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DEPARTMENT OF DEFENSE INTERFACE STANDARD

SECTION 300, PART 2

MEDIUM VOLTAGE ELECTRIC POWER, ALTERNATING CURRENT

AMSC N/A FSC 1990

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FOREWORD

1. Preamble. This standard is approved for use by all Departments and Agencies of the Department of Defense.

2. Purpose. This section defines the standard interface requirements for and the constraints on the design of shipboard user equipment that will utilize shipboard alternating current (AC) medium voltage electric power.

3. Nature of the interface. In any system involving power source, distribution network, and load (user equipment), the characteristics at the system and user equipment interface are mutually dependent on the design and operation of both. In order for the electric power system to perform within the established tolerances, it is necessary to place constraints on the power source, the distribution system and the user equipment. This interface standard defines the electric power system characteristics. User equipment constraints are also established.

4. Structure. The technical content first delineates the characteristics of the shipboard electric power system at the interface in terms of voltage, frequency, continuity, and voltage waveform. Constraints on user equipment design and installation, which are necessary to achieve shipboard compatibility with and to assure these characteristics, are then established. Finally, test requirements are specified to verify conformance of AC user equipment to this standard.

5. Invoking the standard. Naval Sea Systems Command (NAVSEA) will consider the mission requirement of the user equipment being developed or acquisitioned. NAVSEA will then select those conditions under which the user equipment is to operate and those conditions, which the user equipment will withstand without failure, but not necessarily, operate normally. NAVSEA will also specify those tests commensurate with the equipment's mission, which will ensure the user equipment's satisfactory operation, the user equipment's compatibility with the shipboard electric power system and other equipment, and the equipment's survival.

6. Numerical quantities. Numerical quantities are expressed in metric (SI) units.

7. Contact information. Comments, suggestions, or questions on this document should be addressed to Commander, Naval Sea Systems Command, ATTN: SEA 05S, 1333 Isaac Hull Avenue, SE, Stop 5160, Washington Navy Yard, DC 20376-5160 or emailed to CommandStandards@navy.mil, with the subject line "Document Comment". Since contact information can change, you may want to verify the currency of this address information using the ASSIST Online database at https://assist.dla mil.

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1. SCOPE

1.1 Scope. This military standard section establishes electrical interface characteristics for shipboard equipment utilizing AC medium voltage electric power to ensure compatibility between user equipment and the electric power system. MIL-STD-1399-300-1 describes low voltage systems. Characteristics of the electric power system are defined and tolerances are established, as well as requirements and test methods for ensuring compatibility of shipboard user equipment with the power system. The policies and procedures established by MIL-STD-1399 are mandatory. This section and the basic standard are to be viewed as an integral single document for use in the design of electric power systems and the design and testing of user equipment.

1.2 Classification. These shipboard voltages are classified at the medium voltage level and are generated voltages of 4,160 V_{rms}, 6,600 V_{rms}, and 13,800 V_{rms}. The corresponding user voltages are also 4,160 V_{rms}, 6,600 V_{rms}, and 13,800 V_{rms} as there is no expected voltage drop due to the relatively short cable runs and relatively low current. Any small drop in voltage will be covered by the tolerance.

2. APPLICABLE DOCUMENTS

2.1 General. The documents listed in this section are specified in sections 3, 4, or 5 of this standard. This section does not include documents cited in other sections of this standard or recommended for additional information or as examples. While every effort has been made to ensure the completeness of this list, document users are cautioned that they must meet all specified requirements of documents cited in sections 3, 4, or 5 of this standard, whether or not they are listed.

2.2 Government documents.

2.2.1 Specifications, standards, and handbooks. The following specifications, standards, and handbooks form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those cited in the solicitation or contract.

DEPARTMENT OF DEFENSE STANDARDS

MIL-STD-461 - Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment

MIL-STD-1399 - Interface Standard for Shipboard Systems

(Copies of these documents are available online at http://quicksearch.dla mil.)

2.2.2 Other Government documents, drawings, and publications. The following other Government documents, drawings, and publications form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those cited in the solicitation or contract.

NAVAL SEA SYSTEMS COMMAND (NAVSEA) DRAWINGS

802-7094558 - CVN 78 Class Aircraft Carrier Electrical Interface Characteristics

(Copies of this document are available from the applicable repositories listed in S0005-AE-PRO-010/EDM, which can be obtained online via Technical Data Management Information System (TDMIS) at https://mercury.tdmis.navy.mil. Copies of this document may also be obtained from the Naval Ships Engineering Drawing Repository (NSEDR) online at https://199.208.213.105/webjedmics/index.jsp. To request an NSEDR account for drawing access, send an email to NNSY_JEDMICS_NSEDR_HELP_DESK@navy.mil.)

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2.3 Non-Government publications. The following documents form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those cited in the solicitation or contract.

IEEE

IEEE 45.1 - IEEE Recommended Practice for Electrical Installations on Shipboard - Design

IEEE 45.3 - IEEE Recommended Practice for Shipboard Electrical Installations - Systems Engineering

(Copies of these documents are available online at www.ieee.org.)

JOHNS HOPKINS UNIVERSITY TECHNICAL PAPER

Power-Specification Frequency-Domain Test and Analysis Methodology for Large Dynamic Loads

(Copies of this document are available online at http://www.jhuapl.edu/DFTProcedure.pdf.)

2.4 Order of precedence. Unless otherwise noted herein or in the contract, in the event of a conflict between the text of this document and the references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

3. DEFINITIONS

3.1 Electric power system. The electric power system is the electric power generation and distribution system (excluding electric propulsion systems) including generation, cables, switchboards, switches, protective devices, converters, transformers, and regulators up to the user equipment interface.

3.2 Electrical interface. The electrical interface is the boundary between the electric power system and the user equipment where the electric power system characteristics (see 5.1) and the user equipment compatibility requirements (see 5.2) apply.

3.3 Electric power system ground. Ground is a plane or surface used by the electric power system as a common reference to establish zero potential. Usually, this surface is the metallic hull of the ship. On a nonmetallic hull ship, a special ground system is installed for this purpose.

3.3.1 Ungrounded electric power system. An ungrounded electric power system is a system that is intentionally not connected to the metal structure or the grounding system of the ship, except for test purposes. An ungrounded electric power system can continue to perform normally if one line conductor becomes solidly grounded. However, an ungrounded system may be subject to over-voltages greater than five times nominal voltage as a result of an inductive arcing ground between one line and ground.

3.3.2 High-resistance grounded electric power system. A high-resistance grounded electric power system is a system that employs an intentional high resistance between the electric system neutral and ground. High-resistance grounding provides the same advantages of ungrounded systems (i.e., the system can continue to perform normally with one line grounded) yet limits the severe transitory over-voltages associated with ungrounded systems.

3.3.3 Solidly-grounded electric power system. A solidly-grounded electric power system is a system in which at least one conductor or point (usually the neutral point of the transformer or generator winding) is intentionally and effectively connected to system ground. A single ground fault from one line to ground will produce high fault current that should cause selective tripping of protective circuit breakers interrupting power service continuity.

3.4 Frequency. Units are in Hertz (Hz). It is denoted by the symbol “f”.

3.4.1 Nominal frequency. Nominal frequency ($f_{nominal}$) is the designated frequency in Hz.

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3.4.2 Frequency modulation. Frequency modulation is the periodic variation in frequency during normal operation, calculated by equation 1 and shown on figure 1; the permitted modulation is provided in table II, Item 2. The periodicity of frequency modulation should be considered as greater than one cycle, but not exceeding 10 seconds.

$$\text{Frequency modulation (percent)} = \left(\frac{f_{maximum} - f_{minimum}}{2 \times f_{nominal}}\right) \times 100$$

EQUATION 1

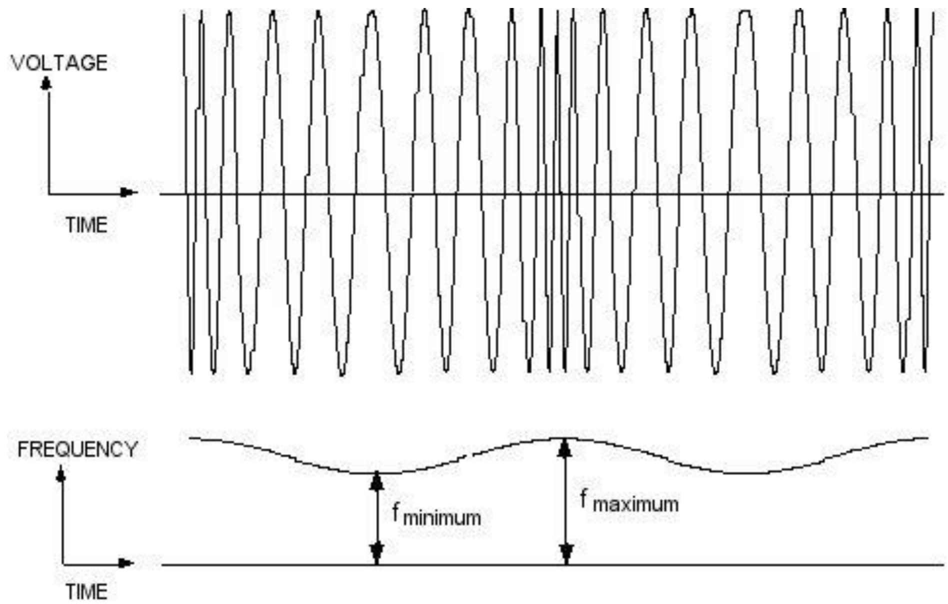

FIGURE 1. Frequency modulation.

3.4.3 Frequency tolerance. Frequency tolerance is the allowed variation from nominal frequency expressed as a percent of the nominal frequency; the permitted tolerance is provided in table II, Item 3. This tolerance is the maximum permitted value during normal operation including variations caused by small load changes, environmental effects (temperature, humidity, vibration, and inclination), and drift, excluding modulation and transients. The frequency tolerance may be calculated using equation 2.

$$\text{Frequency tolerance (percent)} = \left(\frac{f_{measured} - f_{nominal}}{f_{nominal}}\right) \times 100$$

Where:

$f_{measured}$ is the measured frequency and $f_{nominal}$ is the nominal frequency provided in table II, Item 1.

EQUATION 2

3.4.4 Frequency transients. A frequency transient is a sudden change in frequency that goes outside the frequency tolerance limits and returns to and remains within these limits within a specified recovery time (longer than 1 millisecond) after the initiation of the disturbance, such as large load changes.

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3.4.4.1 Frequency transient tolerance. Frequency transient tolerance is the allowed variation from nominal frequency expressed as a percent of the nominal frequency during transient conditions; the permitted tolerance is provided in table II, Item 4. The frequency transient tolerance may be calculated using equation 3.

$$\text{Frequency transient tolerance (percent)} = \left(\frac{f_{transient} - f_{nominal}}{f_{nominal}}\right) \times 100$$

Where:

$f_{transient}$ is the measured frequency transient and $f_{nominal}$ is the nominal frequency provided in table II, Item 1.

EQUATION 3

3.4.4.2 Frequency transient recovery time. Frequency transient recovery time is the time elapsed from the instant when the frequency first goes outside the frequency tolerance limits until the instant when the frequency recovers and remains within the frequency tolerance limits.

3.4.5 Worst case frequency steady-state and transient excursion. The worst case frequency excursion is the allowed excursion resulting from a combination of steady-state characteristics (modulation, tolerance) and transient characteristics with no individual characteristic exceeding its limits in table II; the permitted excursion is provided in table II, Item 5. This does not include emergency conditions.

3.5 Voltage. Units are in Volts (V). Unless specified as peak or DC quantities, voltages in this standard are root-mean-square (rms) values. Tolerances are expressed in percent of the nominal user voltage. It is denoted by the symbol “V”.

3.5.1 Nominal user voltage. Nominal user voltage ($V_{nominal}$) is the designated voltage at the interface.

3.5.2 Voltage unbalance (line-to-line). The line-to-line voltage unbalance is the difference of the maximum and minimum line-to-line voltages divided by the nominal line-to-line voltage; the permitted unbalance is provided in table II, Item 8. Voltages are either all rms or all peak (sinusoidal crest) values as shown in equation 4.

$$\text{Line-to-line voltage unbalance (percent)} = \left(\frac{V_{maximum} - V_{minimum}}{V_{nominal}}\right) \times 100$$

Where:

$V_{maximum}$ is the maximum line-to-line voltage,

$V_{minimum}$ is the minimum line-to-line voltage, and

$V_{nominal}$ is the nominal line-to-line voltage provided in table II, Item 7.

EQUATION 4

3.5.3 Voltage modulation (amplitude). Voltage modulation is the periodic voltage variation (peak-to-valley) of a single line-to-line user voltage, calculated by equation 5 and shown on figure 2; the permitted modulation is provided in table II, Item 9. The periodicity of voltage modulation should be considered to be longer than one cycle time at nominal frequency and less than 10 seconds. Voltages used in the following equation are either all rms or all peak (sinusoidal crest) values. $V_{nominal}$ is provided in table II, Item 7.

$$\text{Voltage modulation (percent)} = \left(\frac{V_{maximum} - V_{minimum}}{2 \times V_{nominal}}\right) \times 100$$

Where:

$V_{maximum}$ is the maximum line-to-line voltage,

$V_{minimum}$ is the minimum line-to-line voltage, and

$V_{nominal}$ is the nominal line-to-line voltage provided in table II, Item 7.

EQUATION 5

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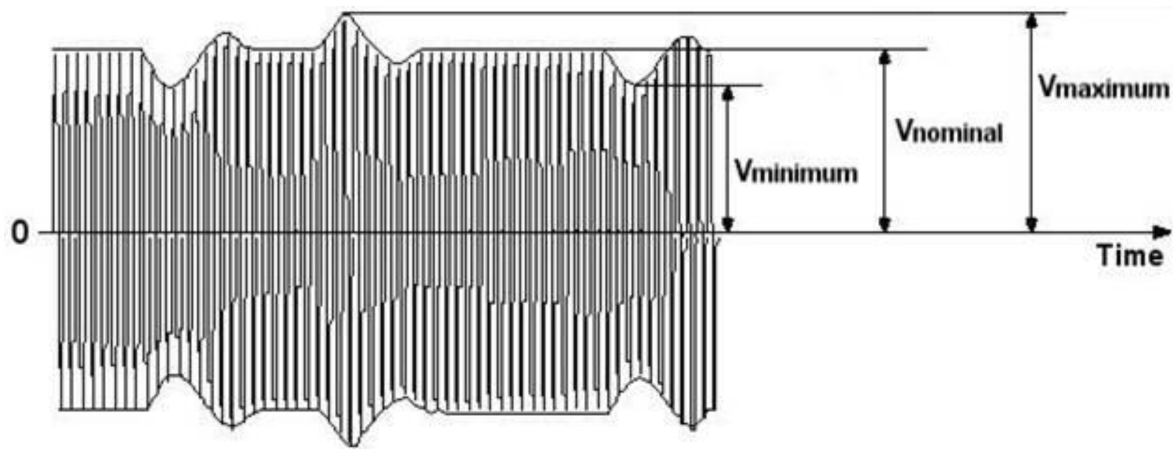

FIGURE 2. Voltage amplitude modulation.

3.5.4 Average line-to-line voltage tolerance. The average line-to-line user voltage tolerance is the allowed departure of the average of the line-to-line voltages from the nominal voltage as a percent of the nominal voltage. This average line-to-line voltage tolerance is the maximum permitted value (provided in table II, Item 10) during normal operation including variations caused by small load changes, environmental effects (temperature, humidity, vibration, and inclination), and drift, excluding voltage unbalance, modulation, and transients. The average line-to-line voltage tolerance is calculated in equation 6. Voltages are either all rms or all peak (sinusoidal crest) values.

$$\text{Average line-to-line voltage tolerance (percent)} = \left(\frac{V_{average} - V_{nominal}}{V_{nominal}}\right) \times 100$$

Where:

$V_{average}$ is the sum of the line-to-line voltages divided by the number of line-to-line voltages and $V_{nominal}$ is the nominal user voltage provided in table II, Item 7.

EQUATION 6

3.5.5 Single line-to-line voltage tolerance. The single line-to-line user voltage tolerance is the allowed departure of any single line-to-line voltage from nominal user voltage expressed as a percent of the nominal voltage. This line-to-line voltage tolerance is the maximum permitted value (provided in table II, Item 11) during normal operation including variations caused by small load changes, environmental effects (temperature, humidity, vibration, and inclination), and drift, excluding voltage unbalance, modulation, and transients. The line-to-line voltage tolerance is calculated in equation 7. Voltages are either all rms or all peak (sinusoidal crest) values.

$$\text{Single line-to-line voltage tolerance (percent)} = \left(\frac{V_{LL} - V_{nominal}}{V_{nominal}}\right) \times 100$$

Where:

V_{LL} is each line-to-line voltage and $V_{nominal}$ is the nominal user voltage provided in table II, Item 7.

EQUATION 7

3.5.6 Maximum voltage steady-state departure. The maximum voltage departure is the allowed departure resulting from a combination of steady-state characteristics (unbalance, modulation, and tolerance) with no individual characteristic exceeding its limits in table II; the permitted maximum steady-state voltage departure is provided in table II, Item 12.

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3.5.7 Voltage transients. A voltage transient (excluding voltage spikes [see 3.5.9]) is a sudden change in voltage (longer than 1 millisecond) that exceeds, positively or negatively, the user voltage tolerance limits and returns to and remains within these limits within a specified recovery time after the initiation of the disturbance such as large load changes.

3.5.7.1 Voltage transient tolerance. Voltage transient tolerance is the allowed variation from nominal voltage expressed as a percent of the nominal voltage during transient conditions; the permitted voltage transient tolerance is provided in table II, Item 13. The voltage transient tolerance may be calculated using equation 8. Voltages are either all rms or all peak (sinusoidal crest) values.

$$\text{Voltage transient tolerance (percent)} = \left(\frac{V_{transient} - V_{nominal}}{V_{nominal}}\right) \times 100$$

Where:

$V_{transient}$ is the measured momentary line-to-line transient voltage and $V_{nominal}$ is the nominal user voltage provided in table II, Item 7.

EQUATION 8

3.5.7.2 Voltage transient recovery time. Voltage transient recovery time is the time elapsed from the instant when the voltage first goes outside the user voltage tolerance limit until the instant when the voltage recovers and remains within the user voltage tolerance limit. A typical low level transient voltage is shown on figure 3.

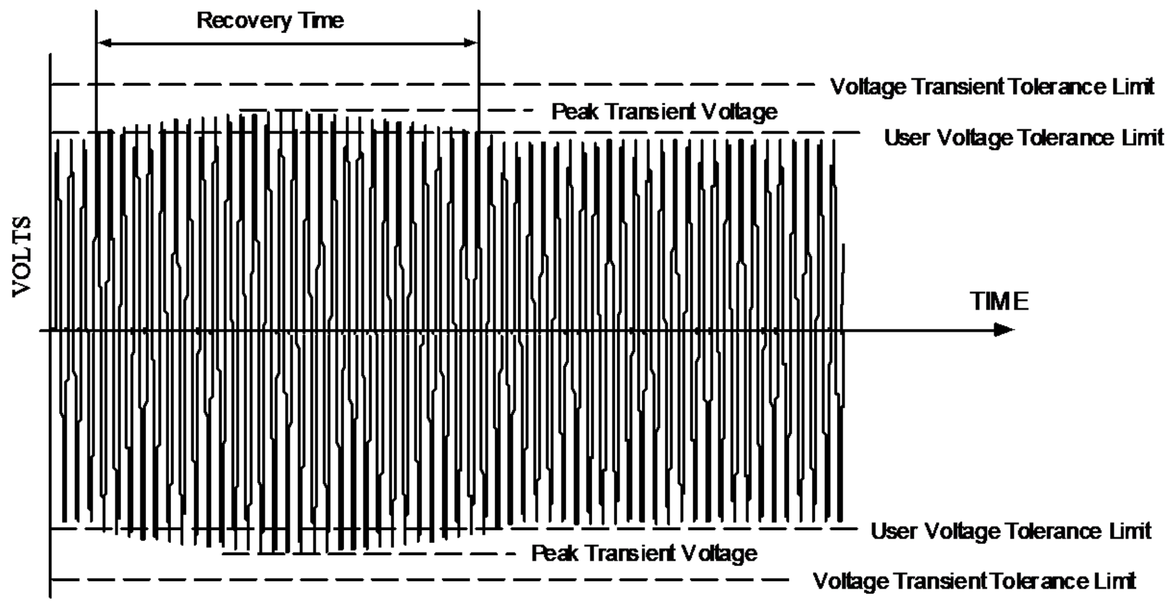

FIGURE 3. Voltage transient tolerance.

3.5.8 Worst case voltage steady-state and transient excursion. The worst case voltage excursion is the allowed excursion resulting from a combination of steady-state characteristics (unbalance, modulation, and tolerance) and transient characteristics with no individual characteristic exceeding its limits in table II; the permitted worst case voltage excursion is provided in table II, Item 14. This does not include emergency conditions.

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3.5.9 Voltage spike. A voltage spike is a voltage change or impulse of very short duration (less than 1 millisecond) represented on figure 4 and figure 15. Voltage spikes in shipboard power systems are generally of an oscillatory nature and not unidirectional as those often used in testing. The spike magnitude is measured in peak voltage (V_p).

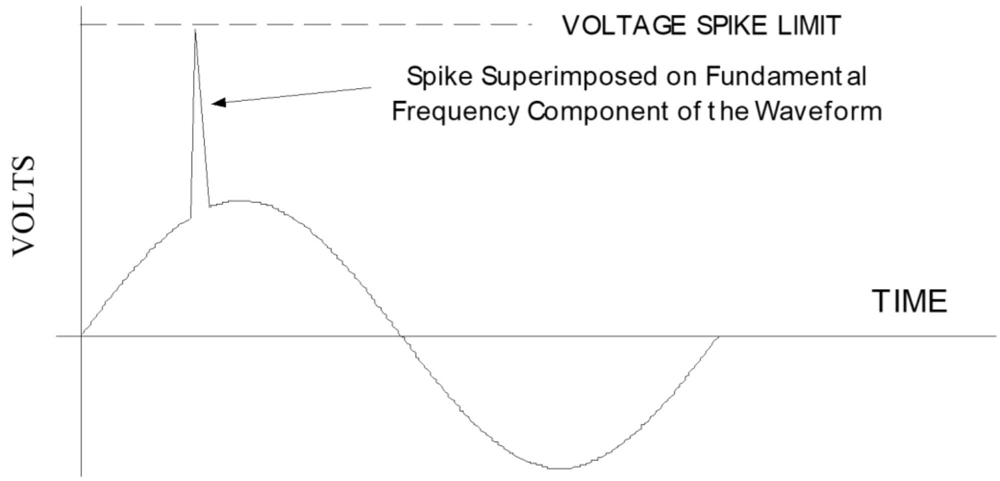

FIGURE 4. Voltage spike.

3.5.10 Voltage waveform. The voltage waveform is a voltage vs. time function.

3.5.10.1 Voltage single harmonic. A voltage single harmonic is a sinusoidal component of the voltage's periodic waveform having a frequency that is an integral multiple of the fundamental frequency.

3.5.10.2 Voltage single harmonic content. The voltage single harmonic content of a voltage wave is the ratio, in percentage, of the rms value of that harmonic to the rms value of the fundamental.

3.5.10.3 Voltage total harmonic distortion (THD). The THD of a voltage wave is the ratio in percentage of the rms value of the residue (after elimination of the fundamental) to the rms value of the fundamental, calculated by equation 9.

$$\text{Voltage THD (percent)} = 100 \times \sqrt{\sum_{h\geq 2}\left(\frac{V_h}{V_{fundamental}}\right)^2}$$

Where:

V_h is the rms voltage of individual harmonics

$h \geq 2$

$V_{fundamental}$ is the rms voltage at 60 Hz

EQUATION 9

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3.5.10.4 Voltage deviation factor. The voltage deviation factor of the voltage waveform is the ratio (a/b) where "a" is the maximum deviation between corresponding ordinates of the waveform and of the equivalent sine wave and "b" is the maximum ordinate of the equivalent sine wave when the waveforms are superimposed in such a way that they make the maximum difference as small as possible. This is calculated by equation 10 and shown on figure 5. NOTE: The equivalent sine wave is defined as having the same frequency and the same rms voltage as the waveform being tested.

$$\text{Voltage deviation factor (percent)} = \left(\frac{\text{Maximum deviation}}{\text{Maximum ordinate of the equivalent sine wave}}\right) \times 100$$

EQUATION 10

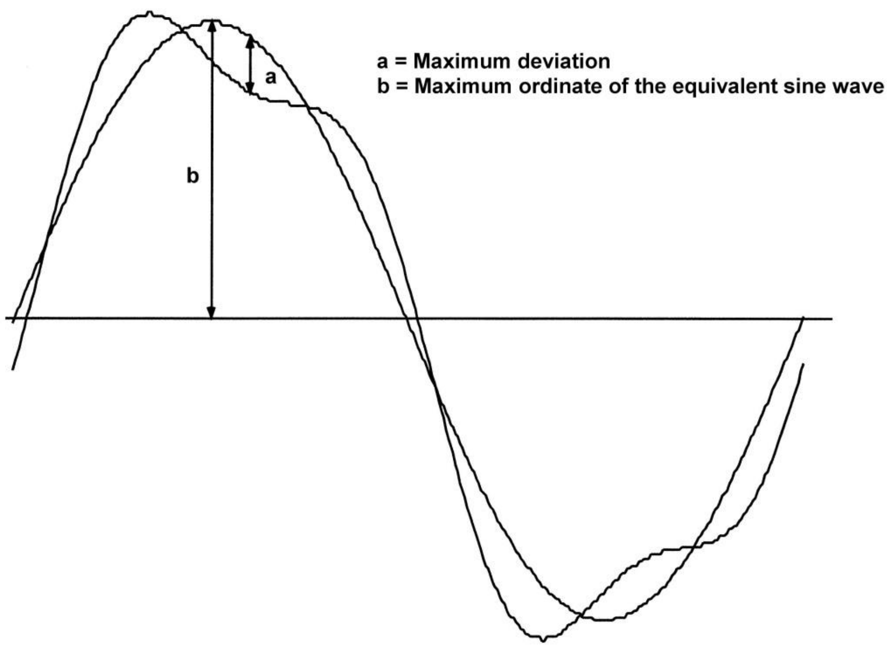

FIGURE 5. Voltage deviation factor variables.

3.6 Current. Units are in Amperes (A). Unless specified as peak or DC quantities, currents in this standard are rms values. It is denoted by the symbol "I".

3.6.1 Current unbalance. Current unbalance for three-phase loads is the ratio of the maximum line current minus the minimum line current to the average of the three line currents in amperes, shown in equation 11. Currents used in the following equation are rms values.

$$\text{Current unbalance (percent)} = \left(\frac{I_{\text{line max}} - I_{\text{line min}}}{(I_A + I_B + I_C)/3}\right) \times 100$$

EQUATION 11

3.6.2 Current waveform. The current waveform is a current vs. time function.

3.6.2.1 Current single harmonic. A current single harmonic is a sinusoidal component of the current's periodic waveform having a frequency that is an integral multiple of the fundamental frequency. There may exist currents at individual frequencies that are not harmonics and may be produced by switching frequencies internal to equipment.

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3.6.2.2 Current single harmonic content. The current single harmonic content of a current waveform is the ratio, in percentage, of the rms value of that harmonic to the rms value of the fundamental.

3.6.3 Surge/inrush current. Surge/inrush current is a sudden change in line current to a user equipment that occurs during start-up or after a power interruption or as a result of a change to the operating mode. Typically, the surge current will rise to a maximum value in a few milliseconds and decay to rated value in several milliseconds to several seconds. The limit in 5.2.10 is evaluated as the ratio of the highest peak surge/inrush current to the peak of the rated current of the equipment.

3.7 Power factor (pf). The pf is the ratio of the real power in watts to the product of the rms voltage and rms current. For voltage waveforms with distortion, pf can be approximated as the product of the displacement pf (dpf) (see 3.7.1) and the distortion (μ) (see 3.7.2). This is shown in equation 12.

$$pf = \frac{P\ (watts)}{V_{rms}\ I_{rms}} \approx \mu\ dpf$$

EQUATION 12

3.7.1 Displacement power factor (dpf). The dpf is defined as the cosine of the angle between the fundamental frequency component of the input voltage and the fundamental frequency component of the current shown in equation 13. The dpf is the same as the pf in linear circuits with sinusoidal voltages and currents. The angle determines whether the pf is leading or lagging. A positive value of the angle means that the current lags the voltage (lagging pf, inductive load). A negative value of the angle means that the current leads the voltage (leading pf, capacitive load).

$$dpf = \cos\left(\phi_V - \phi_I\right)$$

Where:

φ_V is the angle of the fundamental frequency component of the input voltage

φ_I is the angle of the fundamental frequency component of the current

EQUATION 13

3.7.2 Distortion component of pf. The distortion component (μ) of pf is the ratio of the rms magnitudes of the fundamental frequency current to the total current, shown in equation 14.

$$\mu = \frac{I_{fundamental}}{I_{total}}$$

Where:

$I_{fundamental}$ is the rms value of the fundamental frequency current

I_{total} is the rms value of the total current, which is the square root of the sum of the squares of the fundamental and harmonic currents

EQUATION 14

3.8 Power. Quantity that consists of real, reactive, and apparent power.

3.8.1 Real power. Real power is the average of the product of the current and voltage over time. As shown in equation 12, it is also the product of the rms voltage and rms current multiplied by the pf. The unit of real power is the watt. Real power provides work over time. It is denoted by the symbol “P”.

3.8.2 Reactive power. Reactive power is defined as the product of the rms voltage and rms current multiplied by a reactive factor. Reactive power can be calculated as the square root of the difference between the square of the apparent power and the square of the real power. The unit of reactive power is volt-ampere reactive (VAR). Reactive power provides no net energy transfer over time; the average instantaneous reactive power over a fundamental cycle period is 0. It is denoted by the symbol “Q”.

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3.8.3 Apparent power. Apparent power is defined as the product of the rms voltage and the rms current. The unit of apparent power is volt-ampere (VA). Apparent power can be calculated as the square root of the sum of the squares of real and reactive power. It is denoted by the symbol “S”.

3.9 Pulse. A pulse is a brief excursion of power lasting longer than one cycle at nominal frequency and less than 10 seconds.

3.10 Pulsed load. A pulsed load is user equipment that demands infrequent or repetitive power input that could be supplemented by energy storage. Infrequent events are defined as events occurring no more than once every 120 seconds. A repetitive power input creates a dynamic waveform. An example of a pulsed load is sonar or radar user equipment. Pulsed loading may result in unwanted modulation in the system voltage amplitude and frequency and needs to be constrained to enable acceptable responses of the voltage regulation and prime mover speed governor systems.

3.10.1 Peak-to-peak pulsed real power. For a given window of observation, the peak-to-peak pulsed real power is the difference between the maximum instantaneous value and the minimum instantaneous value as shown on figure 6.

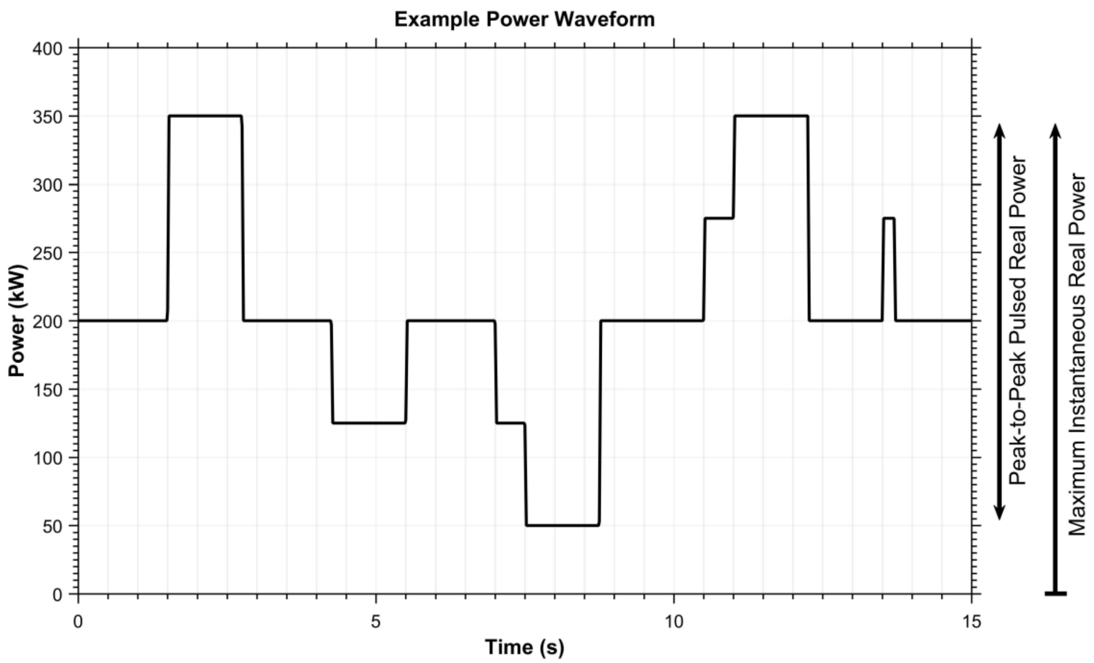

FIGURE 6. Peak-to-peak pulsed real power defined.

3.11 Ramp load. A ramp load is user equipment that is applied to the electrical system causing a smooth rise in power or small increasing step increments of the total load.

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3.12 Power total signal distortion (TSD). The TSD of a real-power waveform is the ratio in percentage of the value of the square root of the sum of squares of the power magnitudes at their individual frequencies to the square root of 2 times the average power magnitude, calculated by equation 15 in its generic form. When performing a DFT on the power signal, which is an estimate of the frequency content, the noise characteristics of the DFT are affected by windowing and zero padding. This effect is captured in a term called equivalent noise bandwidth (ENBW), which requires a modification to equation 15, shown in A.2 Step 11. Further information can be found in The Johns Hopkins University Applied Physics Laboratory technical paper entitled Power-Specification Frequency-Domain Test and Analysis Methodology for Large Dynamic Loads.

$$\text{Power TSD (percent)} = 100 \times \sqrt{\sum_{s} \left(\frac{P_s}{\sqrt{2}} \cdot \frac{1}{Pav} \right)^2}$$

Where:

P_s is the zero-to-peak real power amplitude at individual signal frequency s

1 Hz ≤ s ≤ 2 kHz

P_{av} is the average real power over a specified time period determined by the application

EQUATION 15

3.13 User equipment. User equipment is any system or equipment that uses electric power from the shipboard electric power system.

3.14 Emergency conditions. Emergency conditions are unexpected occurrences of a serious nature that may result in electrical power system deviations. Emergency conditions include, but are not limited to, battle damage and malfunction or failure of equipment. Conditions may include power interruptions, voltage and frequency excursions, and decays. Emergency conditions characteristics are provided in table II, Items 20 through 23.

3.15 Power interruption. A power interruption is a condition where the ship service power is not being supplied for a period of time. Power interruptions are evaluated with respect to two time periods, reconfiguration time (t_r) and generator start time (t_s).

3.15.1 Reconfiguration time (t_r). t_r is the maximum duration of a power interruption that an interface (user equipment) will experience due to source transfer, typically up to 5 seconds. t_r consists of the detection (of non-compliant user power) latency interval, the bus transfer interval, and the transient recovery interval (to compliant user power). The detection latency interval is the period of time from when the bus voltage and frequency deviates from compliant power to the time at which this deviation has been detected. The bus transfer interval is the period of time from when the adverse bus conditions are detected requiring initiation of a transfer up to the completion of the transfer. The transient recovery interval is the period of time from the completion of transfer to compliant power. User equipment will be exposed to power interruption during this time period. t_r does not take into account bringing on additional generation capacity. Reconfiguration time is identified in IEEE 45.3.

3.15.2 Generator start time (t_s). t_s is the maximum duration of a power interruption that an interface (user equipment) will experience due to the time needed to add generation capacity, including system protection coordination time, typically up to 5 minutes. User equipment will be exposed to power interruption during this time period. Generator start time is identified in IEEE 45.3.

3.16 Independent power sources. Two power sources are independent if a single fault cannot result in a power interruption on both power sources at the same time.

4. GENERAL REQUIREMENTS

4.1 Interface requirements. The specific interface requirements and constraints established herein are mandatory and shall be adhered to regarding any aspect of shipboard electrical power systems or user equipment designs to which these requirements and constraints apply, including systems and equipment design, production, and installation (see MIL-STD-1399).

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4.2 Conformance test requirements. Requirements and tests (see table I and 5.3) to ensure conformance of equipment to the interface requirements and constraints incorporated in this standard shall be included in the electric power system and user equipment specifications. Conformance of requirements (see 5.3) shall be verified by test. Formal testing shall not commence without approval of the test procedures by the Command or agency concerned. If necessary, the approval authority for testing shall be as specified (see 6.2). Table I lists the requirement and its corresponding compliance test.

TABLE I. Requirements and compliance tests.

Requirement	Requirement	Compliance
Power Profile: Type of Power	5.2.2	5.3.1.a
Power Profile: Number of Phases	5.2.2	5.3.1.b
Power Profile: Operating Frequency	5.2.2	5.3.1.c
Power Profile: Operating Voltage	5.2.2	5.3.1.d
Power Profile: Line Current Magnitude	Informational	5.3.1.e
Power Profile: Power	5.2.2	5.3.1 f
Power Profile: Power Factor	5.2.6	5.3.1.g
Power Profile: Duty Cycle	Informational	5.3.1.h
Power Profile: Surge/Inrush Current	5.2.10	5.3.1.i
Power Profile: Current (Load) Unbalance	5.2.5	5.3.1.j
Power Profile: Pulsed Loading	5.2.7	5.3.1.k
Power Profile: Ramp Loading	5.2.8	5.3.1.l
Power Profile: Spike Generation	5.2.12	5.3.1 m
Voltage & Frequency Tolerance	Table II: #3, #10	5.3.2
Voltage & Frequency Transient Tolerance	Table II: #4, #11	5.3.3
Voltage Withstand	5.2.11	5.3.4
Emergency Conditions: t_r Power Interruption	5.1.2, 5.2.3.1	5.3.5.2.1
Emergency Conditions: t_s Power Interruption	5.1.2, 5.2.3.1	5.3.5.2.2
Emergency Conditions: Power Source Decay	5.1.3, 5.2.3.2	5.3.5.2.3
Emergency Conditions: Positive Excursion	5.2.3	5.3.5.2.4
Grounding	5.2.4	6.2
Current Waveform	5.2.9	5.3.6
Voltage & Frequency Modulation	5.1.6.3	5.3.7

4.3 User equipment. User equipment shall operate from a power system having the characteristics of table II and shall be designed within these constraints in order to reduce adverse effects of the user equipment on the electric power system. Test methods are included for verification of compatibility. User equipment to be installed on ships built to superseded versions of this standard shall meet the most stringent demands of the applicable version.

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4.4 Deviations, waivers, and tailoring. The power interfaces in this standard are based on knowledge of typical shipboard AC electric power systems. To meet the intent of this interface standard for specific applications, a deviation or waiver of requirements will be considered. The deviation provisions in MIL-STD-1399 shall be adhered to, for deviation or waiver requests, during the early development stage of user equipment, as specified (see 6.2 and 6.4). For large loads (see 5.2.7.1.2.1 and 5.2.7.1.2.2) and loads known to be challenged by specific requirements, the tailoring of requirements may be necessary. Tailoring is done with analysis of the intended system and tradeoffs between the requirements and the equipment designs needed to ensure compliance. The recommended tailoring shall be approved by NAVSEA (see 6.2 and 6.4).

5. DETAILED REQUIREMENTS

5.1 Electric power system characteristics. The shipboard electric power system serves a variety of user equipment such as propulsion motors, weapon systems, communication equipment, and computers. Electric power is generated and distributed throughout the ship to the user equipment served. Characteristics of shipboard electric power systems at the interface shall be as specified in table II. Many of these characteristics are derived from NAVSEA Drawing 802-7094558. The designated nominal frequency and voltage at the interface as shown on figure 1 is given in table II, Items 1 and 7, for the different power types. These designated nominal values are the basis for the characteristics which are presented in the compliance tests of 5.3 to equipment that is to be installed aboard ship. These compliance tests are representative of actual possible shipboard conditions. Equipment to be installed aboard ship is tested to these characteristics and those that pass these tests are electrically qualified to be installed aboard ship for utilization. The generated voltages are also identified in IEEE 45.1.

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TABLE II. Characteristics of shipboard electric power systems.

Frequency	
1. Nominal Frequency	60 Hz
2. Frequency Modulation	0.5%
3. Frequency Tolerance	±3%
4. Frequency Transient Tolerance	±4%
5. Worst Case Frequency Steady-State and Transient Excursion	±5.5%
6. Recovery Time from Item 4 or 5	2 seconds
Voltage	
7. Designated Nominal User Voltage	4,160 V_{rms} 6,600 V_{rms} 13,800 V_{rms}
8. Line-to-Line Voltage Unbalance	3%
9. Voltage Modulation	2%
10. Average Line-to-Line Voltage from Nominal Tolerance	±1%
11. Single Line-to-Line Voltage from Nominal Tolerance	±3%
12. Maximum Voltage Steady-State Departure	±4%
13. Voltage Transient Tolerance	±16%
14. Worst Case Voltage Steady-State and Transient Excursion	±18%
15. Recovery Time from Item 13 or 14	3 seconds
16. Voltage Spike	30 kV_p (4,160 V_{rms}) 75 kV_p (6,600 V_{rms}) 95 kV_p (13,800 V_{rms})
Waveform (Voltage)	
17. Maximum THD	5%
18. Maximum Single Harmonic	3%
19. Maximum Deviation Factor	5%
Emergency Conditions	
20. Frequency Excursion	-100% to +12%
21. Duration of Frequency Excursion	2 minutes
22. Voltage Excursion	-100% to +35%
23. Duration of Voltage Excursion:	
a. Upper Limit (+35%)	2 minutes
b. Lower Limit (-100%)	2 minutes
NOTE: Characteristics are defined in Section 3.	

5.1.1 System grounding. Electric power systems shall be high-resistance grounded. Under faulted conditions, a fault current shall be limited to a value that shall not exceed 10 A. The system shall continue to operate with a single-phase faulted and shall detect the ground and provide notification of the ground.

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5.1.2 Electric plant power interruption. A power interruption experienced by user equipment can occur as a result of normal operations, an equipment casualty, training exercise, or operator error. The length of a power interruption can be specified as t_r or t_s as defined in 3.15. t_r and t_s shall be based on the loss of a single electrical power system component causing the power interruption. Different interfaces may have different values for t_r and t_s during the diverse operating conditions such as anchor, cruising, functional, and emergency conditions. t_r will be affected by the electric plant configuration. For a split plant configuration, t_r will consist of the system protection (detection) coordination time and will include bus transfer and recovery time. For a parallel plant configuration, t_r will consist of the system protection (detection) coordination time and may include bus transfer and recovery time. t_s will consist of the system protection coordination time, but will also include the time needed to add generation capacity. The worst case maximum duration t_r and t_s values shall be determined for use in 5.2.3.1 by the electric plant design agent.

5.1.3 Frequency and voltage excursions and decay. Frequency and voltage excursions and decay can occur on the electric power system during normal operations including training exercises, mechanical or electric power system tests, or during emergency conditions when malfunction or damage has occurred. An excursion can occur on the electric power system as a result of the loss of prime mover, equipment failures, or by the operation of switching equipment and protective devices. The voltage and frequency of a steam driven generator set will decay on loss of prime mover. The voltage may start to decay when the frequency decays to about 40 Hz in approximately 5 to 20 seconds and may not reduce to 0 Hz for several minutes, depending on the initial load and the inertia of the generator set. The output voltage and frequency of generators driven by gas turbine and diesel prime movers will fall off faster than that of the steam prime mover. The output voltage and frequency of solid state sources may be interrupted by protective devices within 2 milliseconds of the start of the voltage and frequency decay.

5.1.4 Phase configuration. The standard system is three phases.

5.1.4.1 Phase sequence. Standard phase sequence for three-phase AC systems in the U.S. Navy is in the following order: AB, BC, and CA. For grounded systems, the phase sequence is AN, BN, CN.

5.1.4.2 Phase angular relations. The ungrounded three-phase source shall have an angular relationship of 120 degrees between phases under balanced load conditions. If the source is a grounded, four-wire system (with neutral), the angular displacement between phases shall be 120 degrees ±1 degree under balanced load conditions.

5.1.5 Electrical power system protection. Some protection through relaying and circuit breakers is provided by the electric power system for voltage and frequency excursions exceeding the transient limits specified in table II. Vacuum circuit breakers (VCBs) may be utilized in medium voltage distribution systems; be aware that VCB switching may introduce transient voltages on user equipment that need to be mitigated based on the circuit design.

5.1.5.1 Conditions not protected against. The electric power system protection shall not interrupt the electric power to the user equipment under the following conditions:

a. High voltage excursions (spikes) of very short duration (see figures 4 and 15)

b. The momentary interruption and restoration of power of less than 100 milliseconds

5.1.6 Electric power system parameters. Electric power system parameters shall be as specified in 5.1.6.1 through 5.1.6.5 and figures 10 through 15 where the time axes are on a logarithmic scale.

5.1.6.1 Nominal frequency. Nominal frequency is 60 Hz. Where there are overriding design features demanding a different frequency, deviations from this requirement are subject to the requirements of 4.4 and 6.4. Characteristics of the frequency are the tolerance and the transient tolerance. The equation for the tolerance is provided in 3.4.3 and the equation for the transient tolerance is provided in 3.4.4.1.

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5.1.6.1.1 60-Hz frequency tolerance and transient tolerance. Figure 7 illustrates the system frequency tolerance and transient tolerance envelope limits specified in table II. The time to reach the transient minimum or maximum varies from 0.1 to 1.0 second after initiation of the disturbance. The frequency shall recover to the frequency tolerance band within 2 seconds.

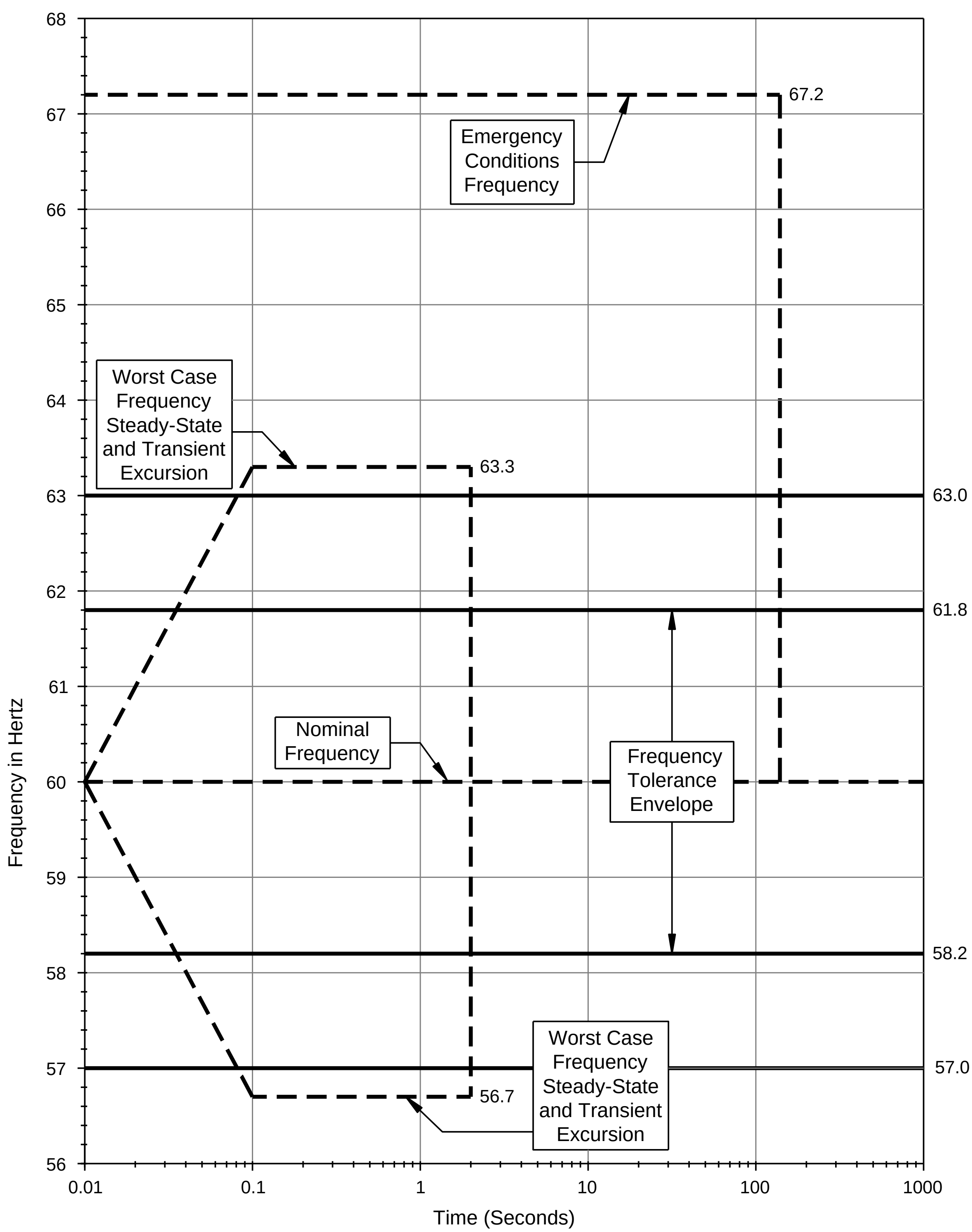

FIGURE 7. Frequency tolerance and transient tolerance envelopes.

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5.1.6.2 Nominal user voltage. The nominal user (equipment) voltage is a line-to-line voltage present at the interface to the user equipment. User voltages are as follows:

a. 4,160 V_{rms}, three-phase, three-wire, high-resistance grounded.

b. 6,600 V_{rms}, three-phase, three-wire, high-resistance grounded.

c. 13,800 V_{rms}, three-phase, three-wire, high-resistance grounded.

Characteristics of the voltage are the tolerance and the transient tolerance. The equation for the tolerance is provided in 3.5.5 and the equation for the transient tolerance is provided in 3.5.7.1.

5.1.6.2.1 60-Hz voltage tolerance and transient tolerance. Figures 8 through 10 illustrate the user voltage tolerance and transient tolerance envelope limits specified in table II. The time to reach the transient voltage limits may vary depending on the rating of the generator and the type of regulator and excitation system employed. The sudden removal of a user equipment from the electric power system may cause the voltage to increase to the transient voltage limit within 0.001 to 0.1 second. The voltage may then decrease to a minimum value that is below the nominal voltage by an amount equal to ⅓ to ⅔ of the maximum transient voltage rise at a rate equal to 20 to 75 percent of the nominal voltage per second. Recovery to within the user voltage tolerance envelope will occur within 2 seconds. The sudden application of a user equipment electric power system may cause the voltage to decrease to the transient voltage minimum value within 0.001 to 0.1 second. The voltage may then increase to a maximum value that is above the nominal voltage by an amount equal to ⅓ to ⅔ of the minimum transient voltage drop at a rate equal to 20 to 75 percent of the nominal voltage per second. Recovery to within the user voltage tolerance envelope will occur within 2 seconds.

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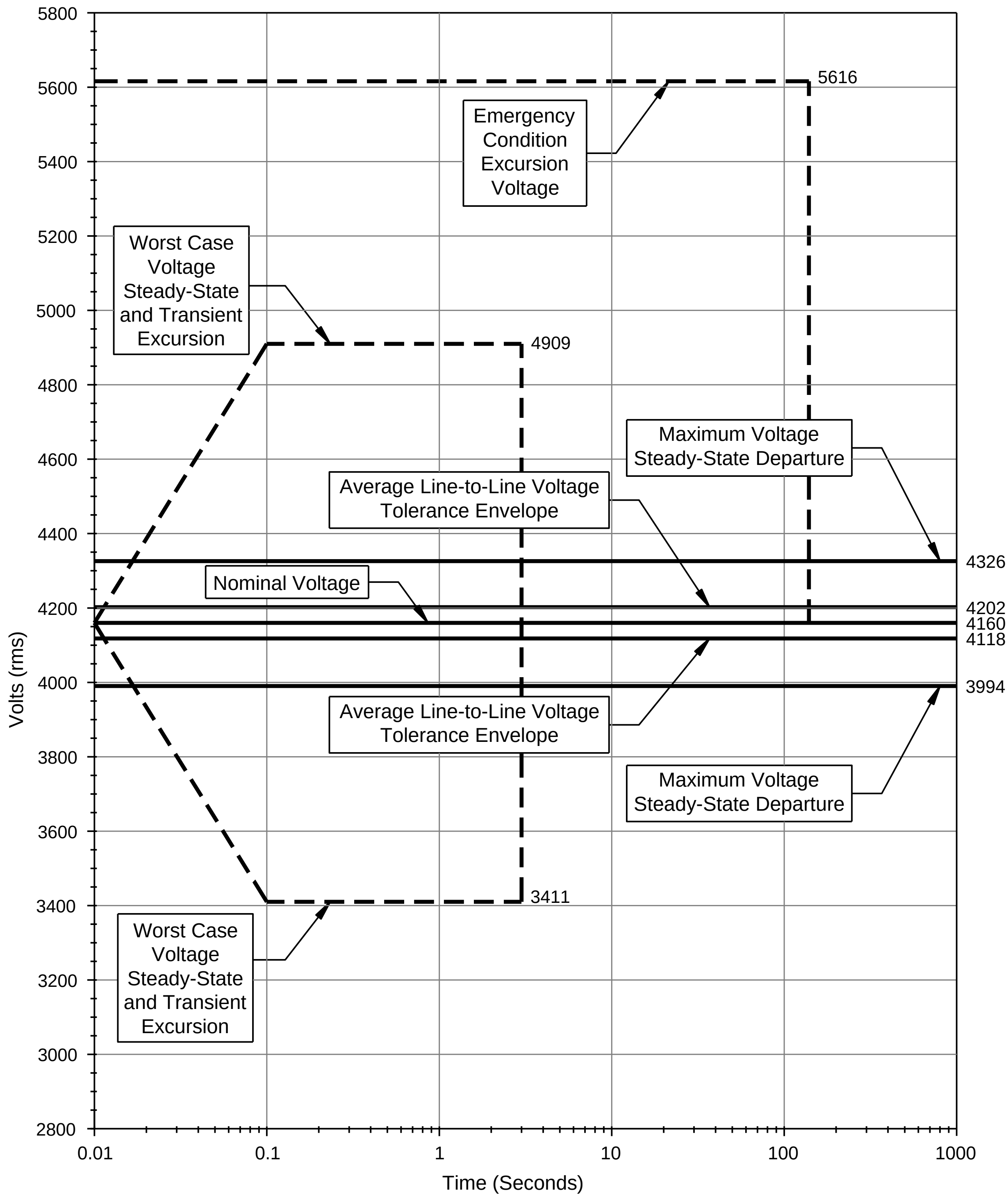

FIGURE 8. <u>4,160-V$_{rms}$ nominal voltage tolerance and transient tolerance envelopes</u>.

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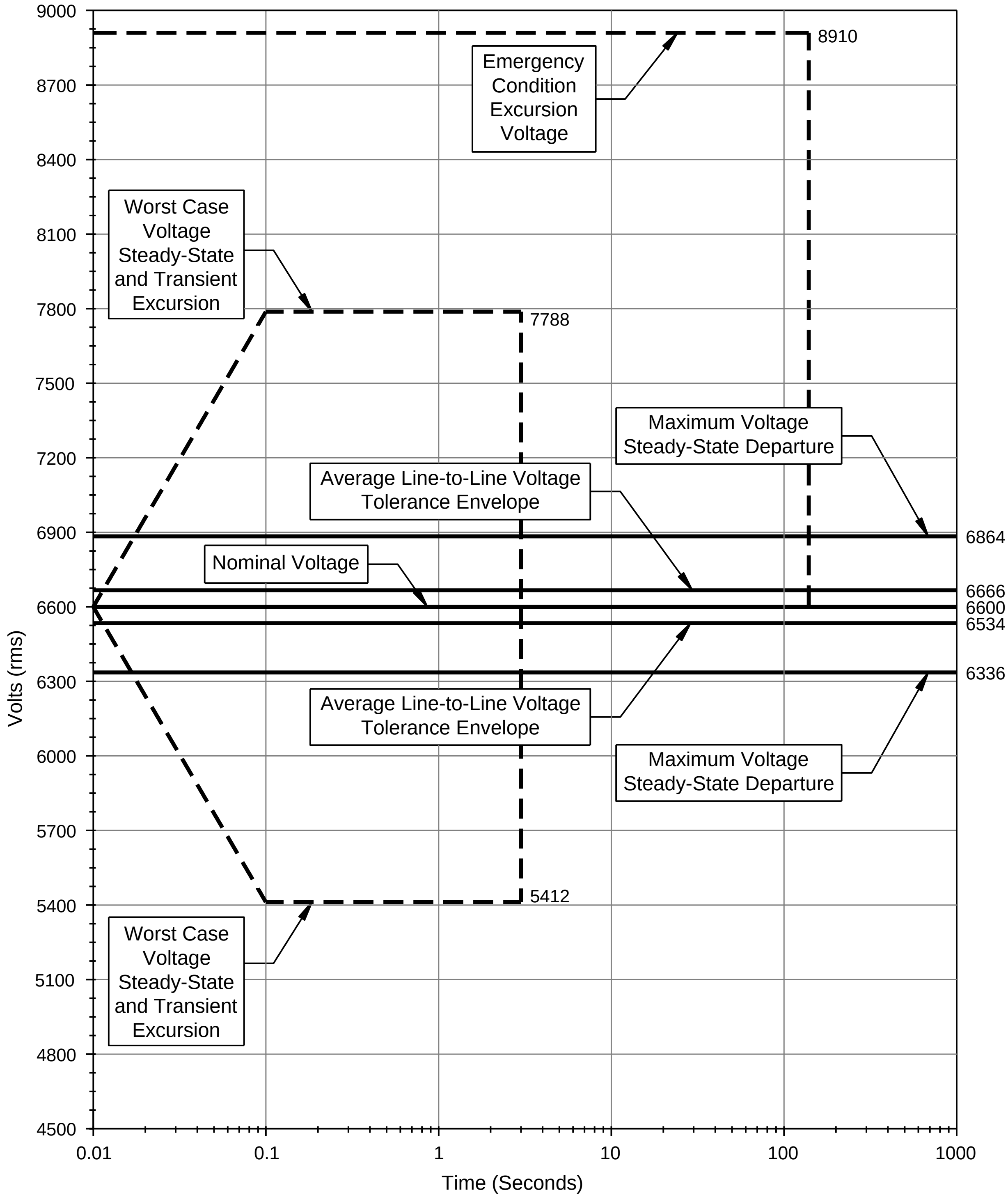

FIGURE 9. 6,600-V_{rms} nominal voltage tolerance and transient tolerance envelopes.

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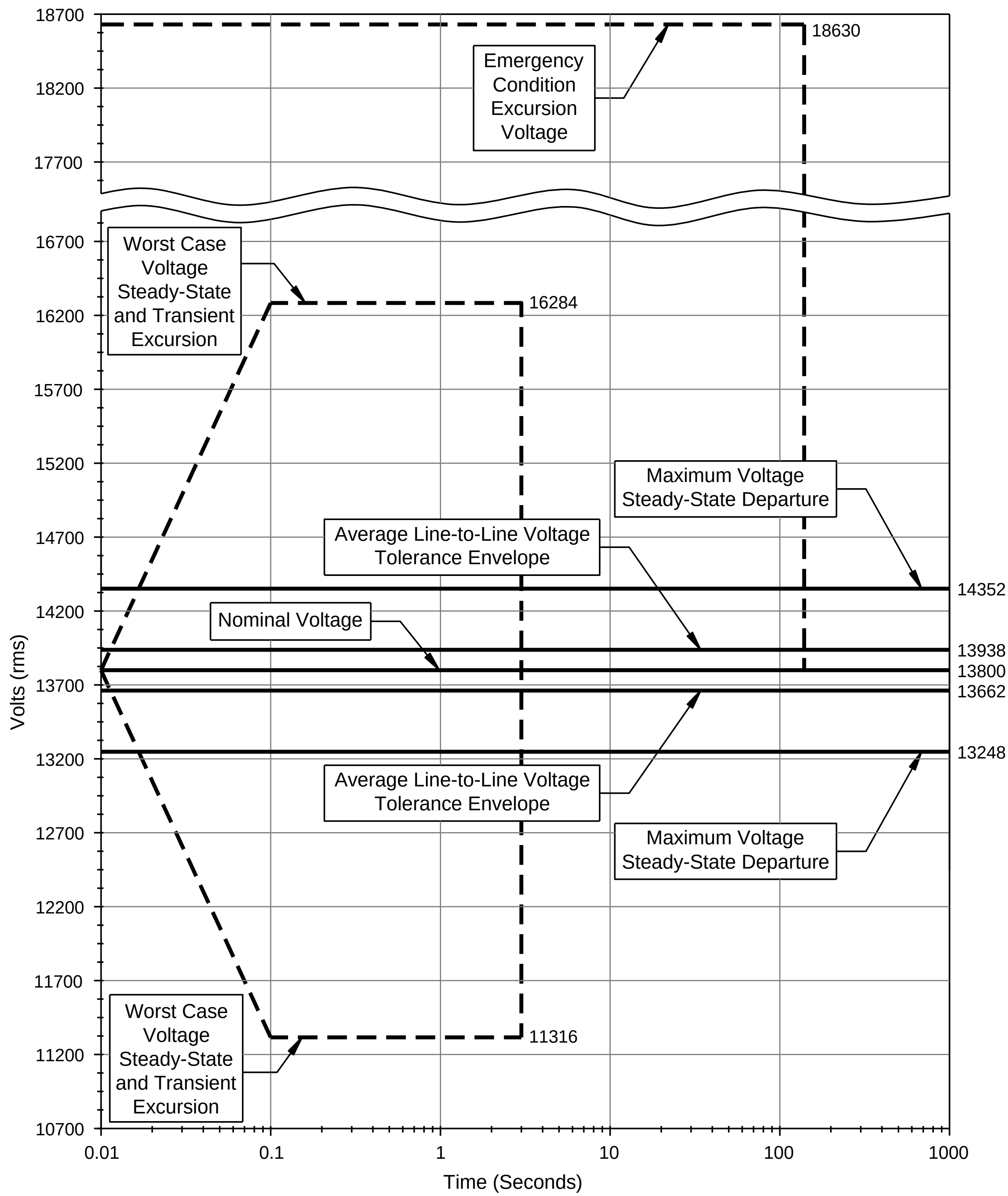

FIGURE 10. 13,800-V_{rms} nominal voltage tolerance and transient tolerance envelopes.

5.1.6.2.2 Voltage spike characteristics. Voltage spikes may be present on the electrical power system between line-to-line and between line-to-ground (or neutral). The amplitude and waveform of a voltage spike will vary depending on system parameters, but it may be compared to the description in 3.5.9.

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5.1.6.3 Voltage and frequency modulation. Shipboard electric power may contain voltage modulation up to 2 percent and frequency modulation up to 0.5 percent. For voltage modulation of 2 percent, the nominal voltage may vary within a range depending on the voltage class over periods from 17 milliseconds to 10 seconds. For frequency modulation of 0.5 percent, the nominal frequency of 60 Hz may vary within a range bounded from 59.7 to 60.3 Hz also over periods from 17 milliseconds to 10 seconds. These modulations shall be limited as they may cause torque and speed ripples that can generate vibration, noise, and mechanical stress in the bearings, couplings, and supports of induction motors. The equation for voltage modulation is provided in 3.5.3 and the equation for frequency modulation is provided in 3.4.2.

5.1.6.4 Voltage unbalance. For surface ships, the voltage provided to user equipment is required to be balanced within 3 percent. The major unwelcome effect of voltage unbalance is additional heating and losses in three-phase motors. Voltage balance shall be assisted by maintaining the current unbalance restriction for individual three-phase loads and by ensuring single-phase loads are distributed as evenly as possible across the three phases during installation on the shipboard electrical power distribution system. The equation for voltage unbalance is provided in 3.5.2.

5.1.6.5 Voltage waveform. The line-to-line voltage waveform supplied by ship's power shall not contain single voltage harmonics or voltages at any frequency greater than 3 percent of the fundamental voltage. The THD shall be not greater than 5 percent and the voltage deviation factor shall be not greater than 5 percent (3 percent for submarines). These characteristics are defined in 3.5.10.

5.2 User equipment interface requirements. User equipment shall meet the requirements specified in 5.2.1 through 5.2.11 to ensure compatibility with the electrical power system characteristics specified in table II.

5.2.1 Compatibility. The construction of user equipment utilizing electric power shall be compatible with the electric power system characteristics as specified in 5.1.

5.2.2 Type of power. User equipment shall be designed to operate at one of the designated nominal voltages in table II using the phase information in 5.1.4.

5.2.3 Emergency conditions. User equipment shall withstand and not be damaged by emergency conditions described as power interruptions, decay, and excursions.

5.2.3.1 Power interruptions. User equipment shall not be damaged due to power interruptions from 5.1.2 and may require a manual restart. To gain knowledge of the interruption time to attempt to maintain power continuity, t_r and t_s are two characteristics of the power system that shall be specified in 6.2 in the acquisition documentation for the vendor for each power interface which feeds the affected user equipment. This will determine the user equipment energy storage needs to operate through t_r or t_s. If t_r is unknown, 70 milliseconds will be the t_r power interruption time period. If t_s is unknown, 2 minutes will be the t_s power interruption time period.

5.2.3.2 Power source decay. User equipment is not required to sustain operation after the voltage and frequency pass below the voltage and frequency tolerance envelopes as defined on figures 7 through 10. However, the equipment shall be capable of returning to normal operation after power within the bounds of table II is suddenly reapplied at the end of the decay transient.

5.2.3.3 Voltage and frequency excursions. User equipment shall not be damaged due to voltage and frequency excursions specified in table II, Items 20 through 23, and shall be capable of returning to normal operation when power is restored within the user tolerance envelope.

5.2.4 Grounding. User equipment shall operate on a distribution system using a high-resistance grounding scheme.

5.2.5 Current (load) unbalance. User equipment that is three-phase or comprised of a combination of single-phase and three-phase loads shall have a resulting input three-phase line current unbalance not exceeding 5 percent (submarines 3 percent) using normal operating current under normal operating conditions during normal operating modes. This current shall be measured at nominal voltage in all operating modes with a voltage source having a line voltage unbalance less than 1 percent. Three-phase current unbalance shall be calculated as defined in 3.6.1. This requirement does not apply to aircraft servicing systems that are designed for a maximum current unbalance of 15 percent of the user equipment rating.

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5.2.6 User equipment pf. User equipment shall operate within the user frequency and voltage tolerance envelopes of figures 7 through 10 as applicable with an overall pf within the range of 0.8 lagging to 0.95 leading for 60-Hz equipment under normal steady state operating conditions, excluding start-ups and pulsed loads. There is no pf requirement for loads operating less than 1 kVA.

5.2.7 Pulsed load requirements. The following pulsed load requirements apply to each designated nominal user voltage.

5.2.7.1 Pulsed load requirement for power by category. A pulsed load may be categorized as infrequent or repetitive load changes, which result in a dynamic waveform.

5.2.7.1.1 Infrequent pulsed load requirements. An infrequent pulsed load shall be limited by the inrush current (see 5.2.10) and the ramp load requirements (see 5.2.8). As stated in 3.10, infrequent events are defined as events occurring no more than once every 120 seconds.

5.2.7.1.2 Repetitive pulsed load requirements. The repetitive pulsed load requirements shall meet the pulsed power deviation limit in the time domain, the pulsed power magnitude/frequency limits in the frequency domain, and the power total signal distortion limit, all covered in the following paragraphs. The limits on the repetitive pulsed power waveform maintain this standard's modulation requirements as well as an acceptable response of the prime mover/generator (see 3.10). Further information can be found in The Johns Hopkins University Applied Physics Laboratory technical paper entitled Power-Specification Frequency-Domain Test and Analysis Methodology for Large Dynamic Loads. The repetitive pulsed load requirements are always invoked except during infrequent events as defined in 5.2.7.1.1.

5.2.7.1.2.1 Pulsed power deviation limit (time domain). The user equipment shall limit the instantaneous three-phase pulsed real power deviation from the average real power level to be less than ±50 kilowatt (kW) over a 1-second integration interval centered on the event. This requirement applies for loads with a maximum instantaneous real power greater than or equal to 100 kW and less than or equal to 2 megawatt (MW) as seen by the ship's electric plant. For loads with a maximum instantaneous real power greater than 2 MW, substitute requirements are needed that address the relevant power system's source impedance and response characteristics of the intended platform for all operating modes. The substitute requirements will be specified in the acquisition documents (see 6.2) and shall have NAVSEA approval (see 6.4). An example showing the ±50 kW pulsed power deviation limit is shown on figure 11; in this example, the maximum instantaneous real power is 350 kW and the peak-to-peak pulsed real power is 300 kW. The average real power level is determined over a 1-second integration interval centered on the event. This 1-second centered rolling-average power level is calculated on the entire power waveform and is given by the middle dotted line in the graph. The ±50 kW limits are shown by the two bounded dotted lines. Violations of the ±50 kW limits are highlighted in gray.

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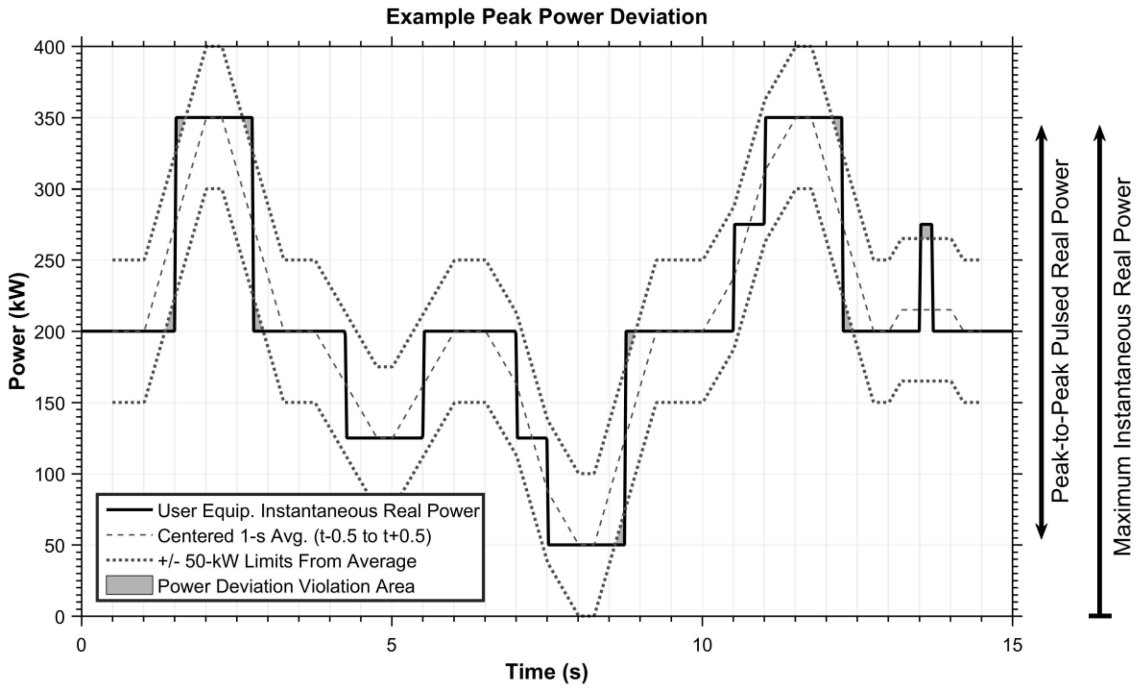

FIGURE 11. Pulsed power waveform and deviation example.

5.2.7.1.2.2 Pulsed power magnitude/frequency limits (frequency domain). The user equipment shall limit the magnitude and frequency of the instantaneous three-phase pulsed real power by the following constraints:

a. This requirement applies to loads with a maximum instantaneous real power level greater than or equal to 100 kW. An absolute limit is also imposed in that the load's allowed peak-to-peak real pulsed power as defined in 3.10.1 shall be less than or equal to 25 percent of the minimum prime mover real power rating. The window of observation for this limit is over a 100-second window. Pulsed loads with peak-to-peak real pulsed power greater than 25 percent of the minimum prime mover real power rating or greater than 2 MW shall be as specified (see 6.2 and 6.4).

b. The repetitive pulsed power magnitude/frequency limits are provided on figure 12. The plot presents the acceptable zero-to-peak real power magnitude in watts at a given frequency as a percent of the average real power in watts (e.g., at 1 Hz the allowed zero-to-peak real power magnitude is 3 percent of the average load). The zero-to-peak real power magnitude is determined with the average power component removed from the instantaneous power waveform. The average real power is calculated from the instantaneous real power waveform integrated over a 100-second averaging window. To use figure 12, the instantaneous real power pulsed waveform shall be decomposed into its frequency components after the average real power component has been removed. This is accomplished by using the Discrete Fourier Transform (DFT), incorporating a long window DFT for frequencies below 1 Hz and a short sliding window DFT for frequencies 1 Hz and above. The corresponding recommended procedure for performing the DFT is found in Appendix A. If the algorithm used to perform the DFT differs from Appendix A, a listing of the modified algorithm shall be as specified (see 6.2).

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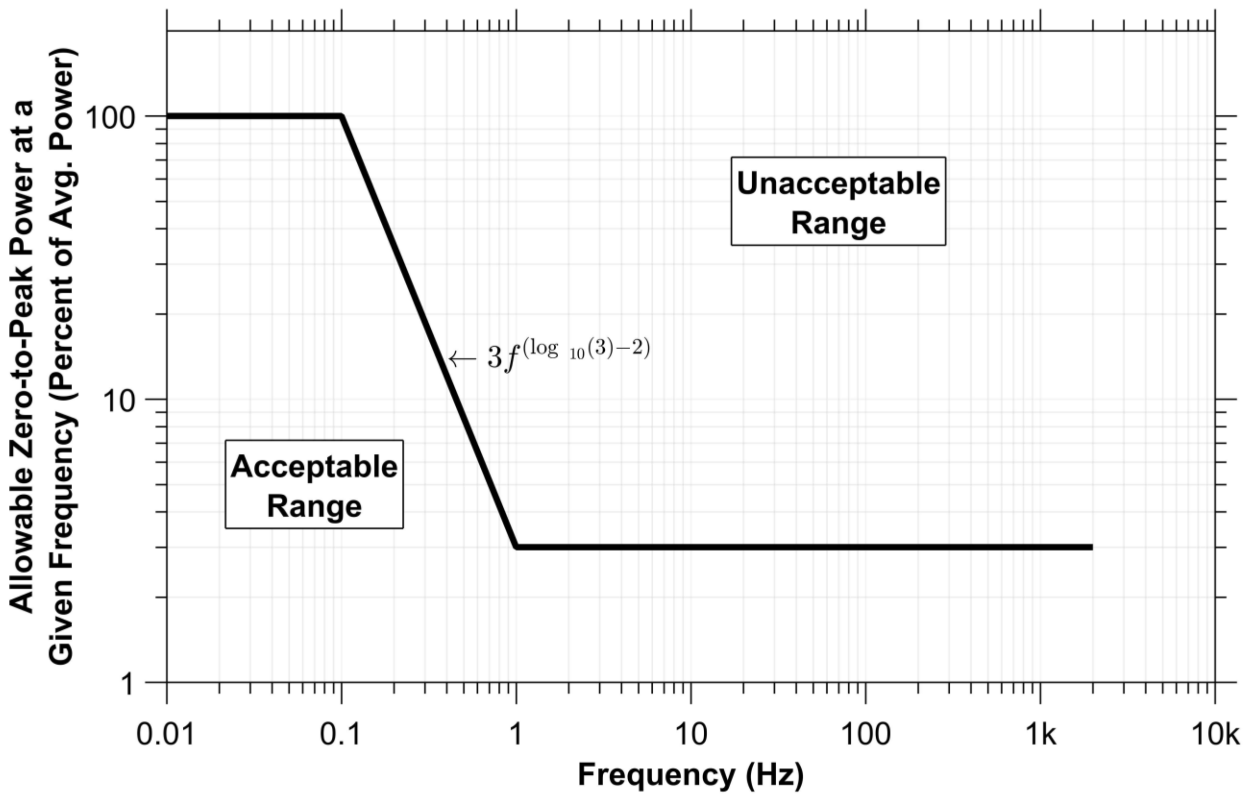

FIGURE 12. Pulsed power vs. frequency.

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c. The time for the long window is 100 seconds and the time for the short sliding window is 4 seconds. Each 4-second sliding window shall have a 3-second overlap with the preceding 4-second window. This process is shown on figure 13.

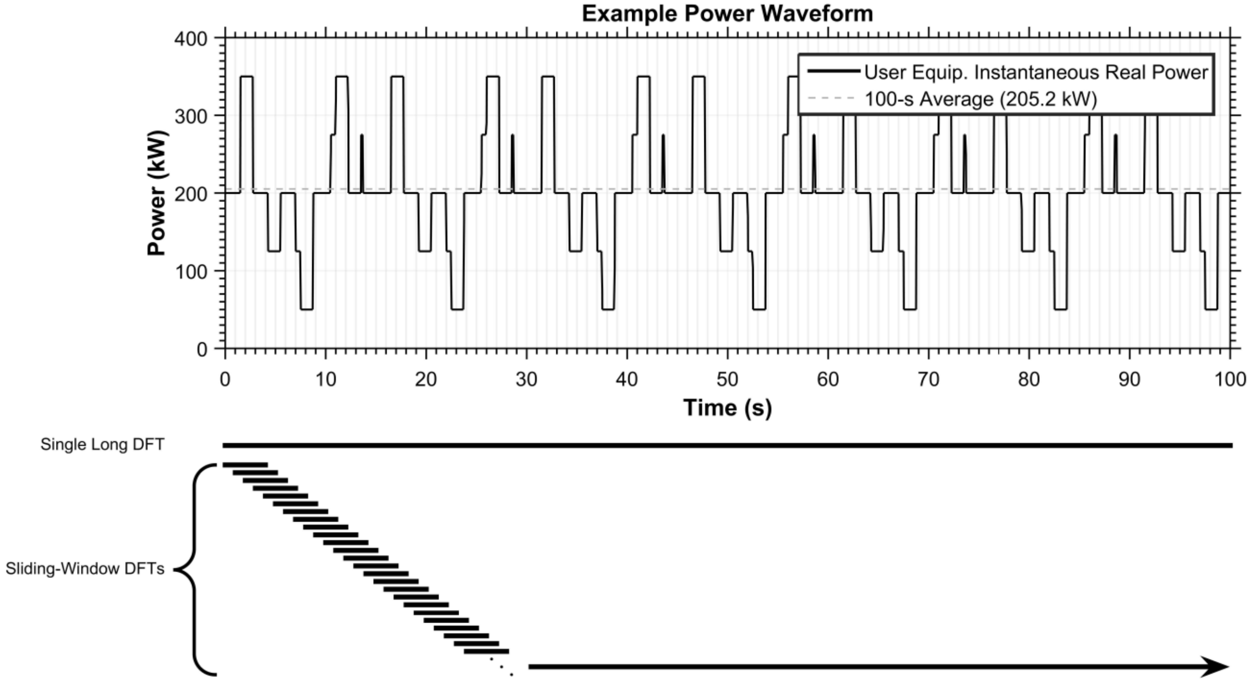

FIGURE 13. Sliding averaging window example.

d. The DFT decomposition of the real power pulsed waveform shall be restricted at any single frequency to the limits shown in the plot on figure 12. The corresponding recommended procedure for performing the DFT is found in Appendix A.

5.2.7.1.2.3 Power total signal distortion (TSD) limit (frequency domain). For Type I power, the load shall limit the calculated power TSD defined in 3.12 to less than 5 percent for frequencies from 1 Hz to 2 kHz where the average power shall be calculated over a 100-second window. As defined in Appendix A, a TSD calculation on each separate 4-second rolling window DFT is performed. The maximum TSD of all 4-second rolling window DFTs is to be the reported TSD value to be compared against the 5 percent requirement.

5.2.8 Ramp load requirement. A ramp load shall be limited to 30 percent of the minimum source rating in VA on a per second basis. The source rating could result from single or paralleled generators or electronic supplies. The resulting average ramp rate can be calculated using consecutive increasing steps. If the ramp load is applied in steps rather than a smooth ramp, the maximum step size shall be 70 kVA. The use of the ramp load allowance is for achieving a desired operational power level and shall only be used for infrequent events. This does not apply for the initial energizing of line filters, converter front end capacitance, transformers, and motors for which the inrush current requirement applies.

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5.2.9 Input current waveform. The operation of user equipment shall cause minimum distortion on the electrical distribution system current waveform and, thus, the voltage waveform. User equipment, for the purposes of this requirement, shall be defined as a standalone unit or the aggregate of a system with multiple like units on a single bus. The rating of equipment with multiple power inputs from the same interface shall be the summation of all the power inputs under steady-state conditions. Harmonic current and other conducted emissions (within the 20 kHz frequency band) introduced by the load are limited in order to allow the source and distribution systems to maintain the bus voltage distortion within specified limits given in table II. Current emission magnitude limits for 60-Hz user equipment at the nominal voltage levels of table II are depicted on figure 14. The criteria defined on figure 14 are similar to the MIL-STD-461 limit criteria for the electromagnetic interference (EMI) test CE101 for 60 Hz fundamental tailored to 20 kHz. MIL-STD-461 CE101 test results shall be used to satisfy input current waveform testing requirements. Input current shall be measured at nominal voltage input for all operating modes and power levels. The operation of user equipment shall have no single harmonic line current or current of any frequency above the fundamental frequency at 60 Hz to 2000 Hz that exceeds the limit line set at 3 percent of the user equipment's fundamental frequency current. Additionally, single harmonic line current or current of any frequency above 2000 Hz through 20 kHz shall not exceed the limit line set at 6000/f percent of the user equipment's fundamental frequency current, where "f" is the variable frequency.

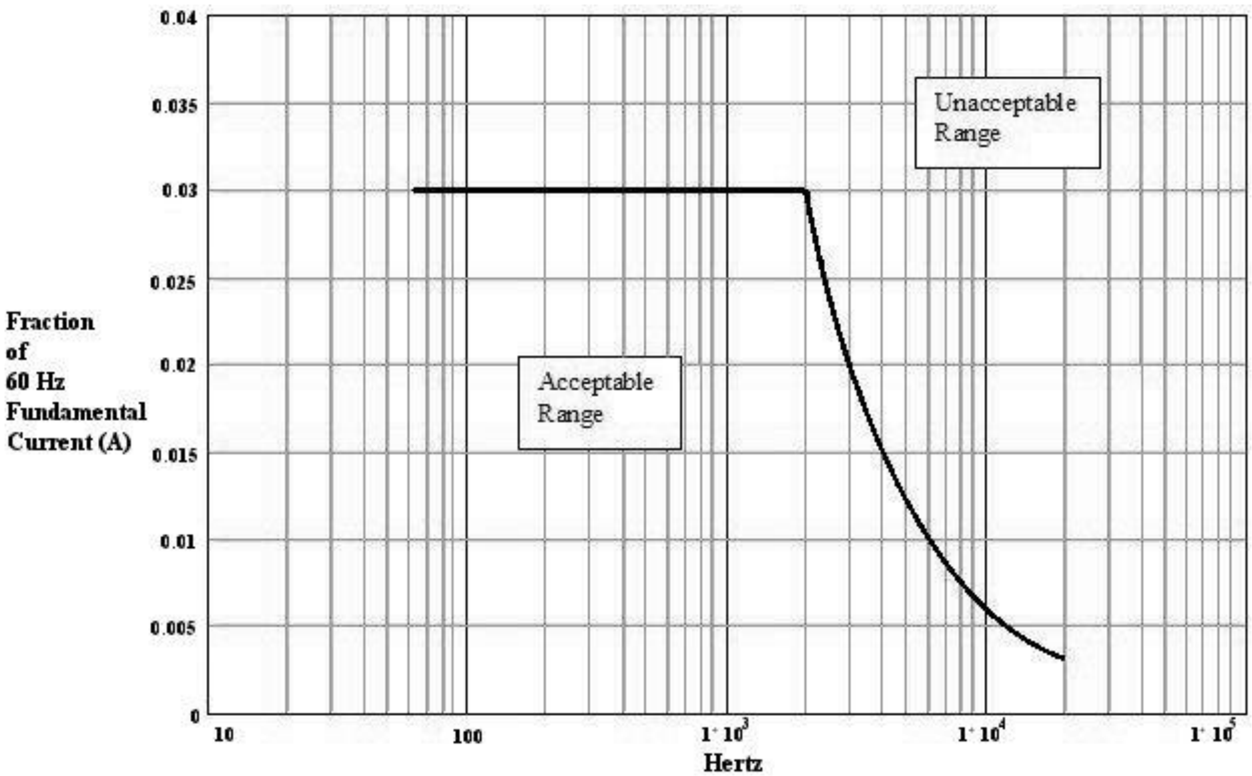

FIGURE 14. Limit line for currents at frequencies greater than 60 Hz.

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5.2.10 Surge/inrush current. User equipment shall be constructed to limit the ratio of surge current to rated current. The ratio of the maximum surge/inrush peak current to the full rated load peak current shall be limited to 10. Load sequencing may be required to maintain an acceptable user voltage envelope at the user interface. Surge/inrush current shall be measured, recorded, and evaluated when energizing the user equipment at the nominal input voltage when the phase voltage source sine-wave passes through 0 degrees for inductive load equipment or when the sine-wave passes through 90 degrees for capacitive load equipment. In order to make allowances for balanced three-phase user equipment where the current will be shifted by -30 degrees; add 30 degrees to the voltage when energizing the EUT. Multiple surge/inrush current occurrences observed on the same event shall be addressed and evaluated individually to determine compliance with the above requirements. There is no surge/inrush current requirement for individual loads rated less than 1 kW.

5.2.11 Insulation resistance. User equipment shall be tested to demonstrate the robustness of insulation systems by performing Basic Insulation Level (BIL) Tests appropriate for the voltage class for the type of equipment.

5.2.12 Voltage spikes (impulses). User equipment shall be designed to withstand voltage spikes (see 5.1.6.2.2) specified in table II. Equipment shall remain operational before, during, and after experiencing a voltage spike with the characteristics shown on figure 4 and described in 3.5.9. Equipment shall not experience any operational interruption, suffer any loss of data, or require a system restart or reboot.

5.3 Test requirements. This section specifies user equipment test requirements and test procedures. User equipment test requirements are intended to verify compliance to the user equipment interface requirements specified in this standard when tested in accordance with the procedures specified herein (see 6.2). For user equipment testing, the hardware and software of the user equipment as the Equipment Under Test (EUT) shall be representative of production. The tests presented herein are written to be adapted to the particular EUT. Test equipment and accessories required for measurement in accordance with this standard shall be calibrated under an approved calibration program traceable to the National Institute for Standards and Technology. The EUT shall be tested in all modes of operation at normal operating load.

5.3.1 User equipment power profile test. This test shall be used to document the EUT electrical interface and verify compliance to requirements for the following:

a. Class of power (see 5.2.2).

b. Number of phases (see 5.2.2).

c. Operating frequency (see 5.2.2).

d. Operating voltage (rms) (see 5.2.2).

e. Line current (at normal operating load and rated load).

f. Power (at normal operating load and rated load) (see 5.2.2).

g. pf (at normal operating load and rated load) (see 5.2.6).

h. Operating duty cycle.

i. Surge/inrush current (see 5.2.10).

j. Unbalance (at normal operating load and rated load) (see 5.2.5).

k. Pulsed loading profile (see 5.2.7).

l. Ramp loading profile (see 5.2.8).

m. Spike generation (see 5.1.6.2.2).

5.3.1.1 Apparatus. The following apparatus is recommended for performing this test:

a. Power source of required capacity and range of voltage and frequency adjustments. A power source with a capability of having an independently programmable voltage and frequency output is recommended.

b. Voltmeters (true rms) having ±0.5-percent accuracy.

c. Frequency meter having ±0.5-Hz accuracy.

d. Ammeters.

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e. pf meter.

f. Storage oscilloscope having ≥500 kHz response per channel.

g. Current and potential transformers and probes as required.

5.3.1.2 Procedure. The power profile test shall be repeated for each normal functional operating mode and for each EUT electrical power input. All test values shall be within limits in accordance with the applicable requirements. The power source used for this test and its characteristics shall be recorded in order to assist in analyzing the impact the equipment may have on a shipboard power system. The test power source rating and its source impedance, as well as the length and type of connecting cable used, shall be included. The following shall be determined:

a. The power input voltage and frequency to the EUT shall be within the user tolerance bands. The type of power shall be listed and the number of phases, frequency, power input voltages (line-to-line), each line current, and power (kVA and kW) and pf, leading or lagging, shall be measured and recorded. The operating duty cycle of the EUT aboard ship shall be stated. These measurements shall be made for each power input from the electric power system.

b. Surge/inrush current is discussed in 5.2.10. The EUT shall be de-energized and re-energized in accordance with the equipment operating procedures. Surge/inrush current shall be measured and evaluated when energizing the EUT at the nominal input voltage for the following cases: when the voltage source sine-wave passes through 0 degrees (for inductive load equipment) and when the sine-wave passes through 90 degrees (for capacitive load equipment). Make allowances for balanced three-phase user equipment where the current will be shifted by -30 degrees; add 30 degrees to the voltage when energizing the EUT. The larger inrush current of the two cases shall be used. During this period of de-energizing and re-energizing, oscilloscope records shall be taken of one line voltage and each line current to determine surge/inrush current during the transition. The data shall be of sufficient resolution to be able to accurately determine the magnitude and duration of the surge/inrush current.

c. Load unbalance for three-phase equipment and equipment suites that are a combination of single and three-phase loads shall be determined at normal operating load and at rated load and checked against the requirement in 5.2.5.

d. Pulsed and ramp loading profiles, discussed in 5.2.7 and 5.2.8, respectively, if applicable, shall be recorded and presented.

e. Spike generation during operation shall be noted and compared to the information in 5.1.6.2.2.

5.3.2 Voltage and frequency maximum departure tolerance test. This test shall be used to evaluate the performance of the EUT under the voltage and frequency conditions of table III, as applicable. The operation of the EUT shall be within the manufacturer's defined operating parameters when tested to the voltage and frequency conditions of table III, as applicable. This test shall be performed at normal operating load.

TABLE III. Voltage and frequency maximum departure tolerance test.

User Voltage	**User Voltage Tolerance (V_{rms})**			**Frequency Tolerance (Hz)**		
	Lower Limit	**Nominal**	**Upper Limit**	**Lower Limit**	**Nominal**	**Upper Limit**
4,160 V_{rms}	3,994	4,160	4,326	58.2	60	61.8
6,600 V_{rms}	6,336	6,600	6,864	58.2	60	61.8
13,800 V_{rms}	13,248	13,800	14,352	58.2	60	61.8

5.3.2.1 Apparatus. The following apparatus is recommended for performing this test:

a. Power source of required capacity and range of voltage and frequency adjustments. A power source with a capability of having an independently programmable voltage and frequency output is recommended.

b. Voltmeters (true rms) having ±0.5-percent accuracy.

c. Frequency meter having ±0.5-Hz accuracy.

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d. Temperature meter having ±0.5 °C accuracy.

5.3.2.2 Procedure. The EUT shall first be operated in a normal operating mode within the steady-state voltage and frequency tolerance envelopes as identified on figures 7 through 10 until the equipment temperature has stabilized. Temperature stability shall be defined as when the variation between successive temperature measurements at the same location does not exceed 1 °C after a 30–minute period. Once the temperature is stabilized, all conditions of testing can be performed. The EUT shall then be subjected to the limits of the user voltage and frequency tolerance envelopes of table III. The following combinations shall be set:

a. Voltage upper limit and frequency upper limit

b. Voltage upper limit and frequency lower limit

c. Voltage lower limit and frequency lower limit

d. Voltage lower limit and frequency upper limit

The EUT shall be operated at each combination until its temperature has stabilized and for 30 minutes thereafter. This test shall be repeated for each mode of equipment operation. Voltage, frequency, and internal equipment temperatures shall be measured and recorded at 10-minute intervals. During and after testing, equipment shall operate normally with a stable temperature and with no operational degradation to show compliance with this test.

5.3.3 Voltage and frequency transient tolerance and recovery (susceptibility) test. The EUT performance shall be evaluated under the transient frequency and voltage conditions specified in table IV. The operation of the EUT shall be within the manufacturer's defined operating parameters when tested to the transient voltage and frequency conditions of table IV. This test shall be performed at normal operating load.

TABLE IV. Transient voltage and frequency tolerance and recovery test.

Condition	Voltage	Frequency
Upper Limit	+18%	+5.5%
Lower Limit	-18%	-5.5%

5.3.3.1 Apparatus. The following apparatus is recommended for performing this test:

a. Power source of required capacity and range of voltage and frequency adjustments. A power source with a capability of having an independently programmable voltage and frequency output is recommended.

b. Voltmeters (true rms) having ±0.5-percent accuracy.

c. Frequency meter having ±0.5-Hz accuracy.

d. Storage oscilloscope having 500-kHz response.

e. Current and potential transformers and probes as required.

f. Temperature meter having ±0.5 °C accuracy.

5.3.3.2 Procedure. The EUT shall be operated in a normal operating mode within the frequency and applicable voltage tolerance envelopes shown on figures 7 through 10 until the equipment temperature has stabilized. Temperature stability shall be defined as when the variation between successive temperature measurements at the same location does not exceed 1 °C after a 30–minute period. Once the temperature is stabilized, all conditions of testing can be performed. The power input voltage and frequency shall then be simultaneously changed within 0.1 second to the applicable upper limit of table IV. Return the voltage and frequency to the user tolerance band within the applicable recovery time of table II, Items 6 and 15. The initial condition of voltage, frequency, and line current shall be measured and recorded before the start of each test. Input voltages, frequency, and input line currents shall be recorded before initiation of the voltage and frequency transient and until the transient is completed. Repeat the test at the applicable lower limit of voltage and frequency given in table IV. Repeat the test for each normal mode of operation at the applicable upper and lower limits of transient voltage and frequency of table IV. During and after testing, equipment shall operate normally with no operational degradation to show compliance with this test.

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5.3.4 Voltage withstand (susceptibility) test. Electric power and distribution apparatus assigned a given insulation class shall be capable of withstanding, without flashover or apparent damage, a high-potential voltage and a 1.2/50 full-wave impulse voltage (see figure 15) of specified crest kV. This specified crest voltage is the basic insulation level (BIL) of the equipment. Electric power and distribution apparatus, such as circuit breakers and switchgear, shall be tested using the high potential and BIL voltages specified in table V, as appropriate. This test shall be performed at normal operating load.

TABLE V. High-potential and BIL test voltages per voltage classes.

User Voltage	High-Potential (2 x nominal +1000)	BIL
4,160 V_{rms}	9.32 kV_{rms}	60 kV
6,600 V_{rms}	14.20 kV_{rms}	75 kV
13,800 V_{rms}	28.60 kV_{rms}	95 kV

The impulse/surge wave-shape is illustrated on figure 15. The 1.2/50 designation means that a voltage impulse increases from virtual 0 volts to its crest value in 1.2 µs (t_1) and declines to one-half crest value in 50 µs (t_2). A current wave of the same wave-shape accompanies the voltage wave.

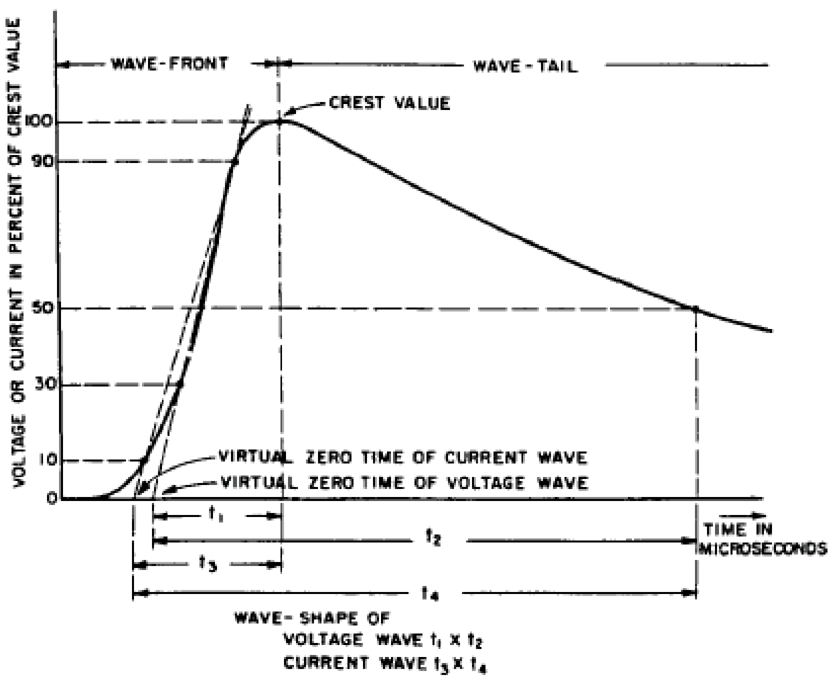

FIGURE 15. Voltage and current waves.

5.3.4.1 Procedure. Electrical power and distribution equipment assigned a given insulation class shall be subjected to high-potential and BIL test voltages as specified in 5.3.4. Test equipment and procedures commercially approved for similar testing may be used.

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5.3.5 Emergency conditions (susceptibility) test. The emergency conditions test is composed of the following subtests to evaluate EUT performance. This test shall be performed at normal operating load.

a. t_r power interruption subtest (simulated automatic bus transfer [ABT/SABT]).

b. t_s power interruption subtest (simulated power interruption due to emergency power reconfiguration).

c. Power source decay subtest (simulated loss of generator set prime mover).

d. Positive excursion subtest (simulated loss of generator voltage regulation).

5.3.5.1 Apparatus. The following apparatus is recommended for performing this test:

a. Power source of required capacity and range of voltage and frequency adjustments. A power source with a capability of having an independently programmable voltage and frequency output is recommended.

b. Voltmeters (true rms) having ±0.5-percent accuracy.

c. Frequency meter having ±0.5-Hz accuracy.

d. Storage oscilloscope having 500-kHz response.

e. Current and potential transformers as required.

f. Frequency to voltage transducer.

g. Temperature meter having ±0.5 °C accuracy.

5.3.5.2 Procedure. The EUT shall be operated in a normal operating mode within the frequency and applicable voltage tolerance envelopes shown on figures 7 through 10 until the equipment temperature has stabilized. Temperature stability shall be defined as when the variation between successive temperature measurements at the same location does not exceed 1 °C after a 30-minute period. Once the temperature is stabilized, all conditions of testing can be performed.

5.3.5.2.1 t_r power interruption subtest. If t_r is unknown, 70 milliseconds shall be used. The input power at nominal voltage and frequency shall be suddenly interrupted. After an interval no less than t_r, the input power shall be suddenly reapplied to nominal voltage and frequency. This power interruption shall be accomplished by switching the power at the power source and not by using the power switch or equivalent at the EUT. This cycle shall be repeated in all operating modes. Power source frequency, line voltage (one-phase), and line current shall be measured at the EUT power input terminals and recorded before the start and during each cycle. Equipment shall operate as specified in 5.2.3.

5.3.5.2.2 t_s power interruption subtest. If t_s is unknown, 2 minutes shall be used. After the EUT has been operated long enough to detect any performance degradation and with the equipment in normal operating mode, the power to the EUT shall be suddenly interrupted for an interval of t_s followed by the sudden reapplication of input power to the EUT. This power interruption shall be accomplished by switching the power at the power source and not by using the power switch or equivalent at the EUT. No manual intervention shall be allowed until the power is reapplied after the power interruption. This test shall be repeated in all operating modes. Equipment shall operate as specified in 5.2.3. Inrush current surges observed during power interruption tests shall be addressed as described in 5.2.10.

5.3.5.2.3 Power source decay subtest. The power source shall be modified as required to provide a voltage and frequency decay characteristic approximating that for the "Half-load on Generator" curve with the voltage falling from nominal at a rate of -15V/sec from 450 to 0 V_{rms} and the frequency falling at a rate of -2 Hz/sec from 60 to 0 Hz. With the EUT operating in one of the normal operating modes and with the power input voltage and frequency at nominal, initiate the power source output voltage and frequency decay characteristics specified above. If the test equipment source frequency does not extend down to 0, lower the frequency to the 50-percent value or lower and de-energize the test equipment source. After the time specified in Item 23b of table II since the initiation of the decay characteristic has passed, the power source output shall immediately return to nominal voltage and frequency. Line voltage, line current, and frequency shall be measured and recorded before the initiation of and during the power source decay test. This test shall be repeated in all operating modes. Equipment shall operate as specified in 5.2.3.

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5.3.5.2.4 Positive excursion subtest. The EUT shall be subjected to the emergency conditions positive excursion tolerances specified in table II, Items 20 through 23, and duplicated in table VI. The EUT shall be operated in a normal mode with the power input voltage and frequency at nominal. The power input voltage shall be varied from nominal in accordance with the positive excursion limits and time duration specified in table VI. At the end of the excursion duration, the power input voltage shall be immediately returned to nominal voltage. Then the power input frequency shall be varied from nominal in accordance with the positive excursion limits and time duration specified in table VI. At the end of the excursion duration, the power input frequency shall be immediately returned to nominal frequency. Finally, the power input voltage and frequency shall be varied simultaneously from nominal in accordance with the positive excursion limits and time duration specified in table VI. At the end of the excursion duration, the power input voltage and frequency shall be immediately returned to nominal voltage and frequency. Line voltage, one line current, and frequency shall be measured and recorded before, during, and after each positive excursion test. Repeat the positive excursion test for each operating mode of the EUT. Equipment shall operate as specified in 5.2.3.

TABLE VI. Emergency conditions test.

Emergency Conditions	Voltage Tolerance	Frequency Tolerance
Maximum Excursion	+35% of nominal	+12% of nominal
Duration	2 minutes	2 minutes

5.3.6 Current waveform (emission) test. The MIL-STD-461 CE101 test shall be performed from just above nominal input line frequency up to 20 kHz on the current waveform in the EUT power input lines for each operating mode, with the limits as shown on figure 14. The EUT shall be placed in an operating mode with load that produces maximum emissions. For EUTs with several available modes, a sufficient number of modes shall be tested for emissions such that all circuitry is evaluated. The harmonic current of the EUT shall be in compliance with the requirements in 5.2.9. A non-regulated power source shall be used for this test as regulated power source switching produces inconsistent current waveform data. The CE101 test results shall be provided as specified (see 6.2).

5.3.7 Voltage and frequency modulation (susceptibility) test. EUT performance shall be evaluated under the voltage modulation and frequency modulation conditions specified in table II, Items 2 and 9. The operation of the EUT shall be within the manufacturer's defined operating parameters when tested to the voltage modulation and frequency modulation conditions specified in table II, Items 2 and 9. This test shall be performed at normal operating load.

5.3.7.1 Apparatus. The following apparatus is recommended for performing this test:

a. Power source of required capacity and range of voltage and frequency adjustments. A power source with a capability of having an independently programmable voltage and frequency output is recommended.

b. Voltmeters (true rms) having ±0.5-percent accuracy.

c. Frequency meter having ±0.5-Hz accuracy.

d. Storage oscilloscope having 500-kHz response.

e. Current and potential transformers and probes as required.

f. Temperature meter having ±0.5 °C accuracy.

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5.3.7.2 Procedure. The EUT shall be operated in a normal operating mode within the frequency and applicable voltage tolerance envelopes shown on figures 7 through 10 until the equipment temperature has stabilized. Temperature stability shall be defined as when the variation between successive temperature measurements at the same location does not exceed 1 °C after a 30–minute period. Once the temperature is stabilized, all conditions of testing can be performed. The voltage and frequency modulation test produces a voltage and frequency modulation on the input waveform from nominal to within the modulation limits defined by table II, Items 2 and 9 for the applicable voltage class. The input voltage and frequency shall be varied separately and then simultaneously. The input voltage (at least two phases for three-phase power equipment), input line current (at least two line currents for three-phase equipment), and frequency shall be recorded before initiation of modulating voltage and frequency and continue throughout each test run. The following are the periods for the individual tests:

a. Voltage modulation test: With the frequency held constant at nominal, vary the voltage from minimum to maximum for periods of 50 milliseconds, 500 milliseconds, 1 second, and 10 seconds. Repeat each cycle of modulation ten consecutive times before moving to the next modulation period, starting at 50 milliseconds and ending at 10 seconds.

b. Frequency modulation test: With the voltage held constant at nominal, vary the frequency from minimum to maximum for periods of 50 milliseconds, 500 milliseconds, 1 second, and 10 seconds. Repeat each cycle of modulation ten consecutive times before moving to the next modulation period, starting at 50 milliseconds and ending at 10 seconds.

c. Combined voltage and frequency modulation test: Simultaneously vary the voltage from minimum to maximum and the frequency from minimum to maximum for periods of 50 milliseconds, 500 milliseconds, 1 second, and 10 seconds. Repeat each cycle of modulation ten consecutive times before moving to the next modulation period, starting at 50 milliseconds and ending at 10 seconds.

The EUT shall operate normally with no operational degradation during all test conditions to show compliance with this test. The recording quality shall be sufficient to show that the proper modulation limits were conducted.

6. NOTES

(This section contains information of a general or explanatory nature that may be helpful, but is not mandatory.)

6.1 Intended use. This standard is intended to be used in designing surface ship and submarine AC electrical power systems and in designing and testing user equipment.

6.2 Acquisition requirements. Acquisition documents should specify the following:

a. Title, number, and date of this standard.

b. The approval authority for testing, if necessary (see 4.2).

c. Requirements for deviations, waivers, and tailoring requests (see 4.4 and 6.4).

d. Values for t_r and t_s (see 5.2.3.1).

e. Requirement for grounding scheme verification (see 5.2.4).

f. Requirements for repetitive pulsed loads for pulsed loads with peak-to-peak real pulsed power greater than 25 percent of the minimum prime mover real power rating or greater than 2 MW (see 5.2.7.1.2.1 and 5.2.7.1.2.2.a).

g. Requirement for a listing of the modified algorithm used to perform the DFT, if the algorithm differs from Appendix A (see 5.2.7.1.2.2.b).

h. Report of results derived from tests listed in 5.3.

(1) Create test procedures by tailoring DI-EMCS-80201 so requirements 1 through 2.2; 2.4.a; 2.6.a, b, e, and f; and 2.7.b, c, and e are used, substituting “interface” for “EMI” and MIL-STD-1399-300-2 as the applicable military standard.

(2) Create a test report by tailoring DI-EMCS-80200 so requirements 1 through 2.2.a, b, f, g, i, m, and o and 2.3 are used, substituting “interface” for “EMI” and MIL-STD-1399-300-2 as the applicable military standard.

i. Requirements for CE101 test results (see 5.3.6).

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6.3 Subject term (key word) listing.

Delta and wye connected systems

Frequency decay

Leakage current

Power factor

Transient limits

Worst case frequency excursion

6.4 Deviation, waiver, and tailored requirement requests. Requests for deviations, waivers, and tailored requirements are to be submitted for approval to the NAVSEA technical authority for ship electrical power systems (NAVSEA 05Z32).

6.5 Changes from previous issue. Marginal notations are not used in this revision to identify changes with respect to the previous issue due to the extent of the changes.

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POWER RIPPLE ANALYSIS PROCEDURE

A.1 SCOPE

A.1.1 Scope. The power ripple analysis requires digital signal processing. This section provides a step-by-step guide to performing the analysis, along with example code that will execute the necessary calculations when provided a power waveform signal and sampling period. There is also a section titled "Additional DFT Notes" (see A.6) that may be useful to someone new to DFT analysis. This Appendix is not a mandatory part of the standard. The information contained herein is intended for guidance only.

A.2 PROCEDURE

The power ripple analysis procedure is as follows:

Step 1. Collect 100 seconds of the instantaneous power waveform sampled at 4 kHz or greater. It is recommended to keep the sampling frequency below 50 kHz to keep the memory usage of the computer reasonable during the DFT calculation. It is assumed that an even number of samples are taken, which will have an effect on the Nyquist-frequency bin location in later steps.

Step 2. Compute the average value of the 100-second sampled signal and subtract this average value from the signal prior to performing the DFT. Keep the average power for later use.

Step 3. Generate the 100-second long Kaiser window (beta = 7) and calculate the coherent gain (CG) and equivalent noise bandwidth (ENBW). CG and ENBW can be calculated with the following equations:

$$CG = \sum_{n=0}^{N-1} w(n)$$

$$ENBW = N\frac{\sum_{n=0}^{N-1}(w(n)^2)}{(\sum_{n=0}^{N-1} w(n))^2}$$

Where N is how many samples long the window is and w is the values of the Kaiser window. Note that the ENBW includes zero padding in the number of samples, N, while the CG does not include zero padding.

Step 4. Sample multiply the 100-second long power waveform by the window function and divide by the CG of the window, which corrects the DFT output amplitude error to the gain of the windowing function and the window length, N. Add zero padding, equal to nine times the length of the signal, after the windowing function is applied. If using the Fast Fourier Transform (FFT) for faster computations, zero padding can be added such that the new total signal length (including zero padding) is a power of 2 and at least 10 times longer than the original signal length.

Step 5. Perform the DFT with the necessary zero padding and take the absolute value for each frequency component. For real signals, because the negative frequencies have the same information as the positive frequencies, multiply all the amplitudes of the positive frequency components (except 0 Hz and the Nyquist frequency, bins 0 and N/2) by two to achieve the proper amplitude.

Step 6. All negative frequency components may be discarded.

Step 7. The sampling frequency is f_s. The bin frequency spacing is f_s/N, where N includes zero padding. The bin numbers are now 0 to N/2, where N includes zero padding. With only the positive frequencies present, convert the bin numbers to frequencies by multiplying the bin numbers by f_s and dividing by the total number of samples, N, where N includes zero padding.

Step 8. Save the spectrum from 0.01 Hz to 1 Hz. The higher frequencies will be determined from the 4-second rolling window.

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Step 9. Perform multiple DFTs on the 100-second time-domain signal by using a rolling 4-second window, whereby each subsequent 4-second window will have 75 percent overlap with the preceding window (shift the window by 1 second each time). Adjust the amplitudes as done for the 100-second DFT to account for windowing, the sample number, and the negative frequency components from steps 3 through 6. Remove the average value of each 4-second window of data before taking the DFT. Record the results of each 4-second DFT calculation.

Step 10. Record the maximum amplitude at each frequency bin across all 4-second rolling-window DFTs from the above step. These maximums will represent the DFT results for frequencies from 1 Hz to 2 kHz. This is similar to a "Max Hold" function on a spectrum analyzer.

Step 11. Perform a TSD calculation on each separate 4-second rolling window DFT from step 9 above. The maximum TSD of all 4-second rolling-window DFTs is to be the reported TSD value to be compared against the 5 percent requirement. In this case, including a value for the equivalent noise bandwidth correction term, the equation for TSD is:

$$TSD = \frac{\sqrt{P_k^2 + P_{k+1}^2 + P_{k+2}^2 + \cdots + P_n^2}}{\sqrt{2 \cdot \mathrm{ENBW}} \cdot P_{av}}$$

where P_k is the 1-Hz bin, P_n is the 2-kHz bin (if 2 kHz is the Nyquist frequency, ending at the preceding bin is acceptable), ENBW is the equivalent noise bandwidth of the DFT window, and P_{av} is the average power calculated over the entire 100 seconds of power waveform data.

Step 12. Normalize all DFT results by dividing by P_{av}, the average value over the 100 seconds of power waveform data calculated in step 2.

Step 13. Combine the 0.01 Hz to 1 Hz DFT results from the 100-second window with the 1 Hz to 2 kHz DFT data from step 10. This is the final data to be reported and compared against the power ripple frequency requirement.

A.3 TEST EQUIPMENT SETTINGS

Test equipment settings are as follows:

A.3.1 Instrument accuracy. The combined full-scale accuracy of the measuring instrument and full-scale accuracy of the measuring probes should be better than 3 percent.

a. Errors in the full-scale measurement will primarily result in gain and offset errors in the measured amplitudes and error in the subsequent TSD results. This is separate from resolution, which must have higher precision.

b. Assuming all error in the measurement is due to gain and offset errors (i.e., negligible nonlinearity of the measuring instrument and probe), this results in a reported DFT amplitude accuracy of ±0.1 percent. For example, if a power ripple frequency exists at 3 percent of the average power, the reported amplitude will be between 2.9 and 3.1 percent.

A.3.2 Digitizer resolution. The digitizer of the measuring instrument should have at least 10 effective bits of resolution.

a. The resolution is needed to accurately capture the power dynamics as well as define the maximum noise floor.

b. 10 effective bits of resolution provides approximately 0.1 percent resolution.

A.3.3 Measurement skew. The skew between all simultaneous measurements, at all required frequencies, should be less than 15 microseconds (~11 degrees at 2 kHz).

a. When two sine waves separated by 11 degrees are multiplied (i.e., voltage and current), the resulting sine wave (i.e., power) has an amplitude within 0.2 percent of the two original sine wave amplitudes being multiplied together (no phase shift).

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A.3.4 Anti-aliasing filters. Proper anti-aliasing filters should be used to prevent energy at frequencies higher than the Nyquist frequency from being folded into the frequency spectrum of interest.

a. This also drives the minimum sampling frequency of the measurement equipment, such that there is sufficient room between the maximum measured frequency component and the Nyquist frequency for the anti-aliasing filter to reach the desired attenuation level.

A.4 RECOMMENDED EQUIPMENT

A.4.1 Dranetz HDPQ Guide.

a. Source information: http://www.dranetz.com/product-services/current-dranetz-products/dranetz-hdpq-guide/, or equal.

b. This can capture and store 10,000 60-Hz cycles of data (166 seconds of data at a 32.5-microsecond sample rate), which has a fixed configuration of eight channels (four voltage, four current). It has internal 4GB memory with universal serial bus (USB), Ethernet, and wireless connections to retrieve data. One of the channels could be used to trigger the 100-second recording event.

A.4.2 Yokogawa PX8000.

a. Source information: https://tmi.yokogawa.com/solutions/products/digital-power-analyzers/digital-power-analyzers/px8000-precision-power-scope/, or equal.

b. The base model can capture 10 million samples per channel with a maximum sample rate of 100 million samples per second (e.g., 200 seconds of data at a 20-microsecond sample rate), which is configurable up to eight channels. It has secure digital (SD) card and USB mass storage device support, as well as Ethernet, GP-IB, and USB communications support to retrieve data. Numerous triggering options are available, including remote single-shot manual trigger for the 100-second recording event.

A.5 EXAMPLE CODE

A.5.1 MATLAB functions. The following example could be performed with any suitable analysis software. MATLAB software was chosen due to its wide use in industry. The following code provides working MATLAB functions that will execute the above steps and plot the results. There are two functions. The first, powerDFT, is a support function that executes the actual DFT given a power waveform signal, sampling period, window length (in seconds), and overlap percentage. The second, powerRippleAnalysis, provides the parameters to the first function and pieces together the different parts of the DFTs, as well as calculating TSD. To aide in the understanding of the code, a script is provided that comes with a test signal and calls the powerRippleAnalysis function.

A.5.2 MATLAB function usage. To use the code, save each function and script in a common directory. Use the name powerDFT.m for the first function, powerRippleAnalysis.m for the second function, and example m for the short test script. To test the code, run example.m, and MATLAB will output two graphs in a single figure as shown on figure A-1 (a time domain of the test signal and the DFT output of the test signal with the corresponding calculated TSD).

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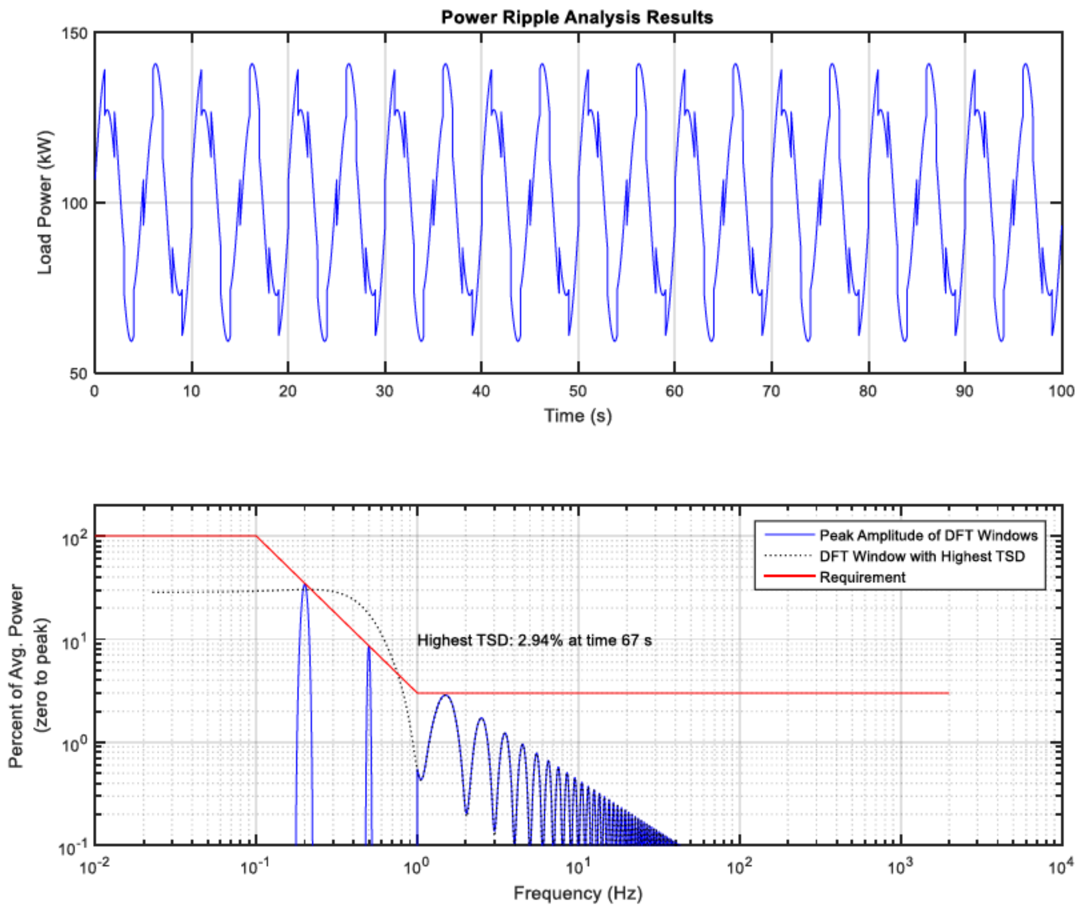

FIGURE A-1. MATLAB output - time domain test signal with corresponding DFT with TSD results.

A.5.3 MATLAB Function powerDFT.m.

```
function [ frequency, DFT, Pavg, ENBW ] = powerDFT( P, Ts, windowLength,
overlapPercent )
%powerDFT - outputs the results of the DFT process used for the
%MIL-STD-1399-300-2 power ripple requirement. This is a support function
%that is called from powerRippleAnalysis(). Please use powerRippleAnalysis
%for evaluating against the power ripple requirement.

    % Convert window length to the number of samples
    N_win = round( windowLength / Ts );
    % How much zero padding to add in multiples of the length of data, plus
    % one for the original data length
    zeroPadMultiplier = 9 + 1;
    % Define the length of the DFT that will be run. Make sure it's even.
    NDFT = round(N_win*zeroPadMultiplier);
    if ( mod(NDFT,2) )
        NDFT = NDFT + 1;
    end
    % If faster speed is desired, increase NDFT to the next power of 2 so
```

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```
    % that the Fast Fourier Transform algorithm can be used
    NDFT = 2^nextpow2(NDFT);
    % Define the number of samples the DFTs slide between windows
    FFTslide = round( (1 - overlapPercent/100) * N_win );
    % Define the number of DFTs to run
    N = floor( (length(P)-N_win)/FFTslide ) + 1;

    % Create the Kaiser window of length N_win with Beta = 7
    beta = 7;
    % same as kaiser(NDFT,beta)
    n = 0:(N_win-1);
    win = besseli( 0, beta*sqrt(1-(2*n/(N_win-1)-1).^2) )';
    % Calculate the Coherent Gain of the window
    CG = sum(win);
    % Calculate the Equivalent Noise Bandwidth of the window
    ENBW = sum(win.^2)/sum(win)^2 * NDFT;

    % Initialize arrays
    DFT  = zeros(N,NDFT/2);
    Pavg = zeros(1,N);

    % Calculate the DFTs
    for i = 1:N
        % Where to start and end the DFT within P
        iStart = 1 + (i-1)*FFTslide;
        iEnd = iStart + N_win - 1;

        % Grab the part of the waveform we want
        X = P(iStart:iEnd);
        % Find the average value
        Pavg(i) = mean(X);
        % Subtract the average before running the DFT
        X = X - Pavg(i);
        % Perform the DFT with a window length of NDFT
        Y = fft( X(:) .* win/CG, NDFT);

        % We only want positive frequencies, but the DFT creates both
        % positive and negative frequencies with half amplitude of a purely
        % real input. This corrects for the half amplitude. The zeroth bin
        % for the DFT does not need to be doubled. We also do not want the
        % complex values, but the absolute values. The Nyquist bin is
        % thrown out.
        DFT(i,:) = [abs(Y(1)) 2*abs(Y(2:(NDFT/2))')];
    end

    % Generate the frequency vector for the DFTs.
    % f = (bin number)*(sampling frequency) / (DFT length with zero padding)
    frequency = ( 0 : NDFT/2-1 ) * (1/Ts) / NDFT;
end
```

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A.5.4 MATLAB Function powerRippleAnalysis.m.

```
function [ f_final, DFT_final, TSD_max ] = powerRippleAnalysis( P, Ts )
%powerRippleAnalysis - Calculates and plots the DFT analysis for the
%                      MIL-STD-1399-300-2 power ripple requirements.
%-
%   Usage:
%   [ f_final, DFT_final, TSD_max ] = powerRippleAnalysis( P, Ts )
%-
%   Input:
%   P is the input power waveform and Ts is the sampling rate. It is
%   recommended to downsample the power waveform to under 20 kHz in order
%   to keep the memory usage to a reasonable amount (~1 GB at 20 kHz for
%   100 seconds).
%-
%   Output:
%   f_final is the pieced-together frequency bins from the 100-s DFT and
%   the 5-s DFT windows. DFT_final is the pieced-together DFT outputs from
%   the 100-s DFT (<1 Hz) and the maximum for each frequency across all 5-s
%   DFTs (>=1Hz). TSD_max is the maximum TSD of any single 5-s DFT.

    % Define the window length in seconds
    windowLength = 5;
    % Define the overlap percentage
    overlapPercent = 80;
    % Create a time vector
    time = ( 0:(length(P)-1) ) * Ts;

    % Run the DFT analysis with the long window
    [f_long,DFT_long,Pavg_long,ENBW_long] = powerDFT(P,Ts,time(end)+Ts,0);
    % Run the DFT analysis with the rolling short window
    [f, DFT, Pavg, ENBW] = powerDFT(P, Ts, windowLength, overlapPercent);

    % Calculate the 1-Hz bin indexes
    index1Hz_long =  ceil( 1.0 * Ts * (length(f_long)-1)*2 + 1 );
    index1Hz      = round( 1.0 * Ts * (length(f)-1)*2 + 1 );
    % Find the bin number for 2 Hz in the rolling DFT outputs
    index2kHz     = round( 2e3 * Ts * (length(f)-1)*2 + 1 );
    % If 4-kHz or lower sampling rate is used, use the last non-Nyquist bin
    if (index2kHz > size(DFT,2))
        index2kHz = size(DFT,2);
    end

    % Initialize array
    TSD = zeros(1,size(DFT,1));
    for i = 1:size(DFT,1)
        % Calculate the total power distortion (TSD) using the short window
        % for 1Hz <= f <= 2kHz
        TSD(i) = sqrt( sum( DFT(i,index1Hz:index2kHz).^2 ) ) ...
                / ( sqrt(ENBW) * sqrt(2) * Pavg_long ) * 100;
    end

    % Find the maximum amplitude of each frequency across all DFT windows
    DFT_peaks = max(DFT,[],1);
```

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```
    % Find the DFT window with the highest TSD
    [TSD_max, TSD_max_index] = max(TSD);
    % Find what time (in seconds) the highest TSD occurred.
    TSD_max_time = TSD_max_index * windowLength * ...
                    (1 - overlapPercent/100) + windowLength/2;

    % Generate the final results by concatenating the long window DFT with
    % frequencies below 1 Hz and the rolling window peaks (maximum of each
    % frequency over all windows) with frequencies 1 Hz and above.
    DFT_final = [DFT_long(1:index1Hz_long-1), DFT_peaks(index1Hz:end)] ...
                / Pavg_long * 100;
    f_final = [f_long(1:index1Hz_long-1), f(index1Hz:end)];

    % Generate the requirement to compare against
    req_f   = [0.01, 0.1,                  logspace(-1,0,100), 1, 2e3];
    req_amp = [ 100, 100, 3*logspace(-1,0,100).^(log10(3)-2), 3,   3];

    %% Plot the results
    figure(1)
    set(gcf,'Position',[100 100 1000 800])

    subplot(211)
    plot((0:length(P)-1)*Ts, P/1e3, '-b', 'LineWidth',2)
    grid on
    xlabel('Time (s)')
    ylabel('Load Power (kW)')
    title('Power Ripple Analysis Results')

    subplot(212)
    loglog(f_final, DFT_final, '-b','LineWidth',2); hold on
    loglog(f, DFT(TSD_max_index,:)/Pavg_long*100, ':k','LineWidth',1)
    loglog(req_f, req_amp, '-r','LineWidth',2); hold off
    axis([0.01, 10e3, 0.1, 200])
    grid on
    xlabel('Frequency (Hz)')
    ylabel({'Percent of Avg. Power','(zero to peak)'})
    legend('Peak Amplitude of DFT Windows','DFT Window with Highest
TSD','Requirement')
    text(1.5,80,['Highest TSD: ' num2str(TSD_max,'%5.2f') '% at time ' ...
         num2str(TSD_max_time,'%3.0f') ' s'])
end
```

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A.5.5 MATLAB Script example m.

```
%% Example Power Ripple - example.m
% Use the following as a test signal to ensure the functions have been
% copied or implemented correctly. The main lobes at 0.2 Hz, 0.5 Hz, and
% 1.5 Hz should all be very close to the requirement. The remaining lobes
% above 1.5 Hz should be placed in 1 Hz increments above 1.5 Hz (e.g. 2.5
% Hz, 3.5 Hz, etc.) and are gradually decreasing. The highest TSD should be
% 2.938%.

Ts = 1/20e3;
t  = 0:Ts:(100-Ts);
P  = 100e3 + 34e3*sin(0.2*2*pi*t) + 6.75e3*square(0.5*2*pi*t);

[ f_final, DFT_final, TSD_max ] = powerRippleAnalysis(P, Ts);
```

A.6 ADDITIONAL DFT NOTES

A.6.1 MATLAB's DFT function. MATLAB's DFT function decomposes a time domain signal into a set of cosine and sine waveforms. The DFT function returns an array of real and imaginary numbers at both positive and negative frequencies. When the components of the positive and negative frequencies are appropriately combined, the real numbers represent the amplitude of the cosine waveforms and the imaginary numbers represent the amplitudes of the sine waveforms (following Euler's formula). The location of the real and imaginary numbers in the array gives the bin number, or frequency value, for each cosine and sine wave, and the location in the array will define if the frequency is negative or positive for each real and imaginary number.

a. For real signals, the components in the negative frequency bins are the complex conjugate of the components stored in the positive frequency bins, c = a + jb and c* = a - jb. Hence, the magnitudes of the positive and negative frequency components are equal.

b. A single cosine real tone (with no phase shift) is represented as two real numbers in the frequency domain: one with a positive frequency and one with a negative frequency, with the imaginary components being equal to zero. The amplitude of each of the frequencies is half the value of the original single-tone amplitude. This result can be shown via Euler's formula. For purely real signals, the time domain amplitude can be computed by multiplying the DFT amplitude of the positive frequency components by two.

c. In a similar fashion for a single sine real tone (with no phase shift), the real components are zero and the imaginary values represent the sine waveform.

d. If the decomposed signal consists of cosine terms and sine terms, or cosine terms with a phase shift, then both imaginary numbers and real numbers will exist in the DFT amplitudes of the associated frequency bins. By taking the absolute value of the DFT output at each frequency and multiplying by two, the amplitude of the equivalent cosine waveforms can be determined. The corresponding phase shift of the cosine waveform can be found by computing the arctangent of the imaginary component over the real component. Recall that the summation of a cosine wave with a sine wave for a given frequency can be represented as a cosine wave at the same frequency with the added phase shift, θ; $A\cos(x) + B\sin(x) = M\cos(x + \theta)$, where $M = \sqrt{A^2 + B^2}$ and $\theta = \arctan(B/A)$.

A.6.2 Sampling frequency. If the sampling frequency is f_s (samples per second), then the highest frequency component that can be determined is $f_s/2$ (the Nyquist frequency) and $1/f_s$ is the sampling period, T_s.

A.6.3 Windowing. Windowing is a technique used to mitigate the spectral leakage effect due to sampling a non-integer number of cycles. When non-integer cycles are sampled, discontinuities between the beginning and end point exist. The non-rectangle windows intentionally taper the beginning and ending points to get rid of this discontinuity and, hence, mitigate the spectral leakage. In so doing, the time domain signal is distorted and the resulting amplitude of the DFT is reduced and will need to be adjusted accordingly.

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A.6.4 Signal window width. The width (in time) of the signal window determines the frequency resolution, $df = 1/T_{window}$. For instance, if you want to be able to resolve 61-Hz and 60-Hz components from one another, then you need at least 1 second's worth of samples, not including any zero padding samples. As such, the length (in time) of the sampled signal must be long enough to capture at least one full cycle of the frequency of interest.

A.6.5 Bin frequency. The frequency of a DFT bin is found by, (Bin Number)*f_s/(total # of samples including zero padding). The MATLAB indices correspond to (bin# + 1) because the first MATLAB index is 1 not zero.

A.6.6 Zero padding. Zero padding can be used to effectively eliminate scalloping losses, as well as increase the number of frequency bins to pin-point the exact frequencies of the signal. Zero padding increases the number of frequency bins and subsequently decreases the space between frequency bins. Zero padding means you are doing the DFT for more frequencies, achieving more resolution, such that $df = f_s/N_{dft}$, where N_{dft} is the total number of samples, including the zero padding length. Zero padding is helpful when you have a full cycle of data, but the window is not an integral number of cycles, hence, the frequency components will lay between the frequency bins if zero padding is not used. Note that zero padding does not add any information to the signal; it only helps in distinguishing frequencies. It simply adds more sampled data points to the DFT, or more data points along the sinc-like shape of the DFT output.

A.6.7 Scalloping losses. Scalloping losses are terms used to describe the reduction in amplitude of the DFT output when the frequency of the time domain signal does not match a specific DFT frequency bin. The maximum loss in amplitude occurs when the frequency of the signal lies exactly in the middle between two bins. For a single tone, centering a continuous-time-domain Fourier Transform of the window function (the DFT filter) on the frequency location corresponding to actual frequency value of the signal and observing where the first bins above and below this frequency value intersects the DFT filter will give the actual observed reduced DFT amplitudes for the two bins closest to the real frequency value. In other words, the DFT of a single frequency is a sampled version of the continuous sinc-like function that is the DFT filter. Zero padding can be used to add more samples along this sinc-like function.

A.6.8 Rectangle window with zero padding. If using a rectangle window and zero padding the time domain signal prior to taking the DFT (by simply adding zeros to the time-domain signal), the value $1/T_{window}$ is the space between nulls of the side-lobes of the resulting frequency domain sinc function, whereby T_{window} does not include the zero padding samples, and $2/T_{window}$ is the width of the main lobe between nulls of the sinc function.

A.6.9 Windowing for low level signals. Windowing (such as using the Taylor or Kaiser windows) allows the resolution of low level signals when strong signals are in the near vicinity due to the decreased side lobe levels.

A.6.10 Windowing for frequency resolution. Windowing functions increase the main lobe width, but decreases the side-lobe amplitude when compared with a rectangular window. By increasing the signal window length, the main lobe width can be decreased, hence, increasing the frequency resolution.

A.6.11 Coherent gain. The amplitudes of the DFT must be divided by a correction factor, the Coherent Gain (CG), specific to the window. The CG compensates for the change in amplitude of the DFT output due to applying the window function as well as the window length, N. For the simplest case of using a rectangle window, CG equals N where N does not include zero-padding.

A.6.12 TSD calculation. When the TSD is calculated, the correction term, called the Equivalent Noise Bandwidth (ENBW), is used to negate the inflation of the TSD value due to the energy that appears in the side lobes as well as the additional energy due to the main lobe bandwidth increase.

A.6.13 MATLAB FFT frequency bins. The MATLAB function fft(. . .) outputs frequency bins 0 to $N - 1$. The frequencies between 0 to N/2 are positive, and the frequencies from N/2 to $N - 1$ are negative. Sample N/2 corresponds to frequency $f_s/2$, the Nyquist frequency, provided an even number of samples were fed into the fft function.

A.6.14 MATLAB FFT frequency bin order. For MATLAB, the order of fft frequencies or bins is defined as [0, 1, 2, …, (N/2), (−N/2) + 1, (−N/2) + 2, …, −2, −1]. Performing a DFT on a time-domain signal with eight samples, N = 8, will produce the frequency bin order [0, 1, 2, 3, 4, −3, −2, −1] while the corresponding MATLAB indices will be [1, 2, 3, 4, 5, 6, 7].

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A.6.15 References.

[1] F. Harris, "On the Use of Windows for Harmonic Analysis with the Discrete Fourier Transform", *Proceedings of the IEEE*, Vol. 66, No. 1, pp. 51–83, January 1978.

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[4] R. G. Lyons, *Understanding Digital Signal Processing*, Pearson Education, 2011.

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CONCLUDING MATERIAL

Custodians:
Army – AV
Navy – SH

Preparing activity:
Navy – SH
(Project 1990-2017-003)

Review activity:
Navy – AS

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