakers generally become more sensitive with increasing temperatures. Thermal sensing is useful for loading detection; however, magnetic sensing is required for rapid fault interruptions. The magnetic trip mechanism may be modified to provide additional features such as overvoltage sensing and ground fault interruption.

TABLE 5-1. LOW-VOLTAGE FUSES (600 V AND BELOW)
(Adapted from Ref. 4)

Type	UL Standard*	Voltage, V	Current, A	Interrupting or Short Circuit Rating, A	Comments
Noncurrent Limiting					
Plug	198F	125	0-30	Short circuit 10,000	Edison base and Type S types
H	198B	250,600	0-600	Short circuit 10,000	Interchangeable with K series and RK series fuses
Current Limiting					
K	198D	250,600	0-600	Interrupting 50,000, 100,000, and 200,000	Types: K1—High degree of current limiting K5—Medium current limiting K-9—Fair current limiting
G	198C	300	0-60	Interrupting 100,000	Optional time delay
J	198C	600	0-600	Interrupting 200,000	
L	198C	600	601-6000	Interrupting 200,000	
R	198E	250/600	0-600	Interrupting 200,000	Types: RK1—High degree of current limiting RK5—Medium degree of current limiting
T	198H	250/600	0-600	Interrupting 200,000	
CC	198C	600	0-20	Interrupting 200,000	

*Fuse References:
UL 198B Class H Fuses, Underwriters Laboratories, Northbook, IL, 1982. (Ref. 5)
UL 198C High-Interrupting Capacity Fuses, Current-Limiting Type, 1981. (Ref. 6)
UL 198D High-Interrupting Capacity Class K Fuses, [____], 1982. (Ref. 7)
UL 198E Class R Fuses, [____], 1982. (Ref. 8)
UL 198F Plug Fuses, [____], 1982. (Ref. 9)
UL 198H Class T Fuses, [____], 1982. (Ref. 10)

Circuit breakers use switching technology appropriate for the voltage and current of lines. For circuits operating at voltages up to 600 V, air circuit breakers are used, i.e., circuit breakers in which the switch contacts are surrounded by the atmosphere. Higher voltage lines—up to 15 or 20 kV—may be interrupted with devices that use an air blast or magnetic field to lengthen and break up the arc. For extremely high voltages, circuit breakers with immersed or sulfur hexafluoride (SF_6) insulated switchgear are used. The oilless breakers are more widely accepted, especially for indoor use, because of the fire hazard associated with oil.

For systems of the size being discussed in this handbook, the most common type of breaker is the air-insulated, molded-case circuit breaker. These breakers have molded-composition bodies with provision for panel mounting, magnetic and/or thermal tripping mechanisms, and one to three sections to accommodate single or polyphase circuit interruption. Units with higher interruption capacity incorporate arc chutes for extinguishing the arc upon opening a circuit with a fault.

In all but the smallest sizes, circuit breakers have a "trip-free" handle. Once the breaker has been tripped, "trip-free" handles come to rest in a position between "off" and "on" to provide a visual indication that the breaker has been tripped. The handle must then be moved beyond the off position to reset the breaker before it can be returned to the on position. This action reduces the chances of an inadvertent restoration of power to a circuit containing a fault.

Breakers for separate phases should be ganged together so that an overcurrent condition in one phase will cause all three phases to be disconnected.

A useful accessory—used on ground fault interrupters—is the push-to-trip feature, which allows the testing of a magnetically operated switching function. Other accessories include a solenoid operated reset that allows remote tripping of the breaker, auxiliary switches for remote indication of breaker status, and handle locks to prevent operation of the circuit breaker during repair or maintenance of lines fed by the circuit breaker.

The air-blast circuit breakers used in higher voltage applications are typically housed in metal cabinets in drawout drawers for maintenance and inspection. Interlocks should be provided to prevent the withdrawal of a breaker if it is not in the open position.

As with fuses, the selection of circuit breaker ratings at a location in a system must be coordinated with other circuit breakers, reclosers, sectionalizers, and fuses located elsewhere in the distribution system. Breaker rating and time before tripping should be selected so that the lowest level branch circuit breaker trips and isolates minimal portions of the network. Procedures for coordination of circuit interrupters are discussed in Ref. 4.

Reclosers are circuit breakers that reclose after opening to clear a fault. If the fault still exists after a preset number of reclosings, the recloser locks out in the open condition.

Sectionalizers are breakers that operate before other breakers attempt to clear the fault. This serves the purpose of reducing the amount of load that is interrupted when the final fault-clearing operations clear the system. Also these breakers and the main breakers can be of a lower rating than the breakers that would be required if sectionalizers were not used. Oil circuit breakers depend upon the quenching action of the oil to extinguish the arc that is created when contacts part. Blast (air and magnetic) breakers rely on the lengthening, cooling, and breaking up of the arc, which results from blowing the arc into an arc chute.

During maintenance operations on a breaker, it must be separated from the system by disconnects that can be locked in the open position. Both sides of the breaker must be so separated to prevent "back feed" on the load side of a breaker. When breakers cannot be physically disconnected from the line for maintenance or repair, the terminals of the breaker must be tied together by an external shorting bar and grounded by an adequate grounding connection during maintenance or repair operations.

5-2.5 COMPATIBILITY AND INTEROPERABILITY

In the event that additional equipment must be added to an existing distribution system, a careful review must be made. Considerations for integration of equipment into, or replacement of equipment in, a distribution network are

1. Replacement equipment must have a voltage rating equal to that of the equipment originally specified. In most cases a higher rating may be tolerated. (An example of a case where a higher voltage rating should not be used is current-limiting fuses that can cause excessive transients on the line when a fault occurs.)
2. Replaced items must have a current capacity compatible with that originally specified, and fuses and breakers should be replaced with units of equal characteristics.
3. Polyphase equipment should have the same electrical configuration, i.e., wye (3ϕ-3W) or delta (3ϕ-3W).
4. Equipment should be capable of operation in the same environment. Equipment characteristics related to environmental conditions include operational temperature range, resistance to humidity, tolerance of solar radiation, and resistance to corrosive atmospheric pollutants.
5. For portable distribution equipment, connectors should mate with those used in existing equipment.
6. Care must be taken that circuit breakers used for replacement have a physically similar case. Although fuses are well standardized, circuit breakers are available in slightly different configurations, which may prevent their installation in existing panels.

5-2.6 TEST CRITERIA FOR ITEM DESIGN AND ACCEPTANCE

It is assumed that all components used in an installation have been individually tested or inspected before assembly into a distribution system. The tests described in this paragraph should be performed on the complete system before it is put into service.

5-2.6.1 *Inspection*

A visual inspection is necessary to determine whether a hazardous situation exists so that it may be corrected prior to use of the switchgear. Example points to be covered during the inspection are

1. Verify that all connections are secure and made in accordance with design diagrams.
2. All sensing and control instrumentation must be connected properly.
3. Current transformer secondaries must be connected to a metering device, relay, or short circuit. *Current transformer secondaries should not be left open-circuited when in service* because extremely high open-circuit terminal voltages may be produced.
4. Transformers should be checked for proper tap settings based on the primary supply voltage and the required load voltages.
5. Signal lights on panels must be verified to give the proper indication, i.e., circuit breaker closed or open.

5-2.6.2 High-Potential Testing

High-potential tests should be applied to all bus structures to verify the adequacy of the insulation. High-voltage tests of overhead lines and cables should be made before application of power. Control wiring should be subjected to suitable high-voltage tests.

5-2.6.3 Relay Test

Extensive tests must be performed on relays to verify that they will operate at the appropriate value and energize the intended circuit breaker trip coil and will not operate when they should not.

5-2.6.4 Ground Resistance Testing (Ref. 3)

Ground resistance tests are performed to verify the adequacy of the grounds of the system. A high-resistance or inadequate ground can allow the development of unsafe touch- or step-potentials in the event of a fault.

An approximation of the resistance of a ground can be obtained by the following test. Two additional ground rods are driven. A known voltage is applied between the ground being evaluated and the first test ground rod to obtain the current flow. This procedure is repeated with the second test ground rod and then again with the voltage applied to the two test rods.

The resistance of the ground rod being evaluated may be determined by solving the following equations simultaneously:

$$R_G + R_1 = E/I_{G-1}, \Omega \qquad (5\text{-}1)$$

$$R_G + R_2 = E/I_{G-2}, \Omega \qquad (5\text{-}2)$$

$$R_1 + R_2 = E/I_{1-2}, \Omega \qquad (5\text{-}3)$$

where

E = test voltage, V

I_{G-i} = current that flows when test voltage is applied between ground system being evaluated and ith test rod, A

I_{1-2} = current that flows when test voltage is applied between two test rods, A

R_G = resistance of ground system being evaluated, Ω

R_i = resistance associated with ith test ground rod, Ω.

This is not an accurate test, but it does provide a good approximation for the ground resistance R_G.

5-2.7 OPERATIONAL PRECAUTIONS

Installation of a distribution system should conform to Section 2 of the National Electrical Safety Code for overhead lines and Section 3 for underground installations (Ref. 2).

In a tactical environment time and facilities may not permit strict adherence to the safety code. In such cases the installation should be made to conform to the code as nearly as possible given the constraints imposed by time and availability of equipment. For installations that are not temporary, the installation should be brought into compliance as quickly as possible under the existing conditions.

Work on or near distribution lines that must remain in-service must be done in a safe manner. The use of rubber blankets, rubber hoses, and rubber gloves is mandatory. All items in the National Electrical Safety Code, Section 4, shall be followed (Ref. 2). Any equipment that may be deenergized should be removed from service during the maintenance or repair operations. (See Section 422 of Ref. 2.) Switches and disconnects that have been opened must be tagged and remain open until the tag is removed by the foreman in charge of the maintenance. (See Section 423 of Ref. 2.) Grounds must be placed on equipment to eliminate induced voltages that might endanger personnel. (See Section 424 of Ref. 2.)

Disconnects and grounding switches provided with locks should be locked as well as tagged during the maintenance.

Equipment should be tested for voltage before workers begin their repair work. Tests to be performed are

1. Test the electroscope on equipment known to be alive.
2. Test the work area to determine that there is no voltage present on the equipment.
3. Retest the electroscope to verify that it is still functioning properly.

Periodic inspections of the following items should be made at regular intervals:

1. Poles. Condition of poles and change of terrain—washouts, slides, etc.—affecting support
2. Crossarms and insulators for damage caused by flashovers, gunshot, etc.
3. Conductors for flashover damage, mechanical wear, etc.
4. Inadvertent storage or placement of flammable materials near switches and circuit breakers.

5-3 DISTRIBUTION TRANSFORMERS

A distribution transformer is a static device, having no motion or rotation, that consists of two or more windings magnetically coupled by a steel core common to all windings. The function of the transformer is to change the voltage of the source to the voltage of another part of the network that requires a different voltage. For example, the voltage of the primary network, e.g., 12.8 or 34.5 kV, is reduced to the voltage load (120-240 V). This change in voltage is produced by the difference between the number of turns in each winding wound around a common iron core.

The windings of the coils are insulated by solid insulation—cotton, plastic, etc.—and are cooled by a liquid (transformer oil) or by air.

Transformers come in a wide variety of designs. Transformers can be mounted on a pole, mounted on a platform between two poles, or mounted inside buildings. Larger transformers are designed for mounting on concrete pads or in specially constructed vaults. Transformers used for temporary service may be mounted on trailers or railroad cars.

Transformation from high to low three-phase voltages may be made with either three single-phase transformers or a three-phase transformer, i.e., usually three sets of identical windings on separate legs of an iron core. The primary and secondary of either configuration may be connected in a delta or wye configuration: the appropriate choice is determined by the power source and load configuration. Fig. 5-2 shows a typical three-phase step-down transformer connection. Windings A-A', B-B', and C-C' may each be single-phase transformers or paired windings in a three-phase transformer. If the common point of connection of the three wye-connected windings is grounded, less insulation is required around the grounded end of the windings, and therefore, the transformer could be manufactured less expensively.

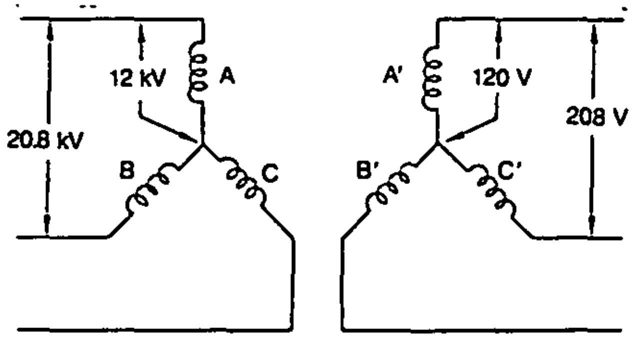


Figure 5-2. Wye-Wye-Connected Transformer

Another commonly used connection is the delta connection. Fig. 5-3 shows a wye-delta-connected transformer. Again A-A', B-B', and C-C' are three single-phase transformers or paired windings in a three-phase transformer.

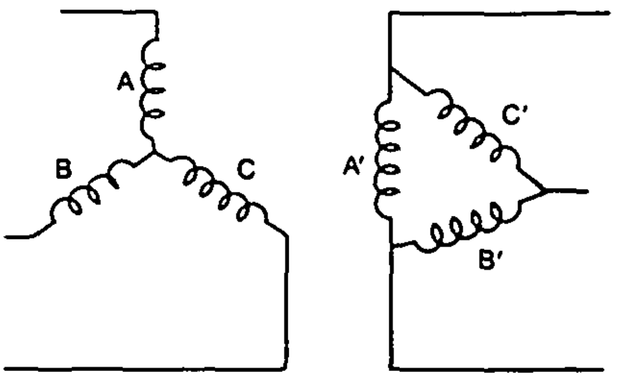


Figure 5-3. Wye-Delta-Connected Transformer

Many special configurations are available using tapped windings or multiple windings to provide combinations of voltages for special loads. Examples include the center-tapped single-phase transformer used to supply 120- and 240-V loads and the wye-connected transformer, which can power a 208 V-3ϕ motor load while simultaneously powering 120-V loads. Common configurations are described in Ref. 14.

Because of the nonlinearity of the iron in the magnetic circuit of the transformer, a third harmonic magnetizing current is required. If the power to the transformer is sinusoidal and contains no third harmonic energy, the energy will be taken from the output winding and thereby distort the output voltage. The secondary windings of a wye-connected transformer will have a strong third harmonic component even if the input were a pure sine wave. The delta-connected transformer provides a path for the third harmonic magnetizing current around the loop formed by the delta, and therefore, the output voltage will not be distorted.

Wye-connected transformers are used to provide a well-established ground that maintains all phases at an equal rms voltage level with respect to ground. If the delta configuration is used, the load must supply the ground—i.e., be balanced and be wye-connected—or one corner of the delta must be grounded to prevent the buildup of induced phase-to-ground voltages. However, this grounded-corner configuration is not recommended because it is incompatible with common three-phase practice.

Other combinations are available and are described in Ref. 14.

5-3.1 INDUCED ENVIRONMENT

There are magnetic losses in the steel core of a transformer when the transformer is energized even if there is no load connected to the transformer. Other losses include resistance losses, sometimes called copper losses, which vary with the square of the current and which cause heating of the transformer. The rating of the transformer is determined by the maximum heating that can occur without causing damage to insulation. Unless the transformer is protected, overload conditions will cause the transformer to overheat and possibly cause internal faults.

Other environmental effects of transformers are the noise associated with the third harmonic magnetizing current magnetostriction, the presence of high voltage typical of primary distribution systems, and the presence of environmentally damaging oil that possibly contains PCBs.

5-3.2 HAZARDS

A short circuit on or near the load-side terminals of a transformer supplied by a low-impedance source will subject the windings to extremely high magnetic forces. The DC component of the fault current can result in an rms value that is double the steady state AC current value. The transformers have low impedances on the order of 3Ω. These two factors combine to cause the fault current to be in the range of 60 times normal current rating. Magnetic forces on the conductors are proportional to the square of the current. Thus the braces on the winding itself could be subjected to 3600 times the normal force. A poorly designed or constructed transformer could fail internally and possibly create the hazard of an oil fire.

A short circuit near a transformer can cause destructive forces on bus bar insulators.

Damage to the case of a transformer resulting in a leak of the coolant is complicated even further if the coolant is PCB.

Lightning arrestors are installed on the high side (source) of transformers to protect them from lightning and switching surges. Failure of the arrestor to limit the surge can cause the insulation of the winding to fail with the associated hazard of fire.

5-3.3 DESIGN CONSIDERATIONS

Several protective devices or elements of design are incorporated in building transformers to protect them from overcurrent and surge voltages (lightning and switching).

Protection from overcurrent in addition to external devices, such as fuses and breakers controlled by relays, are built into transformers by hot-oil thermometers and hot-spot thermometers. Both of these devices are usually used as advisories (warning lights); they do not operate breakers. However, they can be used to activate cooling fans and pumps. They have the disadvantage of time lag between application of a suddenly applied heavy overload and the change in oil temperature. The hot-spot temperature and the top-oil temperature, even on a constant load, will be quite different. Several designs of hot-spot thermometers are in use in which the oil temperature is augmented by a heat that is proportional to the load current. Matching the time constant of the heater to that of the transformer hot-spot is difficult if not impossible. These devices can act as a guide, but the ultimate protection must be a circuit breaker or fuse external to the transformer.

Surge protection includes internal surge protection as well as external surge protection. External protection takes several forms, namely,

1. Lightning arrestors
2. Spark gaps
3. Installation of insulators close to transformers that have a lower sparkover voltage.

The inductance of the winding inhibits an impulse charge from immediately flowing into the winding. This delay causes the charge on the capacitances between turns, or pancakes, to charge at different rates. The stress on the line-side turns is greater than on the turns at the neutral end (Ref. 14).

By proper location of capacitor plates in the winding of the dielectric, stress can be made more uniform between turns of the transformer and thereby increases the amount of surge voltage the transformer can withstand.

Each transformer location on a system is subjected to a different voltage level for a given impulse voltage that is applied to a system because of the different reflection and refraction characteristics of each node of the network. Also the impulse that is applied to each transformer is a function of the network parameters and is different for every configuration. Because of the large number of combinations of conditions that can exist, the problem can become extremely complex. Therefore, rather than selecting a transformer to withstand a particular surge voltage based upon the voltage that could be expected at the particular location, all transformers in a particular system are selected from one of a number of standard impulse, test strength transformers designated as "basic insulation level" or BIL. The basic insulation level is defined to be the lowest voltage of one of the standard voltage strengths available that will not be exceeded at any transformer location in the network. All equipment at a given location has a common level of surge-voltage withstand rating.

In selecting the basic insulation level, consideration must be given to other protection devices incorporated into the system. As an example, when a spark gap flashes over, the sudden interruption of the current in the traveling wave causes the voltage difference between phase end-turns to be extremely high (Ref. 14). When a circuit breaker opens a heavy fault current, the arc may restrike at the next voltage peak by reason of the "trapped charge" on the network. This subjects the system to a crest voltage of double the original value. This can repeat several times and result in six times the crest voltage to appear at the transformer terminal. Modern high-speed breakers usually open quickly enough to limit this value to 2.5 times the normal value (Ref. 14).

The use of fans blowing on the cooling fins can increase the load that can be carried by nearly 100%. The design of the cooling of the transformer greatly influences this figure. Pole-top-type transformers never use forced air cooling because ambient cooling is available in the atmosphere. Transformers in confined spaces are limited in ability to carry load in direct relation to the ambient temperature of the confined space. Forced ventilation can partially eliminate this derating of transformers in these confined installations.

Transformers in high altitudes must be derated in proportion to the rarity of the atmosphere available for cooling. A compensating effect is the cooler temperature at the higher altitude.

Pole-mounted transformers are hung on the poles on a bracket for easy installation or replacement. The mounting position of the bracket on the pole is usually at right angles to the direction of the overhead conductors. The transformer must be placed on the pole with other equipment so that the following conditions are satisfied:

1. Adequate clearance must exist between the energized conductors associated with the transformer, lightning arrestor, fuse, switchgear, etc., and grounded objects, such as the transformer case, guy wires, and the lightning arrestor ground connection.

2. Blast direction of fuses and cutouts must not be directed toward live equipment, such as phase wires, transformer bushings, and lightning arrestors.

The location of transformers on pads and trailer mountings relative to the other associated equipment—switches, breakers, fuses, and lightning arrestors—should allow easy accessibility for replacement and repair and should provide adequate spacing for the safety of personnel.

A primary transformer (transmission to distribution primary) usually is connected to the transmission system through a disconnect and a circuit breaker. Between the breaker and the transformer a lightning arrestor is connected to the phase wire and ground. The voltage drop in the lightning arrestor ground load and the earth resistance produced by an impulse current will cause the line voltage to be considerably higher than the lightning arrestor rating. For this reason, the lightning arrestor ground lead is connected to the transformer case. The other winding must be protected against high tank voltage by a protective gap. The voltage drop in the lightning arrestor ground lead is the reason for the relatively high impulse level of the low-voltage winding.

Secondary transformers (distribution primary to load voltage) are connected to the primary by external fuses to protect the line, not the transformer. In some transformer designs, an internal circuit breaker actuated by a bimetal strip is included.

At each transformer, a ground connection that has a resistance of not greater than 25 Ω must be provided. In addition, the neutral of the primary line must have at least four ground connections per mile (Ref. 2, Sections 96A2 and 96A3).

5-3.4 COMPATIBILITY AND INTEROPERABILITY

The parameters that describe a three-phase transformer bank are

1. Primary voltage
2. Secondary voltage
3. Internal connection: wye-wye, wye-delta, delta-delta
4. Polarity indication
5. Impedance
6. Taps
7. Number of windings (primary, secondary, and possibly tertiary).

Modern transformers are designed to operate near the knee of the iron magnetic-saturation curve and, therefore, are limited in the allowable overvoltage. To accommodate the variation of primary voltages encountered in field installations, taps are provided on the primary winding. In small installations these taps are preset before placing the bank in service. Large installations have transformers with the ability to change taps under load (TCUL). Taps are usually in the range of ±10%. Taps can be incorporated in the secondary winding and not the primary (see par. 5-4.4). Several secondary voltages are in common usage. The most common voltages are 120-240 V and 120-208 V. The 120-240 V combination results from a single-phase transformer with a center tap in the secondary winding or a three-phase, delta-connected secondary with one secondary provided with a center tap. The 120-208 V combination results from a wye-connected secondary with the 120 V obtained from a phase-to-neutral connection and the 208 V obtained from a phase-to-phase connection.

Polarity indications are usually designated as H1-H2 for the high-voltage winding and X1-X2 for the low-voltage winding. By definition H1 and X1 have the same polarity and are simultaneously positive. Dot polarity markings are also used. These polarity markings must be carefully considered in forming a three-phase bank out of three single-phase transformers.

The impedance of the transformers is important in the determination of voltage regulation, i.e., the change in terminal voltage caused by a change in load. Impedance is also important in the parallel operation of transformer banks. Transformers with different impedances will not share the load as intended.

Taps (ratios and phase angle) can be used to adjust the division of real and reactive power between banks operating in parallel.

Insofar as it is possible, the location and configuration of the high-voltage connection to transformers should be uniform for a given installation to enable ready replacement or exchange of equipment and for the safety of personnel.

Extreme care must be exercised in replacing a transformer bank, especially if the bank is operating in parallel with another bank.

Transformers having identical windings will provide higher voltage when connected in a wye configuration than they provide in a delta configuration. The wye-delta-connected transformer has a phase shift of 30 deg, whereas the wye-wye has no phase shift.

Transformer nameplates contain all the pertinent data that describe the transformer.

5-3.5 TEST CRITERIA FOR DESIGN AND ITEM ACCEPTANCE

Excessive loss will lead to heating of the transformer, which can lead to premature insulation failure. Loss testing is performed to insure that losses are within the design limits for the transformer.

Measurements of the load loss are made by connecting the high-side winding to an adjustable low-voltage source with the transformer low-side winding short circuited. The voltage of the source is adjusted until the current is equal to the rated high-side current. See Fig. 5-4 for the test setup.

Measurement of the load loss includes the loss in the voltage and the voltage coil of the wattmeter. The connection to the transformer is opened, and the wattmeter is read without adjusting the source voltage. (A separate source is essential for this test.) The losses in the meters must be subtracted from the original measurement to give the transformer load loss.

The measurement of no-load (iron) losses is made by using the meter connections shown in Fig. 5-5. The voltage of the source is adjusted until the average voltage

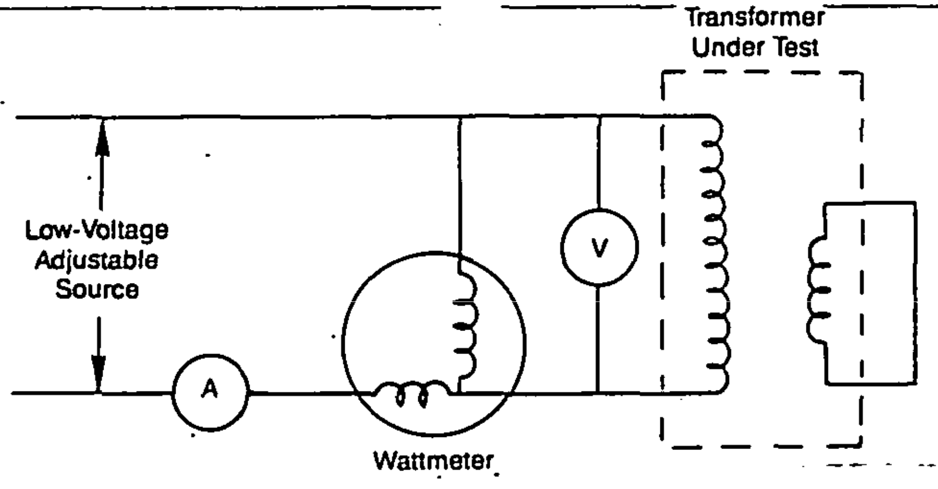


Figure 5-4. Transformer Load Loss Measurement Test Setup

meter AV reads 1.11 times the rated rms voltage. The wattmeter will record the total system losses including those in the wattmeter potential coil, the voltmeter, and the potential transformer, in addition to the iron loss in the test transformer. Corrections must be made to eliminate these losses. The details of the corrections and refinements are beyond the scope of this handbook but can be found in Ref. 15.

The turns ratio, the ratio of primary voltage to secondary voltage, is verified to insure that the transformer will deliver the desired voltage when connected to a primary distribution system of a specified voltage.

The voltage withstand test is conducted to insure that the transformer can withstand voltage impulses caused by lightning strikes on a distribution network. Even though lightning arrestors are generally mounted directly on the transformer, voltage spikes of thousands of volts will be induced by lightning. Permanent breakdown or temporary arcing induced by the lightning-induced transient could cause a fault that would interrupt the electrical service or, if the transformer were not properly grounded, could cause high voltages on exposed conductors. The voltage withstand test is conducted to determine whether the transformer can withstand transient voltages of a magnitude equal to the BIL rating of the transformer. In the test a transient voltage is applied to terminals of the transformer twice, once at a level well below the rating of the transformer and a second time at the desired testing level. Waveforms are recorded for both cases and compared. Failure of the test is indicated by a difference between the recorded waveform other than amplitude or by evidence of arcing. Details of the test procedure are given in ANSI C57.98 (Ref. 16).

Transformer winding resistance is measured to verify that there are no winding defects or internal connections that have a high resistance and would develop "hot spots" during operation. These measurements can be made with a Wheatstone or Kelvin bridge. Care must be taken in making the measurement to allow the transient caused by the inductance of the winding to die out before making the reading.

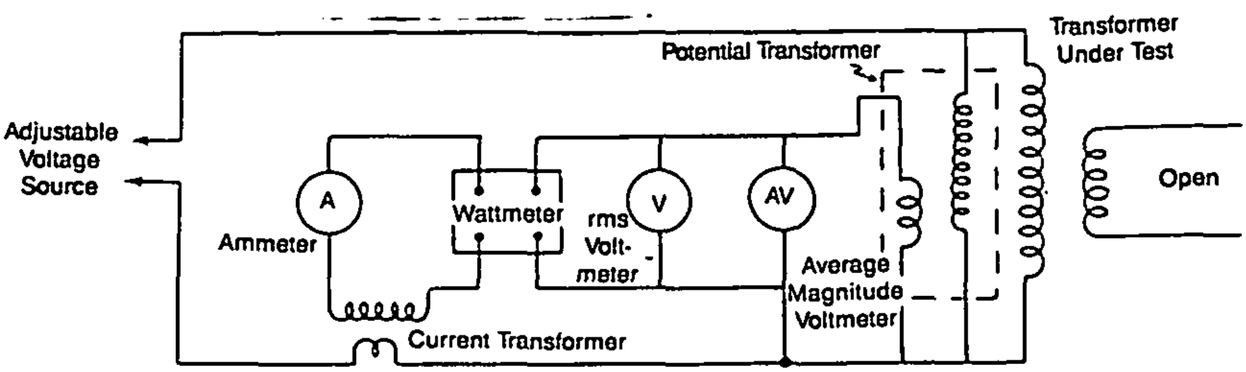


Figure 5-5. Transformer No-Load Loss Measurement Test Setup

5-3.6 OPERATIONAL CONSIDERATIONS

Although all transformers are tested in the factory, winding resistance and turns ratio should be verified before placing the transformer in service to insure against damage in shipment.

The ratio of a single-phase transformer can be measured by applying a small voltage, e.g., 120 V, to the high-voltage winding and reading the voltage of both windings with a high-impedance voltmeter (one having an impedance greater than 500 times the winding impedance).

The polarity of a single-distribution transformer in a radial distribution system is not important. The ratio and polarity tests of transformers are of prime importance, however, in installations that will operate in parallel with existing transformers or if the transformers are to be connected in delta configuration.

Before connecting a wye-delta transformer, a test must be made in polarity before closing the delta. Two corners of the delta are connected, leaving one corner unconnected as shown in Fig. 5-6. The wye connection is energized with a three-phase source, and the voltage is measured between A and B. If the voltage A-B is less than A-C, the delta may be closed even if the voltage A-B is nonzero. If $E_{AB} > E_{AC}$, one of the windings—either A-C, C-D, or B-D—must be reversed and the transformer retested.

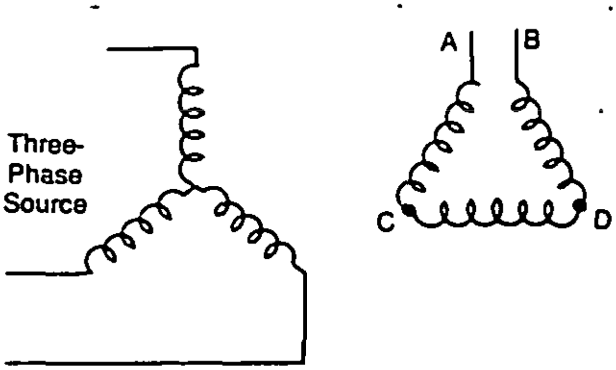


Figure 5-6. Polarity Test for a Delta-Connection Transformer

The three-phase polarity and phase sequence tests must be made if a new transformer bank is to be connected in parallel with an existing bank. There are many ways to connect the windings. Only a few connections are described to illustrate the procedure. The relationships between voltages are more clearly presented by vector diagrams in which the voltage magnitude is represented by the length of the vector and the phase is represented by the angular position. Note that arrowheads are unnecessary since the direction of a voltage is indicated by the labeling at each end.

Fig. 5-7 is a vector diagram of delta-delta bank voltages after terminals H_1 and x_1 have been tied together.

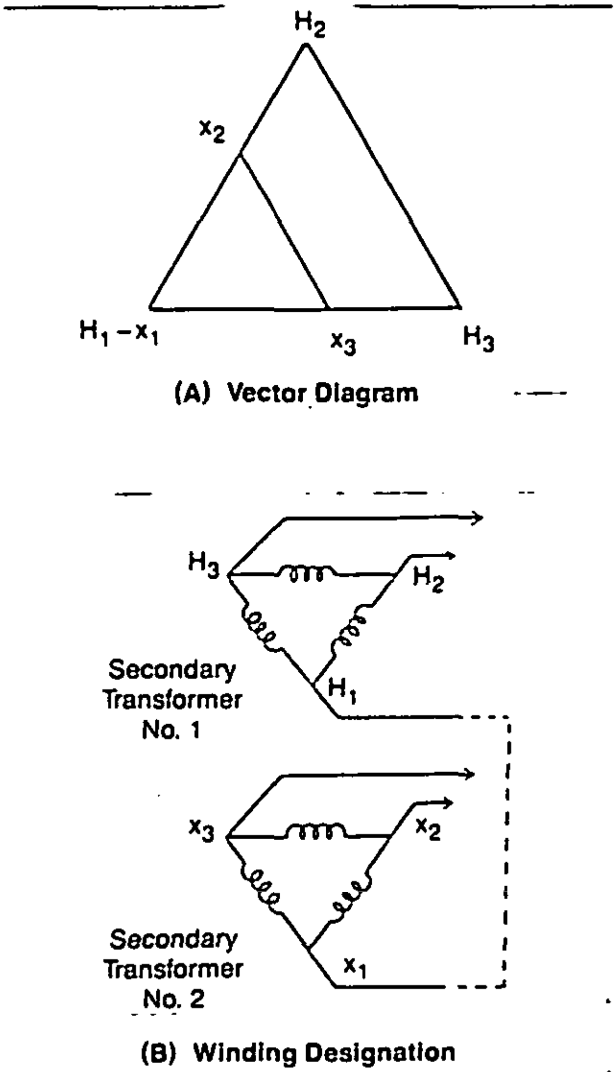


Figure 5-7. Vector Diagram of a Properly Connected Delta-Delta Bank

The conditions indicated by Eq. 5-4 must be satisfied before transformers may be connected in parallel.

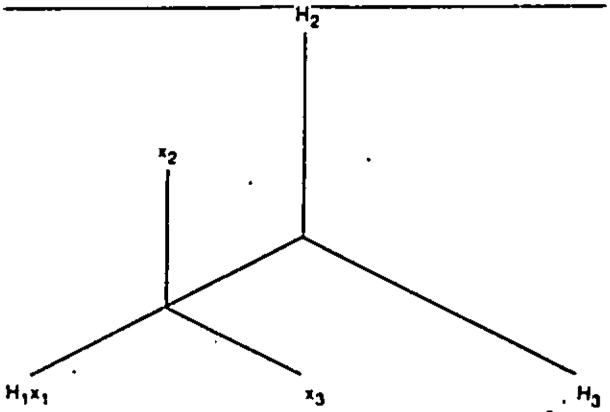
$$E_{H_1-H_3} > E_{H_3-x_2}, \text{ V}$$
$$E_{H_1-x_3} = E_{H_3-x_3}, \text{ V} \quad (5\text{-}4)$$

where

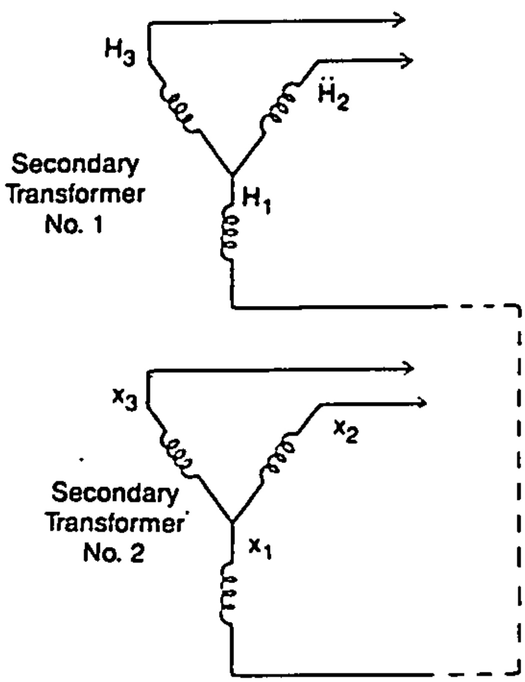
E_{i-j} = voltage measured between terminal i and j, V.

If these conditions are not satisfied, either one transformer is off ratio, connected backward, or both.

Fig. 5-8 is a vector diagram of a wye-wye-connected transformer bank after connecting H_1 and x_1. The condition indicated by Eq. 5-5 must be satisfied before the transformers may be connected in parallel.



(A) Vector Diagram



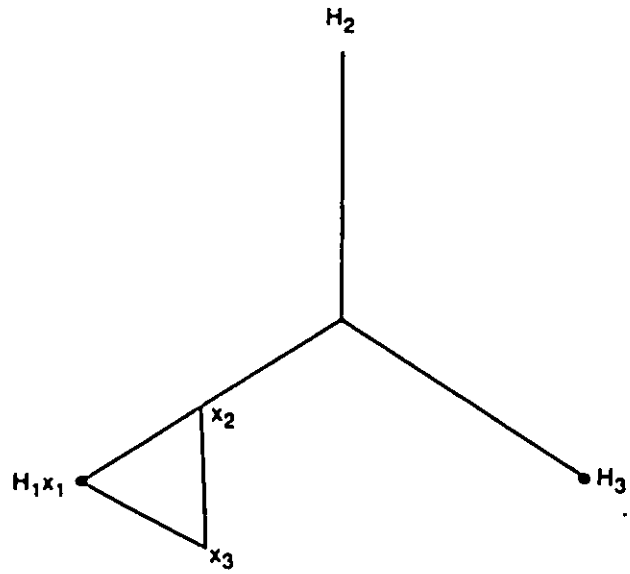
(B) Winding Designation

Figure 5-8. Vector Diagram of a Properly Connected Wye-Wye Transformer

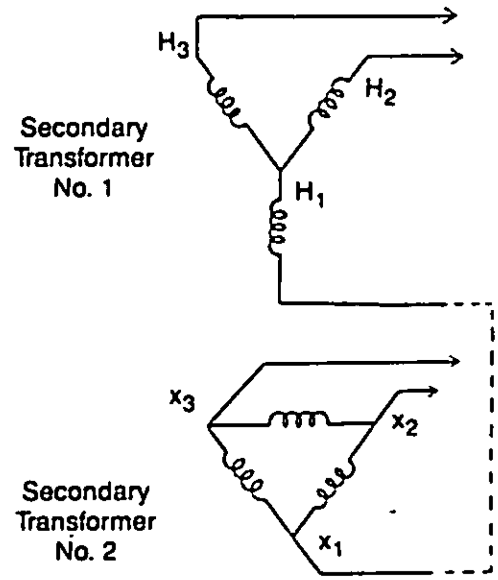
$$E_{H_3-x_1} = E_{H_1-x_3},\ \mathrm{V}$$
$$E_{H_1-H_3} > E_{H_3-x_3},\ \mathrm{V} \qquad (5\text{-}5)$$
$$E_{H_3-x_1} > E_{H_3-x_3},\ \mathrm{V}.$$

If these conditions are not satisfied, one transformer is off ratio, connected backward, or both.

A wye-delta transformer has an inherent phase shift of 30 deg. The vector diagram of a properly connected transformer after H_1 and x_1 have been connected together is given in Fig. 5-9. The conditions indicated by Eq. 5-6 must be satisfied.



(A) Vector Diagram



(B) Winding Designation

Figure 5-9. Vector Diagram of a Properly Connected Wye-Delta Transformer

$$
\begin{aligned}
E_{H_1-X_2} &= E_{H_1-X_1}, \text{ V} \\
E_{H_1-H_2} &> E_{H_1-X_2}, \text{ V} \\
E_{H_2-H_1} &> E_{H_2-X_2}, \text{ V} \\
E_{H_1-H_2} &> E_{H_2-X_2}, \text{ V}.
\end{aligned} \qquad (5\text{-}6)
$$

If these conditions are not satisfied, the transformer bank is improperly connected, one transformer is off ratio, or both are off ratio and backward.

A properly designed and constructed transformer should last 30 yr or longer if it is not abused by being consistently overloaded. Overloading causes (1) the oil to break down and produces acids that attack the insulation and (2) sludging that clogs oil circulation passages and reduces the cooling capability.

The cost of complete maintenance of all transformers, e.g., pole top, is not economically justified because the cost over a 30-yr period would be much greater than the replacement of the small number of unmaintained transformers that would fail.

Larger transformers should be tested periodically for the dielectric strength of the oil, dissolved moisture (which should be less than 80 parts per million (ppm)), and acidity (which should be less than that which can be neutralized of 0.2 mg of potassium hydroxide (KOH)). Other tests check amounts of dissolved oxygen and copper salts in the oil. Transformers can continue to operate for long periods of time with oil that has deteriorated far beyond test guidelines. An economic assessment weighs the costs of maintenance, i.e., replacing the oil, against the expected increase in service life of the transformer.

Transformers also should be inspected at regular intervals for deterioration of paint on the tank, bushings, seals, connections, etc.

If the oil in the transformer contains polychlorinated biphenyl (PCB), regular inspections for leaks are required. If the transformer is located where leaks could possibly contaminate foodstuffs, the transformer must be moved, replaced, or converted to a non-PCB-filled unit. Conversion of PCB-filled units to non-PCB involves flushing the transformer periodically until the PCB concentration in the transformer is expected to remain below 50 parts per billion (ppb). However, periodic filtering of the transformer oil will probably be necessary to maintain the PCB concentration below that level. Periodic chemical analysis of the oil is required to monitor the PCB concentration in all transformers that have used PCB-based oil (Ref. 17).

5-4 POWER CONDITIONERS

5-4.1 INTRODUCTION

Power conditioners include a wide variety of devices that modify one or more of the variables that describe the voltage of a source or a load. Magnitude, phase angle, frequency, power-factor correction, and constancy of the voltage are some of the attributes that are controlled by power conditioners. Various conditioning devices are presented in the paragraphs that follow.

5-4.1.1 Transformers

The input winding of a transformer is connected to an AC source of power at one voltage, and it delivers power to a load at a different (or the same) voltage. The frequency of the voltage is unchanged by the transformer. Tap-changing transformers are used to regulate the output voltage ±10%. Transformers can also be used to shift the phase of AC power. A wye-wye- or delta-delta-connected three-phase transformer has no phase shift between the primary and secondary voltages. A shift of 30 deg can be produced by a simple three-phase bank by connecting it in a wye-delta or a delta-wye arrangement. Specially built transformers can shift the phase angle in small steps through a range of values. (See Fig. 5-10.) Note that windings A and A′ are wound on the same core as are B and B′ and C and C′.

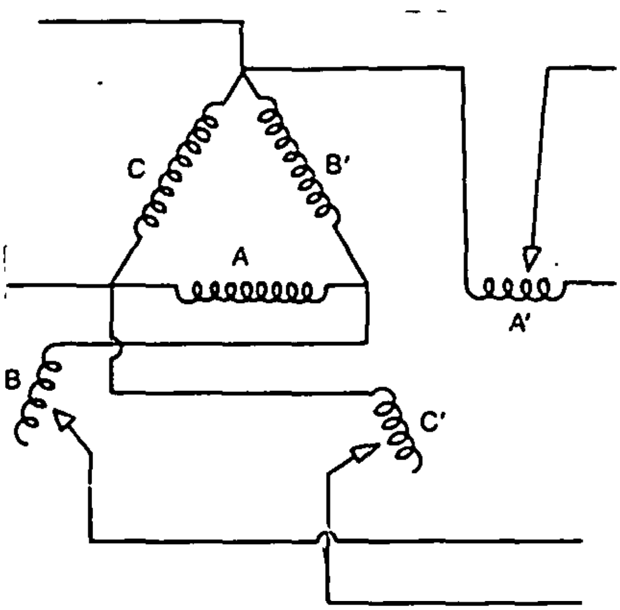


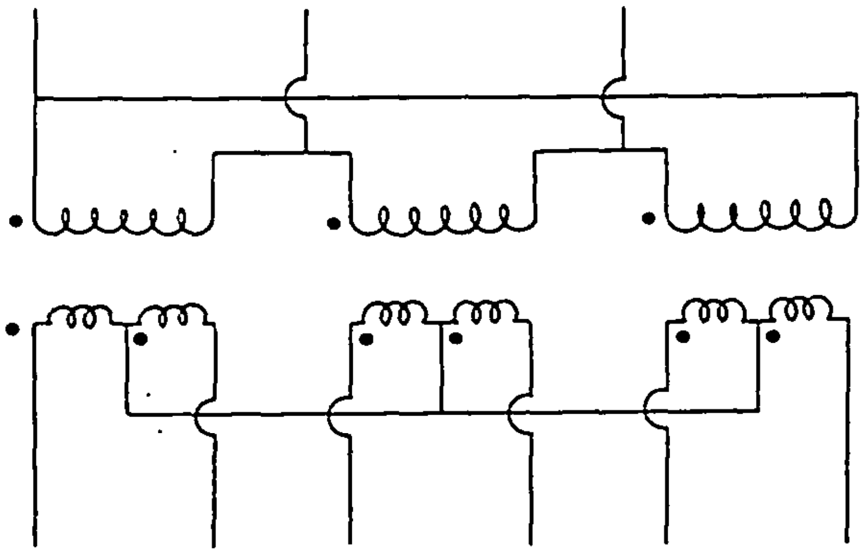
Figure 5-10. Phase-Shifting Transformer

In some applications requiring DC, rectifiers are used. The ripple in the DC output is reduced if the source is six-phase rather than three-phase. Transformers can be connected to make the change of three-phase to six-phase. (See Fig. 5-11.)

The transformer is an extremely simple device with no moving parts, but the connection can be extremely complex.

5-4.1.2 Motor-Generators

Motor-generator sets have several applications. Certain loads are extremely sensitive to voltage fluctuations



Note: Winding polarity is indicated by dots.

Figure 5-11. Three-Phase to Six-Phase Transformer

of the source; digital equipment is an example. A motor-generator set can be used as a buffer between the source and the load. Except in very severe voltage disturbances, the motor is unaffected and the voltage of the generator remains constant.

Certain applications require a frequency different from the available source. The source voltage is rectified by a rectifier or motor-generator set. The DC is then used to drive an inverter or a DC motor of a motor-generator set. The AC frequency output of the inverter or generator can be varied over a wide range by changing the switching rate of the inverter or the speed of the DC motor.

5-4.1.3 Power-Factor Correction Capacitors

Capacitor banks or synchronous condensers are used for power-factor correction of a load. Overloads on distribution lines resulting from low power-factor loads can be relieved by connecting power-factor correcting capacitors across the load. Low voltage at the end of moderately long distribution lines can be reduced by adding capacitors at the load end of the line. Extremely long lines, near a quarter wavelength in length, are aggravated by the addition of capacitors. This is not a consideration unless the frequency of transmission is high.

5-4.1.4 Rectifiers

Rectifiers are used to convert AC power to DC. A transformer is used if voltage conversion is necessary to step the source voltage up or down. The rectifier filter circuit furnishes the desired DC voltage. Account must be taken of the average value, root-mean-square, and maximum value of a sine wave voltage in selecting the transformer ratio to be used in this installation, as indicated by Eqs. 5-7 and 5-8.

For half-wave rectifiers

$$E_{DC} = 0.45\ E_{rms},\ \text{V} \qquad (5\text{-}7)$$

and for full-wave rectifiers

$$E_{DC} = 0.9\ E_{rms},\ \text{V} \qquad (5\text{-}8)$$

where

E_{DC} = DC output voltage of rectifier, V
E_{rms} = rms voltage input to rectifier, V.

5-4.1.5 Voltage Regulators

Voltage regulators take several different forms. Tap-changing transformers are used in conjunction with larger transformer banks. In motor-generator sets, silicon-controlled rectifiers (SCR) are used to control output voltage. Other methods of control include saturable reactors and ferroresonant transformers.

5-4.2 INDUCED ENVIRONMENT

Motor-generator sets have rotating parts; transformers have no moving parts. Motor-generator sets will raise the ambient temperature more than a transformer of equal capability. The losses in the motor and the generator are much higher than in a transformer because of frictional losses and windage, in addition to the iron and copper losses.

The noise of a motor-generator set, although much less than an engine-driven-generator set, is much greater than the magnetostriction noise produced by a transformer.

Capacitor banks create virtually no heat or noise. During normal operation, their presence has very little effect on the environment.

Mercury arc rectifiers produce noise and ultraviolet light from the arc discharge, whereas dry-type rectifiers generally have no environmental effects other than heating.

5-4.3 HAZARDS

Power conditioners have hazards associated with their operation in addition to the high-voltage hazard that they share with distribution transformers.

Since motor-generators have rotating parts, the couplings between motor and generator, if exposed, are especially hazardous to personnel. The sparking of the commutator and collector-ring brushes can provide a source of ignition of combustible vapors from lubricants or other volatile materials. Motors must be protected against a low supply voltage that might cause the motor to stall, overheat, and cause a fire.

Capacitors have a fairly high failure rate compared to the expected life of a transformer. A failure may result in tank damage or an oil spill. Banks must be protected by a fuse or cutout that will blow in case of failure. Capacitors have the additional hazard of retaining a charge after they have been disconnected and momentarily shorted. The shorting device must be left in place for a considerable length of time during any associated maintenance work.

5-4.4 DESIGN CONSIDERATIONS

Motor-generator sets have the hazard of the rotating coupling between the units. Consequently, they should be installed so that no rotating parts are exposed. Means must be provided to prevent start-up of a set when maintenance personnel are working on the unit—e.g., brush replacement, coupling inspection, or maintenance.

In the design of an automatic tap-changing voltage-regulator installation, the sensing device must have a larger deadband, i.e., the magnitude of the error permitted before the tap-changing action is initiated, than the magnitude of adjustment steps; otherwise, "hunting" action will result.

Solid-state regulators provide accurate regulation of voltage by varying the fraction of time that the input waveform is passed to the output using SCRs to perform the switching. The sensitive control system required for precise regulation necessarily includes high-gain components that are potentially unstable. These regulators must include filters to prevent line transients from affecting the switching of the SCRs and to prevent interference generated by the switching from reaching sensitive electronic apparatus.

Tap-changing transformers consist of a transformer with a tapped primary, a tapped secondary, or tapped primary and secondary. An internal switch facilitates the changing of taps. Tap changing can be designed to change at no-load or to change while carrying load. In the first case, the tap changer must be removed from service, and the tap connections are made manually. In the second case, the tap changing is accomplished by internal switches that must be able to carry full-load current.

In load tap-changing transformers, two taps are bridged during tap changing. In Europe the two tapping switches are bridged with a resistor. Tap changing must be very rapid to avoid overheating the resistor. Failure of one of the switches could burn open the resistor, vaporize the oil, and possibly cause an explosion and fire. In the United States, a reactor—a closely coupled autotransformer with two equal windings—is used to bridge the two contacts during tap changing. This method is more expensive but safer. The reactor is designed to saturate when a voltage slightly higher than the voltage between the taps is impressed on it. This limits the surge voltage induced during tap changing to very little more than the tap-to-tap voltage (on the order of 2.5%). The tap changer requires two switch contacts and a bridging reactor, which operate in the sequence shown in Fig. 5-12 to switch between taps safely without introducing transients on the line. An air gap is introduced in the iron core of the reactor to further limit the peak voltage of the surge introduced when taps are changed.

All tap-changing transformers must be installed with adequate clearance to insure the safety of personnel involved in their routine activities. All compartments of the control mechanism must remain closed when the changer is in-service except for inspection ports for use by trained personnel. The tap changer contains oil and incorporates switching devices and must be segregated from other equipment to limit damage from possible explosion or fire (Ref. 2, Section 172 and Section 180 B1).

Capacitors must discharge to 30 V or less within 2 s per Ref. 18. If filters are used, automatic capacitor discharge devices such as bleeder resistors should be used.

5-4.5 COMPATIBILITY AND INTEROPERABILITY

5-4.5.1 Transformer

Transformer banks can be built from single-phase transformers connected in wye-wye, wye-delta, or delta-delta configurations. The bank has a primary and a secondary winding and can also include a tertiary. If a three-phase bank, or connection of three single-phase transformers, is to be used as a replacement in a system where another transformer is operating in parallel, the replacement must agree in every detail—kVA rating; primary, secondary, and tertiary voltages; winding voltage; transformer connection; tap changer settings; and phase-shifting taps. If the transformer is not operating in parallel, it must have the same kVA rating, voltage ratings, and tap connections as the transformer being replaced.

5-4.5.2 Motor-Generators

Motor-generator sets have ratings of both the motor and the generator. These ratings include the motor (hp or kVA); DC, single-, or three-phase; voltage; speed; maximum line current; and power factor (AC motors only).

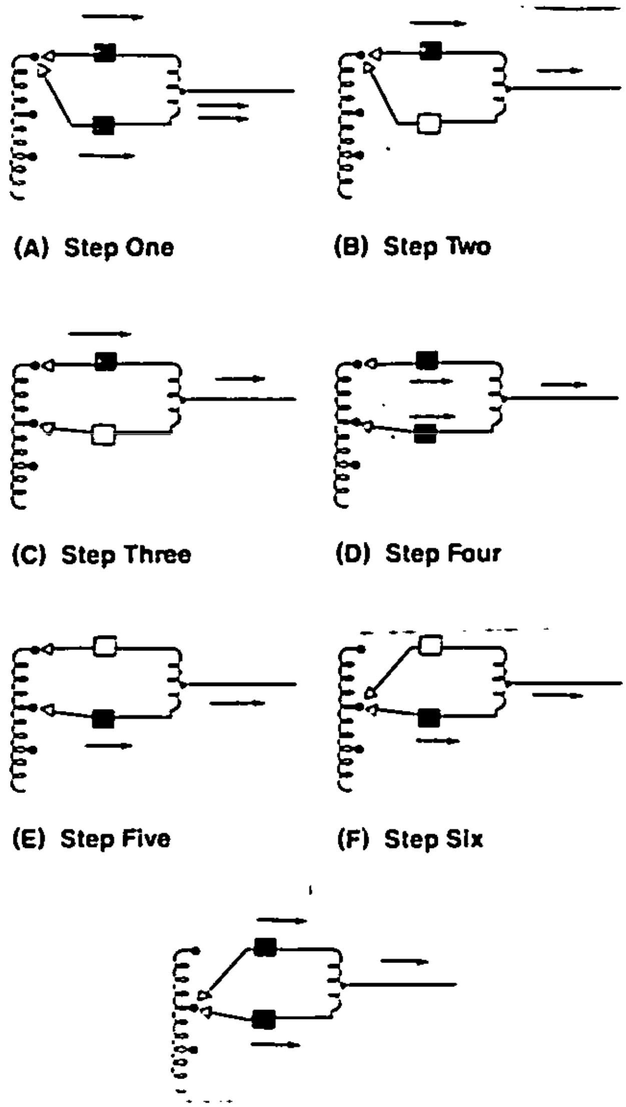


Figure 5-12. The Seven Steps Required to Transfer From Between Taps on a Transformer

Generators are rated DC, AC single- or three-phase, AC frequency, kVA, voltage, and current.

A replacement set must duplicate the intended purpose of the set—i.e., AC to DC, AC to AC, DC to DC, or DC to AC. The motor input voltage must be the same. The motor speed, single- or three-phase (if AC), and the rating must be at least equal to the rating of the original set. The generator output must be at the same voltage level, frequency, and single- or three-phase if AC. (A DC generator has a zero frequency.)

5-4.5.3 Capacitor Banks

Capacitor banks are rated as to kV and kVAR. Replacements should duplicate the original installation.

5-4.5.4 Rectifiers

Rectifiers are rated as to kVA, AC voltage input, single- or three-phase, and DC output voltage. Replacements should duplicate the original installation.

5-4.5.5 Voltage Regulators

Voltage regulators may include tap changers or SCR devices. The ratings include input voltage and percent regulation. Tap changers must carry the load current. SCR regulators control some auxiliary device that regulates the output voltage, e.g., the DC-exciter voltage of an AC generator. The rating of the SCR can be small compared to the capability of the device it is controlling.

The output waveform of voltage regulators must be compatible with the load. Certain SCR voltage regulators and ferroresonant regulators may generate excessive harmonics, which may damage or interfere with susceptible loads.

5-4.6 TEST CRITERIA FOR DESIGN AND ITEM ACCEPTANCE

Complete specifications for acceptance tests of the various pieces of equipment are detailed in various ANSI, IEEE, NEMA, and UL publications. The tests are too voluminous to reproduce here; however, equipment features that should be tested to assure safe operation are

1. Insulation must withstand rated low-frequency and surge test voltages without flashover or puncture.
2. The device must carry fully rated current without exceeding the permitted temperature rise above the ambient temperature.
3. The voltage regulation, i.e., amount of voltage drop at the terminals when the device (generator) is carrying full load, must not exceed the allowable percentage.
4. Capacitor banks must deliver the rated kVAR when energized at the rated voltage.
5. The deadband of automatic tap changers should be greater than the step size of the taps to prevent excessive tap changing during operation.
6. The feedback within an SCR controller should be negative and have a ramp rate that will not produce instability.

5-4.7 OPERATIONAL PRECAUTIONS

Operations that should be given in documentation of the system for various power conditions will necessarily depend on the principle of operation of the power conditioner since the hazards to be avoided will vary between types. For all types clear specifications—including procedures for checking phase balance and rotation if required for motor-driven conditioners and any external circuit protection that should be provided for the equipment—should be provided for connection to the power system.

For rotating components that contain brushes, cautions should be specified for the installation of the unit in flammable or explosive atmospheres. If shielding of rotating components is not provided by the physical design (as it should be), the specification of enclosures or guards should be given. Procedures for checking alignment and balance of rotational equipment should be described for equipment using separate motors and generators since out-of-alignment operation can lead to excessive vibration or premature bearing failure. Cleaning procedures should be described because machinery must be kept clean to permit proper cooling; however, equipment may be damaged if improper cleaning agents are used. Water-based cleaners may create undesired conductive paths, and oil-based products may deteriorate certain insulations. Acceptable cleaning agents should be specified.

Power conditioners using solid-state components—e.g., semiconductor devices, ferroresonant transformers, and filter components—should be mounted in locations where heat may be dissipated through convective cooling. These installation considerations should be specified in the instructions provided for the unit. If necessary, warnings should be given against mounting the unit near sources of heat, in locations where precipitation on the equipment is possible, or in sunlight.

For equipment using capacitors that may remain charged after equipment is disconnected, operational instructions should specify procedures for the safe discharge of capacitors.

5-5 UNINTERRUPTIBLE POWER SUPPLIES

5-5.1 INTRODUCTION

Uninterruptible power supplies (UPS) are used where power interruptions cannot be tolerated. Possible applications include computer applications, hospital operating room lighting, hallways, and exit lights associated with auditoriums or places of assembly. Only battery-operated installations will be discussed in this paragraph, although other uninterruptible supplies are available—such as the motor-generator that uses the rotational inertia of the armature to supply energy for the period between the loss of the primary power and the time when a standby engine-driven-generator set can be brought on-line.

5-5.2 INDUCED ENVIRONMENT

Lead-acid batteries introduce sulphuric acid liquid and fumes into the environment. Charging the batteries produces hydrogen and oxygen gases. The exhaust from the necessary ventilation of the battery storage space can contaminate adjacent equipment space with the corrosive sulfuric acid vapor.

5-5.3 HAZARDS

During charging of lead-acid batteries, hydrogen and oxygen gases are generated. If ventilation is inadequate, the atmosphere of the confined space can reach an explosive mixture. No smoking in battery rooms should be permitted because of the possibility of an explosion.

Adding distilled water to batteries and testing the specific gravity of the electrolyte exposes personnel to the extremely corrosive action of the liquid and fumes. Provision for neutralizing the acid on skin or in eyes must be instantly available—even complete shower equipment should be provided for serious accident cases.

During accidental short circuiting of batteries, extreme bubbling can occur, which will throw acid droplets into the atmosphere. The action during a short circuit can be sufficiently violent to rupture the battery cases. Lithium chemistry batteries require special design, use, and handling considerations.

Failure of an uninterruptible power supply may lead to an unanticipated loss of power to equipment whose failure could result in injury, loss, or, in severe cases, death. Critical loads powered by uninterruptible power supplies include hospital life-support systems and large computer systems.

5-5.4 DESIGN CONSIDERATIONS

The requirement for speed of response generally establishes whether transfer switches may be used in a configuration like that depicted in Fig. 3-6(A)—except with a response inverter replacing the engine-driven-generator set—or whether the power must be supplied continuously from the same source as shown in Fig. 3-6(B). The latter case is necessary if severe phase discontinuities cannot be tolerated (motor loads) and if even transient power outages cannot be tolerated. If power outages of short duration (lasting for few line frequency cycles) cannot be tolerated, switches can be used to transfer the load from the normal source to a quick-starting source, such as a solid-state inverter. Where continuous operation is required, either a continuously running inverter must be used, or an AC motor, a DC motor, and a generator having a common armature shaft must be used. As long as power is available, the generator is turned by the AC motor. Upon interruption, the rotation of the generator is maintained by the DC motor powered by batteries, which were charged by the line when it was operational.

When an interruption in service of the main source occurs and the UPS is activated, the transfer must be designed so that there can be no conflict between the two sources. For lighting circuits the safest approach is to use two sets of lighting—one set operated by the line and a separate set of lower capacity, battery-powered lights that are energized upon loss of power. If transfer switches are used, attention must be given to the timing of the transfers. Considerations for switching motor loads are given in par. 3-3.2.1.

Relaying and system protection must be carefully studied. The use of a UPS should not be attempted to keep alive a portion of a system that has been deenergized due to a phase-to-ground fault. Further damage could be done to the system and the UPS equipment by closing in on a short circuit. Also the UPS equipment usually must be grounded. If the UPS ground connection introduces an alternative path for neutral currents, the ground fault protective devices of the system may not function. Interconnection of UPS with existing power distribution requires careful evaluation of the grounding scheme for safety and adherence to local codes. (See par. 3-3.4.3.4.)

5-5.5 COMPATIBILITY AND INTEROPERABILITY

The characteristics—type, class, category, and level—of a UPS are defined in par. 1-3.1.2.3. For compatibility, i.e., the ability to replace another system, the replacement systems must have

1. A type indicating the same or a longer operational period
2. A class indicating the same or a faster response time
3. The same category
4. The same level of reliability.

Also the waveform quality of the UPS must be equal to or better than the one it is to replace, e.g., systems with an output waveform that only approximates a sine wave—stepped or square wave waveform. UPS systems with a stepped or square wave waveform are not generally compatible replacements for sine wave output UPS systems.

Interoperability is not usually a critical issue with UPS systems since they typically do not operate in parallel; rather, they drive loads individually.

5-5.6 TEST CRITERIA FOR DESIGN AND ITEM ACCEPTANCE

Batteries used for emergency lighting should have a guaranteed discharge rate and ampere-hour rating sufficient to handle the expected load for the length of time required to restore the normal supply or the time required to place in service generators used for backup in an emergency.

Battery-driven motor-generator sets used to supply crucial AC-operated equipment should have a generator voltage with a kVA rating sufficient to supply the load for the expected lengths of time. The motor must have a voltage rating compatible with the batteries and a power rating sufficient to drive the generator. The automatic start-up equipment should be matched to the motor. The start-up of the set should be tested, but the ratings of the motor and generator will be taken as being correct. The batteries must have the voltage and ampere-hour rating required. Testing the batteries is hardly practical.

To be worthwhile, the UPS should have a reliability of an order of magnitude greater than the normal source of supply.

Testing of the UPS is done through the testing of individual components prior to installation and by manually interrupting the primary service after the system is installed.

5-5.7 OPERATIONAL PRECAUTIONS

Battery rooms are to be accessible only to qualified personnel. Rooms containing lead-acid batteries must be well ventilated to reduce the exposure of personnel to the corrosive fumes of the battery. The ventilation system must not exhaust in a direction that will have a deleterious effect on other equipment in the total installation. During charging of the batteries, hydrogen is emitted. Ventilation must be adequate to prevent a combustible mixture of hydrogen in the atmosphere in the battery room. Smoking is prohibited in these rooms.

Batteries should be mounted in metal racks or frames anchored to the floor. However, anchoring to both the floor and walls is not recommended. Adequate spacing should be provided for inspection and for maintenance and testing, and there should be adequate headroom for lifting equipment to remove and replace battery cells.

Safety equipment should include

1. Goggles or face shields
2. Acid-resistant gloves
3. Protective aprons and overshoes
4. Portable or stationary water supply for rinsing skin and eyes
5. Neutralizing agent.

5-6 SWITCHGEAR

5-6.1 INTRODUCTION

Switchgear equipment is used to connect or disconnect energy sources or loads in distribution networks in case of trouble or for maintenance, repair, or control. Certain switchgear operates automatically when a short circuit occurs in the sytem; circuit breakers are actuated by relays or by a fuse that blows when a certain current value is exceeded. Other switching devices (disconnects) are operated manually and are incapable of interrupting current. Switchgear is discussed in great detail in Chapter 6.

5-6.2 INDUCED ENVIRONMENT

In addition to the presence of high voltage on the bushings of oil circuit breakers, switchgear introduces oil into the environment and introduces the associated hazards of oil spills and fire. Arcing in open-air, low-voltage (600 V) switchgear operated under load or fault conditions may generate intense heat and light that could affect nearby personnel and equipment. Certain fuses and cutouts blow with explosive force. The area around high-voltage switches is extremely hazardous because of the intense heat, molten metal, intense light, and loud noise associated with the arc. Every precaution should be taken to make the area inaccessible to unauthorized personnel, and authorized personnel must take every precaution possible in performing any type of work in these areas.

5-6.3 HAZARDS

The hazards associated with switchgear used with distribution systems include

1. Electric shock from current-carrying parts that were thought to be dead but are alive through back feed or through static or electromagnetic induction
2. Mechanical shock resulting from a breaker opening under stress (short-circuit clearing)
3. Air breakers opening with an arc in open air
4. Rupture of the tank of an oil circuit breaker with the possibility of an oil fire

5. Operating error in manually opening a disconnect that is carrying a load with the sustained arc spreading to other equipment

6. Improper procedure in replacing a fuse that has blown on a permanent fault operator in the line of the blast.

5-6.4 DESIGN CONSIDERATIONS

Air breakers (600 V) that break the arc in air must be located high enough on the vertical panelboard to pose no hazard to personnel by the arc resulting from a switch opening. No other equipment should be mounted on the board above the breaker because of the possibility of arc damage.

Oil breakers in open yards must be located far enough from the fence to prevent contact with the high-voltage bushing by a wire or other material poked through the fence by unauthorized persons. This will also guarantee sufficient clearance for maintenance and operating personnel to perform their duties safely. The space horizontally between the breaker and other equipment shall be not less than 3 m (10 ft) in open yards or 7.6 m (25 ft) in a confined space. (See Ref. 2, Code 172 and 180 B1.)

Enclosed switch rooms must have at least two exits.

5-6.5 COMPATIBILITY AND INTEROPERABILITY

Specified characteristics include capacity (kVA rating), interrupting time (cycles), and BIL (volts). An evaluation of the maximum kVA to be interrupted and the surge voltage level encountered in a particular system provides an adequate basis for defining the switch characteristics. Replacements should be made only with equipment that has equal or greater ratings. Disconnects have a current-carrying capability and a BIL rating; they are not designed to break load current or fault current and must be replaced by equipment with an equal or higher capacity.

Since the blowing times of fuses are coordinated in an installation, replacements must be made with the identical fuses that were installed in the original design. Also time-current curves of fuses must be duplicated.

5-6.6 TEST CRITERIA FOR DESIGN AND ITEM ACCEPTANCE

A thorough fault study of a network must be made in which the total fault at each junction point is obtained for three-phase and single-phase faults. The flow in the lines connected to the fault location must be determined; however, a radial system does not need this detail because there is no flow in lines beyond the fault location. These data must be used in coordinating the selection of fuses and switches.

Manufacturers' data must be accepted for time-current curves of fuses because testing is impractical.

Each type of breaker should be tested for its interruption ability at rated kVA and kV. The equipment should also be subjected to a standard impulse test of the rating of the equipment.

Disconnects should be tested at rated current to verify that they do not overheat when carrying full load.

Further test details are given in Chapter 6.

5-6.7 OPERATIONAL PRECAUTIONS

Routine inspection of air circuit breakers that are in-service must be done with the knowledge that the breaker may be called upon to operate at anytime. The arc in open air that takes place on opening is a real hazard, and extreme caution must be used to avoid burns and eye damage. Maintenance on this switchgear must be undertaken only with the switch out of service, i.e., isolated by disconnects and grounded. No flammable material should be left in close proximity to the arc contacts.

Disconnects that are not interlocked with the breaker to which they are connected—to prevent opening load current—must have ample signs to warn against operating the disconnect unless the breaker is open.

Work on oil circuit breakers must not be done unless their disconnects are open. The initial step is that a ground connection of ample ampacity must be connected first to ground and then to the breaker. An external jumper must then be connected between the two high-side bushings of the break. At completion of the work, the safety precautions are removed in reverse order—first the jumper, then the ground from the breaker, and finally the ground from the ground. The breaker must be opened before the disconnects are closed, and finally, the breaker is closed.

Similar procedures are required with metal-clad breakers. First, open the breaker, unrack it (This is equivalent to opening the disconnects.), and ground the breaker. Restoration of service requires verification that the ground has been removed and that the breaker is open before the switch is racked into position. Interlocks should be incorporated to prevent inadvertent insertion of high-voltage switchgear while the switch is closed. Finally, the breaker is closed.

During actual operation of the open switch, especially opening of switches, the operator should exercise extreme caution in the event that the current being switched is greater than expected. For disconnects unloaded switches should be opened by using an "inching" technique, whereby the switches are opened slowly. If a large arc results because of the presence of load current, then the switch is reclosed immediately until the load can be removed. Note that this technique is not applicable to load-breaking switches because of the resulting arc. Appropriate protective clothing should be worn, including rubber gloves, protective head covering, eye protection, and a coat to protect individuals from the hazards associated with arcing. The operation of switchgear is discussed more thoroughly in par. 6-7.

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CHAPTER 6

SWITCHING SYSTEMS

In all electrical distribution systems, switching systems are necessary for the removal of power to allow system maintenance on load control. Several general safety considerations associated with switching gear are discussed in this chapter. First, switchgear components are described briefly, and the ratings that determine their suitability for specific applications are identified. Environmental effects of operating switchgear are discussed to include arcing and mechanical shock; the safety hazards associated with these effects are identified. Safety considerations for switchgear design are discussed, especially switch access and arc extinction and suppression. Compatibility and interoperability of switchgear are discussed, as well as tests that are typically performed on switchgear. Finally, safety considerations in installing, maintaining, and operating switchgear are discussed.

6-0 LIST OF SYMBOLS

e = 2.71828, base of natural logarithm, dimensionless
I = instantaneous current, A
I_{max} = maximum fault current, A
L = inductance of line and fault, H
t = time, s
R = resistance of the combination of the line and fault, Ω
V = voltage between line and ground, V
V_{max} = maximum fault voltage, V
$|Z| = \sqrt{R^2+(\omega L)^2}$, magnitude of the Thevenin impedance between source and fault, Ω
α = phase angle of line at time of fault, rad
$\theta = \mathrm{Tan}^{-1}(\omega L/R)$, rad
ω = radian frequency of line, rad/s

6-1 INTRODUCTION

Stated generally, the term switchgear refers to "switching and interrupting devices and their combination with associated control, instrumentation, metering, protective and regulating devices" (Ref. 1). Switching equipment used in electrical distribution networks takes several different forms. Fused cutouts use fuses to interrupt current automatically when the current values reach predetermined levels. Circuit breakers interrupt the current by mechanically separating current-carrying contacts—either in response to a detected overload condition or as a result of manual activation. Manually controlled switching is effected by the use of disconnects in circuits not carrying full-load current and by cutouts in circuits carrying full-load current. Cutouts interrupt current flow either by fuse action or by mechanical separation of contacts.

6-1.1 APPLICATION OF SWITCHING SYSTEMS

Switchgear is used for various purposes including

1. Reconfiguration of power distribution systems to provide power to loads from an alternate source or through an alternate route
2. Control of the current flow to a load
3. Isolation of sections in a distribution system for maintenance and repair
4. Interruption of current flow during a fault condition.

6-1.2 SWITCHING COMPONENTS

Normally, switchgear consists of components that can alternately interrupt and reconnect circuits through the mechanical movement of electrical contacts, although fuses are often incorporated into the unit to provide the capability for interrupting full-load current. Most commonly encountered switchgear components are cutouts, disconnects, and circuit breakers. Each is discussed.

Cutouts are disconnecting switches that are opened or closed manually by operating personnel by means of insulated poles. Usually, a fuse is part of the switch blade to provide overcurrent protection for the line. The fuse blows if there is a short circuit "downstream" of the cutout. The cutout can be used to sectionalize the distribution system and is to withstand manual operation when carrying loads up to its rated current value.

Disconnect switches are manually operated switches that are capable of carrying rated current but are incapable of interrupting load or fault currents. A highly inductive or capacitive circuit with no resistive load cannot be interrupted by a disconnect because of the phase difference between the voltage and current wave. The arc is extinguished when the current falls to zero, but the voltage is maximum and restrike occurs. Disconnects are used to isolate line sections and circuit breakers (after being opened) for maintenance or repair.

Circuit breakers are switching devices that are operated either manually or automatically as a result of fault detection devices, relays, or tripping mechanisms in the breaker. They must be capable of interrupting any load up to the rating of the breaker. In certain installations the breakers are not capable of interrupting the maximum fault current that could occur if a short circuit occurred. In these cases the breaker is installed in series with, and is protected by, a fuse that is capable of interrupting the fault current.

Circuit breakers are of several different designs. These designs include low-voltage breakers that break the arc in the open air, e.g., pole-top mountings and the highest position on a vertical switchboard. Metal-clad switches are modular, enclosed switches that can be removed from the panel. Metal-clad switchgear includes self-aligning connector contacts, which connect the switch to the line when the switch module is inserted in the panel. Interlocks prevent withdrawing or restoring the switch while it is closed. Automatic shutters prevent exposure of the primary circuits when the removable element is in the disconnect, test, or removed position. The interrupting device has a metal front panel so that only grounded conductors may be touched by personnel. A metal-enclosed breaker differs from metal-clad switchgear in that access to the interior is possible by removing panels or doors.

The extinction of the arc that results when a breaker is under load is achieved in several different ways. The contacts in an oil circuit breaker are submerged in oil, which cools and quenches the arc column, so that a much higher voltage can be interrupted for the same contact separation in air.

Air blast or magnetic blowout components in the circuit breaker force the arc, that forms when the contacts separate, into an arc chute. The chute elongates, breaks up, cools, and deionizes the arc path.

In vacuum breakers, the number of air molecules available for ionization is so extremely small that an arc does not develop even if the contact separation is small.

Circuit breakers operate as required by relay action or manual intervention. They are capable of interrupting full-load current and may be required to interrupt short-circuit current. If a breaker is incapable of breaking short-circuit current, it must be connected in series with a fuse that can interrupt the short-circuit current.

The maximum current to be interrupted must consider the DC component of the fault current produced because the short circuit can occur at a point in the voltage wave that is not zero. A DC component of current results and causes the AC current wave to be offset and the magnitude of the current to be interrupted to be nearly twice the steady state AC current obtained by dividing the voltage of the system by the equivalent impedance between the point of the fault and the source voltage (generator). The instantaneous current I is given by

$$I = \frac{V}{|Z|} \times \left[\sin(\omega t + \alpha - \theta) - e^{-Rt/L}\sin(\alpha - \theta)\right], \text{ A} \quad (6\text{-}1)$$

where

e = 2.71828, base of natural logarithm, dimensionless
V = voltage between line and ground, V
t = time, s
$\theta = \operatorname{Tan}^{-1}(\omega L/R)$, rad
$|Z| = \sqrt{R^2 + (\omega L)^2}$, magnitude of Thevenin impedance "seen" from source through fault, Ω
L = inductance of line and fault, H
R = resistance of the combination of the line and fault, Ω
α = phase angle of line at time of fault, rad
ω = radian frequency of line, rad/s.

The resulting current described by Eq. 6-1 is a combination of a sinusoid predicted by the first term within the brackets and a decaying exponential predicted by the second term. The current waveform is shown in Fig. 6-1. The peak current is determined by several factors including the line voltage, the magnitude and phase angle of the impedance of the line/fault combination, and the line voltage phase angle at the instant the fault occurs. If the phase angle α of the voltage at the time of the occurrence of the fault is that $\alpha - \theta = \pi/2$, the current magnitude to be interrupted is the maximum and may be approximated by

$$I_{max} \approx \frac{2V_{max}}{|Z|}, \text{ A} \quad (6\text{-}2)$$

where

V_{max} = maximum fault voltage, V
I_{max} = maximum fault current, I.

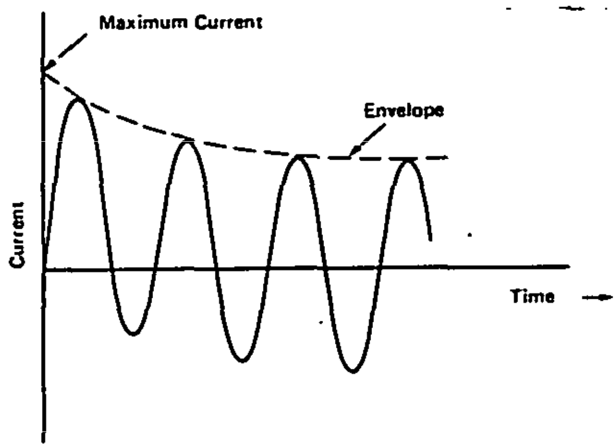

Figure 6-1. Completely Offset Current Wave

6-1.3 RATINGS OF SWITCHING COMPONENTS

The parameters used in rating switching equipment are

1. *Rated Maximum Operating Voltage.* The rms voltage for which the equipment was designed
2. *Rated Frequency.* The frequency of the voltage for which the frequency was designed—60 Hz in the US
3. *Rated Insulation Level.* Specified as either a 1-min withstand voltage or an impulse-withstand voltage. The 1-min withstand voltage is the maximum AC voltage at the appropriate line frequency that can be applied to the switchgear for 1 min without breakdown. The impulse-withstand voltage is the maximum pulse voltage that can be applied without breakdown. A standard pulse shape is used, i.e., one in which the voltage rises to its peak in 1.5 μs and falls to 50% of that level in 50 μs.
4. *Continuous Current Rating.* The rms current that the switchgear can carry continuously without exceeding the temperature allowed by the most limiting insulating material
5. *Rated Momentary Current.* The maximum rms total current that can be carried without electrical, mechanical, or thermal damage or permanent deformation of any parts. The maximum current includes the DC transient component as discussed in par. 6-1.2.
6. *Maximum Current-Interrupting Capability.* The maximum load current that the switch can interrupt without significant damage for a specified number of switch cycles.

6-2 INDUCED ENVIRONMENT

6-2.1 ARCING

When the contacts of a breaker begin to separate during an opening operation, a voltage appears between the contacts. The voltage gradient, due to the increase in the original infinitesimal distance between contacts, is extremely high. This high-voltage gradient ionizes the dielectric—air, oil, etc.—that surrounds the contacts and thereby creates a conducting path. The current that flows across this path elevates the temperature to such an extreme that intense light and heat are radiated. The resultant hot, gaseous conducting path is called an electric arc. An electric arc can form on other parts of an electrical distribution system when the effective dielectric length of insulation between energized parts is reduced sufficiently. Some examples of circumstances in which arcing can be initiated are

1. Wet material blowing across open, uninsulated conductors will reduce the effective electrical separation between conductors. The voltage gradient across the reduced air gap can reach the ionization threshold and cause arcing across conductors.
2. Kite strings falling across uninsulated conductors can cause arcing between overhead lines.
3. Squirrels or birds bridging part of a porcelain insulator cause the air across the unbridged part to be stressed beyond the ionization point, and arcing occurs across the entire insulator.
4. A transient voltage on a distribution network resulting from a nearby lightning stroke—cloud-to-cloud or cloud-to-ground—can be higher than the impulse rating of insulators. Voltages of over 500,000 V on 4000-V distribution systems have been reported (Ref. 2). A static spark over the insulator will establish an ionized path that can lead to a high-current arc through the same path.

6-2.2 PRESENCE OF HIGH VOLTAGE (Ref. 3)

Like other line-powered electrical apparatus, switchgear has high voltages on line conductors, including switch contacts. The high voltage can produce an electrical shock hazard when insulation and conductor guarding are insufficient. Also malfunction of the insulation may cause exposure of grounded conductors, which, in the event of a line-to-ground fault, can lead to hazardous step- or touch-potentials.

6-2.3 MECHANICAL SHOCK

Mechanical forces can be produced by two different mechanisms in electrical switching systems: (1) mechanical shock from the opening of contacts and (2) stresses induced by high current surges. The mechanical features of switchgear contact assemblies must be sufficiently strong to withstand large currents; therefore, their mass is significant. To extinguish the arc effectively, the switch action must occur very rapidly. This action requires very rapid acceleration and/or deceleration of switch components and can transmit shock or vibration to attached structures. The breakers, therefore, must be isolated to prevent undesirable transmission of the breaker motion to adjacent equipment. If transmitted, the undesired vibration could cause inadvertent closing of relay contacts, shorting of flexible conductors, or physical damage to delicate mechanisms.

The extremely heavy short-circuit currents in bus bars and cables induce magnetic fields, which, in turn, may exert large forces on magnetic materials or other current-carrying conductors. The bus bar support insulator must have mechanical strength sufficient to withstand the lateral thrust resulting from a short circuit.

6-3 HAZARDS (Ref. 4)

6-3.1 ELECTRICAL SHOCK FROM EXPOSED CONDUCTORS AND CONTACTS

The presence of high voltage on electrical apparatus poses an electrical shock hazard to personnel in the vicinity, especially when the apparatus must be accessible for service or repair. Energized switchgear creates a special hazard for two reasons: (1) the switchgear must be accessible for operation and (2) the presence of a switch in a line adds some uncertainty about the presence of high voltage on a given conductor. This uncertainty can lead to accidents when a conductor, erroneously believed to be not energized, is touched. Exposed switchgear sometimes found on obsolete live front panelboards is especially hazardous because of the presence of high voltage on exposed knife switch components at working height. Also maintenance operations on the switches can present hazards because it may be difficult or impractical to remove power from the "hot" side of the switch; or, if the switch is removable, energized contacts may be exposed when the switch is removed. The hazard of electrical shock associated with switchgear is increased by improper installation (inadequate guarding and/or improperly grounded protective enclosures); moisture, which induces electrical leakage paths across insulators; and improperly labeled switch-operating levers, handles, etc.

6-3.2 IGNITION OF FLAMMABLE MATERIAL

The arcs produced when switchgear interrupts line currents are a source of heat that can lead to the combustion of flammable materials. Even small arcs in switches associated with low-power apparatus can ignite fuel vapors or other combustible gases that could cause a large explosion or ignition of other, less flammable, materials. The often unanticipated large arcs—resultant from the operation of a switch onto a circuit containing a fault—may produce heat sufficient to melt metal outside the immediate region of the switch contacts and to ignite materials thought to be located a safe distance away. Arcs from switchgear can ignite oil that has leaked from transformers or oil circuit breakers.

6-3.3 ARCING TO ADJACENT CIRCUIT

Open-air switches frequently extinguish an arc simply by lengthening it. If wind currents or magnetic forces cause the arc to pass near other conductors, e.g., the other phases of a polyphase system, the arc may attach to those circuits and sustain itself for a considerable period. A sustained arc may be initiated in this manner even though the conductors are separated by a distance that is normally sufficient to prevent breakdown.

The arcing hazard is increased in a polyphase system when arcs initiated by switch action in several phases mix and cause a "polyphase arc". In a polyphase arc the current does not decrease to zero every half cycle as it does with single-phase arcs or with arcs between phases. Thus the arc is continuously sustained under conditions that would otherwise extinguish it between cycles. The additional energy of an arc of longer duration causes greater damage, especially if the arc encounters conductors that are not designed to resist damage due to arcing.

If an arc occurs between a power conductor and a nearby signal cable, considerable damage to the equipment connected to the low-level cable can result; such equipment is not designed to withstand additional line voltage.

6-3.4 PHYSICAL DAMAGE FROM ARCING

Disconnects are not provided on switchgear whose contacts cannot withstand arcing because there is no means for interrupting an arc that forms if the disconnect is opened inadvertently while carrying a load. The intense heat of the arc would damage the disconnect to the point that it could not be reclosed and successfully carry a rated load. Damage could also be produced to load interrupters if the mechanism jams during opening and thereby sustains an arc. Resultant damage could include melting of nearby insulation or conductor materials, deposit of soot or metal vapors on electrical circuitry, or deposit of molten metal on, or welding of, mechanical components.

6-3.5 COMPONENT EXPLOSION OR HEATING FROM FAULT CURRENT

A breaker capable of opening the circuit in the case of a short circuit would probably suffer irreparable damage if it were accidentally closed on a line that has been grounded with a safety ground strap. Once the switch is closed, the opening mechanism must be recharged before it can be reopened. A delay permits the high-fault current to flow for a much longer time than the rated clearing time of the breaker. The damage would be extensive, and in the case of oil circuit breakers, there is the risk of a ruptured oil tank and subsequent fire.

6-3.6 ENERGIZED CONDUCTORS WHEN A SWITCH IS OPEN

In conventional single-path circuits, opening a switch in the circuit normally removes power from all parts of the circuit controlled by that switch. As a result, there is a natural expectation that opening a single switch will remove all power from a circuit. However, if power to a circuit is supplied by two or more routes, e.g., in a loop configuration, then opening one switch will not deenergize the circuit and thereby increases the chance that maintenance personnel may mistakenly touch a "live" circuit.

In a similar manner, if two or more circuits in the same area are exposed and the switchgear for each is not appropriately marked and/or not collocated, maintenance personnel may incorrectly assume that the area is clear of electrical hazards after deenergizing only one of the circuits. Unless they are careful to check all exposed conductors for the presence of voltage, they may assume the area is safe to work in and thereby expose themselves to a severe hazard.

6-4 DESIGN CONSIDERATIONS

6-4.1 PHYSICAL LAYOUT

In an installation the location of phases on ganged breakers and all single-phase equipment should be consistent. Phases should be designated 1,2,3 counting from front to back, top to bottom, or left to right as viewed from the main switching device on the operating mechanism side. The sequence by which the phases reach their peak value is 1 followed by 2 and then 3. All equipment should be clearly marked as to voltage level and phase.

During a switch-operating operation, an arc that has a length longer than the spacing necessary to prevent arc-over may be produced. Therefore, it is necessary to provide separation or barriers between phases in polyphase switches to prevent the arc from contacting a grounded conductor, another phase conductor, or another arc. Any of these occurrences could result in a sustained, damaging arc or a fault. If the switches are separated insufficiently such that arcs between various phases mix, a polyphase arc—which will be difficult to extinguish—may be generated.

The handles and control mechanisms should have a uniform position for the open position, and the open or closed condition of the switch should be clearly indicated.

Mechanical switchgear controls should be mechanically sound and designed so that excessive play is not introduced into the mechanism as a result of component wear or material deterioration. This feature is especially important with remotely operated switchgear, e.g., pole-top mounted, or switchgear mounted in a protected area but operated mechanically from a remote position with a shaft or lever. Excessive backlash, or play, in the operating lever or handle could cause an incorrect indication of the switch position or could allow the switch to change position by itself. To minimize this possibility, well-fitting parts and substantial construction should be used. Knobs or levers on shafts should have keys or flatted shafts to prevent misalignment between position-indicating knobs or handles and should be clearly labeled.

6-4.2 ACCESS

Breakers that open in air should be located on pole tops or high enough on a switchboard that the arc that forms when the breaker operates would pose no danger to operating personnel. Pole-top disconnects or other switches whose operating handles are accessible to unauthorized personnel should be locked in either the open or closed position. Keys for these locks should be available only to authorized personnel.

Other breakers should be enclosed in metal enclosures to contain arcs. The metal-enclosed breakers afford the additional safety protection of isolating all current-carrying parts from possible contact by personnel. Only the ends of the bushings leading into the equipment are unguarded. Dead-front power breakers have the uninsulated rear connections in an isolated rear compartment. Panels for metal-enclosed switchgear that can be withdrawn should have covers that prevent possible contact with exposed conductors by personnel when the switching unit has been removed for servicing. Breakers should be equipped with interlocks to prevent withdrawal or reinsertion of a breaker that is closed to eliminate the possibility the current will be interrupted by contacts other than those that are designed for that function. Some provision should be made, however, that will allow trained personnel to defeat the interlock so they may observe the breaker in operation if necessary. The ability to override the interlock creates less of a hazard than that created by service personnel improvising or modifying the switchgear to obtain access during operation.

Breakers could also be provided with a feature to insure being locked in the open position to provide for the safety of personnel during maintenance and repair of associated circuits.

Cabinets containing switchgear should enclose the units completely and should not have openings that would permit dropped objects to contact energized conductors. If openings are required, louvered openings or grills that are separated sufficiently from live conductors should be used to minimize the likelihood of conductor contact by metallic objects inserted from the outside. Switchgear to be installed outdoors, or in locations where moisture may be present, should be mounted in weatherproof enclosures except for open switchgear intended for pole-top mounting.

Interlocks must be provided for metal-clad (removable) switchgear to prevent the withdrawal of the switch when the handle is in the closed position. A typical switchgear component has a three-position interlock system whereby the switch unit may be fully *withdrawn* for servicing, *partially inserted* to a *test position*, or moved to the operational *fully inserted position*. In the withdrawn position the switch is electrically isolated from all line and control voltages, and shutters or barriers prevent access to those voltages. As the switch is inserted to the intermediate test position, contacts of the switch are grounded, but control circuitry is energized so the mechanical operation of the switch may be observed safely. As the unit is moved toward the fully inserted position, the interlock system keeps the switch in the open position. Energized conductors remain covered. Once the switch is fully inserted, the front panel of the switch is fitted against the enclosure and thus prevents access to the switch. The contacts are ungrounded and then are connected to the line.

Any interlock configuration may be used provided the high-voltage conductors remain covered and any possible arcing occurs at the switch contacts and not at the socket for the switch plug.

6-4.3 ARC SUPPRESSION AND EXTINCTION

Switchgear must be designed to interrupt a specified current—either full-load current for circuit breakers and load control switches, or line-charging currents for disconnects. When the switch contacts separate, the current in the circuit tends to keep flowing and causes an arc across the contacts. The arc, once initiated, continues until the arc channel (a path of ionized gases), is cooled, elongated, or broken so that the arc does not restrike after the current falls to zero at the end of each half cycle. If the arc is allowed to persist, damage to the switch is likely, e.g., contact erosion or charring of insulation. Design features that are incorporated to extinguish the arc and prevent damage from it are

1. Mechanical leverage that causes the contacts to separate quickly

2. Dual contact systems including primary contacts that are designed to conduct the full-load current continuously and secondary contacts that are designed to withstand and extinguish arcs. The contacts are mechanically sequenced so that, during switching operations, current is

diverted from the primary to secondary contacts. Typically, each secondary contact incorporates a rod-shaped extension. These contacts are mounted so that the rods form a "V" with the point of contact at the vertex. As the contacts separate, the arc forms at the vertex and is driven outward along the rods by electromagnetic forces. The arc is lengthened as it travels until it is extinguished.

3. An arc chute to contain the arc. Within the chute the arc is driven onto the edges of a series of plates, which segment and cool the arc.

4. Air or inert-gas bursts that cool and disperse the arc channel.

Arc extinguishing is further described in par. 3-3.9 and in Refs. 5 and 6.

To reduce problems associated with arcing, switchgear is sometimes immersed in oil to quench the arc. However, this adds the hazard of an oil fire if the circuit breaker fails.

Some circuit breaker designs include a power resistor connected in parallel with the main contacts. When the main contacts open, this resistor allows a limited amount of current to flow and thereby reduces the voltage across the main contacts and prevents the establishment of an arc. A set of auxiliary contacts then disconnect the power resistor, and since the current is limited by the resistor, the arc of the auxiliary contacts is extinguished easily.

On higher voltage breakers, sets of contacts are connected in series to extend the voltage-interrupting capability of breakers.

6-4.4 MATERIAL SELECTION

Contacts on disconnects are often made of silver or are silver plated because (1) the oxidation of silver does not increase its contact resistance excessively and (2) silver is more resistant to corrosion than copper or other contact materials. (The corrosion problem is aggravated by the certain air pollutants—see pars. 3-2.1.4 and 3-2.1.5.) Elevated temperatures of the contacts caused by heavy current flow also increase corrosion. Where contacts must withstand arcing, silver- or copper-tungsten alloys are used (Ref. 7).

Dielectric materials must be flame-retardant to prevent excessive damage from arcs. Information concerning the arc resistance of common insulation materials is given in par. 3-3.7.

The compartments and barriers between phases of metal-clad switches should be constructed of steel to prevent arcs from spreading between phases and combining as a polyphase arc. Cabinets must be given a phosphatizing treatment, or equivalent, before painting with a corrosion-resistant paint.

6-4.5 FAULT PROTECTION

Switchgear is not designed to tolerate fault currents for extended periods. Therefore, overcurrent protection must be used to protect the switch from damage due to excess current and, more importantly, to prevent damage that would occur if a switch operation were attempted while fault current was flowing. Generally, the requirements for overcurrent protection for lines and loads are more restrictive then the requirements for the switchgear itself; the fuse size being determined by the current capacity of the cable and load also protects the switchgear.

For reasons of economy, it may be desirable to install a breaker with an interrupting capacity sufficient to interrupt only load currents. In this case, a fuse that has a rating somewhat above the full-load current is installed in series with the switch. Then if a short circuit occurs, the fuse will blow and the fault will be cleared before the breaker operates. This scheme also protects a breaker in closing in a short circuit. Fusing of low-voltage circuit breakers is discussed in Ref. 8.

6-4.6 CAPABILITY FOR SWITCHING UNDER LOAD

Switchgear intended for operation in a circuit when load current is flowing must be designed to interrupt the maximum current that may exist in the circuit. Since fault currents can be many times higher than the maximum load current, the interrupting capacity of a circuit breaker should be much higher than the rated continuous current, typically 5000 A for the smallest lighting-panel circuit breaker (15-20 A). Design features for the interruption of load currents include the arc-extinguishing mechanism, clearance between terminals, clearance between contacts and conductor material, conductor sizes, and mechanical strength of conductors. An important design consideration is not only must the conductors carry the current without excessive heating, but also they must be sufficiently strong to withstand the mechanical forces induced during current surges.

Disconnects are switchgear that is not designed to interrupt load currents. They may be combined, however, with load-interrupting switches to provide the required continuous current capability and the required current-interrupting capability.

Switchgear that is designed to interrupt full-load current but not fault current should incorporate a fuse either in the switchgear or in the electrical circuit that feeds it.

6-4.7 TERMINATIONS

Switchgear designed for pole-top mounting typically will have bolt-on terminations so that the cable clamp characteristics can be selected to match the conductor characteristics. Terminations must be compatible with conductor material, especially where aluminum conductors are used.

Generally, metal-enclosed switchgear plugs into sockets to allow removal of the switch for servicing. Bolt-on terminals on the sockets are desirable to allow fastening of either the bus bars or screw-type compression terminations. Generally, smaller, molded-case circuit breakers with a capacity up to a few hundred amperes use screw-type compression wire clamps that are intended for connection to insulated, round conductors.

6-4.8 GROUNDING

Metallic operating, handling, and connecting mechanisms—such as a remote operating handle for pole-top switchgear—must be well grounded to prevent hazardous voltages from reaching accessible conductors through current leakage paths, arc-over from line conductors, or induced voltages. Flexible bonding straps should be used to insure the integrity of the ground across bearings or flexible joints. All support structures of switchgear assemblies must be tied together with an adequate grounding bus, and the grounding bus of each group of equipment must be connected to the station ground. Paint on steel cabinets, steel structures, etc., must be removed at the point of connection to the grounding bus to insure a good electrical connection. Switchgear components that can be removed from the assembly while the unit has power applied should be grounded through a flexible conductor with length sufficient to allow removal of the component to a safe place before the ground connection is broken.

Instrument cases must be mounted by using metal screws to secure the metal cases to the switchboards. Instrument-mounting bolts of instrument transformers should provide adequate grounding for these devices.

The grounding buses must be capable of carrying the expected fault current for 2 s on switchgear rated at 2.4 kV or above and for 0.5 s on 600-V equipment for the rated fault current of the protective device of the assembly.

6-5 COMPATIBILITY AND INTEROPERABILITY

6-5.1 CLASSIFICATION OF SWITCHGEAR

The characteristics, defined in par. 6-1.3, are used to specify switchgear:

1. Rated maximum operating voltage
2. Rated frequency
3. Rated insulation level
4. Rated continuous current
5. Rated momentary current
6. Current-interrupting capability.

Additional switchgear characteristics to be considered in the selection of switchgear for replacement of existing units or operation along with other switchgear include

1. Presence of oil
2. Features required to assist in extinguishing an arc, e.g., compressed air or SF_6
3. Mounting provisions.

Also if the switchgear is remotely controlled, then levels and types of interface and/or control signals and switching or response times may also be significant considerations. Selection considerations of specific characteristics of switchgear depend on the specific functions and interface requirements served by the switchgear.

6-5.2 COMPATIBILITY AMONG CLASSES

Substitution of different devices due to lack of exact replacement must be based on careful consideration of compatibility requirements. The following considerations should apply:

1. A disconnect may only be used to replace a disconnect. It cannot be used to replace a current-interrupting device because it is not designed to extinguish a high-current arc.
2. It may not be possible to replace an air blast, magnetic blowout, or other metal-clad breaker with an oil circuit breaker because oil circuit breakers must be isolated from other equipment by greater distances than are usually allowed in switching equipment not containing flammable material. (See par. 6-4.1 of this handbook and pars. 172 and 180 B1 of Ref. 9.)
3. An air blast breaker may not be a replacement for an oil circuit breaker because compressed air may not be available at the location.
4. Cutouts can be used as a replacement for a fuse, but a fuse may not be a suitable replacement for a cutout because the manually operable disconnect feature of the cutout may be required, and it is not part of a fuse installation.
5. Current transformers, relays, and other metering devices are often incorporated in metal-clad breakers but may not be part of oil circuit breakers. System protection may be jeopardized by the nonavailability of monitoring signals.

The current-interrupting capability of a device may differ from the maximum momentary current rating. A disconnect, for example, is not designed to interrupt current regardless of its current-carrying rating. A circuit breaker may or may not be able to interrupt a higher current than its full-load rating. If a breaker is unable to interrupt a current greater than full load, the breaker must be protected by a fuse in series with the breaker. Ref. 4 requires that, within a metal-clad switchgear assembly, removable switching elements with different current ratings must be configured differently to prevent the interchanging of units—i.e., it must be impossible to insert a switching unit into a cubicle designed to receive a unit with a different current rating.

6-5.3 SWITCHGEAR TYPES IN COMMON USAGE (Refs. 8 and 10)

6-5.3.1 Open-Air Switches

The most commonly encountered types of open-air switchgear are those units intended for pole-top mounting. Typically, these switches are operated manually either with a tool ("hot stick") or with a long operating rod to allow operation of the switch from a safe distance. Specific configurations include fused cutouts that include cartridge fuses as the movable arm of the switch, air-break switches, and disconnects. The air-break switch is a manually operated, load-interrupting switch that incorporates arc horns, arc chutes, or auxiliary contacts to extinguish the arc. Air-break switches may be used individually for single-phase control or ganged on a single operating control arm for polyphase control. Horizontal or vertically ganged configurations are available to accommodate the line configuration of the aerial distribution system in which they are to be used. The open-air disconnect is similar to the air-break switch except that it lacks the arc-extinguishing provisions and cannot interrupt load currents. The open-air switchgear is available for voltages up to 34.5 kV.

6-5.3.2 Other Air-Dielectric Switchgear

Molded case circuit breakers are perhaps the most common switchgear used in low-voltage systems. These devices are typically used at voltages up to 600 Vac with continuous current ratings ranging from 15 A up to 1200 A. Both single-phase units and three-phase units are commonly encountered. The devices usually are designed to interrupt fault currents that are much greater than the rated continuous current (fault currents that are up to 40,000 A). Small, molded case circuit breakers used for residential protection typically use a thermal mechanism to trip the breaker during an overcurrent condition; the larger breakers use a magnetic or a combination thermal-magnetic mechanism. Most molded case circuit breakers are designed to snap into a panel; however, cases are available that will house a single breaker so it can be used in applications where only a single switch is needed.

Metal-clad air circuit breakers are used in low-voltage distribution systems. Most metal-clad switchgear units are removable, modular units that plug into metal cabinets that totally enclose the switch units when they are in use. Interlocks prevent the removal of switches unless they are in the "open" position. Metal-enclosed switchgear is available for indoor or outdoor installation in low-voltage systems and is produced with current ratings up to 6000 A, although lower current units are more common.

6-5.3.3 Oil-Filled Switchgear

Oil-filled switchgear is generally available for medium-voltage systems for which the insulating and arc-quenching characteristics of oil make possible more compact construction. Models are available for manual operation, remotely controlled operation, and automatic operation (for overcurrent protection). Both individual-phase and three-phase units are available. Commonly encountered configurations of oil-filled switchgear are pole-top reclosers and sectionalizers used to protect low- and medium-voltage distribution systems against temporary faults and to isolate faulty sections.

Oil-filled units also may be included in metal-enclosed switchgear for indoor and outdoor, when mounted in weatherproof enclosures, use. These units, however, are more typically found in medium- to high-voltage systems—34.5 kVac indoors or 765 kVac in outdoor installations.

6-5.3.4 Vacuum Interrupters

Switchgear incorporating vacuum switches is used as a replacement for air-insulated switchgear operating at medium voltages, i.e., up to 34.5 kVac. Replacement vacuum switch units are made with the same external physical configuration as certain metal-clad air switchgear to allow direct replacement. The additional expense of vacuum switches, however, precludes their economic feasibility as air switch replacements in low-voltage systems such as those that derive power from an engine-driven-generator set.

Vacuum switches are also used in reclosers and circuit breakers operating at 34.5 kVA at continuous current ratings up to 3000 A.

6-6 TEST CRITERIA FOR DESIGN AND ITEM ACCEPTANCE

6-6.1 TESTS REQUIRED BY STANDARDS AND SPECIFICATIONS

Tests for switchgear equipment are specified in numerous specifications and standards pertaining to switchgear (Refs. 4, 11, 12, 13, 14, 15, 16, 17, 18, and 19). Representative tests are briefly described in the paragraphs that follow.

6-6.1.1 Dielectric Tests

Dielectric tests are voltage breakdown tests conducted on insulation materials used in the switchgear and are conducted to determine whether faults are likely to develop when the equipment is energized and exposed to normal transients likely to be encountered. These tests are applied to new, clean equipment that is in good condition and is under the temperature and humidity conditions specified in IEEE Std 4-1968 (ANSI C68.1-1978) (Ref. 20), with corrections applied for nonstandard conditions. Test voltages are listed in Table 6-1.

The dielectric tests on stationary equipment are

1. Phase-to-phase and each phase-to-ground with the switch both closed and open
2. Between the line and load terminals with the switch open.

On drawout equipment the following tests are repeated on the stationary element with the removable element in the test position and the main element in the closed position:

1. Phase-to-phase and phase-to-ground on both the line and load terminals
2. Between line and load elements at 10% higher voltage than the voltage specified in Table 6-1.

6-6.1.1.1 Power-Frequency Withstand Test

The power-frequency withstand test voltage is a low-distortion sine wave. The test voltage is applied for 1 min with a frequency not less than the rated frequency.

6-6.1.1.2 Impulse Voltage Test

The impulse voltage withstand test is a series of applications of three positive and three negative impulse voltages that reach their crest in 1.2μs and fall to 50% of crest in no less than 50μs. The complete specifications of the impulse voltage test are given in ANSI C37.20 (Ref. 4). If no insulation failure or flashover occurs in the series of tests, the equipment has successfully passed the test. If only one flashover occurs, three more tests are made. If the equipment passes the three additional tests, the equipment is considered to have successfully passed the battery of tests.

6-6.1.1.3 Wet Tests on Entrance Bushings

Insulators that are to be exposed to the natural environment are tested for voltage breakdown under simulated rain conditions by wet dielectric tests (Ref. 24). In these tests the insulator is sprayed with water or salt solutions of specified resistivity while the insulator is being tested to determine its breakdown or arc-over voltage.

TABLE 6-1. VOLTAGES AND INSULATION LEVELS FOR AC SWITCHGEAR ASSEMBLIES (Adapted from Refs. 21, 22, and 23)

Rated Maximum rms Voltage, V	Insulation Levels, kV		
	Power Frequency Withstand, rms	DC Withstand[a]	Impulse Withstand
Metal-Enclosed, Low-Voltage Power Circuit Breaker Switchgear			
254	2.2	3.1	—
508	2.2	3.1	—
635	2.2	3.1	—
Metal-Clad Switchgear			
4760	19	27	60
8250	36	50	95
15,000	36	50	95
38,000	80	[b]	150
Station-Type Cubicle Switchgear			
15,500	50	[b]	110
38,000	80	[b]	150
72,500	160	[b]	350
Metal-Enclosed Interrupter Switchgear			
4760	19	27	60
8250	26	37	75
15,000	36	50	95
15,500	50	70	110
25,800	60	[b]	125
38,000	80	[b]	150

[a]This column is given as a reference only for those using DC tests and represents values believed to be appropriate and approximately equivalent to the corresponding power frequency withstand test values specified for each voltage class of switchgear. When making DC tests, the voltage should be raised to the test value in discrete steps and held for a period of 1 min.

[b]Because of the variable voltage distribution encountered when making DC withstand tests, the manufacturer should be contacted for recommendations before applying DC withstand tests to the switchgear.

6-6.1.1.4 Bus Bar Insulation Tests

Bus bar insulation is tested by applying the AC voltage in Table 6-1 at the rated frequency for 1 min. The voltage is applied between the conductor and an electrode of conducting paint, lead foil, or the equivalent, which was applied to the outer surface of the insulation.

6-6.1.2 Current Tests

Current tests are conducted to determine whether the switchgear can conduct its rated current and momentary overloads without excessive heating that could damage insulation materials and remove the desired temper from springs and other support components. Failure of either could lead to switch failure and/or damaging fault currents.

6-6.1.2.1 Continuous Current Tests

The test determines whether the rated rms current will produce a hot-spot temperature rise above ambient that is within the limit specified for the type of insulation being used.

Ambient temperature is measured by three thermometers. One is level with the top of the switch enclosure, one is 300 mm (1 ft) above the bottom, and the third is midway between. The thermometers are placed 300 mm (1 ft) from the structure in such a position as to not be adversely affected by ventilation or radiation.

Temperature measurements of the surface of the device are made by means of thermocouples. A hot-spot location is difficult to locate; therefore, the placement of the thermal junctions for the test requires judgment.

The test continues until there is no further temperature rise above ambient in three successive readings at 30-min intervals.

6-6.1.2.2 Momentary Current Test

The momentary current test determines electrical, thermal, and mechanical adequacy of buses, connections, and devices to withstand the momentary currents specified. The momentary current is the rms current including the DC component. Its value is the maximum obtained from the envelope of the current wave for a period of at least 10 cycles. See Fig. 6-1.

6-6.1.2.3 Current-Interrupting Test

Current-interrupting tests are conducted with the switchgear in its normal enclosure and in accordance with test procedures for the particular device being tested.

6-6.1.3 Weatherproofing Tests

Weatherproofing tests verify the ability of outdoor switchgear to operate in the intended environment without excessive degradation of the electrical characteristics. The unit to be tested is subjected to artificial precipitation from a sufficient number of nozzles to give a uniform spray over the surface to be tested. The surfaces can be tested in sections or as a complete unit. The spray should deliver at least 5 mm (0.2 in.) of water per unit surface per minute with a velocity equivalent to that of rain in a 29-m/s (95-ft/s) rainstorm produced by using a nozzle pressure of 448 Pa (65 lb/in.^{2}). The spray nozzles should not be more than 3 m (10 ft) from the nearest vertical surface.

After a test of 5 min, the equipment is inspected to determine whether there is evidence of leaking.

6-6.1.4 Mechanical Tests

Mechanical testing is performed to verify that switch operation is smooth and vibration free. Rough operation may be a precursor to unreliable operation or premature failure of the switchgear and may have undesirable effects on adjacent equipment through transmission of mechanical shock.

6-6.1.4.1 Sequence Testing

The switches are tested to determine whether the switchgear parts operate in the proper sequence. This test can be performed in slow motion, i.e., unlatch the breaker and retard the operation with the manual operation handle or with oscillograph equipment at normal operating speed.

6-6.1.4.2 Mechanical Operation Test

Mechanical tests are made to verify that shutters, mechanical interlocks and mechanical parts on removable units, etc., perform properly.

6-6.1.5 Flame-Retardant Tests

Flame-retardant tests are performed to determine whether insulation materials are capable of withstanding the effects of electrical fires. The ability to withstand these temperatures is necessary so that in the event of fire loss is restricted to direct damage due to the fire and is not compounded by additional electrical faults in the switchgear.

Tests for flame-retardant characteristics of insulating material are conducted in accordance with procedures specified in NEMA, LI1-1983 (Ref. 24). The material should have a 60-s or greater ignition time, a maximum burning time of 100 s, and a maximum weight loss of less than 25%.

6-6.2 ADDITIONAL TESTS

In addition to the tests specified by ANSI C37.20, other tests may be appropriate for verification of switchgear operation, especially if the switchgear includes automatic or remote control capability. Example tests that might be appropriate are

1. Insulation resistance measured at voltages below breakdown provides an indication of leakage paths across insulation surfaces.
2. The response time of a switch is measured by determining the time interval between submission of a remote control signal and the time electrical continuity is made or broken. The delay in operation of a switch may become critical when multiple switches are controlled from a common source: Time-travel analysis of the operating mechanism may be performed to verify mechanical operation. Devices for performing these tests provide a graphical representation of contact velocity and position versus time, which may be compared to the manufacturer's specifications.
3. Inspection of the unit while it is in operation may be appropriate to verify the operation of ancillary equipment, such as indicating lights and meters, and interlocks.
4. Internal instrumentation may be checked for accuracy by calibration procedures that are appropriate for the instrument used.
5. Contact resistance may be measured by impressing a known low voltage across the terminals and measuring the current through the contact. Similar information

may be determined by passing the rated current through the switch and measuring the induced voltage drop across the switch. Contact resistance may be used as an indicator of the amount of heating expected in normal service.

6-7 OPERATIONAL PRECAUTIONS

6-7.1 INSTALLATION

All switchgear should be installed according to the manufacturer's directions. Switching devices should be inaccessible to unqualified persons. Isolation can be accomplished through the use of walls, barriers, fences, locked doors, or other means to protect personnel from energized parts and/or arcing.

The space provided for the equipment must be adequate for qualified personnel to operate, replace, or repair all switching equipment without undue hazards from limited working space. For equipment operating at 600 V or less, the National Electrical Safety Code (NESC) (Ref. 9) specifies requirements for working space around any components that need replacement, inspection, adjustment, or repair. A 0.9-m (3-ft) clearance in front of a dead-front switch panel and a 2.1-m (7-ft) floor-to-ceiling clearance are required. Also a 0.9-m (3-ft) clearance is required around exposed 0-to-150-V components. For components operating at 150 to 600 V, a 0.9-, 1.1-, or 1.2-m (3-, 3.5-, or 4-ft) clearance is required, depending on whether energized components are located on one side of the working space, energized components are on one side and grounded on the other, or energized components are on both sides, respectively (Article 125 of Ref. 25). Also switchgear must be separated from flammable-liquid or gas-storage containers by 7.6 m (25 ft) indoors or 3.0 m (10 ft) outdoors unless a suitable barrier is placed between them (Article 180 of Ref. 25). Oil-filled switchgear must be segregated from other equipment by physical separation, fire resistant barrier walls, or by metal cubicles. Also provisions must be provided for safely containing oil, which could be spilled through venting or tank rupture.

If the space provided for the installation is outdoors, special precautions must be taken to insure that the enclosure is tamperproof. It must be designed so that

1. Sticks, wire, or liquids that may interfere with the proper function of the installation cannot be inserted.
2. Entry by unauthorized persons is difficult or impossible.
3. Ventilating openings should have deflectors or angled openings to prevent objects inserted in them from touching energized conductors.

All equipment should be clearly marked as to voltage level and phase. The mechanical-operation indicators that indicate the status—open or closed—of switching equipment should be clearly visible. In addition, signal lights should be provided for remotely controlled systems or switchgear that does not have an operating handle that indicates switch status—e.g., push-button switches with a red light indicating "closed" and a green light indicating "open".

Unless the switchgear is physically attached or adjacent to the equipment it controls, it should be plainly labeled either with the name of the equipment or system it controls (for distribution switchgear) with the designation corresponding to an overall scheme of labeling branch or feeder lines. The label should be mounted permanently on a nonmoving, nonremovable surface of the operating handle of the switch. Labeling for outdoor use should withstand weathering without excessive deterioration of legibility.

Each installation should be provided with the complete set of handling devices or tools required for the removal or operation of switchgear. A convenient storage place for the tools should be provided and clearly labeled.

Each installation should be provided with a suitable ground bus for grounding enclosures and lightning suppression devices.

In the original installation all interlocks must be checked to verify that they operate properly, i.e.,

1. Metal-clad, removable units cannot be removed or restored if the breaker is closed.
2. Disconnects cannot be opened or closed unless the associated breaker is open.
3. Circuit-breaker doors are to be interlocked to prevent opening unless the circuit breaker and disconnects are open. These interlocks should be inspected from time to time to verify they are still in good operating condition.

All installations should be provided with surge voltage protection (lightning arrestors) to prevent insulation damage including

1. Power arc tracking over bushings, potheads, and bus support insulators
2. Destruction of porcelain insulators
3. Puncture of time insulation of transformers, bus wrapping, etc.

No equipment should be installed above switches (breakers) that open in air because of the remote possibility that the switch might not complete its stroke and the arc between the contacts would be sustained. Convective air currents, caused by the heat of the arc, would move the arc close to or into the equipment located above the arcing switchgear and would cause considerable damage. If the overhead equipment included control wiring or parts of other circuits, the difficulty could be further compounded. (See par. 3-3.8.)

6-7.2 ROUTINE MAINTENANCE AND INSPECTION

Switchgear should be inspected routinely to identify problems that could affect the reliability of the switching equipment or could create an unsafe condition. As soon as possible after circuit breaker operation at or near its rating, the breaker should be inspected for possible damage, and indicated maintenance should be done promptly.

Disconnects should be inspected for possible corrosion of the contact surfaces, and such repairs, e.g., silver plating, should be undertaken when necessary. Connections should be inspected for tightness by using a torque wrench for large, critical connections. Insulation materials should be checked for breakage or damage due to corona, tracking, arcing, or overheating.

The temperature of switchgear components should be checked periodically to detect unacceptable resistive heating of conductors. Temperature-sensitive paint can be applied to the exterior of bus insulation to detect unusual temperature rises resulting from overloads or deteriorating bus connections. Periodic use of infrared surface-temperature-measuring devices is highly recommended to detect heat from high-resistance contacts or connections without having to shut down the equipment for installation of sensors.

Arc-suppression devices (arc chutes) are removable on some switchgear. These devices should be inspected to insure that they are installed properly and are in serviceable condition.

Certain tests should be performed periodically to verify the serviceability of the equipment. Appropriate tests include high-potential tests and insulation-resistance tests. These tests should be performed periodically at an interval specified by the manufacturer. For oil-immersion switchgear the oil should be checked periodically for contamination, and its dielectric strength should be measured.

Maintenance, repair, or inspection of low-voltage, open-air switchgear must be undertaken with great care because of the proximity of equipment that remains alive (including the breaker). Equipment that remains alive in the vicinity of this work should be covered with rubber blankets, hoses, etc., and the personnel must use rubber gloves and "hot line" tools as required.

Insulator surfaces should be cleaned regularly to remove deposits that could lead to arcing across the insulator surface. Loose dust may be removed by vacuuming or wiping with a lint-free cloth. Stubborn deposits may be removed by using solvents recommended by the manufacturer. Water, steel wool, sandpapers, or industrial compressed air should not be used because the materials left behind can introduce leakage paths or interfere with mechanical apparatus. Power should be removed from the apparatus during cleaning. Personnel should never rely on the solid wire insulation within electrical apparatus for protection because pinholes and/or nicks can destroy the integrity of the insulation.

During periodic maintenance, old lubricant residue should be removed and the switch mechanism lubricated to prevent sluggish switch operation. While the equipment is deenergized, it should be cycled to insure that the mechanism operates smoothly without binding.

6-7.3 OPERATION (Refs. 25 and 26)

The operation of switchgear almost always exposes the operator to the potential hazard of arcing when the switch is opened or to the potential for large currents that occur when the switch is closed on a fault. These hazards, along with possible implications of operating the wrong switch or operating the switch at the wrong time, make necessary careful preparation before large switchgear is operated.

For distribution systems, all switching operations should be well planned and documented in a switching order. These orders should specify completely the switches to be operated, the sequence, the time of operation, the person(s) who must be contacted before the operation commences, and any other pertinent conditions. Orders should be proofed and verified to eliminate errors.

Switches should be closed with the realization that the current could contain a fault that could trip a circuit breaker or blow a fuse. The switch should be closed with a decisive motion, i.e., use of sufficient force to seat the mechanism in the closed position. If the switch in a loaded line does not seat completely, it should be seated by application of additional force. The switch should not be reopened unless it is designed to be capable of extinguishing the resultant arc.

Sticks or poles ("hot sticks") used for operating pole-mounted switchgear should be carefully stored when not in use to protect them from dirt, moisture, heat, and sunlight. Poles kept outdoors may be stored in a tubular housing with screw-on end caps and vent holes to prevent accumulation of moisture. Poles stored indoors should be stored vertically to prevent accumulation of dust. Poles should be long enough to allow the operator to maintain steady footing. In all cases, the stick should allow the operator to operate the switch while remaining clear of electrical lines and explosive fuses. A minimum clearance of 0.6 m (2 ft) is required when switching 2.1- to 15-kV lines via an uninsulated switch using a "hot stick".

Air-insulated switches should be opened carefully because of the arc that could be produced if the switches were carrying load current. The operator should wear protective clothing, including protective headgear, insulating gloves, and a protective coat. Disconnects, which are not designed to interrupt the load current, should be opened by using the inching technique. In this technique the switch is opened slowly while the operator observes that there is either a small arc or no arc produced. If a large arc is produced, the switch is immediately reclosed until the current can be reduced by other means.

Load-interrupting switches should never be operated using the inching technique; they should be operated quickly to break the arc as promptly as possible.

The auxiliary arc contacts or arcing horns used to break the arc should be checked visually prior to operation. If arc-extinguishing devices are missing parts or are defective, an alternative method of interrupting the power must be used.

Where switchgear is used to deenergize distribution lines or equipment for maintenance or repair, a lock should be placed on the circuit breaker by the servicing person to insure against the reapplication of power before service operations are complete. This lock should have only two keys—one stored at a central location by supervisory personnel and one carried by the worker. If more than one team is servicing the equipment, each team should lock the equipment so that all the locks have to be removed before the switch or breaker may be returned to the energized position.

Where power distribution lines are being serviced, ground straps should be installed (1) to prevent the buildup of induced voltage on lines from coupling to other circuits and (2) to prevent application of voltage to the lines being serviced from any source by introducing an intentional fault, which will trip the overcurrent.

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CHAPTER 7

END-ITEMS

Described in this chapter are the most common end-items that interface with, and are powered directly by, electrical polyphase power distribution systems. Items discussed in this chapter include motors, transformers (as the interface between the polyphase electrical distribution system and an electrical load or loads), heaters, lighting, controls or controllers, and load banks. Discussion of each item follows the same format used throughout the rest of this handbook and includes the following topics: definition of the equipment, affect of it on the environment, associate hazards, design considerations, compatibility and interoperability considerations, and operational precautions.

7-0 LIST OF SYMBOLS

E = relative emissivity of surface (1 = blackbody; 0 = mirror surface), dimensionless
h_b = heat loss through convective cooling, W/m^2 ($W/in.^2$)
h_c = heat loss through conduction, W/m^2, ($W/in.^2$)
h_r = heat loss through radiation, W/m^2, ($W/in.^2$)
I_c = capacitor current, A
I_m = main-winding current, A
k_m = thermal conductivity of material, W/m·K (W/in.·R)
ℓ = length of thermal conductor, m (in.)
T_{amb} = temperature of ambient or sink, K(R)
V_I = power input, V
T_{pt} = temperature of heated plate, K(R)
C_{r_1} = constant = 5.69×10^{-8} $W/m^2 \cdot K^4$
C_{r_2} = constant = 0.35×10^{-11} $W/in.^2 \cdot R^4$
C_{b_1} = constant = 2.26 $W/m^2 \cdot K$
C_{b_2} = constant = 8.10^{-4} $W/m^2 \cdot K$

7-1 INTRODUCTION

An end-item, in the context of polyphase systems, is any piece of electrically powered equipment connected to a powered distribution network for purposes other than further distribution of the polyphase power. End-items convert the polyphase electrical energy to another desired energy form—e.g., mechanical energy, heat, light, or "nonpolyphase" electrical energy.

This chapter discusses only end-items that are connected directly to the polyphase system. Typically these are large electrical loads that either do not operate economically from a single-phase supply or operate more efficiently from a power source that delivers power continuously. (See par. 1-3.2.) These items include motors, heaters, and high-intensity lighting. Transformers that convert three-phase power to lower voltages or to different phase configurations are described here because, even though a transformer does not use or dissipate the power, it forms the electrical interface to the polyphase electrical distribution system. (The transformers described here are those associated with a specific load or clustered group of loads. Distribution transformers that transform voltage levels to facilitate efficient distribution of power are described in par. 5-3.)

This chapter primarily presents safety issues related to types of electrical loads used with polyphase systems. No attempt is made to describe completely each end-item since such a treatment would be voluminous due to the variety of devices that could be connected to the system and to the uniqueness of safety considerations for each variety. The reader is referred to various texts, handbooks, and specifications to obtain detailed information about specific end-items.

7-2 MOTORS

7-2.1 INTRODUCTION

The electric motor performs the inverse function of a generator, i.e., it converts electric energy to mechanical energy of a rotating shaft. A variety of motor configurations are available to provide the required speed(s), starting torque, running torque (or power), environmental protection, or mounting configuration required by the application. This paragraph briefly describes the available electrical and physical configurations.

AC motors are divided into two types: induction and synchronous. Both depend upon a magnetic field rotating in the air gap surrounding the armature. In the induction motor the rotating field links the windings of the squirrel cage or the wound rotor. The rotor never attains the speed of the rotating magnetic field; thus the changing flux linkages to the rotor winding or squirrel cage induce a current in the same manner as a transformer with a short-circuited secondary. The resulting current flow in the rotor reacts with the rotating flux to produce the torque. The starting torque and maximum torque can be varied by changing the design of the squirrel cage or the resistor used to short-circuit the wound rotor. The speed of the wound rotor motor can be adjusted somewhat by changing the shorting resistor. These motors, however, are essentially constant-speed motors and operate at speeds slightly below synchronous speed. Synchronous speed is determined by the number of pairs of poles in the winding—3600, 1800, 1200, 900 rpm, etc. The types of polyphase electric motors described in Ref. 1 are summarized in Tables 7-1 and 7-2. The effects of voltage and frequency variation on these motors are described in Table 7-3.

Single-phase induction motors are the most common AC motors used for applications requiring 3 hp or less. These motors typically contain a squirrel cage armature and two sets of windings, i.e., a main winding and an auxiliary winding used for starting. The windings are constructed to have different reactances so that when voltage from a single-phase source is applied to both windings (in parallel), the resultant currents in the two windings will differ in phase. The two most commonly used designs for achieving this phase difference are the split-phase and the capacitor-start methods. In the split-phase method the auxiliary winding has a high-resistance auxiliary winding, which presents a more resistive reactance to the line than the more inductive main winding. The more effective capacitor-start system relies on a capacitor in series with the auxiliary winding as shown in Fig. 7-1. The capacitor current I_c leads the source voltage while the main-line current I_m lags the source voltage V. Thus the windings have currents differing in phase by approximately 90 deg. A rotating field is produced and torque develops, which starts the motor. After the motor comes up to nearly synchronous speed, a centrifugal switch opens the auxiliary winding and the motor maintains its speed from the field supplied by the main winding.

Synchronous motors are used when a constant speed is required, and they are driven up to nearly synchronous speed by an induction motor or by a squirrel cage in its own rotor. When the motor comes up to speed, a DC voltage is applied to the rotor winding, which pulls the rotor into step with the rotating field. The DC for the field is furnished by batteries, a DC generator on the same shaft (shaft end exciter), or any other DC source. If the motor is overloaded and falls below synchronous speed, it will stall.

7-2.2 INDUCED ENVIRONMENT

7-2.2.1 Vibration

It is not possible to balance a motor armature dynamically so that a rotating motor will not impart some vibration through its housing to the mount. A rotating load driven by an engine that is not balanced or a load that varies throughout its rotation, e.g., a compressor,

TABLE 7-2
DESIGNATION FOR SQUIRREL CAGE MOTORS (Ref. 1)

Design Designation* A	B	C	D	Specified Characteristics
X	X	X	X	Full Voltage Starting
X	X	X	X	Specified Locked Rotor Torque
	X	X	X	Specified Pull-Up Torque
		X	X	Specified Breakdown Torque
	X			Breakdown Torque up to Specified Values
			X	Locked Rotor Current Above Specified Values
X	X	X		Locked Rotor Current Below Specified Values
	X			Special High-Torque Capability

*See Table 7-1 for identification of design designation.

TABLE 7-1
TYPES OF POLYPHASE ELECTRIC MOTORS (Ref. 1)

Design	Squirrel Cage Characteristics	Running Characteristics		Starting			Applications
		Slip	Breakdown Torque	Current	Torque	Voltage	
A	Single Cage—Low Resistance	<5%	High	High	Moderate	Reduced	Fans, Centrifugal Pumps
B	Double Cage or Deep Bar	<5%	Medium	75% of A	Good	Full	Same as A
C	Double Cage and Deep Bar	<5%	Normal	Low	High	Full	Compressors, Crushers, Conveyor
D	Single-Cage—High Resistance	<5%	*	Low	High	Full	High-Inertia Loads, Punch Presses, Hoists

*Breakdown torque is the applied torque loading that, if exceeded, will cause the motor to stall with a sudden decrease in supplied torque. The D-design motor is designed for heavy, intermittent loads and provides continuously increasing torque as speed is reduced from increasing loading. Hence a D-design has no breakdown torque.

TABLE 7-3
GENERAL EFFECT OF VOLTAGE AND FREQUENCY VARIATION ON INDUCTION MOTOR CHARACTERISTICS (Ref. 2)

Characteristic	Alternating-Current (Induction) Motors			
	Voltage		Frequency	
	110%	90%	105%	95%
Torque:[a]				
Starting and maximum running	Increase 21%	Decrease 19%	Decrease 10%	Increase 11%
Speed:[b]				
Synchronous	No change	No change	Increase 5%	Decrease 5%
Full load	Increase 1%	Decrease 1.5%	Increase 5%	Decrease 5%
Percent slip	Decrease 17%	Increase 23%	Little change	Little change
Efficiency:				
Full load	Increase 0.5 to 1 point	Decrease 2 points	Slight increase	Slight decrease
3/4 load	Little change	Little change	Slight increase	Slight decrease
1/2 load	Decrease 1 to 2 points	Increase 1 to 2 points	Slight increase	Slight decrease
Power Factor:				
Full load	Decrease 3 points	Increase 1 point	Slight increase	Slight decrease
3/4 load	Decrease 4 points	Increase 2 to 3 points	Slight increase	Slight decrease
1/2 load	Decrease 5 to 6 points	Increase 4 to 5 points	Slight increase	Slight decrease
Current:				
Starting	Increase 10 to 12%	Decrease 10 to 12%	Decrease 5 to 6%	Increase 5 to 6%
Full load	Decrease 7%	Increase 11%	Slight decrease	Slight increase
Temperature Rise	Decrease 3 to 4 deg C (5 to 7 deg F)	Increase 6 to 7 deg C (11 to 12 deg F)	Slight decrease	Slight increase
Maximum Overload Capacity	Increase 21%	Decrease 19%	Slight decrease	Slight increase
	Slight increase	Slight decrease	Slight decrease	Slight increase

[a]The starting and maximum running torque of AC induction motors will vary as the square of the voltage.
[b]The speed of AC induction motors will vary directly with the frequency.

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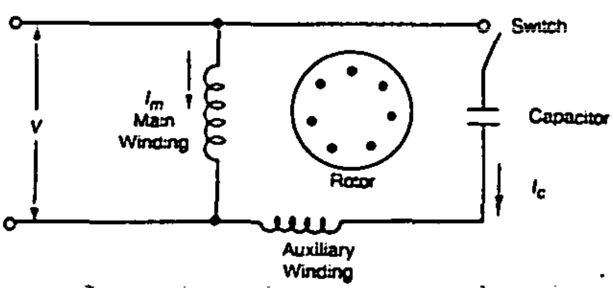


Figure 7-1. Capacitor-Start Motor With a Squirrel Cage Rotor

also increases vibration. Vibration may be transmitted into the atmosphere as acoustical noise or through structural members, and vibration loosens fasteners and causes metal fatigue or chafing. Vibration isolators attenuate the amount of vibration transmitted through the motor mounting. A reduction in transmitted vibration, however, is gained by permitting movement of the motor. This accommodation, however, increases the wear of interconnecting cables that must flex with the motor. Vibration of any apparatus that is attached directly to the motor is also increased.

The actual degree of vibration is difficult to predict since it depends on numerous factors including motor speed, mass of rotating armature, degree of imbalance, and system resonances.

7-2.2.2 Arcing

Motors that have driven coils on the armature couple energy to those coils through slip rings or a commutator. Variations in the height of rotating contact or engine vibration will cause the contact between the brush and slip ring intermittently to open slightly and produce a small arc. This arc, although physically confined to a small area, nevertheless, is capable of igniting flammable atmospheres. Also the intermittent contact and nonlinear action of the arc introduce high-frequency components into the current flow through the commutator. The high-frequency energy then may be conducted through power lines or radiated electromagnetically to interfere with sensitive electronic gear.

7-2.2.3 Elevated Temperatures

Resistive losses in motor windings cause heating of the motor coils. This heat is conducted to the motor case and conducted and radiated to the atmosphere and surrounding objects. The amount of heat lost by the motor is proportional to the input power and the inefficiency of the motor. Increased mechanical loading on the motor shaft increases the power drawn by the motor, which in turn increases the heat dissipated by the motor. Fortunately, efficiencies of electric motors are high so only 5 to 20% of the input power is lost as heat.

The actual temperature rise of the motor is dependent on the heat dissipation and the ventilation around the motor. Layers of dust or dirt insulate the motor, reduce heat dissipation, and cause the motor to operate at a higher temperature. Frequently, thermal protection is incorporated into electric motors and will remove power from the motor when temperature limits are exceeded. The maximum internal temperature the motor is designed to withstand is specified by the insulation class. Insulation Classes A, B, F, and H imply approximate hot-spot temperatures of 105°, 130°, 155°, and 180°C, (220°, 270°, 310°, and 360°F), respectively. Actual exterior temperatures will be somewhat lower, depending on the flow of air across the motor.

7-2.2.4 Presence of Rotating Components

Motors are used to provide rotational energy and, consequently, have rotating components including shafts, pulleys, and fans. The presence of a smooth rotating shaft has little effect on the environment; however, pulleys, couplings, fans, and irregularly shaped components introduce vibration (discussed in par. 7-2.2.1), air circulation, and the potential for entanglement with foreign objects.

7-2.3 HAZARDS

The presence of rotating components constitutes a potential hazard for several reasons. Clothing of personnel may become entangled in unguarded shafts, which will draw the person toward the apparatus and possibly cause serious injury. Unguarded fans or other irregularly shaped objects may not be visible when spinning and may inflict serious injury if personnel or objects come within range of their rotational sweep.

The arcing associated with motor brushes or contacts may ignite flammable atmospheres, i.e., those containing flammable gases or dusts. Even if brushless or sealed motors are used, arcs on opening contacts in motor controllers can set off explosions in a hazardous environment. The damage produced by such an explosion depends on the volume of flammable mixture and the characteristics of the mixture.

Failure of temperature-protection devices—due to overloading or stalling of the motor—or the absence of such devices incur temperature-related hazards. Overheating of the windings occurs, and the motor insulation or nearby flammable materials may be ignited. In less severe cases, the insulation may smolder—releasing dense smoke into the atmosphere—and thereby degrade the integrity of the motor insulation and possibly introduce electrical safety hazards. Cases of extremely high temperatures—193° to 211°C (380° to 412°F)—have been reported for commercial motors operating at rated load (Ref. 3). These temperatures are sufficient to cause severe burns.

An electrical shock hazard may be introduced in electric motors if insulation is damaged due to motor overheating or if interconnecting wiring is damaged by failure of a motor mount. In addition, electrically conductive paths may be introduced into motors through ingestion of metallic particles or fibers into the motor or by moisture. These unintentional current paths may produce hazardous voltages on exposed conductors unless those conductors are properly grounded. Even then, the unintentional grounding of energized windings or conductors may damage the windings.

Vibration associated with motors may produce additional hazards through the degradation of structural integrity of structures associated with the motor. Unless proper precautions are taken, the vibration may cause loosening of fasteners or metal fatigue in motor supports and rotating components. The ensuing mechanical failure can produce damage to nearby equipment, especially if the stored energy in rotating components is released in an unanticipated manner. Possible failures include projectiles thrown from rotating components, wiring or piping damaged through contact with the rotating shaft after the failure of a motor support, or damage to bearings due to misalignment.

7-2.4 PHYSICAL CONFIGURATION AND ENVIRONMENTAL PROTECTION

Most motors are configured to meet the following "normal service conditions" specified in Ref. 1:

1. Ambient temperature between 0° to 40°C (32° to 104°F)
2. Altitude below 1000 m (3300 ft)
3. Installation on a rigid surface
4. Installation where airflow is not restricted.

Other configurations, however, are described to satisfy requirements of environment other than the typical service environment. Some of the configurations identified in Ref. 1 are

1. *Drip Proof.* A ventilated motor protected from liquid or solid particles falling within 15 deg of the vertical
2. *Splash Proof.* A ventilated motor protected from water falling within 100 deg of the vertical
3. *Guarded.* A ventilated motor in which baffles or grilles are incorporated to prevent access to rotating or energized components

4. *Semiguarded.* A ventilated motor provided with guarded construction on the top half but having an open construction on the bottom half

5. *Open, Externally Ventilated Motor.* A motor provided with a separately powered cooling fan

6. *Open, Pipe-Ventilated Motor.* A motor configured so that air is supplied to the motor by a pipe or hose, which can be attached to the frame of the motor

7. *Weather Protected.* A motor designed to prevent the entrance of rain, snow, and airborne particles

8. *Totally Enclosed, Nonventilated.* A motor that is totally enclosed but not airtight with no external cooling mechanism

9. *Explosion Proof.* A motor built to contain an internal explosion without allowing sparks or hot gases to escape

10. *Dust-Ignition Proof.* A totally enclosed motor designed to exclude ignitable particulate matter

11. *Waterproof.* A totally enclosed motor that withstands water from a hose

12. *Totally Enclosed, Air Over.* A totally enclosed motor intended for exterior cooling by a separate ventilation system.

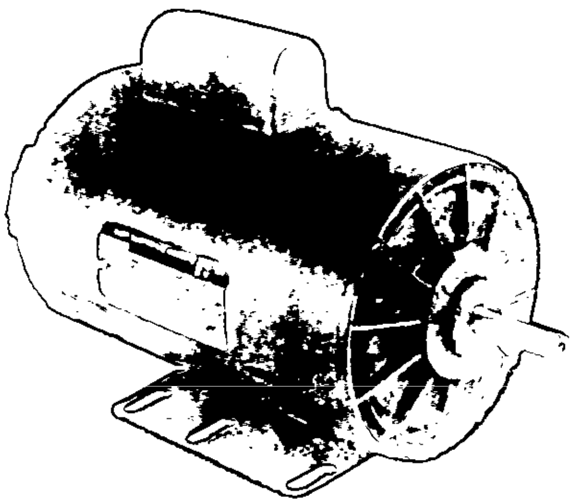
More detailed discussions of these configurations are given in Refs. 1 and 4.

Provisions for environmental requirements generally are made in the motor housing, although modifications to the internal configuration or material selection also may be necessary. Fig. 7-2 shows two representative configurations: a drip-proof motor with ventilation openings only in the lower half of the housing and a totally enclosed motor with a cowl-covered fan, which blows air across the outer surface of the motor. The latter configuration is used in environments containing dust or abrasive particles that might be detrimental to the operation of the motor.

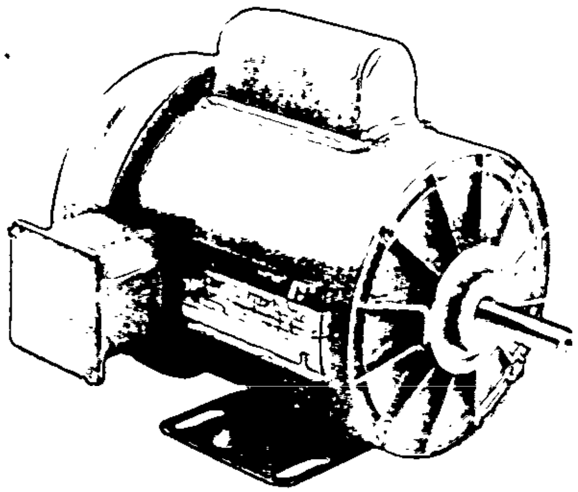
There are alternative motor constructions that enable the cooler, open-frame motors to operate in environments containing dust or abrasive particles. Encapsulating the coils protects them from corrosive chemicals and provides a smooth surface that will not collect particulate matter. Protection to bearing surfaces is provided by the use of shielded or sealed ball bearings. (Shielded ball bearings have shields that cover the space between the inner and outer race. Sealed bearings incorporate additional flexible seals to prevent the leakage of fluids into or out of the bearing.) These bearing types typically do not have provision for lubrication but are packed with high-temperature grease.

Guards or shields must be provided around the motor-driven apparatus to prevent personnel injury due to contact with moving parts or entanglement with clothing. Pulleys, belts, all moving parts—except smooth rotating shafts—should be covered to prevent accidental contact. (See par. 4-4.1.) Ref. 1 requires that openings in a "guarded" motor be no larger than 19 mm (0.75 in.) and that it be impossible to insert a special, jointed, 12-mm (0.5-in.) diameter, 100-mm (4-in.) long probe into the motor in such a way that it will contact a rotating component or a film-insulated wire.

Explosion-proof motors are designed to contain an explosion within the motor enclosure and to release only cool gases to the atmosphere. Explosion-proof enclosures are totally enclosed but are not airtight. The housing is strong enough that an explosion within the atmosphere for which the housing is designed will not damage the case or seams in a way that allows entrapped gases to escape easily. The housing is designed to present a high resistance to gas flow as a means of controlling escaping gases. Upon escaping, the gases expand and are cooled naturally by thermodynamics. To provide the necessary resistance to gas flow, the housing must be strong with close-fitting seams and minimal clearance between the motor shaft and the housing.



(A) Drip Proof



(B) Totally Enclosed Motor

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Figure 7-2. Examples of Motors Configured to Withstand Environmental Conditions

7-2.5 DESIGN CONSIDERATIONS

7-2.5.1 Motor Electrical Protection (Ref. 2)

Protective devices are included in motor circuits to protect the motor and the wiring associated with the motor and to remove power in the event of a line-to-ground fault as shown in Fig. 7-3. Protection devices may be incorporated as either internal or external to the motor.

7-2.5.1.1 External Protection

Protection for motors against overcurrent or overheating is provided by a variety of devices selected in accordance with protection needs. Types of protective devices include the following items:

1. *Fuses*. These devices provide overcurrent protection for lines to the motor and protect the motor against severe faults. A fuse must have a current rating considerably above the rated current of the motor so the fuse will pass the starting current without blowing. Consequently, fuses do not provide adequate overload protection unless the overload is severe.
2. *Magnetic-Type Overload Relays*. These devices are circuit breakers that incorporate time delays so that the short-duration, starting-current surge does not trip the breaker, but a persistent overcurrent condition, even if slight, will cause the line to be opened. The relays provide precise overcurrent protection.
3. *Thermal Overload Relays*. These are externally mounted devices that incorporate a heater and either bimetallic strips or a low melting point soldered support that holds contacts in a closed position. Passage of overcurrent through the heater causes the bimetallic strips to deform and to release the contacts and allows them to open. In the soldered version the overload current melts the solder and allows the contacts to open and interrupt the motor current. These devices possess an inherent delay arising from the time required to heat the assembly. If the time delay characteristic of this protective device closely matches the heating characteristic of the motor, near-ideal protection for the motor is provided.
4. *Low-Voltage Protection or Release Devices*. These devices interrupt the power to the motor during low-voltage conditions to prevent overheating of loaded motors. Low-voltage protectors interrupt the service when the voltage falls below a preset threshold and remain off until the device is manually reset. A low-

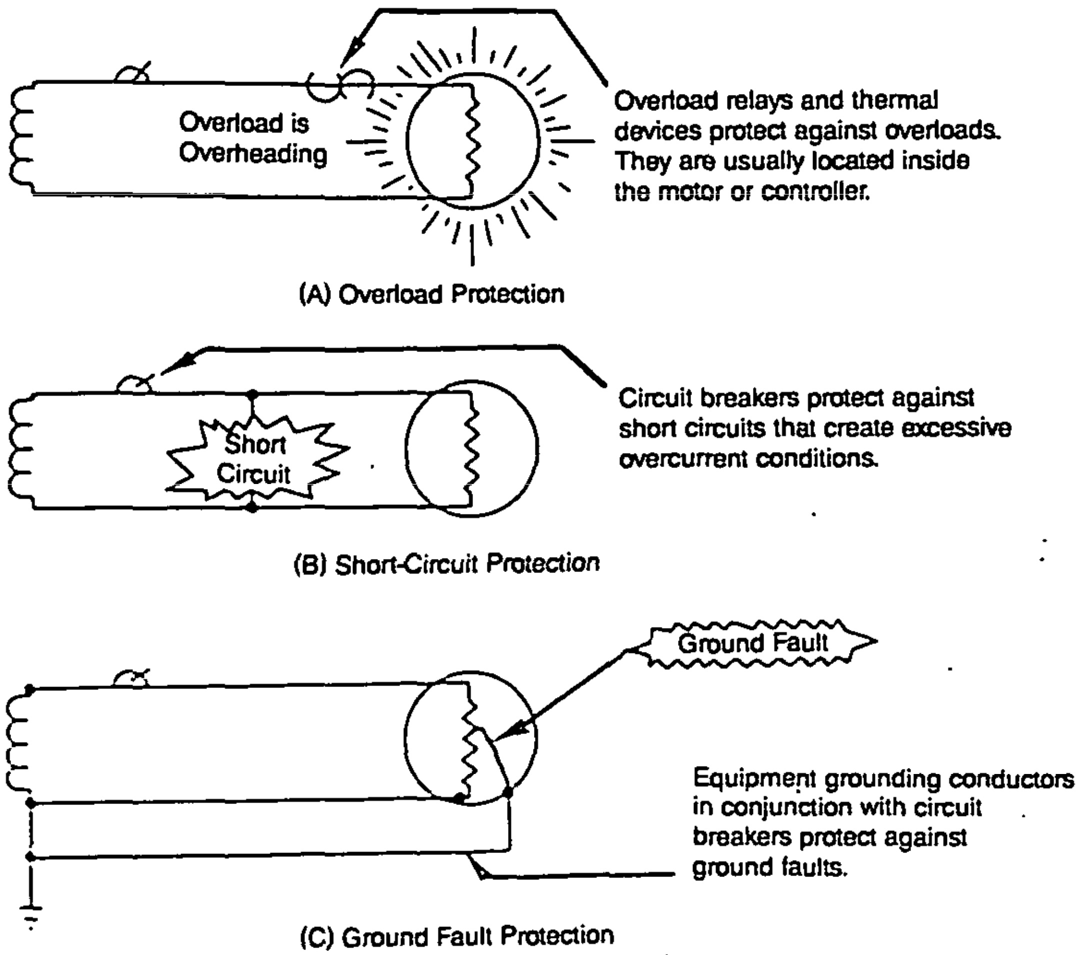


Figure 7-3. Types of Electrical Protection for Motors (Ref. 5)

voltage release device automatically restores power when the voltage returns to the normal level.

5. *Phase Failure Protection.* These devices remove power from all phases when power is interrupted on one phase to prevent overheating of the motor due to imbalanced operation.

6. *Phase Reversal Protection.* These devices remove power from the motor upon detection of a phase reversal condition to prevent the unintended operation of the motor in the reverse direction.

7-2.5.1.2 Internal Protection

Thermal protection can be provided internally to the motor either by thermal fuses or by bimetallic relays that open when exposed to excessive heat from the overcurrent condition or from restricted ventilation in a loaded motor. Motors marked "Thermally Protected" contain protection to insure that the winding temperature remains below the limits specified for the class of insulation under continuous-run conditions and locked rotor test conditions. Also the minimum current sufficient to trip the thermal protective device must be less than a specified percentage of the rated full load current (Ref. 1). The percentage depends on the motor size and is given in Ref. 1.

Motors with internal thermal protection that meet some, but not all, requirements for the "Thermally Protected" rating are marked with "OVER TEMP PROT" followed by a "1", "2", or "3". The "1" designation indicates that the protective device meets winding temperature criteria for continuous current and locked rotor conditions but is not certified to meet the trip current criteria. The "2" designation indicates that the protective device is certified to meet only the continuous current test. The remaining designation, "3", indicates thermal protection is incorporated but that its type and performance are not specified, and performance information must be obtained directly from the manufacturer.

7-2.5.2 Motor Labeling

All motors should be labeled with a permanent marking to indicate the motor characteristics and to designate the internal connection of terminals.

The motor characteristics are identified on a permanently attached nameplate. Listed in Tables 7-4 and 7-5 are the information items that must be included on the nameplate of polyphase squirrel cage motors manufactured according to Ref. 1. The data on this plate provide the means of identifying the characteristics of a defective motor so that a replacement for it can be readily specified. Also the information allows personnel installing the motors to verify that the motor being installed is appropriate. Additional items of information can be marked on the motor to aid during the installation. Information, such as proper wiring connections for different voltages or different operating speeds, or warnings of potential hazards may be specified.

Terminal marking of motors is similar to that of generators; letter designations are given in Table 7-6 (Ref. 1). Typically terminals will be marked with one or two letters

TABLE 7-4
MOTOR NAMEPLATE LABELING (Ref. 1)

Type of Information	Possible Entries or Unit of Measurement
Manufacturer's Name	—
Motor Frame Designation	See NEMA MG-1
Time Rating (expected operating time of motor)	5, 15, 30, 60 min or continuous
Maximum Ambient Temperature	°C
Insulation System Class Stator/Rotor	A, B, F, or H
Motor Speed	rpm
Line Frequency	Hz
Number of Phases	1 or 3
Rated Load	A
Voltage	V
Locked Rotor kVA	See Table 7-5
Design Designation Letter	See Tables 7-1 and 7-2
Efficiency	%
Service Factor (factor by which horsepower rating may be exceeded under specified conditions)	—
"*Thermal Protected*", "OVER TEMP PROT 2", "OVER TEMP PROT 3" (for motors with thermal overload devices)	—

TABLE 7-5
LOCKED ROTOR CURRENT DESIGNATION (Ref. 1)

Letter	VA per Watt Output	kVA per Horsepower
A	0-4.223	0-3.15
B	4.223-4.759	3.15-3.55
C	4.759-5.36	3.55-4.0
D	5.36-6.03	4.0-4.5
E	6.03-6.70	4.5-5.0
F	6.70-7.51	5.0-5.6
G	7.51-8.45	5.6-6.3
H	8.45-9.52	6.3-7.1
J	9.52-10.72	7.1-8.0
K	10.72-12.06	8.0-9.0
L	12.06-13.40	9.0-10.0
M	13.40-15.01	10.0-11.2
N	15.01-16.76	11.2-12.5
P	16.76-18.77	12.5-14.0
Q	18.77-21.45	14.0-16.0
S	21.45-24.13	16.0-18.0
T	24.13-26.81	18.0-20.0
U	26.81-30.03	20.0-22.4
V	30.03 and up	22.4 and up

TABLE 7-6
TERMINAL MARKING FOR MOTORS
(Ref. 1)

Application	Terminal Marking*
AC Rotor Windings	Mn
Armature	An
Brake	Bn
Capacitor	Jn
Control Signal Attached to Commutating Winding	C
Dynamic Braking Resistor	BRn
Field, Series	Sn
Field, Shunt	Fn
Line	Ln
Magnetizing Winding	En
Resistance, Miscellaneous	Rn
Resistance-Shunt Field	Vn
Shunt Braking Resistor	DRn
Space Heaters	Hn
Stator	Tn
Starting Switch	K
Thermal Protector	Pn

*n is a sequential number to distinguish connections to different phases, components, or ends of a component. (See par. 4-4.6.)

followed by a number. The letters designate the winding or component connected to the terminal, and the number indicates which ending of the winding or which of several windings is brought out. Multiple stator windings in polyphase motors are numbered in the manner shown in Fig. 4-2. Where a terminal is intended to be connected to neutral, e.g., a common internal connection of three-phase windings, the number zero is used.

7-2.6 COMPATIBILITY AND INTEROPERABILITY

Because of the proliferation of motors in commercial, industrial, and residential applications, the standardization provided by NEMA-MG-1 (Ref. 1) has been readily accepted by US motor manufacturers and consumers. This specification defines motor types, standard dimensions, mounting provisions, shaft configurations, and labeling, as well as performance requirements. Sufficient variations in motor configurations are provided under Ref. 1 so that motors for a wide latitude of applications may be procured under this broad specification, which covers a variety of AC and DC motor types. Some of these types are

1. *AC Motors*. Fractional and integral horsepower; single- and polyphase; and induction, synchronous, universal, and definite purpose configurations
2. *DC Motors*. Fractional and integral horsepower; and series-wound, shunt-wound, compound-wound, or permanent magnet configuration.

The International Electromechanical Commission (IEC) publishes motor standards, which are currently used in Western Europe. Major differences between the IEC and National Electrical Manufacturers Association (NEMA) standards are

1. Use of metric units in IEC standards
2. Allowable temperature rise with Class F insulation
3. Measurement of temperature rise by imbedded sensor.

Selected IEC specifications are given in Refs. 6 through 14. Differences between IEC and NEMA specifications are discussed in Ref. 15.

NEMA MG-1 specifies various performance characteristics for motors or methods of expressing characteristics that may vary with design, e.g., locked rotor current. Characteristics discussed in this specification that must be specified appropriately for a given application are

1. Power output (operating voltage, phase configuration)
2. Speed(s)
3. Torque (locked rotor, pull-up, breakdown)
4. Current (operating, locked rotor)
5. Physical dimensions (case or frame size, mount, shaft)
6. Labeling.

In most applications it is sufficient to specify the motor frame size, enclosure type (environmental protection), speed, power, motor types, and shaft configuration to provide sufficient information to obtain a replacement compatible with the original. Some applications, however, will accommodate a wide latitude of replacement motors, whereas others can use only an extract replacement, especially motors that are definite or special purpose machines.

Operation of motors under conditions that differ from the design conditions should be attempted with care. Of particular importance are the voltage and frequency requirements specified for the motor. The following considerations should be reviewed before operating a motor under conditions other than those for which the motor was designed:

1. If the motor is operated at rated horsepower at a voltage 10% higher or lower than rated, the motor will dissipate more heat, which may lead to premature insulation failure if this operation continues for extended periods.
2. Locked rotor and breakdown will increase with the square of applied voltage.
3. Operation at a higher-than-normal frequency decreases torque and increases losses and speed. For some motors close regulation of speed may be essential.
4. If a 60-Hz motor is operated at 50 Hz, the applied voltage and output load should be reduced by 5/6. Speed will be 5/6 of the rated speed.

7-2.7 TEST CRITERIA FOR DESIGN AND ITEM ACCEPTANCE

A series of tests has been developed to verify specified performance and to evaluate service-life performance. These tests are summarized briefly as follows:

1. *Running Light Test*. The unloaded motor is excited at various voltage levels, and power input and current are measured. Power drawn from the line under these conditions is due to winding resistance, friction, and windage losses. Graphical analysis of the data is used to

compute electrical resistance losses, mechanical losses, and efficiency estimates.

2. *Locked Rotor Test*. The motor under test is rigidly mounted so that the armature cannot turn, but the torque it exerts can be measured. Additional instrumentation is attached for measurement of line current and voltage. The measured current, called locked rotor current, is indicative of the loaded starting current; the measured torque indicates the load that may be started by the motor.

3. *Temperature Rise Tests*. The motor is operated at a rated load and ambient temperature until an internal temperature equilibrium is established. The motor is then shutdown and additional temperature measurements are made on rotating components and other components that are inaccessible when the motor is operating. Alternatively temperature measurements may be made by measuring winding resistance immediately after shutdown or during operation using a Seeley bridge. The measured temperature data indicate whether the temperature limits of the insulation will be exceeded during operation of the motor at a rated load.

4. *High-Potential Tests*. Overvoltages are applied between windings and the case to test the integrity of the insulation. Low resistance readings indicate possible susceptibility to a fault or excessive leakage resistance.

5. *Balance and Vibration*. The motor is operated in a specified mounting condition. The vibration amplitude and/or noise generated are (is) measured.

6. *Power Output Torque*. The motor under test is coupled to a prony brake or gimballed dynamometer having an arm of known length extending laterally to a scale. The load on the motor is varied by adjusting the friction of the brake or the electrical load on the dynamometer. Recorded values of motor speed and torque are plotted and analyzed to determine the suitability of the motor for applications with specified speed-torque requirements.

Additional information on test procedures is given in Refs. 16 and 17.

7-2.8 OPERATIONAL CHARACTERISTICS (Ref. 18)

When delivered, motors are lubricated with greases selected to withstand the operating temperature of the motor. Lubrication of the motor after installation with a different type of grease could reduce the lubricating properties of the original grease if the two lubricants are not compatible. Therefore, the motor should be procured with the same lubricant to be used during periodic maintenance, or the manufacturer's recommended lubricant should be procured for periodic maintenance.

Motors should be kept free of dust and dirt since these materials reduce heat dissipation and may increase wear of bearing surfaces. If dust mixes with oil or grease in the motor, a gummy mixture can be produced, which is difficult to remove and is a fire hazard if the motor overheats or arcing develops. Dust should be removed periodically by wiping, vacuum cleaning, or blowing off with low-pressure, compressed air.

Motors should be lubricated according to the manufacturer's recommendations. Oils, however, should be applied only to points at which lubrication is desired. Oil should be kept off the commutators because it deteriorates the mica insulation and increases sparking at the brushes. Also, oil should not be allowed to collect on surfaces since it tends to hold dust, lint, and dirt in place and thereby creates a fire hazard.

Unless the motor is designed for operation in the presence of moisture, the motor should be protected from water to prevent development of hazardous electrical leakage paths. If frequent cleaning with water is anticipated, either a sealed motor should be used or the motor should be mounted such that the cleaning water will not enter the motor. Prevention of exposure to moisture can be accomplished by training personnel or by relocating equipment.

Belts and chain drives should be inspected regularly for appropriate tension and condition, and gearing should be checked for bearing wear and binding. Overtension in belts or bindings will shorten bearing life. Excessive looseness may allow belts or chains to slip off pulleys and sprockets. Slight changes in mounting position could cause misalignments that introduce excessive vibration or bearing wear. Also electrical connections should be checked to insure that they have not become loose due to vibration and that wiring insulation is not worn or cracked.

It is important that polyphase motors be operated from balanced power sources since the maximum power that can be delivered by the motor declines rapidly with increasing voltage imbalance. As shown in Fig. 7-4 (Ref. 1), a voltage imbalance of 5% reduces the maximum power output of a motor by 25%, as well as increasing the temperature rise of the motor.

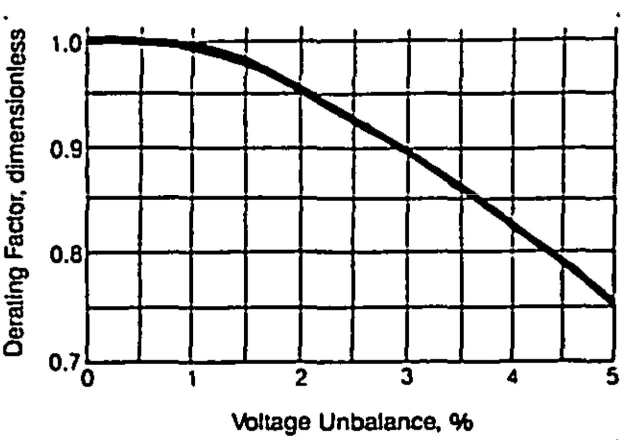


Figure 7-4. Integral Horsepower Motors Derating Factor Due to Unbalanced Voltage (Ref. 1)

7-3 TRANSFORMERS

7-3.1 INTRODUCTION

The transformers covered in this paragraph are required to supply end-item equipment with voltages different from the normal distribution voltages or to provide ground isolation. Normal distribution transformers are discussed in par. 5-3. These transformers include small transformers that produce single-phase power (120/240 Vac) where only three-phase power is available; small transformers that supply a wide range of voltages for electronic equipment; and specialized transformers required for DC power supplies, arc lights, and control equipment.

Examples of specialized transformers are (Ref. 2)

1. *Power Transformers.* Incorporated into electronic or power apparatus to provide voltages required for operation
2. *Rectifier Transformers.* Provide power, up to 15,000 kVA, to rectifier assemblies for DC motors and electrolytic processes
3. *Phase-Shifting Transformers.* Provide power in 6, 12, or even 24 phases from conventional 3-phase lines. Power from the larger number phase configurations, when rectified, has less ripple than the conventional 3-phase configuration.
4. *General-Purpose Specialty Transformers.* Dry-type distribution transformers that supply low-voltage loads, single-phase or three-phase, from secondary-distribution networks that provide power at higher voltages or in a different phase configuration
5. *Control Transformers.* Low-voltage transformers used to power solenoids, relays, indicator lamps, and control apparatus
6. *Class 2 Transformers.* Power-limited transformers that are used in signaling circuits.

7-3.2 INDUCED ENVIRONMENT

The transformers required by end-items are generally small, and therefore, vibration and magnetostriction noises are not significant. They are usually located in very confined spaces, however, and cause a rise in the ambient temperature. The iron in the transformers operates near the knee of the saturation curve, and there are stray magnetic fields that may be troublesome when used where space is limited.

If step-up transformers are used to increase voltage, the high voltage is an environmental concern due to the increased possibility of arcing or corona.

7-3.3 HAZARDS

Transformers used with specific end-items are physically smaller than distribution transformers and operate at lower power levels, and the hazards associated with end-item transformers are similar to those discussed in par. 5-3.2. Although hazards are reduced somewhat because of the smaller capacity of these transformers, potential damage is increased because these transformers are often mounted in or near equipment in inhabited areas. Specific hazards associated with end-item transformers are

1. Short circuits (faults) or overload conditions in the primary circuit of the transformer can lead to overheating of the transformer and, in turn, to insulation deterioration. Possible damage includes development of faults within the transformer, minor smoke damage in the vicinity of the transformer, or ignition of nearby flammable materials.
2. Energized conductors at the transformer terminals present an electrical shock hazard to persons in the vicinity. If the transformer insulation fails, hazardous voltages could be applied to exposed conductors, such as enclosures or wiring conduit, unless those conductors are grounded.
3. Older transformers using oil-filled or oil-impregnated construction may contain PCB, a known carcinogen. Case leakage caused by corrosion, external physical damage, or severe overload may allow carcinogenic material to escape and expose personnel to this hazardous substance.
4. Leakage of flammable insulating oils increases the hazard of fire accompanied by the possible emission of toxic gases. This is particularly important if the transformer is located inside a building. PCB contamination from a burning transformer located inside a building could result in the loss of the building.
5. Overloading transformers can produce heating sufficient to scorch, ignite, or vaporize insulation materials and release smoke and gases that in confined spaces may be toxic or irritating to personnel and may coat electrical contacts.

7-3.4 DESIGN CONSIDERATIONS

Design considerations for end-item transformers are similar to those for distribution transformers; however, allowances must be made for their smaller construction and for the protected environments in which the end-item transformers are used. Considerations other than those described in this paragraph must be taken into account if a transformer with unique requirements is designed for a special purpose.

7-3.4.1 Enclosures

Transformers that are not to be incorporated into equipment should be enclosed in a housing, which must provide the required environmental protection for the transformer and enclosing all energized conductors to prevent inadvertent electrocution. Typically, dry transformers used indoors either have exposed lamination with covers to prevent access to the windings and terminals or the entire transformer core and coil assembly is mounted in an enclosure with openings to permit the passage of air and cabling. Enclosure openings should be covered with a screen or grille to prevent the insertion of fingers or metallic objects into the enclosure and inadvertent contact with any energized conductor that is bare or covered with film insulation.

7-3.4.2 Electrical Isolation (Primary to Secondary)

Transformers used to provide electrical isolation must be designed so that (1) the only significant coupling mechanism between the primary and secondary is the desired inductive coupling and (2) insulation between windings is sufficient to achieve the desired interwinding breakdown voltage. The reduction of coupling mechanisms, especially electrostatic coupling, frequently is required to reduce unintentional electrical leakage currents. Reduction of leakage currents is especially important in hospital electrical equipment that may be in contact with patients. High-voltage insulation between windings is necessary for transformers in power supply circuits for which the secondary is maintained at a high-voltage DC bias relative to the primary or for which impulse transients from the primary source are anticipated. Capacitive coupling is reduced by separating the windings on the core and placing an electrostatic shield between them. The shield should be a sheet of a high-conductivity material physically placed to reduce capacitive coupling between the two windings.

Interwinding dielectric strength is provided by adding additional insulation between windings and between windings and the core. The additional insulation increases leakage resistance as well as dielectric strength.

7-3.4.3 Labeling

Transformer terminals should be marked clearly either by winding designation letters adjacent to the terminals or by mounting a physical layout diagram of the terminals on the transformer to show the relative positions of the terminals and the designations for each.

Terminal labeling, as specified in Ref. 19, consists of one or two letters followed by a numerical subscript. The letters indicate the winding: "H" or "HV" for the high-voltage primary and "X" or "LV" for the low-voltage secondary. Secondary windings, in order of decreasing voltage, are noted by "X", "Y", and "Z". The subscripted numbers indicate the relative phase in polyphase circuits, numbered in the order that the lines reach their crest voltage. Terminals intended for connection to the neutral are indicated by the subscript "0".

Information about transformer characteristics—e.g., capacity, power requirements, and important connection information—should be marked permanently on the nameplate of the transformer. An example of the nameplate information required by Ref. 20 is shown in Table 7-7.

7-3.5 COMPATIBILITY AND INTEROPERABILITY

Depending on the environment in which the transformer is mounted, the cooling classification may be an important criterion in the selection of a replacement transformer. The cooling class may be an important criterion in the selection of a replacement transformer. The cooling classes for dry transformers are (Ref. 21)

1. *Class AA*. Ventilated dry-type, self-cooled
2. *Class AFA*. Ventilated dry-type, forced air-cooled
3. *Class AA/FA*. Ventilated dry-type, self-cooled or forced air-cooled
4. *Class ANV*. Nonventilated dry-type, self-cooled
5. *Class GA*. Sealed dry-type, self-cooled.

TABLE 7-7
NAMEPLATE INFORMATION REQUIRED FOR DRY-TYPE DISTRIBUTION AND POWER TRANSFORMERS (Ref. 20)

Serial Number
Cooling Class
Number of Phases
Frequency
kVA Rating
Voltage Rating
Tap Voltages
Temperature Rise in °C
Polarity Information (Single-Phase)
Phasor Diagram (Polyphase Diagram)
Percent Impedance
Basic Impulse Insulation Level (BIL)
Approximate Weight
Connection Diagram
Name of Manufacturer
Reference to Installation and/or Operation Instructions

For replacement applications, transformers must have the same number of phases, the same voltage rating, and the same or higher capacity. In addition, the replacement transformer must have compatible mounting provisions and, if located in a confined area, must operate with the same or a smaller temperature rise. Transformers can be operated at a slightly higher frequency. For example, a transformer designed for 50-Hz operation may be operated at 60 to 400 Hz. The transformer, however, must be derated—because of the core saturation effects—if it is operated at a lower frequency.

If the transformer is to be operated in parallel with existing transformers, the preceding conditions must be satisfied and the transformer-turns ratio—as determined from voltage tests—and transformer loss characteristics must be matched to insure equitable load sharing between the transformers.

7-3.6 TEST CRITERIA FOR DESIGN AND ITEM ACCEPTANCE

Transformer acceptance tests are described in detail in Ref. 21. The most important tests are the voltage-ratio tests, the no-load excitation test, and the full-load current test—all were described for distribution transformers in par. 5-3.5.

Table 7-8 lists the tests and indicates whether the recommended test is a routine manufacturing or acceptance test or is a test performed on selected samples to verify design adequacy. The type of transformer and its intended application determine which type of test is appropriate. For large transformers, tests for distribution transformers are used to verify that a new transformer has been received without damage and to provide baseline data for comparison with data taken during future tests.

For smaller transformers, testing for losses may not be justified because the power losses in a single transformer are small. However, tests, such as winding polarity, that

TABLE 7-8
RECOMMENDED TESTS FOR DRY-TYPE POWER AND DISTRIBUTION TRANSFORMERS (Ref. 21)

Test	Reason for Test
Winding Resistance	Design Verification
Ratio	Routine
Polarity and Phase Relationship	Routine
No-Load Losses and Excitation Current	Routine
Impedance Voltage and Load Loss	Design Verification
Temperature Rise	Design Verification
Dielectric Tests	
Applied	Routine
Induced	Routine
Impulse	Design Verification
Power Factor	*
Insulation Resistance	*
Audible Noise Level	Design
Short-Circuit Current Capability	*
Mechanical	Routine

*Sometimes required by transformer specifications

can be performed easily and that might prevent improper connection of the transformer, especially in polyphase or paralleled configurations, can be justified.

Appropriate tests for newly designed transformers for use indoors or in confined areas are flammability tests. These tests determine whether the insulation materials used in the transformer could be ignited through a fault or overload condition in the transformer, and they determine the gaseous materials that would be released. These tests have been performed on dry transformers, which use a cast insulation material to encapsulate the coils, to confirm that this construction does not increase fire or health hazards (Ref. 22).

7-3.7 OPERATIONAL PRECAUTIONS

Appropriate installation and mounting of a transformer depends largely on the type of transformer and the environment in which it is to be used. For small transformers used in electronic equipment, major considerations are that adequate ventilation is provided for cooling of the transformer, that vibration-resistant fasteners are used, that the associated wiring is protected adequately, and that overcurrent protection is sized appropriately to protect the transformer.

For larger transformers used to provide power to a large end-item or to a collection of loads, a location must be selected that provides environmental protection commensurate with the construction of the transformer. Weatherproof transformers require minimal environmental protection; however, ventilated dry units must be protected from moisture. Transformers must not be installed near flammable materials—a precaution to prevent overcurrent conditions from introducing a fire hazard. Adequate ventilation must be provided if the manufacturer's capacity ratings are to be realized. Large transformers mounted indoors must be located in a fireproof room, which should not be used for storage (Ref. 23) and should be labeled to indicate that high voltage is present.

A transformer provides ground isolation between primary and secondary circuits. Even if the primary circuit is appropriately ground, the neutral connection on the secondary must be grounded to prevent buildup of hazardous voltages between line conductors and ground and to allow overcurrent devices to interrupt circuits containing faults. Neutral connections and transformer cases must be connected to a group through a ground conductor that is sized in accordance with the secondary power conductors. The National Electrical Code (NEC) (Ref. 23) requires a minimum size American Wire Gage (AWG) No. 8 copper condition, or AWG No. 6 Aluminum, for grounding systems wired with AWG No. 2 or smaller wire. (See par. 3-3.3.)

Maintenance of transformers is minimal provided the transformers are operated within their ratings and are not exposed to an environment more severe than the transformer is designed to tolerate. Maintenance is limited to periodic inspections for overheating, loose connections, broken or cut insulation, and other abnormalities that indicate a potential operational problem.

7-4 HEATERS

7-4.1 INTRODUCTION

The electric heaters discussed in this paragraph are resistive devices that convert electrical energy directly to heat through the "I^2R" loss. Electrically driven, mechanical heating systems, such as heat pumps, are not discussed in this paragraph.

Electric heaters use one or more of the three heat-transfer mechanisms—i.e., radiation, convection, or conduction. The first two mechanisms are the most commonly used with electric heaters. Conductive transfer is sometimes used to transfer heat from the heating element through a retaining vessel to the medium, usually a liquid, to be heated.

Heaters are available in many forms to accommodate a variety of power requirements and physical settings. Several examples of different forms of heaters are

1. Portable space heaters
2. Space heating for a building of several rooms
3. Water heating for both rooms and laundry
4. Environmental conditioning unit in equipment or maintenance van
5. Electric ranges and ovens.

Radiant heat to warm small rooms or food can be provided by an infrared electric lamp. These lamps typically draw about 300 W and may be installed in a conventional, 300-W lighting fixture.

Portable space heaters that heat a single room range in power from 500 to 2500 W and typically are equipped with a line cord and plug for connection to convenience outlets. Units are manufactured with fans for heating by convection or without fans for predominately radiant heating. Most portable heaters are thermostatically controlled.

Heaters can be liquid filled to distribute the heat from a relatively small heating element to a much larger outer surface to allow operation with lower surface temperatures. The liquid insures that the temperature of the outer case remains below the boiling temperature of the liquid provided the heating element is totally immersed. Liquid-filled heaters are used in portable applications and in permanent installations.

Heaters capable of heating an entire building are available in many sizes. Heating requirements of a building depend upon the cubic footage of the building, type of construction, amount of insulation, lowest ambient temperature expected, number of occupants, amount of activity of outside doors, amount of outside air used in the ventilating system, and several other factors. Heat can be supplied by resistor-heater strips and/or heating elements distributed in the duct work of a forced air ventilation system.

Water heaters are available in a number of sizes. Selecting size and power depends upon the hot water requirements of the installation.

7-4.2 INDUCED ENVIRONMENT

The obvious impact of heaters on the environment is the elevation of ambient temperature. For air heaters the temperature rise is dependent on many interrelated factors including the power dissipated in the heater, the temperature of the heater, characteristics of the surface of the heater, and the velocity of the airflow across it. Because of the poor thermal coupling between surfaces and air, the surfaces are usually heated to high temperatures to permit an adequate transfer of heat to the air. The high temperatures can also heat other parts in mechanical contact with the heaters unless proper insulating techniques are used.

Heaters that are used for heating liquids on solid objects, e.g., water heaters and crankcase heaters, also heat the environment due to the coupling between the heated object and the atmosphere. Temperature rise near the heating element may be significant if the heated object is not insulated and the airflow across it is restricted.

7-4.3 HAZARDS

If forced air heaters are placed too close to an object that restricts the normal airflow, the element of the heater operates at a temperature that is higher than the temperature for which the heater was designed. Overheating the element can cause deterioration of insulation, loosening of power connections, or release of toxic fumes from insulation and case lacquer. The guarding screen over an electric air heater can be heated to the point of being a hazard to personnel. Also improper placement of portable heaters can ignite nearby flammable materials.

Heaters that contain liquid can overheat if the heater has lost its liquid for any reason. The thermostat sensing element may depend upon total immersion to function properly; if the thermostat fails, the heater can overheat. Another hazard in liquid-filled heaters occurs if the vessel ruptures. If personnel are nearby at the time of rupture, severe burns can be inflicted.

As with any electrical apparatus, electrical shock from heaters is a potential hazard. This is especially true with heaters because heating element terminals frequently are uninsulated due to the expense of insulating conductors to withstand the operating temperatures. Electrical shock also may occur if open-air heating elements overheat and droop to contact adjacent surfaces. If the surfaces are not grounded, the metal enclosure may assume the potential of the heater at the point of contact. Likewise, loosening of connections from thermal cycling or corrosion can lead to failure of those connections. The unsupported wire may fall from the connection, contact other conductors, and possibly energize them.

7-4.4 DESIGN CONSIDERATIONS

7-4.4.1 Heater Configurations

From the perspective of safety, the primary considerations in designing heating units are to select materials that function properly at the high temperatures required for heating and a configuration that, in the event of failure, minimizes hazards. Electric heaters function over a range of temperatures and can be classified as follows (Ref. 24):

1. Low Temperature. Up to 425°C (800°F)
2. Medium Temperature. From 425° to 1150°C (800° to 2100°F)
3. High Temperature. Above 1150°C (2100°F).

Materials commonly used for heating elements and their respective normal, maximum operating temperature are listed in Table 7-9.

Open-air heating elements must be supported at frequent intervals to prevent the elements from sagging and contacting metallic support structures or other features that could be affected by high-temperature elements. The

TABLE 7-9
OPERATING TEMPERATURE OF HEATING ELEMENT MATERIALS (Ref. 2)

Material	Maximum Operating Temperature °C	°F
ASTM Alloy B82 (Ni-Cr)	1150	2100
ASTM Alloy B83 (Ni-Cr)	900	1650
Silicon Carbide*	1500	2700
Molybdenum*	1650	3000
Tungsten*	2000	3600
Graphite*	600	1100

*These materials are used typically for the filament or rod in resistor (or metal sheath) heaters. The element of the heater is placed in a metal (stainless steel) tube packed with magnesium oxide. This configuration protects the heating material from contamination and allows direct immersion in liquids.

insulating supports are usually fabricated from a refractory ceramic that can withstand the large temperature gradients induced in heaters. Heaters should be placed only where the element is protected during operation. If this is not possible, the heater enclosure should be designed to provide adequate mechanical protection to the heating elements and supports to prevent objects from contacting either the heating element or its supports. Such contact could induce an electrocution hazard, a fault, or mechanical damage to the supports.

In applications involving vibration, immersion, or in which the heater may be subjected to mechanical damage, a metal-sheathed heater should be used. In this configuration the resistive heating element is placed in a protective tube packed with a solid electrical insulation material to prevent contact between the electrically energized element and the sheath while conducting the heat. This configuration also is used where good thermal contact between the heating element and the solid object to be heated is required. Various physical configurations are available, including rods and bolt-on strip heaters. Steel-sheathed units can be operated at temperatures up to 400°C (750°F) and dissipate 15 kW/m^2 (10 W/in.^{2}). Sheath materials with improved corrosion resistance may be operated at higher temperatures. Porcelain-enameled steel or alloy steel sheaths can be operated up to 650°C (1200°F) and dissipate up to 23 kW/m^2 (15 W/in.^{2}) (Ref. 2). Temperature limits for other commonly used materials are summarized in Table 7-10 (Ref. 25).

The insulation used in sheath heaters is usually magnesium oxide with porcelain bushings at the ends to support the element and protect the magnesium oxide. The minimum insulation thickness is 0.41 mm (0.016 in.) for elements used at 300 V or less and 0.79 mm (0.031 in.) for elements rated between 300 and 600 V.

7-4.4.2 Heater Protective Devices

The heating apparatus should incorporate screens or guards to protect the elements from inadvertent contact by personnel. The distance between the guards and the element should be sufficient to prevent the guard from being a burn hazard to personnel.

Overcurrent and overtemperature protection should be provided for the heating apparatus. Overcurrent protection protects against faults that may be induced through the accelerated aging of insulation materials in a high-temperature environment and, in the event of a line-to-ground fault, prevents damage by interrupting the supply current.

Overtemperature protection should be provided to inhibit dangerously high temperatures that could occur from thermostat and/or controller failure or blockage of the air ventilation to the heating element. This protection may be provided by thermal fuse or overtemperature limit switches. The thermal fuse is a conventional fuse with an element that melts at a specified temperature. When the ambient temperature exceeds the melting point of the element, it melts to interrupt the current flow in a manner similar to that of the more conventional fuse. The overtemperature limit switch is a latching thermostat set to some temperature above the normal operating temperature of the heating element. When the ambient temperature reaches the set point, switch contacts are opened and remain open until they are reset manually.

Additional protective devices should be provided for enclosed vessels and portable appliances. Vessels that operate under pressure, e.g., water heaters, should be equipped with overpressure devices to allow liquid to escape through a prepared path in the event of overheating. These devices are intended to prevent rupture of the tank, which can occur if no escape mechanism is provided. Portable heaters such as space heaters should be equipped with "level" switches that prevent operation if the heater is not upright. These devices stop operation of the heater when it is tipped over and thus prevent ignition of nearby floor coverings or materials.

7-4.4.3 Heater Element Size Selection

The selection of the size of the heating element is determined by an analysis of heat transfer characteristics based on energy conservation, i.e., the energy supplied by the heater must equal the amount of heat carried away by

TABLE 7-10
TEMPERATURE LIMITS FOR SHEATH MATERIALS (Ref. 25)

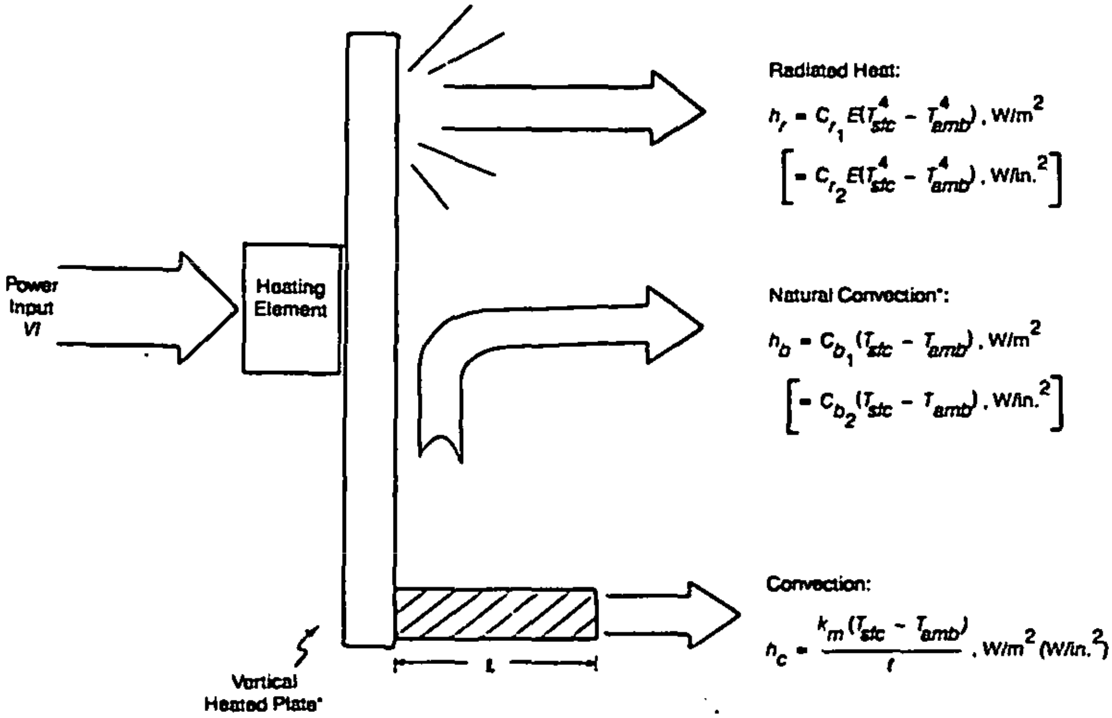
Sheath Material	Maximum Temperature °C	Maximum Temperature °F
Copper	175	350
Aluminum	260	500
Brass	400	750
Cold Rolled Steel	400	750
Nickel Silver	540	1000
Stainless Steel*		
302, 303, 304, 316, 321, 347	760	1400
309S	815	1500
310	870	1600
403, 405, 410, 416, 501	650	1200
430	705	1300
442	760	1400
446	815	1500
Nickel Alloys**		
400	482	900
600	980	1800
800	925	1700
825	590	1100
840	925	1700

*American Iron and Steel Institute (AISI) type designations
**American Society of Mechanical Engineers (ASME) type designations

the heated fluids and conduction. The quantity of heat dissipated is proportional to the temperature of the heated unit. The temperature is established by an equilibrium condition in which the heat input balances the heat output. These relationships for a simple geometry are illustrated in Fig. 7-5 (Ref. 2).

Temperatures in typical applications, however, are more difficult to analyze because of uncertainties in airflow patterns and complex factors such as thermal resistance at junctions. For small applications heater capacities are determined through rough approximations, and heaters with slightly larger capacities are installed. Such heaters are operated from a variable voltage source to observe (1) the temperature of the heating element and (2) the temperature of the object or fluid stream to be heated. The power input to the heater is increased until the desired temperature of the heated medium is reached without exceeding the thermal limitations of the heating element. If the desired heating cannot be obtained without exceeding the temperature limit of the heating element, then either a higher temperature element must be used and/or the thermal coupling between the heating element and the heated object must be improved.

Terminations for heating elements should be capable of withstanding the temperature cycling and extremes associated with the heating element. Typical element connection problems are permanent deformation and subsequent loosening of connections due to the expansion and contraction of the material caused by thermal cycling. The temperature extremes promote accelerated corrosion



*Assumes vertically oriented plate with height = 0.3 m (12 in.)

h_r = heat loss through radiation, W/m^2 (W/in.^{2})
h_b = heat loss through convective cooling, W/m^2 (W/in.^{2})
h_c = heat loss through conduction, W/m^2 (W/in.^{2})
E = relative emissivity of surface (1 = blackbody; 0 = mirror surface), dimensionless

C_{r_1} = constant = 5.69×10^{-8} W/m^2·K^4
C_{r_2} = constant = 0.35×10^{-11} W/in.^{2}·R^4
C_{b_1} = constant = 2.26 W/m^2·K
C_{b_2} = constant = 8.10×10^{-4} W/in.^{2}·R

T_{stc} = temperature of heated plate, K (R)
T_{amb} = temperature of ambient or sink, K (R)
k_m = thermal conductivity of material, W/m·k (W/in.·R)
ℓ = length of thermal conductor, m (in.)

Figure 7-5. Heat Flow Diagram for Vertical, Heated Plate (Ref. 2) rates for materials used in high-temperature environments. Appropriate connection techniques include bolted and crimped connections. Terminations for heating elements also require a nonmetallic grommet to protect against damage from vibration. Teflon (polytetrafluoroethylene) grommets should not be used because the initial thermal decomposition products can result in an acute illness termed "polymer fume fever", the symptoms of which include headache, nausea, aching, weakness, chills, and fever.

All materials used in bolted connections or terminations should have reasonably matched coefficients of thermal expansion or should have an elastic member, e.g., spring washer, that maintains pressure on the electrical connection as components expand and contract.

Crimp connections can be made if appropriate materials are used. Nickel is commonly used at temperatures up to 650°C (1200°F) with iron, manganese-nickel, nickel-chromium, or nickel conductors (Ref. 26).

7-4.4.4 Markings for Heaters

Permanent markings should be placed on all heaters and heating elements and should include information about operating voltage, power, and a manufacturer's identification number or symbol. Other markings may be necessary to warn of possible hazards. Examples of appropriate markings are

1. "Bottom" and "Top" for units that should be mounted in only one orientation
2. Heaters powered by several sources should have a placard indicating the number of sources to be disconnected before service should be attempted.
3. A high-voltage warning should be placed on units that have removable covers that expose energized conductors.
4. Special wiring considerations, such as minimum temperature rating of the insulation or use of copper wire (only), should be noted to prevent use of materials that might deteriorate in that environment.
5. A warning against placing a portable heater too close to a wall, drapery materials, or other features that would introduce a fire hazard
6. Warning of hot surfaces
7. Warning that all removable components must be in place before operation
8. A sign with the format shown in Fig. 4-4 should be used to warn about heated surfaces that are not visibly hot because of their physical configuration. This sign should be located on the nearest permanent, cool surface, i.e., not on a removable guard, or if placed on a heated surface, it should be constructed to withstand the surface temperature.

The application warnings are discussed more completely in Ref. 27.

7-4.5 COMPATIBILITY AND INTEROPERABILITY

Heaters and heating elements tend to be designed for specific applications, and consequently, there has been little standardization in heater design. There are, however, some high-volume applications for which standard heater elements can be used, e.g., water heater.

The characteristics that describe a heater and should be specified to define a unit suitable for a given application are

1. Operating voltage
2. Power consumption
3. Phase configuration
4. Physical configuration, e.g., size and mounting provisions
5. Temperature limit
6. Special limitations, such as restrictions on mounting orientation and support
7. For forced air heating assemblies, airflow and the maximum impedance of the flow path.

7-4.6 TEST CRITERIA FOR DESIGN AND ITEM ACCEPTANCE (Ref. 27)

The following sequence of tests is an example of tests performed to verify the safe operation of heaters:

1. Measure current and watt input while the heater is energized at nominal voltage and frequency.
2. Test the case housing or enclosure for leakage current and voltage aboveground. Repeat with heating element heated and at ambient temperature. The objective of this test is to identify sources of leakage currents that could become hazardous to personnel if the heater case is not grounded.
3. If the forced air heater is to be attached to a particular piece of equipment, verify that the reduction of airflow resulting from this interconnection does not overheat the heater, its motor, and the heater case.
4. Verify operation of safety devices, such as tip-over switches for portable heaters and thermally activated fuses because such devices, if inoperative, can provide a false sense of security and possibly lead to severe hazards if excessive reliance is placed on their performance.
5. For portable air heaters, measure the temperature of protective guards or screens to insure that burns or fires will not be produced from incidental contact.
6. Verify that operation of a portable heater does not introduce the hazards of fire, electrical shock, or personnel injury when operated under conditions of excess power voltage, burned-out element, tip-over, or improper placement, e.g., near wall or furniture. Likewise, checks for rain spray, wet mops, or restricted airflow may be appropriate if such checks are possible during the normal use of the heater.

7-4.7 OPERATIONAL PRECAUTIONS

Resistive heating elements generally require no periodic maintenance; however, they should be checked periodically for loose or corroded connections. Any accumulation of dust, dirt, or grease near or on the heater should be removed to reduce the chance of fire. Scale or other accumulated matter should be removed from immersion heaters to improve thermal contact between the heating element and the liquid being heated, which will lower the internal temperature of the heating element.

Portable or freestanding heaters that are subject to frequent relocation must always be operated in a location that assures safety. An operating manual and/or label should be provided that contains the following types of warning (Ref. 27):

1. Heater may be hot even when not in use. Avoid skin contact.
2. Disconnect heater when not in use.
3. Do not use outdoors (unless unit is weatherproof).
4. Do not use in wet locations.
5. Unit must be grounded during operation.
6. Do not allow foreign objects to enter heater openings.
7. Do not block openings or operate heater on soft surface that may prevent free air circulation through heater.

7-5 ARC LIGHTS

7-5.1 INTRODUCTION

Prior to 1940, high-energy arc lights were used by the military for coastal defense and antiaircraft operations. Later high-intensity lamps were used for battlefield illumination. However, the development of image intensifiers, infrared (IR) imaging systems, and other battlefield sensing systems diminished the need for illuminating the battlefield. Searchlights now are used primarily for special purpose illumination such as providing illumination of large areas for maintenance or construction operations.

The original units used carbon-arc lamps that initiated an arc between two carbon electrodes that, in turn, were vaporized and consumed by the arc. Both the complex feed mechanism needed to maintain a constant arc length and the need for frequent attention during operation, however, have made the use of carbon-arc lamps less popular. Alternative arc lamps are glass-envelope lamps filled with mercury, xenon, or a combination of the two. These lamps are logistically simpler to operate in comparison to carbon-arc lamps but have less output and require high-voltage circuitry (50 kV) to initiate the arc.

A 20-kW, liquid-cooled xenon lamp is used in the A/N TVS-3, which originally was designed for battlefield illumination. Other military applications include a 30-kW airborne-mounted xenon searchlight and a 1-kW signaling lamp, which may use either xenon or incandescent lamps.

7-5.2 INDUCED ENVIRONMENT

The mercury-xenon vapor arc is enclosed in a quartz envelope because of the high operating temperature. Since quartz is relatively transparent to ultraviolet (UV), the ultraviolet rays produced by the discharge are passed to the environment.

The high temperatures associated with lamps induce significant heating of the environment. Fortunately, high-intensity lighting is used outdoors where air circulation is not restricted; hence the heat does not build up.

Ozone is often produced around the quartz envelope by the UV emissions. If the mercury-xenon vapor arc is being used in a confined space, e.g., a movie projection booth, the concentration of ozone can accelerate corrosion of metals and insulating materials and introduces a health hazard to personnel.

7-5.3 HAZARDS

Hazards associated with arc lamps are

1. The mercury-xenon vapor arc emits ultraviolet radiation sufficient to present a serious hazard to eyes and skin subjected to direct exposure. Generally an ultraviolet-absorbing glass plate covers the source to filter out the ultraviolet radiation. If the cover plate must be removed for lamp replacement, it can be broken easily and thus make it necessary to operate the lamp without the protective cover plate until a replacement may be obtained. When the lamp is operated in this manner, personnel are subjected to excessive ultraviolet radiation from either direct or indirect radiation, which can cause eye damage.
2. The hazard of burns is associated with lamp replacement if insufficient time is allowed for the lamp to cool before replacement is attempted
3. Arc lamps in which there is high pressure in the quartz envelope introduce the hazard of possible arc explosion. A special metal enclosure that encases the lamp during its removal and installation provides some protection. Personnel are protected from flying debris of an explosion but not from possible mercury contamination.
4. The deterioration of electrical insulation due to the intense heat and ultraviolet radiation can cause the development of faults, which may lead to the presence of high voltage on exposed components if the equipment is not properly grounded.

7-5.4 DESIGN CONSIDERATIONS

High-intensity lights, such as searchlights, must be configured to reduce the possibility of electric shock and excessive light (especially UV) exposure to the operator and to protect the lamp from any damage that could lead to its explosion.

Necessary design features include an interlock system to remove high voltage from the interior when the unit is opened for adjustment or repair. Electrical wiring materials must be selected to resist damage from high temperatures and high ozone concentrations near the lamp. It may be necessary to provide additional bushings or standoff insulators to isolate the conductor from surrounding conductors or grounded structures in the event of insulation failure from accelerated deterioration in this environment.

Xenon, mercury-xenon, or mercury lamps operate with high internal pressures—approximately 10 to 50 times atmospheric pressure. The highly pressurized gas can propel glass fragments with explosive force in the event of envelope failure. A protective enclosure is designed to (1) prevent any physical damage to the lamp that could result in fracture and (2) contain the flying glass and toxic materials that would be released during an explosion. The lamp should be operated only with protective filters, baffles, or other safety enclosures to protect personnel from potential explosions and the ultraviolet radiation (Ref. 24).

To minimize the chance of lamp fracture, metal or plastic protective cases are used for storing. The lamps should be kept in these storage cases until installation.

Generally sealed-arc lamps operating at power levels up to 2.3 kW can be cooled by natural convection. Higher powered lamps require forced air or water cooling for reasonable lamp life because the lamp enclosure will reach high temperatures during extended operating periods. If the light is operated in an accessible location, guards or perforated shields that allow convective cooling should be used to prevent contact with the hot surface by personnel.

7-5.5 COMPATIBILITY AND INTEROPERABILITY

The design of high-intensity arc lights is generally intended for low-volume, special purpose applications. Therefore, existing designs should be used to avoid a proliferation of special purpose units but only if such designs are not obsolete.

New designs should use standardized bulb configurations to reduce cost and to insure availability of replacement parts. Specifications for these bulbs (Ref. 28) are written to promote interchangeability of lamps manufactured under the specification.

High-intensity lighting features that must be specified to determine the suitability of a lamp as a replacement are

1. Intensity or power input
2. Beam divergence
3. Voltage and phase of input power
4. Physical size/mounting/portability
5. Maximum period of unattended operation.

Features that may be incorporated in a new design to enhance its compatibility with existing and future applications are

1. Capability of operation from various supplies—i.e., three-phase, single-phase, DC at various voltages
2. Variable beam characteristics
3. Acceptance of a range of lamp sizes and types, possibly using adapters to accommodate different lamp-envelope configurations
4. Replaceable starter assemblies may be necessary to accommodate different types of lamps.

7-5.6 TEST CRITERIA FOR DESIGN AND ITEM ACCEPTANCE

The tests that are appropriate for lamp designs are highly dependent on the anticipated applications and the features of the light. Examples of tests that may be appropriate to insure safe operation of lights are (Ref. 29)

1. *Dielectric Strength.* Apply a specified voltage between the power conductors and frame. Monitor current flow, and observe the test device for evidence of arcing. Excessive current could produce hazardous potentials if equipment is not properly grounded.

2. *Insulation Resistance.* Apply a moderate test voltage between the power input and frame, and measure the resulting current flow, which, if equipment is not grounded, could lead to hazardous potentials on exposed conductors. This test may be performed in conjunction with dielectric strength or environmental exposure tests.

3. *Temperature Limits.* Operate the lamp for a period sufficient for thermal equilibrium, and measure the temperature of exposed surfaces to determine whether the operator will be exposed to excessive burn hazards.

4. *Environmental Exposure Tests.* Expose the unit to salt spray, water spray, humidity, and accelerated aging conditions while the unit is operating to determine whether environmental exposure degrades optimal performance or introduces undesired electrical leakage paths and creates the same hazards as high leakage. Also conduct water spray tests to determine whether sudden cooling induces damage to the heated components.

5. *Shock and/or Vibration Tests.* Subject the unit to a pattern of shock and vibration to test fracturing or unfastening of components that cause inoperability, degraded performance, or an unsafe condition, e.g., a power line contacting the case.

7-5.7 OPERATIONAL PRECAUTIONS

Every precaution should be exercised in operating the high-intensity arc lamps to avoid eye damage from exposure to ultraviolet radiation. Also direct exposure to the light beam can cause flesh burns, and precautions against skin exposure should be taken. Searchlight operators must not direct the beam at other personnel.

Lamp replacement should not be attempted until the lamp has had a sufficient cooling-off period. Some types of lamps require a special metal enclosure when the lamp is in its fixture as well as during installation and removal. This enclosure reduces the chance of injury, which could occur in the event of an explosion.

The lamp should be kept clean to minimize the possibility of lamp overheating due to the radiant energy absorption of surface contamination. High-temperature lamps should not be handled with bare hands. This precaution prevents the deposition of skin oils on glass; skin oils produce hot spots when the lamp is operated.

In the case of a damaged quartz envelope and a mercury spill, special precautions must be taken. Notify the commanding officer, industrial hygienist, or responsible organization in the event of a mercury spill of two or more ounces.

7-6 CONTROLS

7-6.1 INTRODUCTION

Controls discussed in this paragraph include on-off proportional controllers, which control the flow of power to polyphase loads based on manual control position, the magnitude of a related parameter, or some combination of the two. Under manual control the voltage applied to the load is controlled by an on-off switch, a variable transformer, or a variable resistor. The level of applied voltage is not dependent on a monitored parameter, e.g., motor speed or heater temperature, except indirectly through observation and control by the operator.

For the purpose of discussion in this handbook, a control consists of a regulating device that exercises control over some aspect—such as speed, power, position, or simply whether the equipment is running or not (on-off control)—of the operation of the machine. Even though control may be implemented mechanically, e.g., clutches or transmission, this discussion focuses on electrical controls that incorporate switches, transformers, or rheostats to regulate the flow of electricity—based on input from an operator—to a piece of electrical apparatus.

A controller provides a sensing and regulating capability to effect automatic feedback control. These devices are usually electrical, although physical mechanisms may be employed for sensing, e.g., the thermal deformation of a bimetallic strip or the expansion of gas in a capillary tube to activate switch contacts physically.

Feedback control systems adjust the applied voltage (or current) to maintain monitored parameter values. These systems also may employ operation input, which is most often a specified set point for the desired value of the parameter being controlled. The applied voltage, however, depends on an "error" signal corresponding to the difference between the desired level (set point) and the electrically sensed value of the same parameter.

Numerous controller configurations exist to satisfy unique requirements of the devices or systems to be controlled. Examples of common control systems are

1. *Motor Controls*. Controllers that vary voltage to provide orderly start-up of electric motors
2. *Temperature Controllers*. Controllers that vary power to electric heater to control the temperature measured by a thermocouple
3. *Position Controllers*. Controllers that vary voltage and phase sequence to motors that drive large doors, cranes, or elevator cars until they reach the desired position.

7-6.2 INDUCED ENVIRONMENT

Electrical controls or controllers generally have little direct effect on the environment but may have significant indirect effect through the electrical apparatus they control. The specific effect depends on the type of apparatus connected and may include increased heat from all types of apparatus or excessive vibration from electrical motors. The design of the controller can significantly affect the levels of these effects.

One environmental effect that is directly attributable to electrical controls or controllers is the generation of electromagnetic interference (EMI). This interference is produced by arcs or abrupt interruption of current, especially if the interruption occurs periodically at the power line frequency. Unless proper filtering and shielding are incorporated, the harmonics generated will be conducted by power cables or radiated through the antenna effects of the wiring to nearby electrical apparatus. The high-frequency energy of the harmonics may interfere with the operation of electronic equipment.

7-6.3 HAZARDS

Improper interaction between the controller and the equipment being controlled represents the primary source of potential hazards attributed to controllers. The specific nature of controller hazards depends on the type of equipment being controlled. Examples of types of potential hazards are

1. Inadvertent activation of machinery during maintenance or setup operation while personnel are within range of rotating or reciprocating components. Activation could be initiated by bumping against the control switch; by depressing the wrong control switch, e.g., "START" or "REVERSE" instead of "STOP"; or by a short circuit within the switch housing due to moisture or physical damage.
2. *Application of full voltage to a loaded motor* could result in a severe overcurrent condition when the starting torque is insufficient to overcome the load.
3. EMI generated by a switching transient could cause improper operation of a programmable controller or computer-based control system and, in turn, cause inappropriate control activation. Outcomes of inappropriate control could include loss of a manufactured product, process "runaway", or activation of machinery that should be idle.

7-6.4 DESIGN CONSIDERATIONS

The design of a control or controller for electrical apparatus depends on the equipment to be controlled, the application of the equipment, and the environment in which it will be operated. Certain general considerations, however, apply to a large portion of the controllers for common applications such as motor control and temperature control. These general considerations are discussed in the subparagraphs that follow.

7-6.4.1 Physical Arrangements for Controls

Control panel layout should be carefully designed so that the function and use of switches or operating levers are clear to the operator. Standardized color and position coding should be employed so the operator does not have to study the panel to determine which button to press. Uniformity in design of control panels, especially among those for a specified application, will minimize operator errors in the use of the control panel.

Conventions have been established by the National Electrical Manufacturers Association for orientation and positioning of machine controls (Ref. 30). "STOP" buttons should be red in color to distinguish them from other switches. Push buttons for a multispeed motor should be oriented in a row, either vertically or horizontally. In a vertical configuration the "STOP" button should be at the bottom, and switches above ordered in the sequence of increasing speed—i.e., with the highest speed switch at the top. Horizontally arranged switches should have the "STOP" button on the extreme left and the highest speed on the extreme right. A green light is used to indicate that the controlled apparatus is operating. A red light also may be used to indicate that the apparatus has been stopped.

Types of controls may be keyed by color; size may also be used to group controls that are functionally related. Size or shape should be used to key commonly used controls to provide a tactile indication to the operator of what control is being adjusted in order to prevent the inadvertent adjustment of the wrong control. The most commonly adjusted controls or the most critical adjustments should be the largest size.

If controls are used to adjust the level of an indicated parameter, the control should be located next to the adjustment-level meter or display for the parameter. Controls should be positioned such that forward, clockwise, or upward movements cause the controlled apparatus to activate, increase in speed, raise, move forward, or rotate clockwise. Controls that should be activated in sequence should be grouped and arranged in the normal sequence of adjustment.

Controls that are used for maintenance adjustment should be covered. Convenient access, however, should be provided for maintenance personnel. Controls that could initiate an action that is potentially damaging to equipment or injurious to personnel should be protected to prevent accidental activation. Protective measures may include

1. Locating the control away from frequently accessed controls
2. Recessing or surrounding the control with barriers to limit access to one particular direction
3. Providing a mechanical interlock that requires the release of a lock mechanism or pull/push to engage before the control may be adjusted
4. Providing "stiff" operating mechanism so that additional force is required to adjust the control.

For critical operations, interlocks may be employed. Interlocks may consist of a separate lever or push button that must be depressed prior to activation of a push-button control or to turning a rotary switch to a critical position. (In tactical equipment, it may be necessary to provide an override to disable the interlock if it fails.) Another example of a mechanical interlock designed to prevent damage is one that prevents rapid transition between two operating switch positions where the sudden transition could cause damage. For example, sudden switching from forward to reverse in a motor controller could cause severe overcurrents in the motors and/or damaging mechanical jolts. Switch units may be designed so that the control must remain in the off position for a specified period of time before moving into the reverse position. If separate speed and direction controls are provided, an interlock between the controls may be appropriate to ensure that the direction can be changed only when the speed is set to zero.

Controls should be labeled clearly, and labels for all control positions should be readable. The location of the labels should be consistent, i.e., always either above or below the control. Generally, a pointer is used on rotary controls to point to a label indicating the selected function. If possible, rotating dials and windows may be used so that only the appropriate label is shown; however, this arrangement may unnecessarily complicate the design of the control unit. Indicating knobs should be keyed to the shaft, i.e., using a flatted shaft, to prevent improper installation of the knob so that a false position is indicated.

Labels for switch positions should describe the function as concisely as possible in terms that are familiar to all personnel who will use the equipment. Common terms, such as "START", "STOP", "OPEN", "CLOSE", "FORWARD", and "REVERSE", are preferred over esoteric alternatives. Symbols should be used only if they are familiar to all personnel who will operate the equipment.

Additional information on the human engineering aspects of control arrangements are given in Ref. 31.

7-6.4.2 Control and/or Equipment Interaction

Controllers used in feedback control systems should be designed to provide an unconditionally stable operation. Since the factors that determine stability can vary with machine loading, sensor location, or any number of application-dependent factors, a control system that is operating in a stable mode may easily become unstable if operating parameters are changed suddenly or if a malfunction occurs. Therefore, it is usually necessary to have preset limit deflectors that will shut down the operation if the control system output exceeds normally encountered control levels by a significant margin. These limit deflectors protect the controlled equipment in the event of sensor or control-system failure.

Controls for high-speed machinery, especially those with material-feed operations, should include provision for low-speed operation so that the operator may check the motion of the mechanism, position material, or initiate a drilling or cutting operation. The slower speed permits the operator to stop the operation before irreversible damage occurs and provides greater safety to human interaction with the machinery while it is in an operating mode. If the slow feature is not provided, operators may use a series of quick, start/stop sequences to accomplish the same functions. During a quick start and stop sequence, however, the control unit could jam or the operator could miss the stop control, and the machine could reach normal operating speed at a time when that is not desired.

7-6.4.3 Electromagnetic Interference

As mentioned in par. 7-6.2, the switching devices used in controllers generate high-frequency energy during operation, and this energy may be coupled to sensitive electronic equipment. Arcing of contacts in switches or relays produces harmonic energy with a fundamental frequency at the line frequency and harmonics extending up to hundreds of megahertz. The duration of the interfering energy is generally short and lasts only as long as the arc—generally only a few cycles of the line voltage.

Controllers that incorporate solid-state switching components vary the delivered power by switching off for a portion of the beginning of each line cycle. The repetitious switching also generates energy with a fundamental frequency equal to the line frequency and harmonic energy into hundreds of megahertz. This energy is emitted continuously and varies in intensity with the rise time of the switching transient, the current and voltage levels being switched, and the electrical resonances in the circuit.

The reduction of interference to sensitive electronic equipment is accomplished by reducing one or more of the following:

1. Energy radiated from the source of interference
2. Coupling between interference source and the susceptible equipment

3. The susceptibility of equipment that is disrupted by the interference.

Various techniques for reducing all of these are discussed in Refs. 32 to 34. The interference generated by equipment is minimized most effectively by incorporating appropriate shielding and filtering during the design phase. The undesired coupling is minimized during installation by appropriate cable routing and grounding.

The emitted energy is reduced by electromagnetic shielding of the switching components, filtering of wiring to the switching devices, contact arc suppression, and good grounding practices. Shielding is accomplished by surrounding the unit in a metal enclosure constructed from conductive material. Although copper is preferred because of its high conductivity, steel is also adequate for almost all applications and has the advantages of economy and strength. The design of the configuration is more important than the election of the shielding material. Large openings, covers, or doors that do not make complete electrical contact with the enclosure or unfiltered wiring passing through holes in the cabinet may couple electromagnetic energy to the external environment and defeat the effectiveness of the shielding. If high-powered controllers are to be located near sensitive electronics, a complete and separate enclosure of the control unit and the instrumentation is necessary to prevent undesired electromagnetic emission radiation and unintended reception.

Power and signal leads that leave a control system enclosure should be filtered and shielded. The filtering prevents the conduction of interference into or out of the shielded enclosure along the wire. The cable shielding further inhibits the coupling of undesired energy to or from the cable. Filters for this application may consist of ferrite beads or low-pass, single-section, LC filters. Note that for power leads, the source and load impedances are typically low and varying. Hence, conventional filter design techniques that rely on known source and termination impedances are not valid.

Usually, contact arc suppression is necessary for contacts used to switch inductive loads. For DC circuits, diodes are used to dissipate voltage surges introduced by the sudden interruption of current through an inductive load. The diodes are placed across the load such that they are reverse biased while the load is powered but are forward biased by the transient produced by the current interruption. For AC switches, various capacitors or resistor and/or capacitor combinations are placed across the contacts. (See Refs. 32, 34, and 35.)

Grounding of control enclosures is necessarily performed for safety considerations. However, in cases where high-frequency noise immunity is important, additional constraints are imposed. The ground connection must be short and direct. Loops or coiled wire add inductance, which raises the impedance and reduces the effectiveness of the ground connection. Also conductors with a large surface area are preferable to round wire in order to reduce wiring inductance. Ground connections should be made to prevent ground currents from being introduced into signal leads, shields of signal leads, or leads used to ground signal instrumentation. Grounding for EMI reduction is discussed in Refs. 32, 34, and 35.

7-6.5 COMPATIBILITY AND INTEROPERABILITY

Controls and controllers are generally designed for specific applications and typically are interchangeable only with units designed for a similar application. Although electrical and physical interfaces form the most restrictive compatibility criteria, the operator interface is also important. For controllers to be interoperable or compatible—i.e., to be used simultaneously in the same system or to serve as replacements—it is necessary that the layout of controls and operating characteristics be similar. Otherwise, the probability of operator error is increased due to unfamiliarity with the control functions.

Compatibility and interoperability of controls are enhanced by following standard practices in control layout discussed in par. 7-6.4.1 and Ref. 36.

Commercially available controllers designed for use in control loops have features that allow flexibility of operation and replacement of a wide variety of special purpose controllers by a smaller number of standard units. Characteristics that facilitate compatibility include

1. Adjustable gain and feedback functions—e.g., proportional feedback, integration, or filtering of input
2. Ability to accommodate different sensors through the use of plug-in input modules or reconfigurable inputs
3. Ability to accommodate different power configurations through the use of reconfigurable switching gear or plug-in components.

The disadvantage of highly flexible controllers that can be configured for a variety of applications is that installation procedures may be quite complex. Personnel with expertise in electronics and training on the specific controller are required for installation and adjustment of the controllers. Therefore, the use of these types of controllers is limited to applications where properly trained people are available.

7-6.6 TEST CRITERIA AND ITEM ACCEPTANCE

The acceptance and performance tests for specific controllers depend on the design and function of the control device. General tests described in Refs. 30 and 36 include

1. Temperature rise of contacts, buses, terminals, or interconnecting straps. Excessive heating could lead to insulation failure or loss of spring tension on contacts. Insulation failure then could result in controller damage, development of excessive voltage on controller outputs, or the presence of hazardous voltages on exposed conductors. Contact heating that results in loss of contact pressure leads to increased contact resistance, further aggravates the problem, and leads eventually to component failure.
2. Dielectric breakdown tests determine the quality of materials that insulate energized conductors from the case or from other conductors. Low breakdown voltages indicate insufficient insulation that could lead to development of hazardous voltages on exposed conductors.

3. Shock and vibration tests verify the ability of the device to survive physical abuse without degradation of operational performance or the introduction of a hazard.

4. Switch characterization tests, e.g., tests for excessive contact bounce or response time, may be performed to verify compatibility between the controller and interconnected equipment. Poor switch operation could cause erratic motor operation or generation transients that could damage solid-state controller circuitry.

5. Tests for electrical interference are performed to determine whether a degradation of performance in equipment located nearby is possible due to conducted or electromagnetic emissions from the unit being evaluated. Interference can cause erratic operation, failure, or undesired responses from nearby electronic equipment. The severity of a created hazard depends on the function of the affected equipment.

6. Short-circuit current-withstand capability is measured to determine the ability of the device to withstand overcurrent situations of short duration caused by faults of improper equipment connections.

Physical inspections of control devices should be made to confirm that controls operate freely without binding and that controls may be operated by personnel under all operating conditions, e.g., while wearing gloves or in dim light.

Performance tests are more application-dependent and should be designed to evaluate the performance of a control or controller when interacting with a load. After installation, feedback-control systems should be tested for stability under all operating conditions. Motor-starting and speed controllers should be tested to determine motor-starting currents and to verify the acceptability of start-up characteristics, e.g., absence of excess vibration or "jolts" when starting.

7-6.7 OPERATIONAL PRECAUTIONS

7-6.7.1 Installation

Control units should be installed securely in a protected location where inadvertent contact activation of controlled equipment or damage to the control unit is unlikely. The control unit should not be installed where it will be a hazardous obstruction, i.e., should not be installed where it will be bumped into, tripped over, or where it may snag clothing of personnel in the vicinity. Machinery controls should be installed in a location where the operator may conveniently operate the control while observing the machine and can quickly and safely reach the controls in the event of a malfunction. Unless the enclosure is weatherproof, it should be installed in dry locations and protected from the weather. Adequate clearance should be provided for maintenance and replacement if necessary.

As with all electrical apparatus, proper grounding of the enclosure is necessary to prevent hazardous exposure to voltages under fault conditions.

7-6.7.2 Care and Maintenance

The operating instructions for control equipment should delineate all items that require periodic inspection, lubrication, and maintenance. Maintenance can include

1. Periodic inspection of terminals and connections, especially where aluminum conductors are used
2. Cleaning of contacts to remove corrosion, dust, or contaminants that could increase contact resistance and heating
3. Cleaning and renewal of lubrication of moving parts in control switchgear
4. Checking for sources of moisture that would lead to condensation in or dripping onto control units
5. Inspecting for heating of wiring or coil windings
6. Inspecting for damage after occurrence of a fault
7. Observing carefully the operation of the controlled device under a prescribed scenario. (Note this is a test not only of the control unit but also of the apparatus that it controls.)

7-7 LOAD BANKS

7-7.1 INTRODUCTION

Load banks are resistive networks capable of harmlessly dissipating large amounts of electrical power. These devices are used for generator loads during tests or as "load-leveling" devices to provide a minimum load on diesel generators to prevent carbonization that builds up if the engine-generator is operated at less than 40% full-load. Reactive load banks, consisting of reactive elements (inductors or capacitors) are used with resistive load banks to provide a nonunity power factor load for generator testing. Load-bank resistors can be selected in 12.5% steps of generator rating at either 120/280 or 240/416 V. Units designed for military applications may be used as balanced, three-phase loads. The three individual load banks, however, may be interconnected to function as a single-phase load. Ancillary control circuits automatically disconnect the load-bank load when the generator load reaches 100% in order to prevent overloading the engine-generator set. If the bank is tripped, it must be reset manually when its use is again required.

7-7.2 INDUCED ENVIRONMENT

The maximum power dissipated by a load bank built according to Ref. 37 is 44 kW. The forced ventilation discharges this heat to the surrounding air. The degree of temperature elevation is dependent on the convective airflow across elements within the load bank.

7-7.3 HAZARDS

In a confined space ambient temperatures may rise to levels that could damage thermoplastic insulation materials and thus allow energized conductors to contact the enclosure or structural members. Also resistive elements are sufficiently hot to inflict severe burns upon contact. Since the resistors used in load banks are essentially heaters, hazards associated with heaters discussed in par. 7-4.3 apply to load banks as well.

7-7.4 DESIGN CONSIDERATIONS

Polyphase load banks generally consist of three, identical load banks, which may be used individually or interconnected in a wye or delta configuration. Each element is composed of switchable resistors so the load may be manually adjusted to the required value. Vernier control may be provided by a continuously variable rheostat wired in series with the resistors.

The intake for the ventilation system is designed according to application requirements to provide protection from meteorological elements. For example, baffles or shields may be necessary to prevent rain from contacting electrical components and creating the safety hazards of excessive leakage currents and possible equipment failure. Air velocity in vents at the bottom should be insufficient to lift dirt particles off the ground or horizontal surfaces.

Resistor materials should have low resistivity-temperature coefficients so that the load resistance does not change significantly as the load bank heats. (The temperature coefficient of nichrome wire is 0.0004 per deg C (0.0002 per deg F); this permits a temperature rise of 250 deg C (450 deg F) above ambient while maintaining a resistance within 10% of the normal value.)

Terminal boards should be capable of withstanding conductor temperature. Terminal blocks that are thermally isolated from the heat-generating resistors may be made of molded or laminated plastic. The studs for connecting the phase leads from the generator should be adequate to carry the load current without excessive heat generation. MIL-L-52366C requires 9.53-mm (0.375-in.) studs for phase wires and 12.7-mm (0.5-in.) studs for the neutral. Standard labeling should be used—i.e., L1, L2, and L3 for phase wires and L0 for the neutral.

A control panel should be provided to allow setting of the load-bank resistance without exposing the operator to hazardous voltages or hot surfaces. No exposed terminals, conductors, switch toggles, or knobs on the face of the panel should be at a voltage different than the voltage of the enclosure (ground). The panel also should contain overcurrent protection for the load bank and a master switch to disconnect the load banks from the engine-driven-generator set. Indicators should be provided for current and overtemperature conditions. The panel should be labeled with readily understandable signs, e.g., "connect load" or "increase". If rotary controls are used to vary the load, the control should be configured so that clockwise rotation increases the load, i.e., decreases load-bank resistance.

The case and associated resistor supports must be provided with a ground connection connected to the ground of the engine-generator set to eliminate the possibility that personnel could receive an electric shock if the insulation failed.

Doors should be provided to protect and limit access to the input terminal board, the operator control panel, the reconnecting circuits, and any other features that do not require frequent access during routine operation. The input-terminal access door should have interlocks to prevent access when the unit is energized. A bypass may be provided to allow access for testing; however, the main breaker and the bypass switch must be constructed so that they cannot be operated inadvertently.

7-7.5 COMPATIBILITY AND INTEROPERABILITY

The electrical characteristics of a resistive load bank that determine its compatibility or interoperability are

1. Phase configuration
2. Load adjustment range
3. Voltage
4. Overcurrent or automatic load-bank-shedding circuitry.

Load banks usually will operate over line frequencies from 45 to 440 Hz unless frequency-sensitive control circuitry is used.

For use as a generator test device, the load bank only needs to have the appropriate phase configuration and operating voltage and be adjustable to the level of desired power consumption.

For the load bank to operate as a continuous loading device for diesel engine-driven-generator sets, the aforementioned electrical characteristics of the load bank must be compatible with those of the generator. Also, a generator load current-monitoring capability must be built into the load-bank unit to disconnect the generator output when the electrical load on the generator reaches a predetermined value.

Load-bank features that increase compatibility include

1. Multivoltage capability
2. Switchable load
3. Switch- or jumper-selectable phase configuration (delta, wye, or single phase)
4. Disconnectable ancillary control circuits, e.g., a circuit that disconnects the load bank when total load exceeds generator capacity.

Operating instructions should be provided on the inside of the control panel door. These instructions list hazards and give specific warnings about incorrect procedures that could result in unsafe conditions. Schematic wiring diagrams should be provided as well.

7-7.6 TEST CRITERIA FOR DESIGN AND ITEM ACCEPTANCE

Load banks constructed according to MIL-L-52366C are subjected to a series of tests to verify their operation. The most significant of these tests are

1. *Insulation Resistance.* With all load resistances connected in parallel, measure the resistance between the line input and the enclosure. Values below the criteria in the specification indicate an undesirable leakage path.
2. *Insulation Withstand Voltage.* With the unit setup for single-phase operation, apply a specified high voltage between the line input and the enclosure for a specified time period. Any arcing indicates a potential for development of high voltages on the load-bank enclosure and constitutes failure of the test.
3. *Functional Performance.* Operate the load bank for a specified time period in various configurations and verify, by examination at the completion of the test, that no physical damage has occurred when the unit is oper-

ated at capacity. Also verify the operation of safety-overheat sensors by removing the cooling air source, which induces an overheating condition. Examine the unit for damage due to the heat.

4. *Control-Circuit Characteristics.* Verify the power drawn by the control circuits does not exceed stated requirements.

5. *Environmental Test.* Verify that the unit may be operated or stored in environmental conditions such as high humidity, including rain, and low temperatures. Also verify shock and vibration resistance to evaluate the transportability of the unit.

7-7.7 OPERATIONAL PRECAUTIONS

Many of the same considerations that apply to other electrical equipment apply to load banks as well—e.g., providing protection for power wiring and grounding of the enclosure when the unit is installed and periodically inspecting the unit for loose connections or signs of overheating during operation. Considerations unique to load banks include insuring that the unit has adequate ventilation and that it is installed where the heat given off will not damage nearby structures or ignite combustible materials. Operating instructions should include recommended minimum clearances and warnings against loose material that could be drawn into and clog ventilation openings.

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CHAPTER 8

TEST EQUIPMENT

In the context of electrical power systems, test equipment includes both indicating instrumentation installed permanently in electrical systems and portable equipment for as-needed hookup and measurement. Test instruments measure electrical parameters to monitor system operations or to diagnose malfunctions. Types of test equipment include voltmeters, ammeters, wattmeters, power analyzers, phase meters, and frequency meters.

First, this chapter discusses general considerations common to all these items. Subsequently, separate discussions of considerations unique to each item are presented. The format of each discussion is the same as that used throughout this handbook — i.e., identification of environmental effects, hazards introduced, design information for safety, identification of recommended tests, and operational considerations.

8-0 LIST OF SYMBOLS

I = rms current, A

I_{line} = current in line to be measured, A

I_{meter} = current into meter from current transformer, A

K_{tr} = correction value for transformer turns-ratio, dimensionless

P = measured power, W

R_t = nameplate turns-ratio of transformer, dimensionless

V = rms voltage, V

ϕ = phase angle between current and voltage, rad or deg

8-1 INTRODUCTION

Instrumentation used with electrical equipment may be divided into three categories, i.e.,

1. Equipment permanently installed that transmits or displays status information continuously. Examples of this equipment include panel meters and electrical sensing equipment that telemeters data.

2. Portable instrumentation used for test and diagnostic purposes. Examples of this type of equipment include portable voltmeters and ammeters, and multifunction test sets. Portable equipment is usually more flexible than permanent equipment because it must be used with many types of electrical equipment operating at different voltage and power levels. Also in contrast to permanently installed equipment, portable equipment is frequently configured for multiple types of measurements—e.g., volt-ohm-milliammeters (VOMs), which measure voltage, resistance, and current.

3. Laboratory instrumentation for servicing and calibrating other test equipment. Included in this category are accurate indicating instruments, which because of their accuracy and inherent stability, serve as transfer standards for the calibration of other equipment through comparative measurements.

This chapter discusses safety issues related primarily to the use of equipment in the first two categories. Due to similarities in function, however, much of the material presented pertains to laboratory instrumentation as well. Additional information regarding operating principles and application of test equipment relevant to power systems described in this handbook is given in Ref. 1.

8-2 GENERAL TEST EQUIPMENT CONSIDERATIONS

8-2.1 INTRODUCTION

Although the design and application of a piece of test equipment depend on the specific parameter to be measured, certain safety considerations are common to different types of instrumentation. For example, although portable voltmeters, ammeters, and wattmeters measure different parameters and are connected to an electrical circuit in different configurations, design considerations common to all three instruments include design of the readout, test-lead connections, enclosure or packaging, and overvoltage and/or current protection. The purpose of par. 8-2 is to discuss safety considerations that are common to several or all of the instruments discussed in this chapter. Considerations that are unique to a specific instrument are discussed separately in the paragraph pertaining to that instrument.

8-2.2 INDUCED ENVIRONMENT

Test equipment generally does not adversely affect the environment other than possibly to increase the negative effects on the environment by the equipment being tested. By design test equipment must provide information on the operation of the equipment with minimum disturbance to it. Any primary environmental effects are produced by temporary modifications made to the item under test to facilitate the measurements. For example, the removal of covers or panels to gain access to internal connections to connect test equipment may cause the redirection of forced-ventilation air paths. This redirection has the potential to remove cooling necessary to prevent overheating of components. The result is increased local heating that could possibly lead to damage. A specific example is the removal of the enclosure around a compressor-condenser refrigeration unit. In certain units this enclosure must remain sealed in order for air drawn by cooling fans to pass over the condenser coils. Opening the unit to measure electrical components disrupts the air circulation pattern. This disruption greatly reduces the airflow over the coils and thereby reduces the cooling and increases the internal pressure of the refrigerant gas.

Perhaps the most significant environmental effect of test equipment is produced when the equipment is connected to energized conductors. The placement of clips on bus bars or closely spaced terminals effectively reduces the air gap spacing between the conductors. This reduced air gap can lead to arcing at voltages lower than those at which arcing would otherwise occur, or if high voltages are present, it could lead to corona. Connection of a test lead to an energized conductor energizes the test lead along its entire length. Improper insertion of the simple pin or banana-plug connector on the test lead into the test instrument causes environmental exposure to high voltage and increases the probability of incidental contact by personnel or contact between the lead and another conductor to produce arcing.

8-2.3 HAZARDS

Test equipment—especially portable, multifunction units—is designed to provide maximum flexibility in terms of parameters to be measured and the types and configurations of equipment to be tested. These instruments usually have switches or multiple connectors, which allow the operator to determine the range and the parameter to be measured. Human error in the setup of the instrument can lead to damage or injury. Examples are

1. Setting the instrument for a current measurement and connecting leads across energized conductors in the manner appropriate for a voltage measurement causes substantial voltage to be applied across the relatively low impedance of the meter. See Fig. 8-1(A). The probable result is damage to the test equipment or possibly arcing at the point of the test-lead contact.
2. An attempt to make a voltage measurement on solid-state equipment with a multifunction meter set for a current-measuring function, which causes the meter to have a low input impedance, may introduce undesirable current paths through the unit under test and could destroy the unit. This situation is shown in Fig. 8-1(B).

Hazardous situations can easily be produced by misreading an instrument and taking inappropriate action based on the erroneous reading. Erroneous readings are quite likely to occur if the instrument scales are not clearly marked or if conversion factors must be applied to scale readings to determine the value of the monitored parameter. If controls and corresponding indicators are not appropriately grouped, the operator is likely to adjust the wrong control when attempting to correct an out-of-tolerance condition and, seeing no immediate response in the indicator, may make an extreme adjustment before realizing the error. Depending on the function of the control that was adjusted, the effects could be disasterous. Similarly, if meter-scale markings are not clear, the operator may make corrective adjustments to correct a perceived out-of-range reading when the reading was actually within range but misinterpreted.

Additional hazards that arise in connecting electrical test equipment with electrical apparatus are

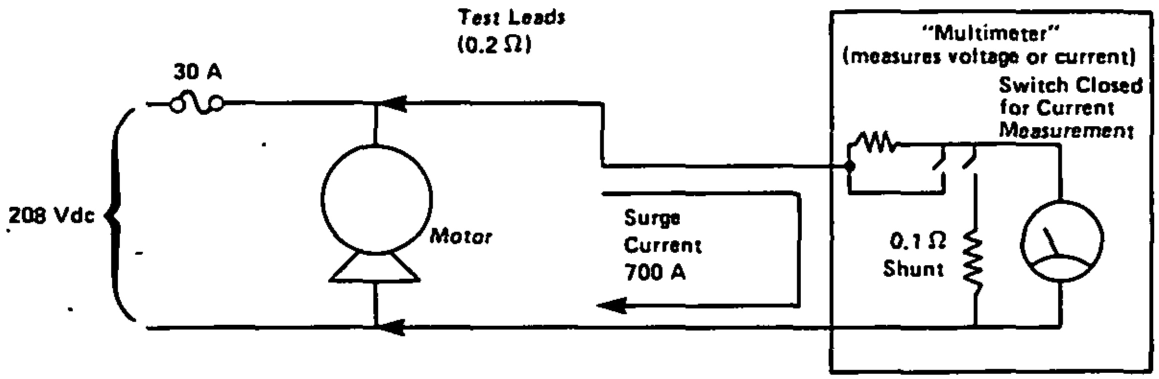
1. Short-circuiting of adjacent conductors when making temporary connections to portable test equipment. The resulting arc can cause burns, eye injury, or equipment damge.
2. Inadvertent contact with high-voltage equipment when making measurements on energized equipment with portable instruments. Injury may result from contact with energized conductors within the equipment under test or from contact with test-equipment leads once they are connected to the energized conductors.
3. Accidental opening of a current transformer secondary and the resultant production of an extremely high voltage.

8-2.4 DESIGN CONSIDERATIONS

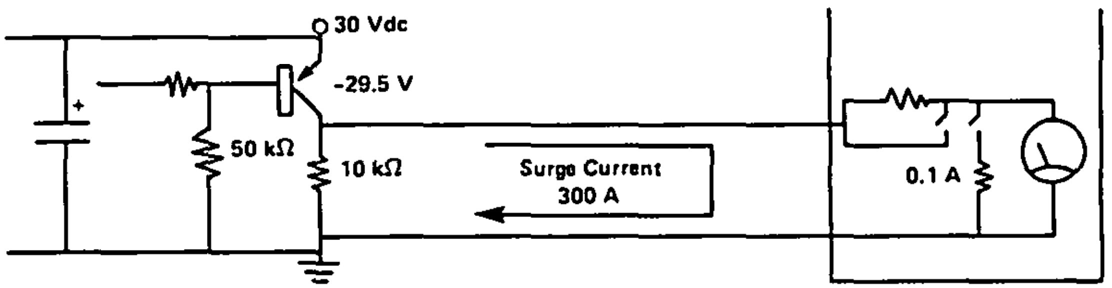
8-2.4.1 Configuration

The most common hazard with test equipment is human error, especially with portable test equipment that must be connected to the unit under test with temporary test leads. The instrument must be designed so that the operation is as simple as possible within constraints of the operational requirements and that operational errors do not produce a hazardous condition, such as instrument damage, or expose the operator to high voltage or other hazardous conditions.

Uniformity in the configuration, labeling, and readout and/or display is an important consideration in the design of test equipment. Panels containing multiple displays and controls should be configured uniformly throughout a system or in equipment designed for similar applications. All indicators should be clearly labeled and positioned in a manner consistent with conventions for the application. For example, indicators showing voltage or current on individual legs of a polyphase system should be placed in the order of the phases, i.e., the indicator for Phase 1 on the left or top, the indicator for the last phase on the right or bottom, and the indicators for intermediate phases placed in order between them. Controls that are closely associated with the indicator should be placed near the indicator of the parameter they control. For example, variable transformers or tap changers should be located adjacent to the voltmeter indicating their output and preferably oriented so that turning the control clockwise causes the meter to respond in an upscale direction. Control and indicator layout in a new design should



(A) Attempted Measurement of Line Voltage Causes Surge Current That Will Likely Damage Meter



(B) Attempted Measurement of Semiconductor Voltage Causing Excessive Transistor Collector Current That Will Likely Destroy Transistor

Figure 8-1. Hazards Created by Attempting Voltage Measurements With Multimeter Function Switch in Current Position

resemble that used in previous designs unless improvements in clarity or convenience with a new layout outweigh the disadvantage that arises when personnel who are used to one configuration must become familiar with the new configuration or, worse, must work with both configurations.

The selection of digital versus analog display is dependent upon the application. Digital-display equipment is more precise and less subject to reading errors than analog equipment. Analog indicators provide a more quickly interpretable indication of an out-of-range condition or sudden fluctuations in value. A rapidly fluctuating load, however, is difficult (if not impossible) to read digitally because of the high speed of these meters and the rapidity of the change of register. The operator can observe the spread of the indication of an analog pointer and at least obtain an indication of the average value of the fluctuating parameter. Analog displays generally are preferred for situations in which a control must be adjusted for peak or minimum level of the indicated parameter; digital meters are preferred for situations in which a high degree of accuracy is required or in which the indicated values are to be manually recorded.

A single digital indicator can be used to display multiple parameters by including a selector switch. This use is not recommended except for situations in which the meter provides information only for maintenance or diagnostic purposes; it should never be used for a parameter that must be closely monitored or for critical or emergency situations. In an emergency valuable time can be lost in locating the proper digital reading, whereas a quick visual inspection of many analog displays is more accurate.

8-2.4.2 Packaging (Ref. 2)

Portable instrumentation should be packaged in durable enclosures that provide the necessary physical and environmental protection. The packing case should be free of sharp edges or corners, which could cause injury to personnel or cut wire insulation in the electrical apparatus in which it is being used. Casings of insulating materials are preferred because of their resistance to corrosion and the fact that they can be used around energizing conductors without the danger of bridging conductors, causing arcs, or introducing undesired leakage paths.

For two reasons, both portable and permanently installed instrumentation should be packaged in enclosures made from material that does not support combustion. First, the combustible materials in electrical equipment should be minimal to diminish the damage from fires initiated by arcing or overheating. Second, instrumentation packaging that is resistant to damage from fire is more likely to maintain separation of conductors within it during a fire; this separation will prevent the development of additional faults. Ref. 3 specifies the resistance-to-flammability requirements for materials in control panel instruments.

Care must be taken in the design of an analog instrument to eliminate reading errors because of parallax. These errors rise from viewing the meter at an angle that leads to erroneous perceptions of the position of the meter pointer relative to the scale. Parallax errors are minimized by meter designs that have either a pointer recessed to the same level as the scale, mirrored scales, or a pointer blade that is perpendicular to the meter scale. If accuracy requirements are less stringent, the placement of the meter pointer within 1.5 to 2.5 mm (0.06 to 0.10 in.) of the scale minimizes parallax errors (Refs. 4 and 5).

If the test equipment mass exceeds 16 kg (35 lb), lifting and/or carrying hazards may exist per Ref. 4.

8-2.4.3 Labeling

All test equipment should be labeled clearly. Analog panel-mounted instruments should be marked with the following information:

1. Manufacturer
2. Model number
3. Basic measurement function (V, W, A)
4. Two of the three following parameters:
   a. Movement voltage sensitivity, V
   b. Movement current sensitivity, A or mA
   c. Internal resistance, Ω.

Note that basic meter sensitivity can differ from scale markings if the meter is intended for use with range-extending devices such as current transformers or voltage dividers.

Panel meters that are polarity sensitive or have one input lead connected to the case should be plainly marked with permanent symbols near the terminals. Polarity is indicated by a "+" symbol located near the positive terminal. Grounded terminals are marked with the standard ground symbol.

Fig. 8-2 gives the International Electrotechnical Commission (IEC) defined symbology specified in Refs. 6 and 7 for use on portable test equipment. The use of these symbols would enable non-English-speaking personnel to operate the equipment.

8-2.4.4 Protection Against Electrical Shock

Test equipment should be designed to prevent exposure of parts that are energized when the unit is in operation. Openings for ventilation should be covered with a screen or grille to prevent fingers inserted through openings in the case from touching live parts. Adequate clearance must be provided between internal conductors energized by the supply and exposed conductors including the enclosure. Table 8-1 gives creepage-distance requirements. Creepage distance is the minimum distance between these conductors measured across insulator surfaces.

Test equipment, like other electrical equipment, must be mounted in a grounded enclosure so that any internal faults do not produce hazardous voltage levels on exposed components. MIL-T-28800D (Ref. 2) requires that leakage current between AC or DC line conductors and any accessible conductive parts of the equipment shall not exceed 5 mA. Likewise, radio frequency interference (RFI) or surge-suppression devices connected between the line power input and the safety ground shall not allow more than 5 mA of current to flow to the ground conductor. The latter limitation is required to prevent lethal currents from flowing through an instrument operator if that equipment ground connection is opened. Instrumentation that normally is installed permanently, but must be removed for maintenance or repair, should be connected so that the equipment will remain grounded until it is

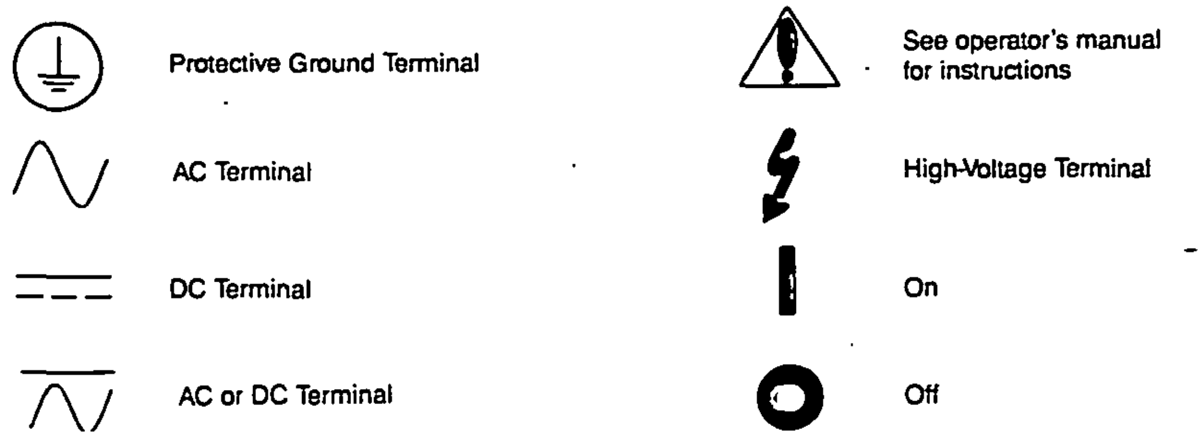


Figure 8-2. IEC Symbology for Electrical Tests and Measuring Equipment (Refs. 6 and 7)

TABLE 8-1
REQUIRED CREEPAGE DISTANCES FOR TEST EQUIPMENT (Ref. 8)

Rated Circuit Voltage AC (rms) If Sinusoidal, V	Rated Circuit Voltage DC, AC Peak or Mixed Voltage, V	Distances: Clearance mm (in.)	Distances: Creepage Distance mm (in.)
Up to 24	Up to 35	1.0 (0.040) [0.5 (0.02)]*	Same
Over 24 up to 60	Over 35 up to 85	2.0 (0.08) [1 (0.40)]*	Same
Over 60 up to 130	Over 85 up to 184	2.5 (0.10) [1.5 (0.06)]	Same
Over 130 up to 250	Over 184 up to 354	3 (0.12) [2 (0.08)]*	Same
Over 250 up to 450	Over 354 up to 630	3.5 (0.14)	4.6 (0.18)
Over 450 up to 650	Over 630 up to 920	4 (0.16)	6.1 (0.24)
Over 650 up to 1000	Over 920 up to 1400	5.5 (0.22)	9.1 (0.36)
Over 1000 up to 1500	Over 1400 up to 2100	10 (0.40)	12.2 (0.48)
Over 1500 up to 2000	Over 2100 up to 2800	12 (0.48)	14.2 (0.56)
Over 2000 up to 2500	Over 2800 up to 3600	14 (0.56)	15.7 (0.62)

*The smaller values enclosed in brackets apply to miniature-type components—printed circuits, micromodules, etc.—and may be accepted only where the spacings are rigidly maintained by constructional means and cannot be reduced during assembly.

completely disconnected from all sources of power. Panel-mounted equipment that is connected to the power source through flexible wiring should have a separate ground conductor to maintain continuity between the case and ground after the mounting screws have been removed. The ground conductor should be slightly longer than the power wiring so that the ground connection does not have to be removed before the power wiring. If power is supplied through a connector pair, the connector must be configured so that the ground contact must make contact before the contacts carrying the line current and so that the ground connection is the last to break when the connector is stressed to failure.

Meter interconnecting cables, especially those for portable equipment, should be constructed so that no energized conductors are exposed during normal operation or in situations that commonly arise from operator error. For example, removable test leads should have a connector that shrouds the contact on the cable. If this protection is not provided and the test lead is connected to an energized conductor, then the exposed contact either may be touched by personnel or may contact another conductor and cause a short circuit. An example of this problem is the test-lead configuration shown in Fig. 8-3. The test leads shown in Fig. 8-3(A), commonly used in the past, use "banana" plugs for connection to the meter. An improved alternative is the shrouded connector shown in Fig. 8-3(B) in which both the male and female contacts remain guarded when the connectors are not mated. The end of the cable that is attached to the equipment under test should be insulated to the extent allowed. If one lead of a meter is connected to an energized conductor, the other lead will assume the same potential. If the meter is a low-impedance ammeter, large currents may result if the unconnected lead contacts conductors at a different potential and thus causes arcing. Even if the meter is a medium-impedance voltmeter, personnel may receive electrical shock from contact with the disconnected probe under these conditions.

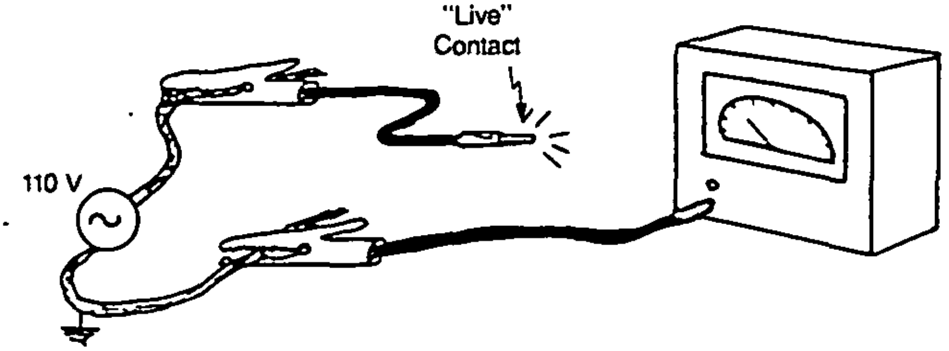
8-2.5 OPERATIONAL PRECAUTIONS

General-purpose test equipment is designed to be flexible to meet the variety of measurement requirements. This flexibility is usually obtained by the incorporation of switches, multiple input connections, or other functions that allow modification of the instrument function. It is important that clear, detailed instructions be provided with each instrument to explain operation of the controls in each of the intended applications. The need is amplified because of the infrequency of test operations and the widespread use by many personnel.

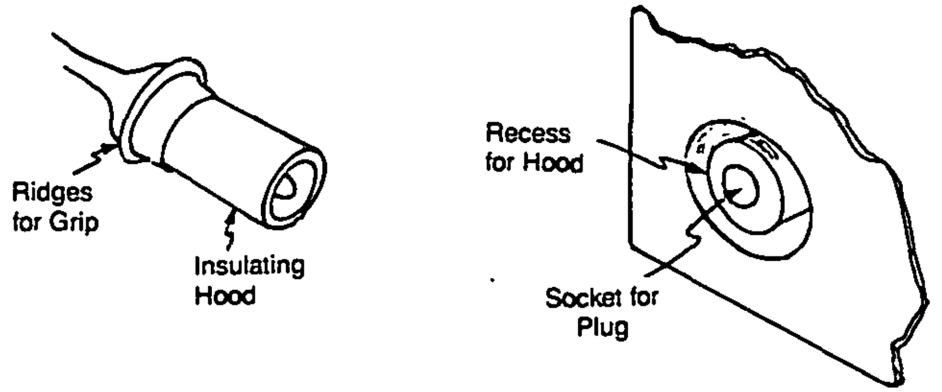
Complete, detailed instruction manuals should include, as a minimum, the following information (Ref. 6):

1. Installation considerations including assembly, grounding, interconnection, and ventilation
2. Explanation of equipment markings and controls
3. Interconnection with accessories or other equipment
4. Operating instructions including safety, storage, and handling precautions.

Instructions for portable instruments should also be available in a concise form, such as a placard or durable booklet, which may be kept with the instrument. Some of the specific issues that should be addressed are discussed in the paragraphs that follow.



(A) Old Style Test Leads Using Banana Plugs for Connection to Meter



(B) Improved Hooded Connector for Test-Lead Connection

Figure 8-3. Test-Lead Connections for Portable Instruments

When it is necessary to connect portable voltmeters by using clip leads, special precautions are necessary, as shown in Fig. 8-4. The clip must be small enough to avoid bridging adjacent conductors and causing a short circuit. First, connect to the conductor nearest to ground potential (ground potential if possible). Then using only one hand, clip the connection to the "hot" lead. These precautions apply equally to the voltage connection of wattmeters, bar meters, or any other instrument potential (voltage) coil.

Typically, power must be interrupted to connect current meters (or current coils of wattmeters) into lines. Where such interruptions cannot be tolerated or where frequent measurements of current with portable instrumentation are anticipated, provision should be made so the current connection may be made without power interruption. One way that is suitable for low-current levels is a two-conductor connector that shorts the two contacts together until a mating connector is inserted. Alternatively, a momentary, normally closed switch can be wired in parallel with a connector to provide a path to maintain the current flow except when a measurement of current is desired. For high-current systems a low-resistance shunt may be wired permanently in line with leads brought out to an accessible connector.

Analog instruments being transported should be placed so that the shaft of the pointer is horizontal. If the instrument is lying on its back, the jarring of the vehicle may damage the lower pivot or jewel. Each time the instrument is connected for a new test, the condition of this lower pivot should be tested for damage as follows:

1. Move the instrument slightly in the horizontal plane—enough to cause the pointer to move slightly off zero.
2. Observe the location of the pointer (avoid parallax).
3. Tap the instrument case gently with one finger and observe whether the pointer moves. Any movement of the pointer indicates a damaged pivot, and the instrument should be sent to a qualified shop for repair and calibration.

When accurate readings are desired from analog meters, care must be taken to avoid parallax errors. The head must be held so that the scale is viewed perpendicularly. If the meter has a mirrored scale, the head must be positioned so the reflected image of the pointer is hidden by the pointer. It is recommended that neither eye be closed nor shielded, but the technician learn how to view the pointer, meter scale, and reflected pointer image with one eye while he ignores the image perceived by the other eye.

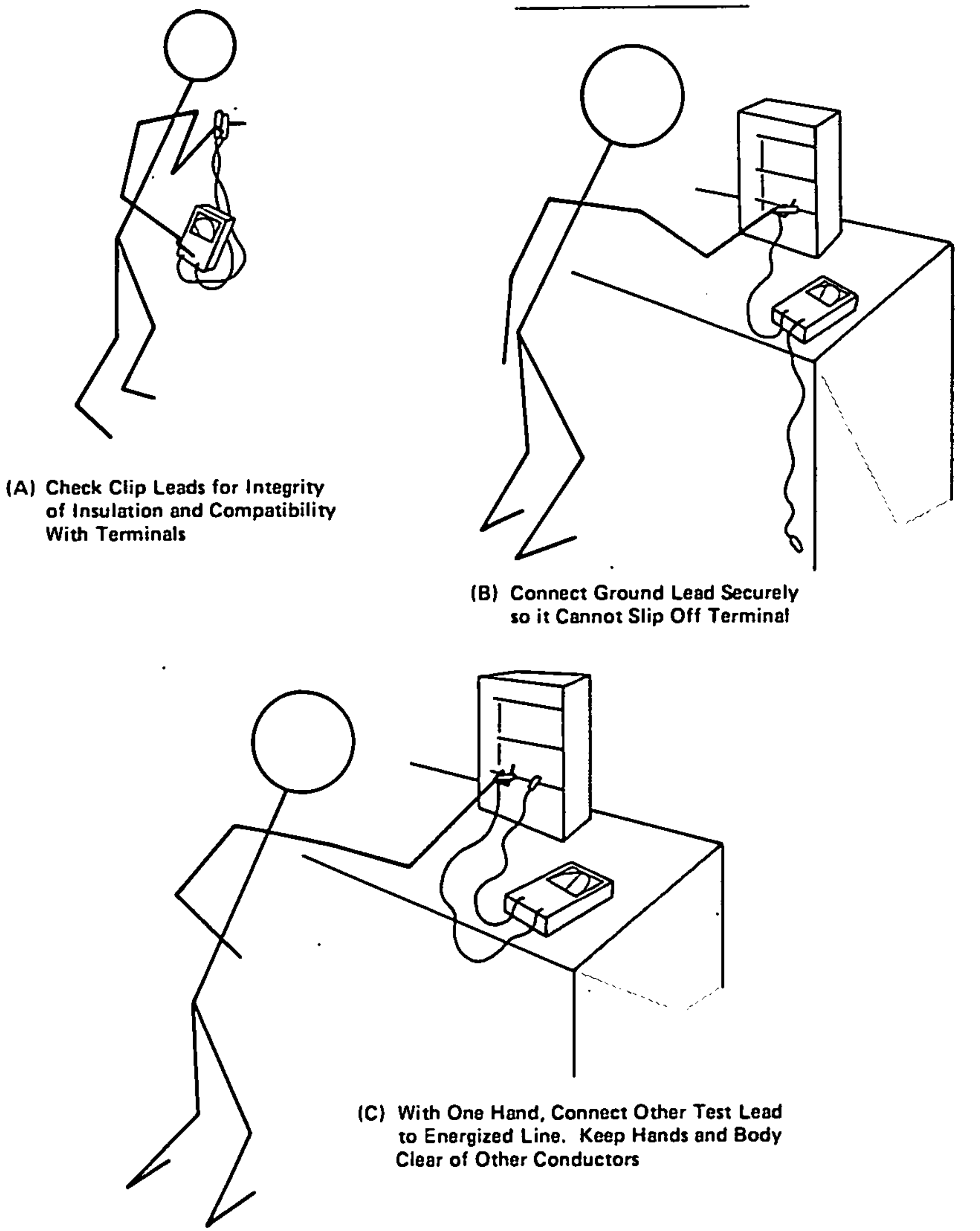


Figure 8-4. Procedure for Connecting Voltmeter Using Clip Leads to Energized Conductors

The cover glass must be kept clean. Wiping the glass with a dry cloth, however, will induce a static charge on the glass and can cause errors in the meter indication. Breathing on the glass will remove the static charge.

8-3 VOLTMETERS

8-3.1 INTRODUCTION

AC voltmeters typically have ranges from 1.5 to 600 V. There are several types of meters, including DC voltmeters with rectifiers or peak detection circuitry, to measure AC voltages. Selection of a meter for a particular test must consider the characteristics of the instrument, what measurement is required (rms, average, peak voltage), and the relationship between instrument impedance and its effect on the quantity being measured.

Analog DC voltmeters generally employ a D'Arsonval meter movement and series resistance to provide the required range. Portable meters usually are made with ranges of millivolts to 600 V with input impedance ranging from 1000 to 100,000 Ω/V full-scale. Higher impedances are obtained in portable meters through the use of field effect transistor (FET) amplifiers. Voltages above 600 V require a voltage divider resistor. Higher voltages may be measured by using external voltage probes containing series resistance.

Digital voltmeters, both AC and DC, are generally high-impedance devices that require separate power for operation. These devices are produced in both portable and panel-mounted designs and can incorporate either incandescent, liquid crystal, or light-emitting-diode numeric displays. Like their analog counterparts, these devices are available with full-scale voltages of 1 to 600 V with displays of three to six digits. The voltage range for portable instruments may be extended with special probes containing resistive dividers.

8-3.2 INDUCED ENVIRONMENT

The impact of voltage-indicating instruments on the environment is generally small and does not differ from that of the general instrumentation discussed in par. 8-2.2. The only unique consideration is that voltmeters, when connected to an electrical system, usually have a difference of potential between their terminals during operation, and at least one of the terminals has a significant voltage with respect to ground.

8-3.3 HAZARDS

Hazards associated with the operation of voltmeters, either permanently installed or portable test equipment, are the same as those described for general instrumentation discussed in par. 8-2.3. In addition, the use of portable voltmeters to measure high voltage increases the possibility of electrical shock or electrocution when the auxiliary high-voltage probes are used. These probes contain a resistive divider and extra high-voltage insulation to extend the measurement capability of the meter. If moisture or dirt causes conductivity across the surface of the probe or if cracks allow the development of conductive paths through the insulation, current from the high-voltage conductor connected to the voltmeter may pass through the person operating the voltmeter.

8-3.4 DESIGN CONSIDERATIONS

Voltmeters usually are not designed to measure voltages in excess of 600 to 1000 V because of the increased danger of arcing at the voltmeter terminals or internally—a condition that poses a severe shock hazard to the operator. For portable instruments a resistive divider incorporated into a high-voltage probe is frequently used to extend the range of the voltmeter. In the design of these probes, the distance between the probe tip and the voltage divider resistor should be kept short to minimize the length of conductors that are energized to the full voltage being measured. The probe should be insulated with a material that is resistant to cracking and breaking and has a high resistance to dielectric breakdown. The insulation materials should have a smooth, easily cleanable surface that is impervious to moisture and one that is shaped for the maximum creepage distance between the probe and handle. Fins or ribs may be added to extend this distance.

For permanent installations in which high voltages are to be measured, a potential transformer is used to allow measurement of high voltages at a safe level. The primary winding has a voltage rating equal to the voltage to be measured, and the secondary supplies a low voltage (usually 150 V) when the rated voltage is applied to the primary. Potential transformers should be fused for protection of the system in case of a failure in the transformer.

Typically, electrical system circuits are low impedance, so no stringent requirements are placed on voltmeter impedance. Some applications, however, related to power systems do require high-impedance meters. Consider the problem of measuring the induced voltage on an ungrounded wire routed parallel to a high-voltage line. The capacitance between the energized line and the line under test and the capacitance between the line under test and ground forms a voltage divider. If the voltage on the line under test—with respect to ground—is measured with a low-impedance meter, the reading will be less than the actual voltage. A high-impedance electronic voltmeter is required for accurate measurement of the induced voltage.

Voltage and current measurements are typically expressed in rms values so the two may be multiplied together to calculate power. Voltage measuring instrumentation typically responds to the average rectified voltage. As shown in Table 8-2, for the sinusoidal waveform

TABLE 8-2
COMPARISON OF MEASURED VALUES FOR SINUSOIDAL, TRIANGULAR, AND SQUARE WAVEFORMS

Waveform	Average Value of Rectified Waveform With 1.0 Peak Amplitude	rms Value of Waveform with 1.0 Peak	Ratio: rms / Average
Sine	0.637	0.707	1.11
Triangular	0.5	0.577	1.15
Sawtooth	0.5	0.577	1.15
Square Wave	1.0	1.0	1.00

used in power systems, the rms value of a sinusoidal waveform is about 11% higher than the average rectified value. This difference is normally incorporated into the calibration of the meter so that the actual readout will be in rms. Errors will occur if this "average-to-rms" calibration factor is incorporated into a meter that is then used to make voltage measurements on a waveform different from that for which it is calibrated. For example, if a meter calibrated for use with sinusoidal waveforms is used with a triangular waveform with the same peak amplitude, the meter deflection will be about 21.5% less. However, the rms value is only 18% less; the net result is an error of about 4% in the measured rms voltage.* In general, the amount of error is dependent upon the waveform. Rectifier-type meters should be calibrated for the particular waveform used and employed only on the voltage waveforms for which they are calibrated. If rms measurements are to be made on arbitrary waveforms, then a "true rms meter" should be used. Usually these meters are instruments that electronically compute the true rms of the input waveform and display it on either an analog or digital display.

Analog meters generally use the D'Arsonval movement, although the less sensitive electrodynamometer and iron-vane movements are sometimes used because their square-law response allows their use as true rms instruments. In the D'Arsonval movement, the pointer is driven by a movable coil suspended in the field of a permanent magnet. The electrodynamometer uses the repulsion between two electromagnets (one mounted on a pivot) to move the pointer. In the iron-vane meter, current through a coil magnetizes the two soft-iron vanes, which then repel each other. One of the vanes is movable and affixed to a pointer, which indicates the amount of current. Any stray magnetic field in the area causes the meter to give an erroneous reading. This type of instrument gives satisfactory accuracy from DC and AC voltages up to several hundred hertz.

Electronic analog test instruments are accurate and very sensitive. They can measure voltages with a negligible loading effect. They incorporate an AC-to-DC converter (rectifier), a DC amplifier, and a D'Arsonval DC meter. Depending on design, these instruments respond to the positive peak value, the peak-to-peak value, or the rms value of the wave and are usually calibrated to read rms that assumes a pure sinusoidal wave input. For other than sinusoidal waves, a correction must be applied except in true rms meters. The same considerations apply to digital voltmeters. These meters typically are designed for higher accuracy because of the greater precision of the indication.

Voltage measurements on circuits above 600 V are made by using a voltmeter with a 150-V range and a potential transformer permanently connected in the circuit. The primary of the potential transformer is fused to protect the system should the transformer fail.

Scale markings should be calibrated with 1, 2, or 4 units per division. Scale calibrations having a noninteger units-per-division should never be used because of the difficulty in determining indicated values and the increased likelihood of error. A combination 150- 300- 600-voltmeter scale should be graduated at 1 V per division on the 150-V scale. Then when the voltmeter is used on the 300- and 600-V ranges, the resolution will be 2 V per division and 4 V per division, respectively. If the desired voltage ranges on a multirange meter are not integer multiples, then separate scales should be provided for each range.

8-3.5 COMPATIBILITY AND INTEROPERABILITY

Significant characteristics that must be considered in selecting voltmeters, either as replacements or for new designs, are

1. Voltage range
2. Input impedance
3. Frequency range
4. Waveform sensitivity, e.g., rms response or average response calibrated for rms indication of sinusoidal waveforms
5. Environmental considerations, e.g., sensitivity to magnetic fields or temperature extremes
6. Movement type
7. Physical size and mounting considerations.

A more complete list of considerations for voltmeters is given in Ref. 9.

8-3.6 TEST CRITERIA FOR DESIGN AND ITEM ACCEPTANCE

Table 8-3 lists tests for analog meters that are described in Ref. 5.

A voltmeter should be calibrated against a standard voltmeter, both upon delivery from the manufacturer and at regular intervals thereafter. At no point on the scale should the instrument have an error greater than the guaranteed accuracy of the particular class of instrument. This accuracy usually is stated as percent of scale. For digital instruments the accuracy may be stated as "the maximum error will not exceed __ % of the range plus __ % of reading plus __ units of the least significant digit". The actual numbers inserted in the blanks in this expression are range dependent.

Examples of tests that may be appropriate for electrical test equipment (Refs. 5 and 8) are described in the sub-

*Since the meter responds to the average value of the rectified waveform, the response of the meter to a triangular waveform with the same peak-to-peak amplitude as a corresponding sinusoidal waveform will be less than the response to the sinusoidal waveform by an amount proportional to the difference in "average" values taken from Table 8-2, e.g., (0.637 − 0.5)/0.637 = 0.215 or 21.5%. Calculations, using values from the same table, show the actual rms value for the triangular waveform to be (0.707 − 0.577)/0.707 = 0.184 or 18.4% below the rms value of corresponding sinusoidal waveform. The difference between 21.5% difference in instrument response and the 18.4% difference in rms value represents a measurement error. The actual error, using an average-responding meter calibrated for rms measurements on a sinusoidal waveform to make rms measurements on a triangular waveform, would be proportional to differences in the rms-to-average ratio for each case given in the right column of Table 8-2. For this situation, the error would be (1.15 − 1.11)/1.15 = 0.035 or 3.5%.

TABLE 8-3
ACCEPTANCE TESTS FOR ANALOG PANEL METERS DESCRIBED IN MIL-M-10304E (Ref. 5)

Visual Inspection:	Operation at Temperature Extremes
Quality of Construction	Thermal Shock
Labeling	Resistance to Soldering Heat
Presence of Required Features	Overload Capacity
Solderability of Terminal Lugs	Dielectric Withstand Voltage
Influence of Meter Orientation on Indication	Insulation Resistance
Effect of Zero Adjustment	Watertightness by Immersion
"Sticking" of Meter Pointer in Off-Scale Positions	Resistance to Moisture (High Humidity)
Accuracy of Indication	Impact Tests for Windows
Response Time and Overshoot	Terminal Strength
Repeatability of Indication	Vibration
Power Consumption at Full-Scale	Shock
Frequency Response	Drop Testing
Susceptibility to Static Effects	

paragraphs that follow. Note that the environmental condition during the tests should be representative of the conditions under which the equipment is to be operated—including temperature extremes, presence of moisture, and salt spray if applicable.

Test examples are

1. *Leakage Current.* The leakage-current test is used to evaluate the electrocution-hazard potential of a test instrument by measuring the amount of current on exposed surfaces that could pass through the operator upon contact. Instrument terminals are connected to a voltage source equal to their maximum allowable voltage level, and the leakage current is measured by connecting a milliammeter having an input impedance of 1500 Ω shunted by a 0.15-μF capacitor between ground and any exposed conductor or conductive surface. For power-line frequencies, instruments are usually required to have leakage currents below 0.5 mA, although more stringent requirements may be specified.

2. *Insulation Voltage (Dielectric Withstand) Test.* The insulation-voltage test detects insufficient insulation within an instrument that could be bridged by a transient and possibly cause hazardous voltages on instrument terminals or external surfaces. After environmental conditioning, e.g., exposure to moisture or accelerated aging, an AC test voltage is applied between terminals and the case or protective ground. The test voltage is variable—beginning at zero and increasing to the value shown in Table 8-4 (Ref. 8). Failure of the test is indicated by current flow due to breakdown or any other indication of arcing.

3. *Torque Test for Terminal.* The terminal torque test verifies the mechanical integrity of panel-meter terminals and determines whether internal connections will be easily broken during the attachment of wires. Although this test is performed primarily for operational considerations rather than safety, it does check for the possibility of internal faults that could be produced by the repositioning of internal wires from terminal rotation. In this test a specified torque is applied to stud-type terminals. Failure of the test is indicated by terminal rotation, obvious breakage, or improper operation of the meter after the test.

TABLE 8-4
TEST VOLTAGE FOR INSTRUMENT DIELECTRIC WITHSTAND TEST (Ref. 8)

Voltage Rating of Instrument (Input Range), V	rms Test Voltage, V
0-30	500
30-130	1000
130-250	1500
250-650	2300

4. *Physical Ruggedness.* Ruggedness tests verify that the materials and construction of the equipment are sufficiently rugged to withstand the expected physical abuse without significant degradation in performance or safety. Specifications may call for impact tests or drop tests to verify the strength of the enclosure and ruggedness of internal construction.

5. *Temperature Rise.* Temperature rise tests verify that no fire hazard, burn hazard to personnel, or other potentially damaging overtemperature conditions will be induced from the normal, continuous operation of the equipment. In these tests temperatures of accessible components and internal, heat sensitive components are monitored while the instrument is operated under conditions that produce the maximum internally generated heat. The unit under test fails if, after reaching thermal equilibrium, any component or surface has a minimum temperature rise in excess of the values specified. Examples of allowable temperature rise for outer surfaces, internal components, and interconnecting wiring are given in Table 8-5 (Ref. 6).

TABLE 8-5
MAXIMUM TEMPERATURE RISE[a] UNDER REFERENCE TEST CONDITIONS (Ref. 6)

Equipment Area or Component	Temperature Rise Above Ambient deg C (deg F)	deg C (deg F)
Accessible Parts:		
Surfaces of enclosures	35 (63)	
Small areas and easily discernible heat sinks (not likely to be touched in normal use)	65 (117)	
Operating Devices and Handles:		
Metallic	20 (36)	
Nonmetallic	30 (54)	
Enclosure Interior Surfaces:		
Wood	65 (117)	
Insulating material	[b]	
Insulating Materials:		
Polymeric	[b]	
Varnished cloth	60 (108)	
Fiber	65 (117)	
Wood and similar material	65 (117)	
Capacitors[f]:		
Electrolytic	40 (72)	
Other types	65 (117)	
Fuses	65 (117)	
Semiconductor devices[f]	75 (135)	
Sealing compound	40 (72) (Less than melting point)	
Selenium rectifiers[f]	50 (90)	
Terminal box	65 (117)	
Surface on which equipment might be mounted in service, and surfaces that might be adjacent to the unit when it is so mounted	65 (117)	
Wires and cords[f]	35 (63)	
Class 105 Windings of:		
Transformers	75 (135)[d]	65 (117)[e]
Relays, electromagnets, solenoids, and the like	85 (153)[d]	65 (117)[e]
Motors: DC, universal, and AC motors with frame diameter larger than 178 mm (7 in.)[c]:		
Open motors	75 (135)[d]	65 (117)[e]
Enclosed motors	80 (144)[d]	70 (126)[e]
AC motors with frame diameter of 178 mm (7 in.) or less[c]:		
Open motors	75 (135)[d]	75 (135)[e]
Enclosed motors	80 (144)[d]	80 (144)[e]
Vibrator coils	75 (135)[d]	75 (135)[e]
Class 130 Windings of:		
Transformers	95 (171)[d]	85 (153)[e]
Relays, electromagnets, solenoids, and the like	105 (189)[d]	85 (153)[e]
Motors: DC, universal, and AC motors with frame diameter larger than 178 mm (7 in.)[c]:		
Open motors	95 (171)[d]	95 (171)[e]
Enclosed motors	100 (180)[d]	100 (180)[e]
Vibrator coils	95 (171)[d]	95 (171)[e]

[a]The heating test can be conducted at any room temperature between 15° and 35°C (59° and 95°F), and the observed temperatures corrected to a room temperature of 25°C (77°F).
[b]Polymeric material must be acceptable for the application when evaluated with respect to temperature.
[c]The diameter, measured in the plane of the laminations, of the circle circumscribing the stator frame, excluding lugs, boxes, and the like, used solely for motor-mounting assembly, or connection
[d]When measured by increase in winding resistance
[e]When measured with thermocouple
[f]Does not apply if investigated and accepted for a higher temperature

8-3.7 OPERATIONAL PRECAUTIONS

To be sure that the voltage to be measured is within the range setting of the instrument, the instrument should initially be set to its highest range. This measurement should indicate the proper range. When voltmeters are used on circuits above 300 V, it is recommended that first one connection (preferably ground) be clamped to the connection point and then the second probe be connected. If high voltages are being measured, it is desirable to make connections with one hand while keeping the other hand clear of any conductors—grounded or energized. *Never* use both hands to make two connections simultaneously.

Any test equipment that is used to measure high voltages should be stored in a dry location and where it will be protected from breakage. The presence of high humidity over an extended period could introduce leakage paths across surfaces of high-voltage insulators and possibly expose the operator to severe electrical shock hazards during use of the probe. Likewise, physical abuse of high-voltage insulations could cause cracks to develop and create leakage paths through the insulator.

Analog panel meters whose accuracy is affected by magnetic materials or fields should be marked or tagged with appropriate warnings and proper installation instructions. It is also helpful to provide a quantitative measure of error that is introduced by improper installation—e.g., mounting a meter, which should not be mounted near ferrous materials, on a steel panel.

The selection of the voltmeter for test measurements must take into account the characteristics of the circuit in which the measurements are to be made, including primarily the expected voltage level and the impedance of the circuits. An example follows.

A voltage is known to be 100 V and the source has an internal impedance of 1000Ω. A 1000-Ω/V meter is used to measure the voltage, which would have an impedance of 100,000 Ω on the 100-V range. The loading effect produced by the 100,000-Ω resistance in series with the 1000-Ω source resistance will cause a 1-V drop in the source resistance and indicate a meter response of 99 V. If the 1-V error is unacceptable, a meter with a higher input impedance must be used.

8-4 AMMETERS

8-4.1 INTRODUCTION

Ammeters are used to monitor loading current in distribution lines or output by generators or to troubleshoot electrical apparatus. Ammeters may measure the current directly or sense the current flowing in an existing conductor by transformer action. Common types of ammeters are shown in Fig. 8-5. The direct-insertion ammeter (Fig. 8-5(A)) must be inserted in the line and thereby requires an interruption of current flow while the ammeter is connected. Some instruments that sense current flow by sensing the fields around a wire may be installed around the wire without disconnecting it.

Analog ammeters use the same type of meter movements used for voltmeters described in par. 8-3.1. One additional type of meter sometimes used is the thermocouple meter.

Thermocouple instruments depend upon heat gener-

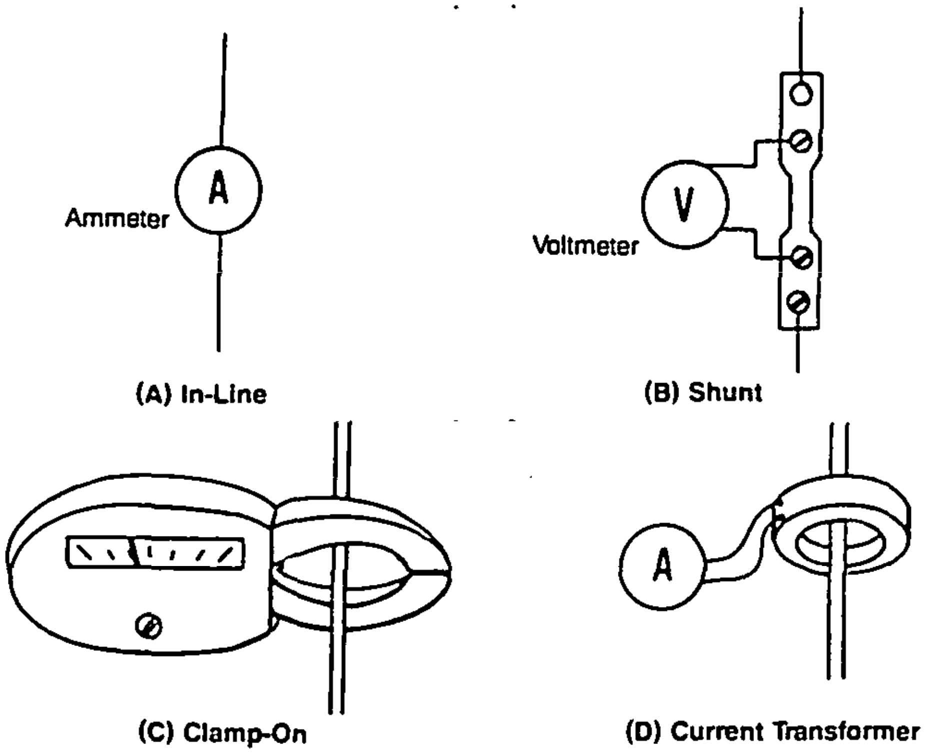


Figure 8-5. Common Types of Ammeters

ated by current in a heater (proportional to I^2) to produce an electromotive force (voltage) by a thermal function. This voltage is measured by a DC D'Arsonval instrument, which reads rms values accurately up to frequencies of up to 50 MHz.

Ammeters generally are limited to instruments with 5-A full-scale capability. To measure currents above this value in AC circuits, current transformers usually are employed as shown in Fig. 8-5(D). Alternatively, current shunts can be used in either AC or DC circuits. Current transformers have a primary with very few turns. High-current transformers have a single turn passed through a window in the iron core. The secondary has many turns wound around the common core. The ratio of turns between the secondary and primary determines the current-transformer ratio. (A 200-turn secondary and 1-turn primary have a ratio of 200:1, which would enable a 5-A meter to measure 1000 A.)

Some multirange ammeters are available that can measure 200 A by means of a self-contained, tapped-current transformer. A clamp-on ammeter shown in Fig. 8-5(C) contains an iron core that is split and hinged. By opening the hinged portion, the core can enclose a single conductor, which now becomes a single-turn primary of a current transformer. A multiturned tapped secondary actuates an ammeter. Because of the split in the core and the hinge, the iron core is less than perfect. The instrument is of limited accuracy, and the location of the conductor in the window of the core may influence the reading. These ammeters are good indicators of the magnitude of the current in a conductor but must not be used when an accurate reading is required.

A current shunt (Fig. 8-5(B)) is a precise resistance, which will produce a known voltage drop when a current is passed through it. Typical shunts are configured to provide a small voltage drop, e.g., 50 mV, when their rated current is passed through them. These shunts usually are used with a voltmeter with a compatible input-voltage range and a display calibrated to read out directly in the current range being measured. The resistance of current shunts and the corresponding output voltages are kept low for two reasons: (1) to minimize losses in the circuit under test and (2) to reduce heating of the shunt and produce a corresponding change in resistance.

Hall-effect sensors can give an indication of the magnitude of AC or DC current in a conductor. A steady current flowing in a constant, uniform magnetic field produces a voltage at right angles to both the current and the magnetic flux, which is proportional to the product of the magnitude of the current, the magnetic flux, and the sine of the angle between them.

8-4.2 INDUCED ENVIRONMENT

Properly installed ammeters and clamp-on portable meters have a negligible impact on the environment beyond the impact discussed for general test equipment in par. 8-2.3.

8-4.3 HAZARDS

Par. 8-2.3 indicates the hazards common to the use of all electrical test equipment. The use of ammeters in connection with current transformers has the extreme hazard that if the secondary circuit is broken when the current transformer primary is carrying a load, a voltage of several thousand volts will appear at the secondary winding terminal.

Ammeters that are designed for insertion directly in the circuit—as opposed to those that use a shunt or current transformer inserted in the line to provide a signal to a remote indicator—will necessarily have the line current flowing through the meter. This current, if more than a few amperes, may cause heating of the meter or connections and possibly lead to meter damage.

8-4.4 DESIGN CONSIDERATIONS

High-quality ammeters most often are made with two ranges—2.5 and 5 A, and 0.5 and 1.0 A. The winding is split so that the two halves can be connected in series (low range) or in parallel (high range). Ammeters of a somewhat lesser quality often have several ranges by incorporating an internal current transformer in the instrument case.

When a range switch is incorporated into an ammeter, it should be configured so that the continuity through the ammeter is not interrupted when the range is changed. If the circuit is interrupted while the ammeter is connected in series with a load drawing significant current, severe arcing will occur at the switch contacts and possibly lead to switch failure or arcing to adjacent conductors.

Current transformers usually are permanently installed because their "doughnut" construction requires that power be interrupted in order to reroute the wiring through the opening in the transformer. There are models, however, in which the transformer core may be separated into two halves and bolted around the conductor to allow installation without interruption of power. In either construction the transformer must be well insulated to prevent short circuits between the transformer and the line and to prevent breakdown between the secondary windings from the high voltages that develop if it is not connected to a load. The secondary of the transformer should be grounded at one point unless grounding affects the functioning of the other equipment connected to it. Therefore, the secondary is usually at ground potential and develops only a low voltage across a low-impedance meter, but the danger of high voltage is always present if the secondary circuit is accidentally opened.

For portable meters that use current transformers separate from the indicating electronics, provision should be made to prevent exposure of the operator to high voltage in the event that the current transformer is disconnected from its load (the indicating meter and/or electronics). Preventive measures include (1) the permanent connection of the transformer to indicating electronics and (2) covered contacts with a voltage-limiting device, e.g., zener diode, built into the transformer to prevent buildup to hazardous levels.

The impedance that a current transformer is designed to drive is called the burden. Ref. 10 specifies nine standard burdens ranging from 0.1 to 8 Ω. Generally, the accuracy is specified for all burdens that the transformer is designed to accommodate and may be different for different burdens..

Errors associated with current transformers may be classified in two categories, i.e., errors due to phase shift and errors in apparent transformer ratio. The phase shift errors do not affect measurements that respond only to current magnitude, such as ammeter measurements. These errors become significant only when the current transformer is used in phase-sensitive applications, e.g., wattmeter measurements. Errors in apparent transformer ratio are corrected by use of a ratio correction factor, K_{cr}. This factor is the ratio between true and design values of the current ratio. A ratio correction factor of 1.010 indicates that the secondary current is lower than the correct value by 1%, i.e., the output of the transformer is

$$I_{meter} = \frac{I_{line} K_{cr}}{R_t}, \text{ A} \quad (8\text{-}1)$$

where

I_{meter} = current into meter from current transformer, A

I_{line} = current in line to be measured, A

K_{cr} = correction value for transformer turns ratio, dimensionless

R_t = nameplate turns ratio of transformer, dimensionless.

Ref. 10 provides standard categories for accuracies of 0.3, 0.6, and 1.2%, which are based on errors that are encountered when using the transformer for power measurements. When the transformer is used for current measurements, the error typically is smaller because the inaccuracy that is attributable to phase errors does not affect the current measurement.

In polyphase and single-phase branches of a distribution network, the neutral conductor generally is grounded at multiple points; consequently, some portion of the load current flows through the ground. Therefore, to measure currents associated with a load, the current meter or current-sensing transformer must be placed in the phase wire or wires, and not in the neutral conductor. If it is placed in the neutral, the indicated current may be only a portion of the total load current.

Panel-mounted ammeters generally are limited to 5 A full scale. If currents above this value are expected, a current transformer or shunt should be used. Ammeters generally have a low impedance—less than 1 Ω—but when used in high-current, low-voltage circuits, the voltage drop through the meter can be significant.

8-4.5 COMPATIBILITY AND INTEROPERABILITY

Ammeters with lower ranges are available to satisfy instrumentation needs, but the standard 5-A meter is the most commonly used instrument in electrical generation and/or distribution systems (used with current transformers to provide higher ranges). Care must be exercised in obtaining a replacement for an existing ammeter that is used with a current transformer since some ammeters may have a different internal impedance. The replacement of a meter with another having a different impedance may cause the current transformer output to deviate from its specified value for the current being sensed. The specifications of the current transformer should be checked to determine whether the required accuracy will be obtained with the burden of the replacement meter. (Current transformer specifications give correction factors and accuracy specifications for all burdens that the transformer is designed to accommodate.)

Where instrument transformers (current transformers) are specified to extend the measurement range, the following parameters should be specified for the transformer:

1. Basic impulse insulation level
2. Nominal system voltage
3. Frequency
4. Accuracy
5. Continuous current rating
6. Peak current rating.

Insofar as it is possible, all high-quality ammeters should be of the same model and the same manufacture for uniformity of scales and the avoidance of errors in scale readings.

8-4.6 TEST CRITERIA FOR DESIGN AND ITEM ACCEPTANCE

The general tests listed in par. 8-3.4 for voltmeters are generally applicable for ammeters as well, except for the tests that verify meter calibration. In calibration tests known currents should be applied through the meter instead of voltages applied across meter terminals.

8-4.7 OPERATIONAL PRECAUTIONS

When a directly connected ammeter is inserted in a line, care must be taken that an excessive voltage drop is not introduced due to the internal resistance of the ammeter and interconnecting leads. This consideration is more important in high-current, low-voltage circuits where greater voltage drops are induced and any voltage drop will be a higher percentage of the source voltage. In low-voltage applications meters with low internal resistance—or low-impedance external shunts—should be used. Multimeters typically have higher internal resistance and may not be suitable for current measurements in certain applications. Connections to the meter should be made with wiring and terminations that are capable of handling the current. For expected current values in excess of 1 A, a bolt-on or other permanent connection is appropriate.

In all cases, ammeter connections should be sufficiently secure to eliminate effectively the chance of connections being accidentally disconnected. If connections are made with "alligator" clips or other temporary clips, the connections should be made with the power off. If power cannot be turned off, the load-side connection should be made secure first; then the line-side connection can be made. If the line side is connected first or if the load side becomes disconnected, the unconnected connector is energized to the full voltage of the line and will arc upon contact with a grounded conductor. The excessive currents will destroy the meter unless suitable overcurrent protection is incorporated within it. Also an exposed test-lead connector poses a severe shock hazard.

The secondary of a current transformer should be grounded at one point unless grounding interferes with the function of the equipment connected. If it is not possible to ground the secondary, a warning of this fact should be posted near the point where connections to a test meter are made.

At regular intervals, or if there is reason to suspect damage, the meter should be recalibrated. Each time the instrument is used, it should be moved enough in the horizontal plane to cause the pointer to move off zero to determine that the pointer smoothly returns to the previous indication. Tap the instrument lightly with one finger while observing the pointer. If the reading changes, the pivot or lower jewel is probably damaged or improperly adjusted and should be repaired. If static charges on the cover glass cause erratic readings, they can be removed by breathing on the glass.

8-5 WATTMETERS

8-5.1 INTRODUCTION

Wattmeters are compound instruments that measure current into and voltage across a load and that compute the electrical power based on the average value of the instantaneous current-voltage product. If the current and voltage are sinusoidal, the measured power P is

$$P = VI\cos\phi, \text{ W} \tag{8-2}$$

where

P = measured power, W
V = rms voltage, V
I = rms current, A
ϕ = phase angle between current and voltage, rad or deg.

Depending on the power factor, the actual power will always be less than or equal to the product of the rms voltage and current.

Mechanical analog wattmeters use the magnetic repulsion between a "current" coil and a "voltage" coil to deflect a pointer over a scale and indicate the average value of the VI product. The inertia of the meter provides the averaging function.

Basic wattmeters read power on a single line and typically have ranges of 750 or 1500 W—corresponding to voltage input ranges of 0-150 V or 0-300 V and a current input range of 0-5 A. Higher power capacities are typically measured by using basic devices with current or voltage transformers to extend the range.

Power may be measured in polyphase systems by using multiple wattmeters and adding the readings. Generally, one less wattmeter than the number of wires is required—i.e., two meters are required for power measurement in three-phase, three-wire systems and three wattmeters are required for three-phase, four-wire systems. The methods of interconnection are discussed in par. 8-5.4.

Alternatively, a composite unit can be used that consists of a single shaft and/or pointer driven by two sets of coils connected as shown in Fig. 8-6. This meter has the advantage of indicating polyphase power on a single readout. For applications requiring remote indication of power, electronic wattmeters that generate a voltage or current signal proportional to the power determined by sensed voltages and currents can be used.

The measurement of watts includes many diverse applications in a distribution system. Some examples of applications are

1. Measurement of the total load on a feeder
2. Measurement of each load connected to the feeder
3. Measurement of copper and iron losses in a transformer.

An instrument to measure volt-amperes reactive (VARs) is very similar to a wattmeter except that the external voltage and current coils are oriented so the meter deflection is produced by the component of voltage and current waveforms that is 90 deg out of phase. These

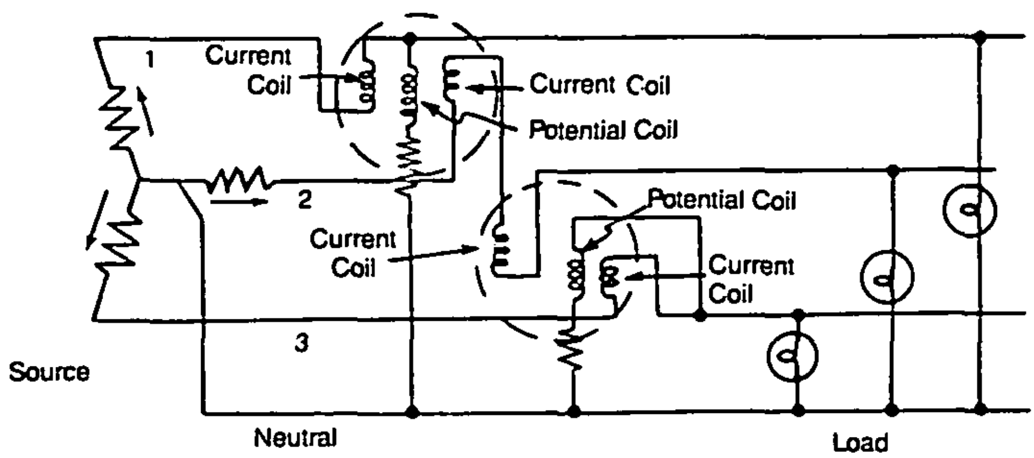


Figure 8-6. Wiring Diagram for Dual Element Wattmeter Used for Three-Phase, Four-Wire Power Measurements

instruments respond to the "imaginary" power flowing in power circuits with a nonunity power factor.

8-5.2 INDUCED ENVIRONMENT

The environmental effects of a wattmeter are minimal. Since the wattmeter consists of a current coil and a voltage coil, the effects on the environment are the same as those discussed for voltmeters and ammeters in pars. 8-3.2 and 8-4.2, respectively. The general considerations discussed in par. 8-2.2 apply as well.

8-5.3 HAZARDS

The hazards encountered by using wattmeters are the same as those discussed for voltmeters and ammeters in pars. 8-2.3, 8-3.3, and 8-4.3.

8-5.4 DESIGN CONSIDERATIONS

A wattmeter can be used to measure power flow by monitoring voltage and current in the single- or polyphase circuits. Wattmeters, in principle, are bipolar devices that have outputs that can be positive or negative, depending on the direction of the power flow in the line. (In some cases physical limitations can prevent the readout of negative power.) The convention has been established that load watts are considered positive and cause the wattmeter to read in the positive direction. Thus if current enters the wattmeter current connection with the plus marker when the voltage is positive on the voltage connection with the plus marker, the meter reads up scale.

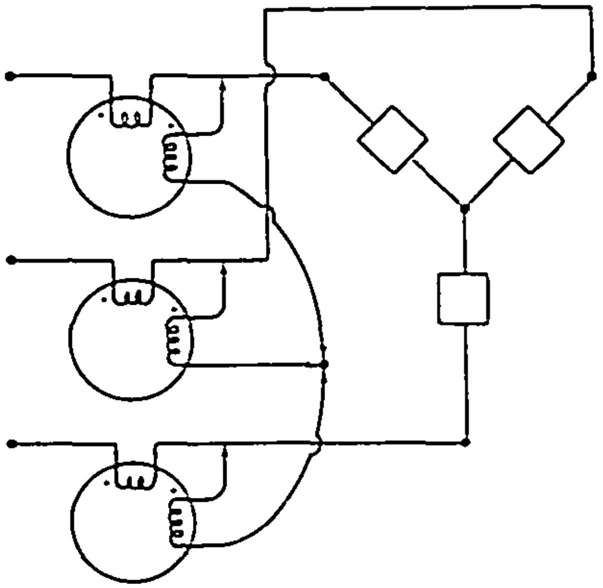
If the network being monitored is a source of power, the direction of the current is reversed and the meter attempts to read down scale. To measure watts delivered by a source, reverse the current connection or the voltage connection, but not both. The voltage connection is usually the safest to reverse because the current path does not have to be interrupted.

A wattmeter is constructed with two coils, i.e., a stationary coil of heavy wire of a few turns (the current coil) and a movable coil of many turns of fine wire in series with a high resistance (the voltage coil). The force produced by the interaction of fields from these coils moves the pointer across the calibrated scale. The average torque developed and the inertia of the moving system cause the reading to be the average of the watts delivered. The wattmeter reads average power, which is the effective power obtained by multiplying the rms values of voltage and current with compensation for the power factor.

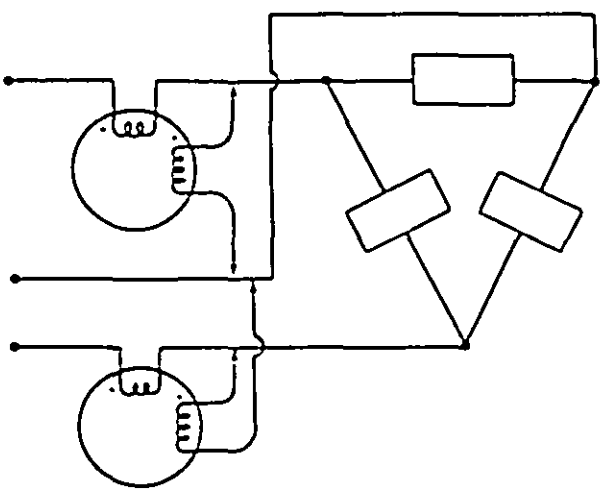
Voltages and/or currents that are not true sine waves but contain harmonic components follow the same analysis, and the wattmeter continues to read true average power for frequencies of up to several hundred hertz.

The measurement of three-phase watts is straightforward. For three-phase, four-wire systems, three wattmeters are connected between each phase and the neutral as shown in Fig. 8-7(A). The total power is the sum of the powers read on the three wattmeters. In three-phase, three-wire (delta-connected) systems, two wattmeters are used in the configuration shown in Fig. 8-7(B). Alternatively, a neutral potential can be derived by using a resistive network consisting of three resistors tied together at one end and each of the other ends is connected separately to each of the three phases. Then the three wattmeters can be used.

Depending upon the power factor of the load, one of the wattmeters may read down scale or negative. If negative readings are not permitted by the meter being used, the voltage connection of the meter reading down scale should be reversed and subtracted instead of added, when calculating the average three-phase power.



(A) Three-Wattmeter Configuration



(B) Two-Wattmeter Configuration

Figure 8-7. Connection of Wattmeters for Measurement of Three-Phase Power

8-5.5 COMPATIBILITY AND INTEROPERABILITY

Measurement of low values of watts, e.g., iron or copper losses in a transformer, require sensitive wattmeters. These meters usually have a low current rating, less than 1A, with a 150/300-V voltage winding. These instruments are used for special tests and are not interchangeable with the standard 5-A, 150- to 300-V wattmeters.

The 5-A, 150-V meters generally are interchangeable. Instrument transformers can be used to provide measurement capability at higher ranges. As stated in par. 8-4.5, current transformers must be designed for the burden (impedance) or the wattmeter current coil.

The scale calibrations of meters with the same full-scale ratings should be identical to prevent misreading or misinterpretation. Each division should be the same increment at all parts of the scale.

Only wattmeters that respond to the true average power, not simply the product of rms voltage and current, should be used for power measurements in electrical power systems. Most electromagnetic analog meters and electronic instruments, however, are true power meters.

8-5.6 TEST CRITERIA FOR DESIGN AND ITEM ACCEPTANCE

A new wattmeter should be calibrated against a standard wattmeter to insure that it was not damaged in shipment. The calibration readings should be within the guaranteed accuracy. The condition of the pivot and jewels in electromechanical meters should be checked as indicated in par. 8-3.7.

Instruments made by reliable manufacturers should meet the standards in Ref. 8, including those for leakage current and breakdown voltage between the energized coils and the case.

8-5.7 OPERATIONAL PRECAUTIONS

Considerations for the connection of a wattmeter are the same as those for connecting a voltmeter and an ammeter as discussed in pars. 8-2.7, 8-3.7, and 8-4.7. Polarity is an additional consideration. If either the current or voltage coil connection is reversed, the meter will read in the negative direction.

Depending upon the power factor and amount of unbalance in a three-phase load, one wattmeter may read backward even if the meter was connected with the plus markers properly considered. A backward reading will require the reversal of either the current connection or the voltage connection and subtraction of the reading instead of addition.

8-6 POWER ANALYZERS

8-6.1 INTRODUCTION

A power analyzer is a set of instruments in a single case. These combined instruments are used to check the magnitude and nature of loads—e.g., motors, lighting, a combination of both, or some other load. For use on three-phase systems, a power analyzer contains two wattmeters (or three wattmeters if a 4-wire system is employed), three voltmeters, and three ammeters. The number of meters can be reduced by using a single meter with a variable phase switch to select the phase in which measurements are desired. The ranges of the instruments are usually as follows:

1. Ammeter, 0-5 A
2. Voltmeter, 150-300 V
3. Wattmeter, 750-1500 W.

If the load being monitored is outside these ranges, instrument transformers can be used to extend the ranges.

Power analyzers necessarily are portable instruments used to troubleshoot or evaluate loading conditions on power lines. Since the power analyzer is made up of the same types of instruments—i.e., voltmeters, ammeters, and wattmeters—discussed previously, considerations particular to this instrument pertain to packaging, interconnecting, and switching of the components to produce a compact, portable instrument, which may be used in a wide variety of situations.

8-6.2 INDUCED ENVIRONMENT

In comparison to standard instrumentation mounted on control or monitoring panels, the portable power analyzers have an additional consideration related to their compactness. The bringing together in close proximity all phases of the polyphase distribution system increases the voltage stress on the air between the phases of the power system.

8-6.3 HAZARDS

The general hazards associated with test equipment are discussed in par. 8-2.3. Specific hazards related to voltmeters are discussed in par. 8-3.3, to ammeters in par. 8-4.3, and to wattmeters in par. 8-5.3.

In addition to hazards associated with the individual instruments, the power analyzer poses two additional hazards. The first hazard is the increased danger of arcing within the analyzer, at its input terminals, or in the temporary wiring used to connect it to the line. The increased electrical stress between phases increases the likelihood that arcing may be initiated by a line transient, condensation, conductive dust, or any other mechanism that further shortens the separation between the conductors. This hazard is further compounded by the proximity of all phases of the distribution system—i.e., if an arc that involves all phases is initiated, energy will be fed continuously to the arc. The resultant polyphase arc does not extinguish as readily because the periodic current "zero" that occurs in AC systems when the current reverses does not occur in polyphase systems. Energy is fed to the arc continuously to sustain it. If switches are used to select phases for measurements or to disconnect the service from the load, then the likelihood of arcing is further increased by the normal arcing during the "break" operation of a switch.

The second hazard is caused by the temporary hookup necessary to connect the power analyzer to the power system. Since the power analyzer has components that must be connected in series with the line and components that must be connected across phases, a number of connections are necessary. Generally, existing power wiring is disconnected from the power source at some convenient terminal, e.g., at a circuit breaker, and connected to the output terminals on a power analyzer. Jumpers are then installed to supply power from the original terminals to the power analyzer. Since the wiring is temporary, it is often installed with the degree of workmanship below that acceptable for a permanent installation. As a result, short circuits, arcing upon contact between phases, or contact by personnel to exposed, energized conductors is more likely.

8-6.4 DESIGN CONSIDERATIONS

Power analyzers for use with low-power systems can be designed so that power to the load passes through the analyzer. A minimum configuration of equipment must include one voltmeter, one ammeter, and two wattmeters. This minimum configuration requires a switch to permit voltmeter measurement of three line-to-line voltages and a voltage range switch that enables voltmeter reading of 150 or 300 V full-scale. A schematic of a power analyzer is shown in Fig. 8-8. A special selector switch for the ammeter must be provided to enable it to measure the three-line currents. This switch must isolate the three phases and sequence the switching so that continuity is maintained between the input and output at all times. This necessitates a special switch with shorting-type contacts, i.e., one that connects the input and output terminals of the ammeter to the line before breaking the "through" connection. Generally more reliable, safer operation may be achieved if the load current-carrying switch is replaced with the simpler unit, which does not have to maintain continuity.

Fig. 8-9 shows a power analyzer with features that eliminate the need for a complicated switch and the need for line-level current and voltage switching. This configuration uses shunts and voltage dividers to produce low-level signals that can be switched safely. Although the ammeter switch does have all three phases connected to it, it has a simpler construction that can provide greater physical separation between phases in comparison to the switch used in the configuration shown in Fig. 8-8. Complete isolation of the ammeter circuitry from the line could be provided by using current transformers to sense the line currents. If this configuration is used, however, it is essential that a way be provided to insure that the current transformer secondaries are never open-circuited. In this configuration, resistors can be connected across the secondary to prevent the buildup of high voltage when the ammeter is not switched to another line. Alternatively, high-level switching could be eliminated by using dedicated meters with each phase.

The input terminals for a polyphase power analyzer must be designed carefully. Typically, terminations are used in which the wire is inserted through a hole and held in place with a screw that compresses the wire against the sides of the opening. The assembly is encased in insulation material except for the opening for insertion of the wire; an access hole is provided for a screwdriver in designs in which a slotted head screw is used to hold the wire in place. If this type of connection is used, certain features must be incorporated to insure safe operation. The terminals must be separated enough so that errant strands from one phase do not make contact with conductors connected to an adjacent terminal or the terminal itself. The terminal must be covered with insulation so that person-

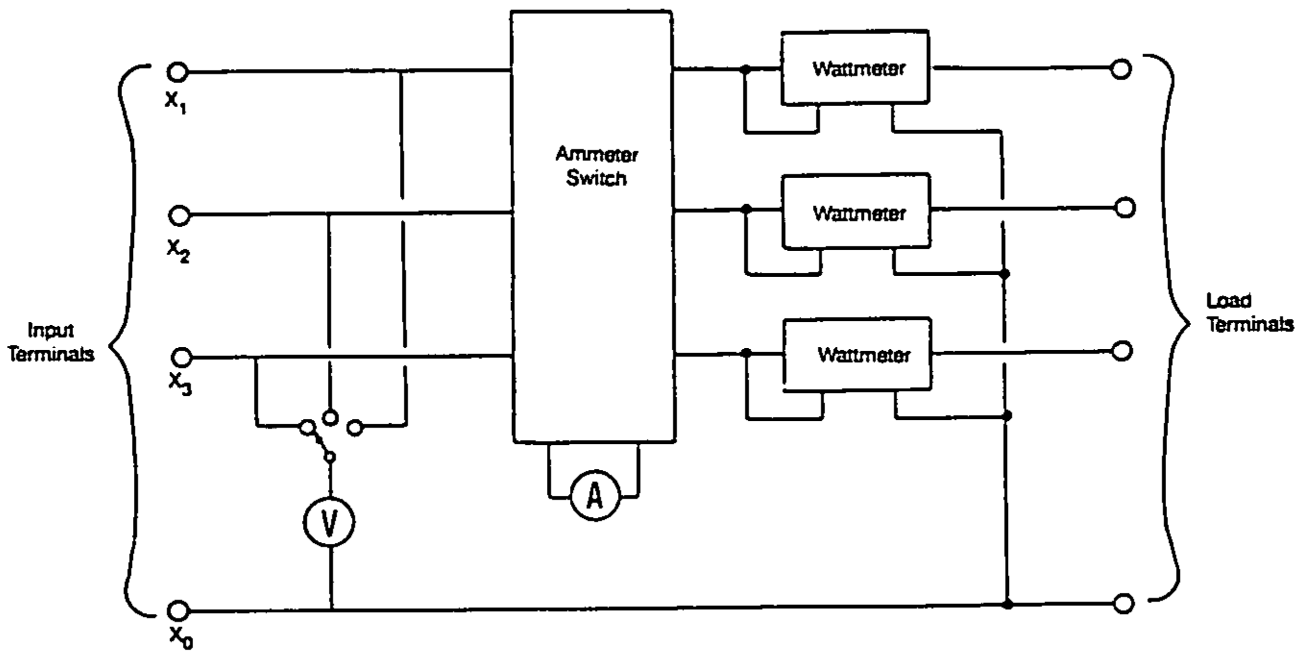


Figure 8-8. Design for Power Analyzer With Complex Ammeter Switch and High-Voltage Switches

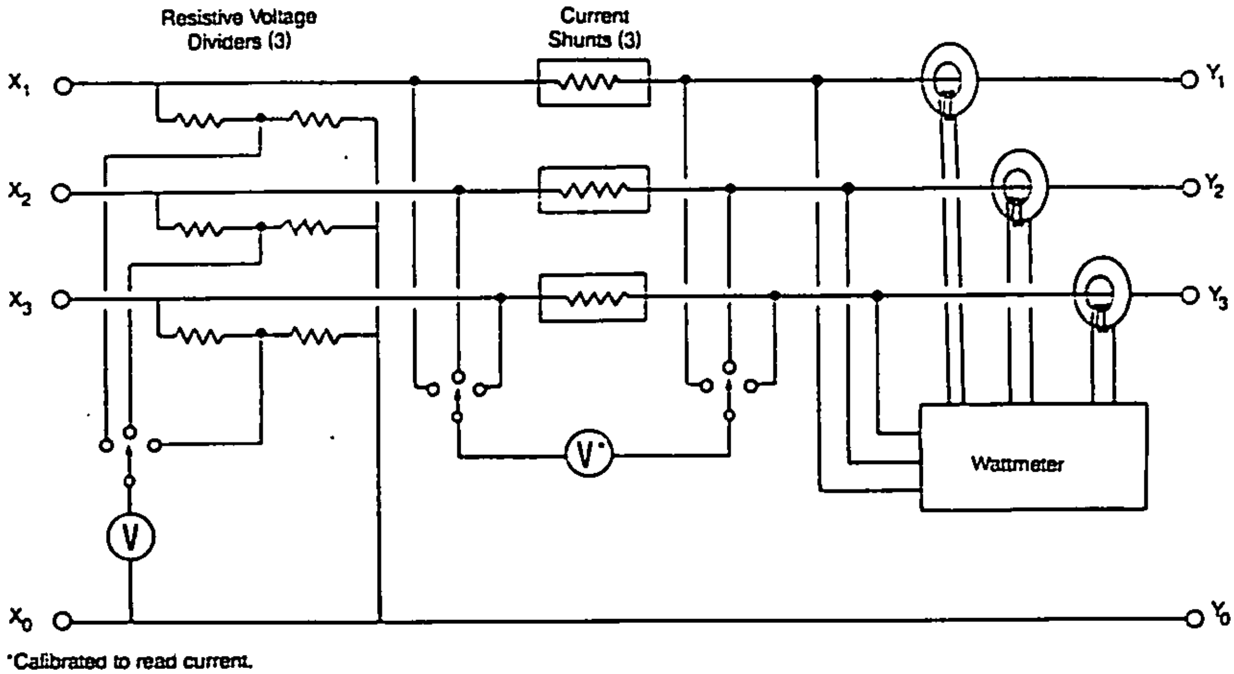


Figure 8-9. Improved Power Analyzer Design With No High-Voltage or Current Switching

nel cannot inadvertently touch any of the energized conductors once the analyzer is connected. It should not be possible to insert the wire through a terminal such that the wire protrudes through the other side.

If power analyzers are to be used with higher capacity lines, it is not practical to bring the power through the analyzer safely. Alternatively, an analyzer with clamp-on current transducers should be used. This configuration would bypass the need for disturbing the system wiring, although power should be removed, using existing switchgear, while the voltage leads and the current transformers are installed. Again, provisions must be made so that a load is always connected to the current transformers—either by means of a shunt resistor that is an integral part of the transformer or by permanently connecting the transformers to the analyzers without the use of connectors.

8-6.5 COMPATIBILITY AND INTEROPERABILITY

Since power analyzers are portable test equipment, they are designed to be used with a variety of systems. Generally, one power analyzer may be used to replace another provided the replacement analyzer has the following characteristics:

1. Can be operated at the same voltage and current level and frequency
2. Has equivalent connections, e.g., direct connections versus current-sensing coils
3. Is approximately the same size
4. Is labeled with the same symbols.

Power analyzers are typically custom designed items. Once a design has been decided upon, all analyzers used by personnel performing the same function should conform to this design to avoid confusion in connection leads, scales, readings, and switch arrangements. Features that might increase the number of systems with which the analyzer might be used are

1. Range switches to allow operation at more than one voltage range
2. Interchangeable current transducers to allow use on lines operating at different current capacities.

8-6.6 TEST CRITERIA FOR DESIGN AND ITEM ACCEPTANCE

When received from the manufacturer, the individual instruments must be tested against standard instruments for accuracy. Leakage currents and voltages on exposed parts should be tested according to ANSI Standard C39.5-1974 (Ref. 8). (See par. 8-3.6.)

Selector switches and range change switches must be checked for proper operation. The current-selector switch—if the analyzer incorporates a single ammeter and selector switch—must be tested for insulation between the three current circuits for all switch positions. The switch must be tested to verify that each current circuit connects the ammeter before the short is removed.

The voltage selector switch must be checked to verify that not only is the voltmeter range changed but also the two-wattmeter potential coils when the switch is operated.

8-6.7 OPERATIONAL PRECAUTIONS

Precautions that must be exercised in using an analyzer depend upon the configuration of the particular analyzer. The voltage selector switch should be set on the high range before connecting the leads to the circuit, and power should be disconnected prior to connection of the analyzer. This disconnection is essential for analyzers in which the power must pass through the analyzer and is necessary for safety on analyzers that use clamp-on current sensors and voltage probes.

If analyzers are equipped with a connection harness that is permanently connected to the analyzer, the unconnected leads become "live" as soon as the first connection is made to any energized circuit. Therefore, the harnesses must be laid out—keeping all leads isolated from ground or other phases while connections are being made.

8-7 PHASE METERS

8-7.1 INTRODUCTION

Phase meters are used to measure or indicate the relative phase angle between two voltages. Phase meters, or indicators, can be any of the following:

1. Laboratory or portable instruments that accurately display the phase-angle difference between a signal of an unknown phase and a reference signal
2. Instruments that indicate, through meter movement or lamps, the direction of phase rotation in a three-phase system
3. Instruments that indicate, through rotating disks or lamps, when the phase difference between two voltages is at minimum and not changing.

The phase meter most commonly encountered in polyphase systems of the scope covered in this handbook is the synchroscope, an instrument that indicates phase difference with a pointer that is free to rotate through the full 360 deg. In the single-phase synchroscope, a dual-coil meter deflects a rotatable iron vane to an orientation that is dependent on the phase difference between the coils and, to some degree, independent of the operating voltage and frequency. Functionally similar instruments are made for three-phase systems that have a three-coil stator and a three-coil armature. The synchroscope is used to monitor the phase difference between a generator output and an energized bus system to determine the time the voltages are in phase so the generator may be switched on-line. If the frequencies of the two voltages are different, the phase will be continuously changing and the synchroscope indicator will rotate at a rate proportional to the difference in frequency. In the generator application, the frequency of the off-line generator is adjusted until the rotation of the synchroscope is slowed as much as possible; the generator is then switched on-line when the synchroscope indicator passes through the position indicating zero phase difference.

A simpler system, sometimes used for the same purpose, has indicating lamps that are illuminated when the relative phase between two lines is such that a voltage difference exists between the lines. The advantage of this configuration is simplicity and, therefore, reliability. The disadvantage is that it provides an indication only when the phase approaches zero and does not indicate whether the monitored phase leads or lags the reference voltage.

Another application of phase meters is the determination of the phase angle across an open breaker in a network in which power is applied to both sides of the breaker. Such a breaker could be used to apply power to a series of branch circuits through an alternate route without interruption. The measurement of phase difference between voltages on each side of the breaker provides an indication of whether the breaker can be closed safely.

A phase rotation indicator is a special type of phase meter. It does not indicate the angle between two voltages but, rather, the phase sequence of three voltages. It is a simple device in which an aluminum disk is completely enclosed in an insulated case about 76 mm (3 in.) in diameter and 25 mm (1 in.) thick. A triplex cable, with three clips at the end of the cable, is an integral part of the instrument. The clips are marked 1-2-3. When these clips are connected to a source of three-phase voltage, the aluminum disk rotates slowly. The rotation of the disk is in one direction if the clips are connected to a system whose phase rotation is 1-2-3 or the reverse direction if the rotation is 1-3-2. This calibration is engraved on the cover of the instrument. The instrument is built for use on any voltage up to 440 V phase-to-phase and is not sensitive to voltage magnitude.

8-7.2 INDUCED ENVIRONMENT

Synchroscopes almost always are panel mounted and practically never used as a portable meter. Therefore, this instrument, once it is installed, has no further impact on the environment. General-purpose frequency-measuring instrumentation is similar in application to general-purpose voltmeters. Considerations discussed in par. 8-2.2 are applicable.

8-7.3 HAZARDS

The hazards associated with a synchroscope and its application are essentially the same as with voltmeters. This instrument responds to the phase of voltages and, therefore, may be connected without breaking existing circuit connections as is done for the insertion of current-sensing devices. Consequently, the hazards associated with a synchroscope and its application are essentially the same as those associated with voltmeters and general-purpose instrumentation as discussed in pars. 8-2.3 and 8-3.3. One additional consideration arises from the fact that phase meters measure the difference in phase between two voltages, which implies that in polyphase systems two sets of polyphase lines from two independent sources are brought together in one instrument. Power drawn by the synchroscope from each source is small. However, if a short circuit or arc developed from lines from one source to the other, considerable damage could be done to the synchroscope and surrounding equipment unless suitable overcurrent protection was provided for the instrument.

8-7.4 DESIGN CONSIDERATIONS

Safety-related design considerations for synchroscopes include the minimization of electrical leakage between the internal coils and the enclosure or the panel to which it will be mounted. If the synchroscope is to be used in the vibrating environment of an engine-driven-generator set, all moving parts should be sufficiently ruggedized so that the possibility of metal fatigue or breakage is minimal for two purposes: (1) to increase the reliability of the device and (2) to prevent the development of short circuits between internal connections and the case. The possibility of internal shorts can be further reduced by the encapsulation of coils and terminations to prevent the development of leakage paths to the case.

To prevent problems due to the development of faults between the two polyphase sources within the meter, some form of overcurrent protection should be provided to protect wiring associated with the meter. This protection could consist of built-in fuses, fuse links, or simply wire sufficiently small that it could act as a fuse. The fuses should be located right at the input of the meter to minimize the possibility of internal arcing "ahead" of the fuse, which would produce currents in excess of the capacity of the wiring of the instrument. In addition, terminals for each input should be separated to the maximum extent possible to minimize the chances of arcing or development of faults between the terminals.

8-7.5 COMPATIBILITY AND INTEROPERABILITY

Laboratory phase meters generally are versatile instruments that can be configured through panel controls to make phase measurements for many applications not just those associated with electrical power systems. Features that allow the instrument to be used for a variety of applications are

1. Selectable input range or autoranging capability
2. Multirange phase-difference measurement capability
3. Operation from a variety of line voltages or from internal batteries
4. Wide frequency input range
5. Phase differences measurements in fundamental frequencies with minimal effect due to waveform distortion.

Phase meters that are included in generator control panels and other power installations generally are compact, line-powered instruments built into the equipment that they test. These units only have to operate at power line frequencies and at reasonably constant voltage levels. The following characteristics of the synchroscopes must be specified to designate requirements for unit replacement:

1. Input voltage range
2. Physical size and mounting provisions
3. Built-in illumination
4. Sensitivity.

The term sensitivity refers to the degree to which small phase differences may be read visually on the meter. The required sensitivity depends on the application. In the most common application, generator monitoring, it is generally sufficient to know phase difference to within tens of degrees; also a clear indication of 0 deg is more important than finely calibrated scales.

8-7.6 TEST CRITERIA FOR DESIGN AND ITEM ACCEPTANCE

The instrument must be tested for temperature rise when both windings, system and new machine, are energized continuously from a source of normal voltage. Any metal parts that are exposed must be tested for leakage current and for the existence of voltages as described in par. 8-3.6.

The synchroscope should be tested with both windings energized from the same source to verify that the pointer indicates exactly 12 o'clock. For synchroscopes used during start-up of a generator, this check is easily made after the generator is switched on-line as the two lines, or sets of lines, monitored by the synchroscope are connected together.

8-7.7 OPERATIONAL PRECAUTIONS

Each time the synchroscope is used, it should be tested to verify that with both windings, energized from the same source, the reading indicates 12 o'clock.

To avoid the hazard due to arcing between the two separate power lines connected to the phase meter, input wiring from the two sources should be isolated as much as possible and current protection should be included in the line to prevent large fault currents from arcing.

8-8 FREQUENCY METERS

8-8.1 INTRODUCTION

There are three types of frequency meters—i.e., the analog vibrating-reed, the frequency-to-voltage converter/meter combination, and the digital meter. The vibrating-reed instrument is simpler, more rugged, and easier for monitoring the effectiveness of throttle adjustments. The range, e.g., 58 to 62 Hz, of these instruments, however, is very restricted. If a generator separates from the system, the frequency of the isolated generator can be considerably beyond the restricted range and the operator would be unable to know what adjustment to make. Digital frequency meters have more extensive ranges and could give an indication that would enable the operator to adjust the generator speed within the range of the synchroscope for resynchronizing the generator to the system.

8-8.2 INDUCED ENVIRONMENT

Frequency meters are generally part of the permanent panel board installation. Temporary connecting leads are not used since a selector switch to measure the frequency of each individual generator connected to the distribution network is provided.

8-8.3 HAZARDS

The usual hazards discussed in par. 8-2.3 do not apply to frequency meters because they have single-scale readings. Provided that the frequency is within range, the indication given by the vibrating-reed instrument is straightforward and not subject to misinterpretation. The indication on the digital instrument is also clear and immediately understandable. The instrument is permanently installed and free of any hazard of temporary connecting leads. Properly installed selector switches do not introduce any hazard.

8-8.4 DESIGN CONSIDERATIONS

A vibrating-reed frequency meter consists of a number of thin, flexible reeds that are attached at one end to a yoke that is subjected to a vibration induced by an electrical current flowing in a coil closely coupled to the yoke. The other end of the reeds is unsupported and free to vibrate. The natural frequency of vibration of each reed is adjusted to correspond to the scale calibration opposite its position in the row of reeds by adjusting the mass (solder) at the tip of the reed. When the coil is energized, the reed with the natural frequency equal to the frequency of the voltage, vibrates. The end of the reed then appears as a white line about 25 mm (1 in.) long below the seal of the instrument. Reeds with natural frequency close to the frequency of the voltage vibrate slightly and all others do not vibrate at all.

Vibrating-reed instruments can be adversely affected by vibration. For example, assume that the panel is subjected to a strong 60-Hz vibration from some piece of equipment that is connected to the main system and the coil is energized by an isolated generator operating at 59 Hz. The instrument could indicate 60, 59, or both 60 and 59 much to the confusion of the operator who might easily take an inappropriate action. In cases of excessive vibration, the vibrating-reed instruments can be mounted with isolators that prevent the coupling of mechanical vibration to the operating portion of the instrument.

The frequency-to-voltage converter/meter combination uses an electric circuit to generate an analog voltage (or current) that is proportional to the measured frequency. An analog or digital meter, driven by the output of the converter, is used as a display device for the frequency measurement system. Since the system is all electronic, it is not sensitive to moderate levels of vibration like the vibrating-reed meter, but it does not have the inherent accuracy of the pure digital meter.

Digital-frequency instruments measure the number of pulses of a high-speed clocking circuit between zeros on the voltage wave and interpret this reading as frequency of the voltage wave in hertz. In one configuration, the cycles of the line are counted for a prescribed period and the total displayed. With this scheme the time interval necessary to accumulate the required count is inversely proportional to the desired resolution. That is, if a frequency readout to the nearest 0.1 Hz is desired, the meter must accumulate the count over a 10-s period. In some applications, such as adjusting the governor of a generator, this display in obtaining an updated reading may be unacceptable. Digital instruments that measure the period between cycles, or groups of cycles, generate a high-resolution frequency measurement much faster. The disadvantage of this configuration, however, is that the instrument is highly dependent on the cycle-to-cycle waveform variation being insignificant. Therefore, any transients or electrical noise on the line may cause error.

8-8.5 COMPATIBILITY AND INTEROPERABILITY

All vibrating-reed frequency meters should have the same frequency range to avoid confusion if it is necessary to replace a defective instrument. The instrument scales should be identically marked.

The range of digital instruments is not inherently limited as it is for the vibrating-reed meter. More accurate readings, however, can be obtained if filters that preclude harmonics and electrical noise from the measurement circuits are incorporated. The incorporation of the filters will limit the response of the frequency meter to 80 to 100 Hz.

8-8.6 TEST CRITERIA FOR DESIGN AND ACCEPTANCE

Vibrating-reed frequency meters should be tested at rated voltages to insure that the reeds do not vibrate with sufficient amplitude to strike the scale window opening or other metal parts. The case of the instrument should be tested to verify that any leakage current or voltage on the case is within requirements of ANSI Standard C39.5-1974 (Ref. 8) as discussed in par. 8-3.6.

Digital frequency meters should be tested at a rated voltage for proper indication. Leakage current to the case and voltage on the case should also be tested for the safety of the operating personnel.

Frequency meters may be checked and calibrated by operating the unit to be tested in parallel with a calibrated frequency counter, both driven from a variable frequency supply capable of delivering the appropriate voltage. The frequency of the supply should be varied over the entire operating range to verify the response of the instrument under test.

8-8.7 OPERATIONAL PRECAUTIONS

Frequency meters should be mounted in a location where the meter may be read easily, at approximately eye level. For vibrating-reed meters suitable illumination must be provided to allow easy determination of the vibrating reed.

In digital frequency meters that have a trigger or threshold control, this control should be adjusted over its range to determine the maximum and minimum settings that provide repeatable readings. The control should then be set to a point halfway between. The operator, however, should also note any points throughout the range at which the reading becomes erratic and should avoid those particular levels. These errors may be produced by repetitive transients on the line caused by solid-state switching circuits.

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GLOSSARY

A

Airbreak switches. A switch in which the contacts are surrounded by air so that upon separation an arc is drawn in and extinguished in the air.

B

Basic insulation level (BIL). The lowest level of one of the standard voltage strengths available that will not be exceeded at any transformer location within the network.

Bus bars. A rigid conductor usually mounted in groups of two or more for the purpose of distributing power within cabinets or raceways.

C

Chilblain. An inflammatory swelling or sore caused by exposure to cold.

Circuit breaker. A switching device capable of disconnecting power to a circuit when the full load current is exceeded. Usually this term refers to a switching device that has an overcurrent detecting feature so it can interrupt current to a circuit when excessive current is detected.

Class, insulation (motors). A designation of the maximum temperature the insulation within motors will withstand over long periods. Classes A, B, F, and H are defined in IEEE-Std-1.

Cogeneration. Generation of electricity on-site in parallel with the utility. Excess power is fed back into the utility to reduce power costs.

"Cold" standby system. A generator that is fueled, maintained, and calibrated so that it can be started and brought on-line anytime the primary power is lost.

Control. A switch, potentiometer, valve, or other manually operated mechanism designed to regulate the flow of energy to or within a device.

Controller. A piece of equipment that regulates the flow of energy within another device based on inputs such as control position and sensor inputs.

Coordination. The procedure of selecting overcurrent protection devices so only the device most closely associated with a fault is tripped.

Creepage distance. The length of the shortest path across an insulator surface separating two conductors.

Current transformer. A transformer intended to transform large line currents to smaller currents, e.g., 5 A, which can be more easily measured with conventional instrumentation. The primary may be a single turn, which is frequently the line conductor carrying the current to be measured. The secondary is intended to be connected to a low impedance so the voltage drop across the primary is small.

Cutout. A switch, typically incorporating a fuse, that is used to interrupt current to a load.

D

Dead-front panel. An electrical panel that has no energized conductors accessible from the front.

Delta (Δ). The three-phase power configuration in which the power sources or loads are connected between three terminals. No neutral is used in the delta configuration. When specified for this configuration, the voltage is the voltage between any two terminals.

Disconnect. A switch that is used for reconfiguration of a distribution system. It is designed to conduct load current but is not capable of interrupting load or fault currents.

Distribution network. *See* primary distribution network.

Distribution system. The system of conductors, transformers, and associated protective devices that distribute the power from a source or multiple sources to various end-items.

Diversity, load. The ratio of the sum of maximum loads of individual components maximum to the composite load for an electricity supply, e.g., generator. Load diversity will always be 1.00 or greater.

Drip proof. A construction such that equipment operation will not be negatively affected by liquid or solid particles falling within 15 deg of the vertical.

Droop. Characteristic of generator systems in which the line frequency drops slightly with increasing load.

E

Earth connection. Electrical connection made directly to soil or water on the surface of the earth.

Engine. An energy conversion device that produces mechanical motion from the combustion of fuel, e.g., gasoline or diesel fuel.

Explosion proof. A construction such that the effects of an internal explosion are contained and the energy in gases is dissipated so that the gases are cooled before escaping to the environment.

F

Fault. An unintentional connection between a line and another conductor, either grounded neutral or another line.

Feeder. Circuit that carries power from primary distribution source to secondary distribution centers.

Flash point. The minimum temperature at which a liquid will give off combustible vapors at a rate sufficient to ignite.

Fuse. An overcurrent protective device containing a thin metal strip that melts or vaporizes when excessive current passes through it.

G

Generator. A rotating machine that converts the mechanical energy in the rotating drive shaft to electrical power.

Ground, electrical. A conducting connection capable of maintaining equipment at the potential of the earth. Electrical ground connections can be made directly to the earth, to structures that are connected to earth, or to a relatively large conducting mass, which serves in place of earth, e.g., vehicle frame.

Guarded (motor). A construction such that all openings that expose rotating or live electrical parts are covered with screens or shields to prevent contact by personnel.

H

Hazard. A condition prerequisite to a mishap or accident.

Hazard probability. The aggregate probability of the occurrence of the individual hazardous events that create a specific hazard.

Hazard severity. An assessment of the worst credible mishap that could be caused by a specific hazard.

Hot-spot temperature. The temperature within motor or transformer windings at location where temperature rise is greatest due to local concentration of heat generation or reduced cooling.

"Hot" standby system. A generator that is operating into a dummy load, or an interruptible load, so that if primary power is lost, the standby generator is already operating and can be immediately (possibly automatically) switched to the primary load.

I

Ignition temperature. The minimum temperature at which a flammable substance will begin burning from its own heat (in absence of spark, flame, or other local ignition source).

Induction motor. An AC motor in which one member, usually the stator winding, is connected to the line and generates a field that induces a current in the other member, usually the rotor windings. Torque is produced by the magnetic forces exerted on the current-carrying rotor conductors when operated in the magnetic field produced by the stator.

L

Locked rotor current. Current drawn by a motor when its rotor is held stationary. An indication of worst case starting current.

Loop. A network configuration in which the supply circuit is closed upon itself forming a loop. Loads attached to various points around the loop are fed through two paths; hence a single break in the loop will not interrupt power to any load.

M

Metal-clad switchgear. A metal-enclosed switchgear assembly characterized by removable switching units, interlocks to prevent removal of such units while in the closed position, and shutters to cover live conductors that would otherwise be exposed when the switching is removed.

Metal-enclosed switchgear. A switchgear assembly that, except for ventilating and inspection windows, is completely enclosed with a solid metal covering.

Motor. An energy conversion device that produces mechanical motion from electrical energy.

Motor-generator. Assembly consisting of an electrical generator that is turned by an electrical motor. Motor-generators are used for voltage conversion and electrical isolation.

O

Oxygen index. The lowest oxygen concentration sufficient to support combustion.

P

Polyphase. An electrical configuration in which power is delivered from multiple sources, e.g., individual windings on a common transformer, each of which produces voltage with the same magnitude and frequency but with a constant phase difference between them.

Power analyzer. An instrument that measures power, voltage, and current and that is connected between a power source and load to measure characteristics of source and load.

Precise. Descriptor for engine-driven-generator sets that have closely regulated frequency and voltage outputs.

Primary distribution network. A system of conductors that distributes power at high voltage to the primaries of distribution transformers.

Prime. Descriptor for engine-driven-generator sets that are designed for long-term use typically in fixed locations.

Prime mover (for generator). Source of mechanical energy for electrical generator. Typical prime movers are gasoline or diesel engines or turbines, although electric motors can be used in special applications.

R

Recloser. An overcurrent protective device that opens the protected circuit, then after a short delay closes to energize the circuit. The process is repeated until the fault condition is cleared or a predetermined number of cycles occur.

Resistance grounding. Grounding configuration in which the connection to be grounded (usually the neutral) is connected to ground through a resistance so fault currents can be detected without interruption of power service, and third harmonic distortion of generated power is reduced.

Risk. An expression of the possibility of a mishap in terms of hazard severity and hazard probability.

Root-mean-square. A nonlinear averaging technique whereby first the average is computed of the series of squared values (or the squared continuous function). The rms value is the square root of that average value. For current or voltage waveforms, the rms value is the magnitude of an equivalent DC current or voltage that would produce the same power dissipation in a resistor.

S

Secondary network. A distribution network operating at load level voltages and usually driven by the secondary of distribution transformers, which supplies power directly to loads.

Sectionalizer. A switch that operates in conjunction with a recloser to isolate a branch or section of a distribution loop.

Service entrance equipment. Connection and protective gear mounted on a building at a point where the electrical service enters. Service entrance equipment includes, but is not limited to, cable and conduit, metering equipment, fuses, and circuit breakers.

Single-phase. A system of AC power distribution in which the power is conducted over two wires: a "hot" wire and a neutral. This system is called single phase because all power delivered by the system is at the same phase.

Solid grounding. Grounding configuration in which the connection to be grounded (usually the neutral) is connected directly to ground through a connection which has minimum resistance.

Splash proof. A construction such that equipment operation will not be negatively affected by liquid or solid particles striking it at an angle equal to or less than 100 deg from the upward vertical direction.

Split-phase. A system of AC power distribution in which the power is delivered over three conductors: a neutral conductor and two power conductors each conducting the same voltage but with opposite polarity (180 deg out of phase).

Standby power system. A system consisting of an alternate power source and a switching circuit that can supply power to a load or loads when the primary power source becomes inoperative.

Standby system. An independent electrical supply system capable of delivering power to critical loads when the primary source fails.

Step-potential. The difference in potential between a person's feet when standing on earth.

Switchgear. Devices (including the contact assemblies and auxiliary apparatus, such as protective and control equipment and monitoring instrumentation) used for switching or interrupting current.

Synchronous motor. An AC motor in which the armature rotates at the same speed as the rotating field within the machine. The resulting speed will be a submultiple of the line frequency.

Synchronous speed. The speed of the rotating magnetic field within an AC motor. Synchronous motors operate at synchronous speed, whereas induction motors operate slightly below.

Synchroscope. A meter or indicator with a rotating pointer that indicates the instantaneous phase difference between two power line voltages.

T

Tactical. Descriptor for engine-driven-generator sets that are designed for mobility or portability and environmental resistance.

Touch-potential. The difference in potential between an object touched by a person and the ground on which the person is standing.

Transformer, distribution. An electrical transformer used either to convert moderately low voltages produced by generators to higher levels suitable for transmission over distance or to convert the transmitted voltage back to lower voltages suitable for operation of end-items.

Tree. A network configuration in which the supply lines at any level, except the lowest, supply power to multiple supply lines at the next lower level.

U

Uninterruptible power supply (UPS). A standby system that supplies power continuously to critical loads that cannot tolerate even brief power outages.

Utility. Descriptor for engine-driven-generator sets having frequency and voltage regulation characteristics equal to or less stringent than the typical characteristics of a commercial utility.

V

Volt-ampere reactive (VAR). The quadrature component of power referred to as reactive power, or imaginary power.

Volt-ohm-milliammeter (VOM). A multipurpose test instrument used to measure voltage, current, or resistance.

W

Weatherproof. Rating of switchgear construction indicating that exposure to the weather will not interfere with successful operation.

Weather protected. A construction such that the equipment can be operated without being affected by rain, snow, or airborne dust.

Wye (Y). A three-phase power configuration in which the power sources or loads are connected between each of the three terminals and a common terminal called the neutral. The voltage specified for this configuration is the voltage between the neutral and any of the terminals.

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STANDARDIZATION DOCUMENT IMPROVEMENT PROPOSAL

(See Instructions – Reverse Side)

1. DOCUMENT NUMBER	2. DOCUMENT TITLE
MIL-HDBK-765(MI)	Guidelines for Safe Design of Polyphase Electrical Systems

3a. NAME OF SUBMITTING ORGANIZATION

b. ADDRESS *(Street, City, State, ZIP Code)*

4. TYPE OF ORGANIZATION *(Mark one)*

- ☐ VENDOR
- ☐ USER
- ☐ MANUFACTURER
- ☐ OTHER *(Specify)*: ______

5. PROBLEM AREAS

a. Paragraph Number and Wording:

b. Recommended Wording:

c. Reason/Rationale for Recommendation:

6. REMARKS

7a. NAME OF SUBMITTER *(Last, First, MI) – Optional*

b. WORK TELEPHONE NUMBER *(Include Area Code) – Optional*

c. MAILING ADDRESS *(Street, City, State, ZIP Code) – Optional*

8. DATE OF SUBMISSION *(YYMMDD)*

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