

Handbook to IEEE Standard 45TM :

A Guide to Electrical Installations on Shipboard

Mohammed M. Islam



Published by
Standards Information Network
IEEE Press



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3 Park Avenue, New York, NY 10016-5997, USA

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Acknowledgement

This Handbook maintains the format of IEEE Std 45™-2002 for easy reference and understanding. It also provides the necessary background to justify the recommendations and provides simple formulae, tables, and diagrams for understanding recommended design features.

This Handbook is a collection of many years of shipbuilding design development experience, as well as the experience of the IEEE Std 45 developmental process. The author wishes to thank all the individuals who have encouraged him and contributed in the preparation of this Handbook. The author also wishes to thank all IEEE Std 45 Working Group members for sharing their technical know-how and expertise over the years, as well as the technical experts in this field whose works may have been quoted in this Handbook.

Special thanks to Joe English, Director of Northrop Grumman Ship Systems, Electrical Engineering, for his encouragement in writing this Handbook.

Special thanks to fellow engineers who have advised and clarified many technical issues over the years.

Dedicated to my parents.

- Moni Islam, July 2004

Author

Mohammed M. (Moni) Islam is R&D Supervisor of Applied Science at Northrop Grumman Ship Systems. He has thirty- four years of diversified shipboard electrical engineering experience and has played significant roles in every part of new shipbuilding and ship modernization engineering. Mr. Islam also currently serves as the IEEE-45 central committee Vice-Chair and is a member of IEEE-1580 working group. He has been involved in the “All Electric Ship” R&D programs for many years and was the principal investigator of the Ship Smart-System Design (S3D) feasibility study, an ONR funded research and development project. He received his Bachelor of Marine Engineering Technology from the Merchant Marine Academy of Bangladesh in 1969, and Bachelor of Electrical Engineering Degree with Honors from the State University of New York, Fort Schuyler Maritime College, in 1975.



Preface

IEEE Std 45™-2002 is a recommended practice for electrical installations on shipboard. The standard is neither a regulatory body requirement nor the rules for building ships. It provides vital guidelines for the safe operation of electrical equipment, for the safe operation of the ship, and for the safety of shipboard personnel. These guidelines emphasize safety and security of electrical and electronic equipment installation, equipment selection, and system coordination. The responsibility for implementing these recommendations belongs to everyone dealing with the shipboard electrical equipment and electrical system, such as the electrical engineers, the electrical designers, the electrical cable pullers, the electrical equipment installers, the shipboard equipment and system testers, and the troubleshooters.

At any voltage level, electricity can be deadly. Traditionally, shipboard electrical voltage ratings have been 12 V, 24 V, 110 V, and 460 V for grounded and ungrounded installations. Until recently, the 460 V level was high for shipboard installation. In recent years the voltage level has risen to 4100 V, 6600 V, 11 000 V, and 13 800 V. The power requirement has increased from a few megawatts to hundreds of megawatts. Power generation and distribution at different voltages and at hundreds of megawatts have become a big challenge. The IEEE Std 45 recommendations are a supplement to American Bureau of Shipping (ABS) rules and United States Coast Guard (USCG) regulations for commercial ships. The advent and proliferation of information technology has made available enormous amounts of technical information related to shipbuilding innovations, rules, regulations, and standards. This access has impacted the endeavor to standardize international rules and regulations surrounding shipbuilding. Information technology has helped tremendously to make necessary information available at the click of a mouse. The responsibility of gaining knowledge of available shipbuilding rules, regulations, and recommendations around the globe and adapting the most appropriate ones must be done at a very fast pace. The adaptation of the very process of technical innovation is also a universal challenge of building a bridge from present to future shipbuilding in order to meet tomorrow's demand.

The concept of IEEE Std 45 arose with the same objective as the National Electric Code® (NEC®). Acceptable standards are needed because no two persons will view something in the same way, interpret it in the same way, and implement it in the same way. These standards are critical in applying technology, which is a time domain domino scenario by the very nature of innovation. As we build for the future, we have to live with the present. We must write down the most probabilistic aspect of an idea and agree to follow it. The accepted norm of today may not be the norm of tomorrow; however, it is appropriate for today because it works to an accepted level and meets safety requirements of shipboard installation.

IEEE Std 45 has been accepted as the recommended practice, not only in the United States, but also globally. It was revised and published in October 2002. Many industry experts have contributed many years of experience in the shipboard electrical engineering field. This task, however, has been presented with a significant challenge due to global cooperation initiative, namely harmonization and globalization. IEEE Std 45-2002 is in compliance with the NEC, the standards developed by the National Electrical Manufacturers' Association (NEMA), the Underwriters Laboratory (UL), and the American Association of Testing and Material (ASTM), as well as ABS Rules, the Code of Federal Regulations (CFR) of the United States Department of Transportation, and various military specifications. The very process of equipment specification, manufacturing, installation, and testing has attained solid ground by the repeated revision of existing standards and the addition of new ones. International Electrotechnical Commission (IEC) standards are also applicable for shipboard installation. The United States is signatory to the IEC standards through the United States National Committee of the IEC, administered by the American National Standard Institute (ANSI). IEC standards differ from US standards in numerous ways, such as

voltage levels, units of measurement, equipment rating, ambient rating, enclosure type, and equipment location classification. One must understand differences to ensure applicability and interchangeability, and to combine use of US standard equipment with IEC standard equipment. Most of the US standards committees agreed to adopt, supplement, or change US standards to comply with IEC standards. The IEEE Std 45-2002 committee has also agreed to adopt IEC standards by directly replacing, or modifying the existing standards. These changes must be clearly understood in order to ensure that the safety and security of life and equipment are not compromised.

This Handbook provides a detailed background of the changes in IEEE Std 45-2002 and the reasoning behind the changes as well as explanation and adoption of other national and international standards. This Handbook provides necessary technical details in a simplified form to enhance understanding of the requirements for technical and non-technical people in the maritime industry.

The maritime electrical industry has been experiencing tremendous changes. The “all-electric ship” and “electric propulsion” are paving the future of shipboard electrical power generation, distribution, and management from a few megawatts to hundreds of megawatts. Innovations such as electric propulsion, podded propulsion, and the Z drive present new challenges to the existing standards. By the very nature of a standard’s publication period, it is not possible to maintain pace with the changes in the shipbuilding industry.



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1 Overview

IEEE Std 45™-2002 is a standard (a set of recommendations and specifications) relating to shipboard electrical installations.

The purpose of this Handbook is to enhance understanding of that standard, describing its application to common steps in shipboard electrical design and relation to other standards, so that ship builders can design and implement a shipboard electrical system in accordance with this standard as well as the other related standards. In addition, ship owners can use this Handbook to help them understand the requirements in the 1998 edition and the changes made in the 2002 edition. Ship owners should understand the regulatory body requirements, such as from the American Bureau of Shipping (ABS), United States Coast Guard (USCG), Det Norske Veritas (DNV), and IEEE Std 45, to prepare better outline specifications that will guide the ship designers. The ship design engineers need to understand the requirements and the changes to the 1998 edition of IEEE Std 45 to design shipboard electrical systems. A ship's electrical power generation has increased to hundreds of megawatts demanding voltage requirements from 460 V to 4160 V, 6600 V, 11 000 V, 13 800 V, 25 000 V, and 35 000 V. This Handbook addresses these changes by providing additional explanation and necessary information. The ship builder needs to understand the changes so that appropriate measures can be taken to build ships in compliance with these recommendations and requirements. Ship crews must also understand these requirements and get proper training to operate shipboard systems.

IEEE Std 45-2002 has made tremendous strides in adapting international standardization guidelines such as the incorporation of SI units, detailed review of the NEMA enclosure and IEC type IP enclosure, and mixing and matching of US standard equipment and IEC standard equipment. This Handbook explains those changes for better understanding of the recommendations.

1.1 Scope

The scope of the Handbook for IEEE Std 45-2002 is to explain the IEEE Std 45 recommendations in line with regulatory body requirements and explain major changes in IEEE Std 45-2002. In this Handbook, the recommendations are further amplified with explanations, simple drawings, and examples. In addition, this Handbook describes related standards and requirements that come into play during the real-world design of shipboard electrical systems; the interaction between IEEE, ABS and governmental standards is addressed in detail.

1.2 Disclaimer

IEEE Std 45-2002 is the recommended practice for shipboard electrical installation. IEEE 45 was prepared by a voluntary consensus body to provide assistance and guidance to the requirements of national and international regulatory agencies governing electrical engineering requirements for shipboard installation. This Handbook is an effort to assist in understanding those recommendations. If there is any conflict with the recommendations of IEEE Std 45™-1983, IEEE Std 45™-1998, or IEEE Std 45-2002, the recommendations of IEEE Std 45-2002 will prevail. If there is any conflict with regulatory body requirements, regulatory body requirements will apply.

1.3 History of IEEE Std 45

IEEE Std 45 dates back to 1920 and has traditionally been a standard for the construction of commercial ships. In recent history, the commercial shipbuilding industry in the United States has experienced a decline; at the same time, however, we have seen a resurgence of military shipbuilding. The military are increasingly looking for Commercial Off the Shelf (COTS) componentry in order to reduce their costs. At the same time, their standards remain very high. Accordingly, standards such as IEEE Std 45 are seeing increasing use in the military shipbuilding arena.

IEEE Std 45 editions were issued in 1920, 1927, 1930, 1938, 1940, 1945, 1948, 1951, 1955, 1958, 1962, 1967, 1971, 1977, 1983, 1998, and 2002.

The first sponsor of IEEE Std 45 was the Marine Committee (MC) of the IEEE Industry Application Society (IAS), which subsequently became the Marine Transportation Committee (MTC). This sponsorship continued until the 2002 revision, when the International Marine Industry Committee (IMIC) of the IEEE Industry Application Society (IAS) became the sponsor.

In 2003, the IEEE 45 sponsor was changed from the International Marine Industry Committee (IMIC) of the IEEE Industry Application Society (IAS) to the Petroleum and Chemical Industrial Committee (PCIC) of the IEEE Industry Application Society (IAS).

1.4 Overall approach of this Handbook

This book takes a *task*-based approach to the subject matter of IEEE Std 45. The task is the design of a shipboard electrical system. Each chapter addresses a component of that design process in a logical, step-by-step fashion. IEEE Std 45-2002 addresses many of these steps, while some other steps are addressed only slightly. The designer of electrical systems must be familiar with many standards, of which IEEE Std 45 is but one. This Handbook therefore touches on many of the standards beyond IEEE Std 45, to provide a complete handbook reference to shipboard electrical systems.

Commercial ship design and development is done in numerous multi-disciplined phases such as Hull, Machinery, and Electrical (HM&E). This allows understanding of the performance requirements and operational needs of the ship, which constitutes baseline requirements for the design solution. We will address electrical design development issues here in support of IEEE Std 45. The development phases are: Concept Studies, System Definition, Preliminary Design, Detail Design, Equipment Procurement, Equipment Installation, and testing. Each phase is briefly summarized below.

- a. **Concept study** – The initial detailed operational concept; for instance, cruise ship for transatlantic voyage, million-barrel tanker for Alaskan Crude Oil, direct diesel drive or electric propulsion drive. Based on the initial concept, the requirements of the electrical system are explored.
 - For direct drive ship, the electrical requirement usually is to support ship service power generation and distribution. The ship service power generation usually consists of multiple ship service generators for redundancy requirement and emergency generator for electrical blackout prevention. The emergency generator usually get automatically started under zero voltage detection in the switchboard and automatically takes over the emergency loads, such as fire pump, emergency lighting, navigation equipment.
 - For electric drive ship, the electrical requirement is to support ship's propulsion power in addition to ship service and emergency power requirement the electrical power generation and distribution can be ten to twenty times the electrical power requirement of non-electric drive ship. The high power requirement often demands a higher voltage requirement. The duty profile of the propulsion drive motors is different from other ship service motors due to the propulsion duty requirement.
 - The ship service power generation and distribution usually is 460 V, the electric propulsion drive power generation and distribution can be 6600 V or higher.
 - The distribution switchboards are medium voltage switchboard, 450 V switchboard and 120 V switchboard and panel boards.
- b. **System definition**– The system definition usually provides the system requirement to support the performance requirement such as the tanker propulsion will be diesel driven and the cargo pumps will be electric driven or hydraulically driven to support the unloading requirement. Another requirement might be the propulsion and cargo pumps will be electric driven. These are the baseline requirement usually established by the ship owner.
- c. **Preliminary design**—Concept study and system definition lead to the preliminary design phase. The preliminary design is performed to support the baseline requirement of the ship. Preliminary electrical one-line diagram and electrical load analysis are performed showing number and ratings of generators, such as ship service generators, propulsion generators, and emergency generator, as applicable. The preliminary design is performed in compliance with established rules and regulations such American Bureau of Shipping (ABS), United States Coast Guard, IEEE Std 45, Lloyd's, DNV etc. as applicable. The preliminary design provides information supporting redundancy requirements as well as emergency requirements.
- d. **Detailed design**—The detailed design phase is usually after the contract award. In this phase every system development is required for equipment procurement, ship construction drawings, equipment installation and testing. The following systems comprise an electrical system ship construction drawing development:
 - Electrical power system calculations, such as electrical one-line diagram, load analysis, voltage drop calculation, fault current calculation, power system deck plans
 - Electrical wire ways development
 - Lighting system – ship service and emergency
 - Internal communications
 - External communications
 - Centralized control system

These detailed drawings are used to procure equipment, make foundations, and install equipment

- e. **Testing**—On completion of equipment installation, appropriate service to the equipment is provided as preparation of equipment testing and system testing. The testing is performed in two phases, dockside testing and at sea testing. Completion of at sea testing is prerequisite for the delivery of ship.



Traditionally, shipboard electric system design is supported by numerous electrical system network analyses in accordance with applicable regulatory body requirements. These electrical system analyses are namely electrical system load analysis, voltage drop calculations, electrical load flow calculations, electrical short-circuit analysis, and circuit breaker coordination and selectivity study.

The advent of all-electric ships and advances in components, such as the development of high-efficiency, power-dense, lightweight motors, transformers, drives, and other devices require careful and, in many cases, entirely unique integration into the ship system design and development. These imperatives motivate the use of tools for the system wide analysis of shipboard electric power systems. In order to perform these analyses, digital simulation of electrical systems is essential. To establish the physical laws governing power-system components and their interactions data are collected in large numbers and analyzed to predict the behavior of a system. Digital modeling and simulation are fast, accurate, and convenient approaches for predicting power-system behavior.

The new technology of electric-driven propulsion power systems requires additional system analyses such as power system dynamic analysis, harmonic analysis, network transient analysis, electric motor drive performance analysis, and extensive modeling simulation of power generation and distribution. These analyses are usually done by the use of computer-aided engineering and design tools.

Some of the most crucial elements of shipboard electrical system design are outlined below, along with their place in this Handbook.

1.4.1 Electrical load flow calculations (Handbook, Section 6)

The aim of the load flow calculations is to determine whether the thermal and mechanical stresses on equipment are below the maximum design values. Load flow calculations are performed to find steady-state values of loads in the generation and distribution network. They are normally done prior to the short-circuit calculations in order to obtain the steady-state power requirement of the system.

1.4.2 Voltage deviation calculations—steady state and transient (Handbook, Section 7)

The steady state voltage deviation requirement is +5% -6% to -10% for 460 V and around 3% for 120 V distribution. Refer to Section 7 for details.

When starting heavy ship service consumers such as motors or energizing large transformers, the startup transient current may be several times larger than the nominal full load current. For a motor typical transient load 5 to 8 times the full load current, and for a transformer, up to 10 to 12 times the full load current. The high startup current will give a voltage disturbance, or voltage drop in the network. The regulatory requirement is to limit the voltage transient at the range of -15% and +20%. There are analytical methods for calculating such voltage transients as well as the steady state voltage drops, although the most accurate result is found by numerical simulations. In order not to exceed the required voltage variations, there may be a need to adjust the characteristics of the generator or the large consumers, or to introduce a means to reduce the startup transients. For motors, such means could be soft-starting, star-delta starters, or autotransformer starters or solid-state adjustable speed drive. For transformers starting transient pre-magnetizing could be evaluated or the incoming circuit breaker must be selected as such the breaker is capable of sustaining the transformer magnetizing period.

1.4.2.1 Network transient analysis—modeling and simulations

In addition to the fault calculations and voltage drop calculations, there is a need for thorough analysis of the transient behavior of the network during and after clearing a fault. Typically, such analysis includes voltage and frequency stability (i.e., will the voltage and frequency of the generators be reestablished after the fault is cleared?) and re-acceleration of motor loads (i.e., will essential motors be able to accelerate without tripping after the fault is cleared?). Such analyses are extensive and require accurate modeling of the network and regulators for voltage and frequency in order to be reliable.

1.4.3 Harmonic distortion (Handbook, Section 4.2)

The harmonic distortion calculation and harmonic management are significant for power electronic driven starting and control systems such as ship service auxiliary motors, and variable frequency driven electric propulsion systems.

Power electronic driven systems such as frequency converters are inherently nonlinear, and the currents to the drive are not sinusoidal but distorted by harmonic components. Assuming that the converter and transformer are symmetrically designed and the output stage of the converter is de-coupled from rectifier current, only the characteristic harmonic components are present in the input currents to the line supply of the frequency converter. For a six-pulse converter drive, these harmonics are

Harmonics (H)th order = $6 \times (n \pm 1)$ where n is integer such as 1, 2, 3, 4, 5....

H = 5th, 7th, 11th, 13th,

In a 12-pulse converter, multiples of sixth harmonics, which are present in the secondary and tertiary windings of the feeding transformer, will cancel in the primary windings. Hence the remaining harmonic current components will be of the order

Harmonics (H)th order = $12 \times (n \pm 1)$ where n is integer such as 1, 2, 3, 4, 5....

$H = 11^{\text{th}}, 13^{\text{th}}, 23^{\text{rd}}, 25^{\text{th}}, \dots$

The total harmonic distortion (THD) is a measure of the total content of harmonic components in a measured current, THD(i), or voltage, THD(v):

$$THD(i) = 100\% \times \frac{\sqrt{\sum_{h=2}^{\infty} i_{(h)}^2}}{i_{(1)}}, \text{ and } THD(v) = 100\% \times \frac{\sqrt{\sum_{h=2}^{\infty} v_{(h)}^2}}{v_{(1)}}$$

1.5 Cross references to other standards

There are many standards related to shipbuilding. IEEE Std 45-2002 is but one of them, and the ship designer must take all of them into account to varying degrees. Accordingly, a major focus of this Handbook is to provide extensive cross-references between IEEE standards and other shipbuilding standards, such as IEC, ABS, USCG, DVN, NEMA, and ANSI.

The sections in this Handbook have been arranged for better understanding of intersystem and intrasystem functionality of shipboard electrical systems, particularly the power generation, distribution, controls, and communications. The reader may be familiar with IEEE Std 45-1998; a cross reference from that standard to the 2002 standard is supplied in Appendix H. Additional details of the changes are provided in appropriate sections in this Handbook. Note that Clause 8 in IEEE Std 45-1998 cable manufacturing was removed from IEEE Std 45-2002 and published in a stand-alone standard, IEEE Std 1580™-2001.

Other relevant standards include the Ship Work Breakdown Sequence (SWBS), promulgated by the US Coast Guard (USCG) and the American Bureau of Shipping (ABS) rules.

1.5.1 Ship Work Breakdown Sequence (SWBS)

The United States Navy uses unique system sequence numbers called ship work breakdown sequence (SWBS). SWBS provides a structured sequence number for shipboard system and sub-system, such as SWBS 304 for electric cables. Refer to the United States Navy, General Specifications for Ships, 1995 edition for shipboard SWBS numbers. The SWBS numbers are sometimes used in commercial shipbuilding as well. The SWBS numbering for electrical engineering sub-systems is provided in Appendix H.

1.5.2 American Bureau of Shipping (ABS)

ABS rules are quoted in this Handbook as have been quoted in the IEEE Std 45. The ABS rules are published in multiple parts: Part 4 is for machinery. In part 4, chapter 8 is for electrical and chapter 9 is for automation.

Part 4, Chapter 8 for electrical system is organized as follows:

- 4-8-1 Electrical System – General
- 4-8-2 System Design
- 4-8-3 Electrical equipment
- 4-8-4 Shipboard installation and test
- 4-8-5 Special Systems

Each group again subdivides by paragraph numbers and subdivisions.

Part 4, Chapter 9 for Remote Propulsion Control and Automation, which is organized as follows:

- 4-9-1 General Provisions
- 4-9-2 Remote Propulsion Control
- 4-9-3 ACC Notation
- 4-9-4 ACCU Notation
- 4-9-5 Installation, Test and Trials
- 4-9-6 Computerized System
- 4-9-7 Equipment

Paragraph numbers and subdivisions further subdivide each group. ABS adapted this numbering system from their 2000 publication.

1.5.3 Safety of Life At Sea (SOLAS)

The International Convention for the Safety of Life at Sea (SOLAS) was adopted on November 1974 by the International Conference on Safety of Life at Sea, convened by the International Maritime Organization (IMO). SOLAS Regulation Part 1 contains eleven chapters:

Chapter I	General Provisions
Chapter II-1	Construction-Subdivision, machinery and electrical installations
Chapter II-2	Construction – Fire protection, fire detection, and fire extinction
Chapter III	Life-saving appliances and arrangements
Chapter IV	Radiocommunications
Chapter V	Safety of Navigations
Chapter VI	Carriage of cargo
Chapter VII	Carriage of dangerous goods
Chapter VIII	Nuclear ships
Chapter IX	Management for safe operation of ships
Chapter X	Safety measure for High Speed craft
Chapter XI	Special measure for maritime safety

1.5.4 Shipboard electrical equipment construction, testing and certification

Marine electrical equipment should be constructed, tested and certified in accordance with the requirements of applicable standards. The equipment testing, certification and labeling should be done by third party with authority having jurisdiction in the field. For an example, the NEMA switchboard for marine application should have UL labeling. However for UL certification, the busbar and the circuit breakers are individually tested and labeled. The shipboard generator should be tested in accordance with applicable NEMA requirements; ABS will go through the testing process, and witness the test and label the generator as compliant with the testing requirements. (For details refer to IEEE Std 45-2002, 1.6 and 1.7)

For ABS class ships, ABS requirements must be met. For ACP (Alternate Compliance Program, promulgated by ABS and USCG together) class ships, both ABS requirements and ACP requirements must be met. IEEE 45 provides recommendations in addition to regulatory body rules and regulations, which are supplemental recommendations for consideration of better operation, performance, etc.

1.6 Notes on the text in this Handbook

The Sections in this Handbook do not follow the sections in IEEE Std 45-2002 one-for-one. Rather, this book takes a *task-based* approach—the task being the design of a shipboard electrical system from the ground up. In each section, the general goal of the task is first described, and then the recommendations of IEEE Std 45-2002 are described. Interactions with other standards such as ABS and SWBS are also described.

The sections will refer to the relevant section of IEEE Std 45-2002 for further detail. In addition, the relevant SWBS and ABS numbers are also called out in the section headers.

This Handbook refers to the IEEE and other standards in varying ways—by quoting, paraphrasing or simply describing. In order to be clear about when we are quoting directly and when we are paraphrasing, the following conventions have been adopted to inform you of whether the Handbook is directly quoting, paraphrasing, or summarizing other standards.

- a. A border with a **solid line** around the text indicates quoted material. Appropriate reference information is provided acknowledging the source of the quotation.
- b. A border with a **dotted line** around the text indicating extract only of quoted material. The extract text may have some changes to simplify the reference material and/or to limit the quoted text space. Appropriate references information is provided, acknowledging source of the quotation.
- c. A border with a **wiggly line** around the text indicates that the encased is extract from quoted material, however may not be the exact quotation. Appropriate reference number may not be shown, as the material may not match the quotation. This is to indicate that the material source is a quotation.

Finally, some sections in this book (particularly the latter sections) describe standards and requirements that are not part of IEEE Std 45-2002. This is done in the interest of completeness. Many of these areas are addressed only scantily by IEEE Std 45 because they have been adequately described by other regulatory bodies. Nevertheless, the task of shipboard electrical design requires a good understanding of these areas, and so they have been included in this Handbook.

Section 2: Ship service and propulsion generator

2 Ship service and propulsion generator (SWBS 235)

2.1 General

The ship service power is generated by ship service generators, propulsion generators, emergency generators, and uninterruptible power sources. This section is dedicated to the ship service generator and propulsion generator. In case of a prime mover-driven propulsion system, the ship service electric power is generated by ship service generators. In case of an electrical propulsion system, ship's electrical propulsion power as well as ship service are generated by the propulsion generator, often supplemented by a smaller ship service generator. The regulatory body requirement is to provide redundant generators, ensuring availability of electrical power under all operating conditions. It is also a requirement to run the generators under the most fuel-efficient condition. The shipboard electrical loading scenarios typically are: at shore, at anchor, maneuvering, cruising and other specific service-related loading. The generator prime movers must be provided with the required starting system, governor system and loading characteristics, ensuring compatibility of the intended service. Number of generators and their ratings are to be properly calculated so that the electrical power generation is sufficient for all operating conditions of the ship. In order to ensure proper control and monitoring of these generators, IEEE Std 45 recommends a number of instruments in the switchboard as a minimum requirement. The propulsion generator ratings are usually much higher than ship service generators, as these generators are required to provide power to ship service loads as well as propulsion loads.

2.1.1 IEEE Std 45-2002 Standard Voltages

Per table 3 of the IEEE standard, the following voltages are recognized as standard.

IEEE Std 45-2002 Table 3—Standard voltages

Standard	AC(V)	DC(V)
Power utilization	115-200-220-230-350- 440-460-575-660-2300-3150-4000-6000- 10600-13200	115 and 230
Power generation	120-208-230-240-380- 450-480-600-690-2400-3300-4160-6600- 11000-13800	120 and 240

The typical usage and frequencies associated with these voltages are briefly summarized in Table 3 below.

AC voltage generation 60 Hz and 50 Hz (V)	AC voltage distribution 60 Hz and 50 Hz (V)	Remarks
120	115	Mostly US applications
208	200	
230	220	Mostly IEC application and some US commercial applications
240	230	
380	350	
400	380	50 Hz
450	440	Mostly military applications
480	460	Mostly commercial applications
600	575	
690	660	Mostly IEC applications
2400	2300	50 Hz
3300	3150	60 Hz and 50 Hz

AC voltage generation 60 Hz and 50 Hz (V)	AC voltage distribution 60 Hz and 50 Hz (V)	Remarks
4160	4000	60 Hz and 50 Hz
6600	6000	50 Hz
11 000	10 600	60 Hz and 50 Hz
13 800	13 200	60 Hz and 50 Hz

Table 2-1: US and IEC Shipboard Power Generation and Distribution Levels at 50 Hz and 60 Hz

2.1.2 Generators

Modern shipbuilding, both military and commercial, employs mostly AC power generation and AC distribution. The generators are synchronous machines, with a magnetizing winding on the rotor carrying a DC current, and a three-phase stator winding where the magnetic field from the rotor current induces a three-phase sinusoidal voltage when the rotor is rotated by the prime mover. The frequency f [Hz] of the induced voltages is proportional to the rotational speed n [RPM] and the pole number p in the synchronous machine:

$$f = \frac{p}{2} \cdot \frac{n}{60}$$

For 60 Hz systems a two-pole generator gives 3600 rpm, a four-pole at 1800 rpm, and a six-pole at 1200 rpm, etc (US standard application). For 50 Hz IEC applications, 3000 rpm, 1500 rpm, 1000 rpm for two-, four-, and six-pole machines. A large medium speed engine normally considered at 514 rpm, 14 poles and 720 rpm at 10 pole for 60 Hz network or for 50 Hz system 600 rpm, 10 poles or 750 rpm, 8 pole.

In synchronous generator design, the DC current is transferred to the magnetizing windings on the rotor by brushes and slip-rings. The new generators are equipped with a brushless excitation system. The brushless exciter generator is a synchronous machine with DC magnetization of the stator and rotating three-phase windings and a rotating diode rectifier. Figure 2-1 shows typical exciters schematics.

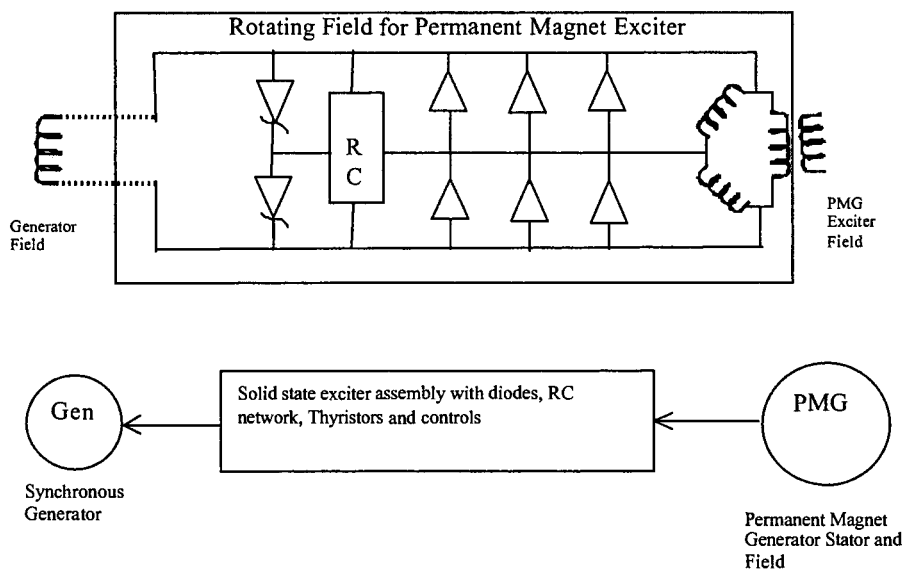


Figure 2-1: Typical Brushless Permanent Magnet Generator (PMG) Exciter for Synchronous Generator (Example Only)

The brushless exciter is typically mounted on the generator rotor shaft. The solid state consists of rotating diodes, thyristors and RC snubber circuit. The permanent magnet generator (PMG) produces the excitation current for the generator. The synchronous generator excitation is controlled by an automatic voltage regulator (AVR) system, which senses the terminal voltage of the generator and compares it with a reference value. According to most applicable regulations, the stationary voltage variation on the generator terminals should not exceed $\pm 2.5\%$ of nominal voltage. For electrical generation system stability, transient load variation should exceed the voltage variation of

–15% to +20% of the nominal voltage. In order to maintain the transient voltage requirement, the AVR is normally also equipped with a feed-forward control function based on measuring the stator current.

In addition to the magnetizing winding, the synchronous generator rotor is also equipped with a damper winding which consists of axial copper bars threaded through the outer periphery of the rotor poles, and short circuited by a copper ring in both ends. The main purpose of the damper winding is to introduce an electromagnetic damping to the stator and rotor dynamics. A synchronous machine without damper winding is inherently without damping and would give large oscillations in frequency and load sharing for any variation in the load.

The determination of power rating for generators and prime movers requires careful calculation and analysis. The regulatory body requirement is to prepare comprehensive electrical load analysis for each electrical power consuming load such as propulsion, propulsion auxiliaries, ship service auxiliaries, heating ventilation and air-conditioning (HVAC), normal lighting, emergency lighting on board ship, and the load classification such as emergency service, vital service, non-vital service etc.

2.2 IEEE Std 45-2002, ABS-2002 and IEC for generator size and rating selection

Ship service generator size, rating and quantity requirements are very well defined in IEEE Std 45, ABS and USCG with some slight differences. IEEE Std 45 requirements are in Section 7, ABS-2002 requirements are in part 4, Chapter 8, Section 3, and USCG requirements are in 46 CFR, Regulations subparts 111-10 and 111-12. The propulsion generator size, rating, and quantity requirements are somewhat different from ship service generators. It is very important to understand the operational requirements prior to adapting a set of rules. Due to the size of the propulsion generator the quantity of generators and redundancy requirement may be different from small size ship service generators. The propulsion generator requirements are given in IEEE Std 45, Section 31. The most relevant generator size, rating, and quantity requirements are quoted below.

2.2.1 IEEE Std 45-2002, 7.4.2, Selection and sizing of generators (extract)

In determining the number and capacities of generating sets to be provided for a vessel, careful consideration should be given to the normal and maximum load demand (i.e., load analysis) as well as for the safe and efficient operation of the vessel when at sea and at port. The vessel must have at least two generating sources. For ships, the number and rating of the main generating sets should be sufficient to provide one spare generating set (one set not in operation) at all times to service the essential and habitable loads. For MODUs, with the largest generator off-line, the combined capacity of the remaining generators must be sufficient to provide normal (non-drilling) load demands.

In selecting the capacity of an AC generating plant, particular attention should be given to the starting current of AC motors supplied by the system. With one generator held in reserve and with the remaining generator set(s) carrying the minimum load necessary for the safe operation of the ship, the voltage dip resulting from the starting current of the largest motor on the system should not cause any motor already running to stall or control equipment to drop out. It is recommended that this analysis be performed when total horsepower of the motor capable of being started simultaneously exceeds 20% of the generator nameplate kVA rating. The generator prime-mover rating may also need to be increased to be able to accelerate motor(s) to rated speed. Techniques such as soft starting (i.e., reduced voltage autotransformer starters, electronic soft starters, and variable frequency drives) may be utilized to reduce the required capacity of generators when motor starting is of concern.

Note: For SOLAS (Safety Of Life At Sea) requirement refer to SOLAS Chapter II-1, Regulation 41

2.2.2 IEEE Std 45-2002, 31.3.1, General (electric propulsion prime movers) (extract)

The design of an integrated electric power system should consider the power required to support ship service loads and propulsion loads under a variety of operating conditions, with optimum usage of the installed and running generator sets.

In order to prevent excessive torsional stresses and vibrations, careful consideration should be given to coordination of the mass constants, elasticity constants, and electrical characteristics of the system. The entire system includes prime movers, generators, converters, exciters, motors, foundations, slip-couplings, gearing, shafting, and propellers....

Systems having two or more propulsion generators, two or more propulsion drives, or two or more motors on one propeller shaft should be so arranged that any unit may be taken out of service and disconnected electrically, without affecting the other unit.

2.2.3 IEEE Std 45-2002, 31.4, Prime movers for integrated power and propulsion plants

Prime movers, such as diesel engines, gas turbines, or steam turbines, for the generators in integrated electric power systems shall be capable of starting under dead ship conditions [see dead ship definition by ABS below] in accordance with requirements of the authority having jurisdiction. Where the speed control of the propeller requires speed variation of the prime mover, the governor should be provided with means for local manual control as well as for remote control.

The prime mover rated power, in conjunction with its overload and the large block load acceptance capabilities, should be adequate to supply the power needed during transitional changes in operating conditions of the electrical equipment due to maneuvering, sea, and weather conditions. Special attention should be paid to the correct application of diesel engines equipped with exhaust gas-driven turbochargers to ensure that sudden load application does not result in a momentary speed reduction in excess of limits specified in Table 4 [see 4.3.2 in this Handbook].

When maneuvering from full propeller speed ahead to full propeller speed astern with the ship making full way ahead, the prime mover should be capable of absorbing a proportion of the regenerated power without tripping from over-speed when the propulsion converter is of a regenerative type. Determination of the regenerated power capability of the prime mover should be coordinated with the propulsion drive system. The setting of the over-speed trip device should automatically shut down the unit when the speed exceeds the designed maximum service speed by more than 15%. The amount of the regenerated power to be absorbed should be agreed to by the electrical and mechanical machinery manufacturers to prevent over-speeding.

Electronic governors controlling the speed of a propulsion unit should have a backup mechanical fly-ball governor actuator. The mechanical governor should automatically assume control of the engine in the event of electronic governor failure. Alternatively, consideration would be given to a system, in which the electronic governors would have two power supplies, one of which should be a battery. Upon failure of the normal supply, the governor should be automatically transferred to the alternative battery power supply. An audible and visual alarm should be provided in the main machinery control area to indicate that the governor has transferred to the battery supply. The alternative battery supply should be arranged for trickle charge to ensure that the battery is always in a fully charged state. An audible and visual alarm should be provided to indicate the loss of power to the trickle charging circuit. Each governor should be protected separately so that a failure in one governor will not cause failure in other governors. The normal electronic governor power supply should be derived from the generator output power or the excitation permanent magnet alternator. The prime mover should also have a separate over-speed device to prevent runaway upon governor failure.

2.2.4 ABS-2002 Section 4-8-2-3.1.3 Generator Engine Starting from Dead Ship Condition (extract)

Dead ship (blackout) condition is the condition under which the main propulsion plant, boiler and auxiliaries are not in operation due to the unavailability of power from the main power source. See ABS 4-8-2-4-1-1/7.7. In restoring the propulsion, no stored energy for starting the propulsion plant, the main source of electrical power and other essential auxiliaries is to be assumed available. It is assumed that means are available to start the emergency generator at all times. The emergency source of electrical power may be used to restore the propulsion, provided its capacity either alone or combined with other source of electrical power is sufficient to provide at the same time those services required to be supplied by ABS 4-8-2/5.5.1 to 4-8-2/5.5.8.

The emergency generator and other means needed to restore the propulsion are to have a capacity such that the necessary propulsion starting energy is available within 30 min of dead ship (blackout) condition as defined above. Emergency generator stored starting energy is not to be directly used for starting the propulsion plant, the main source of electrical power and/or other essential auxiliaries (emergency generator excluded). For steam ships, the 30 min time limit is to be taken as the time from dead ship (blackout) condition to light-off of the first boiler.

Note: For SOLAS requirement refer to SOLAS Chapter II-1, Regulation 42.3.4 and 43.3.4

2.2.5 IEEE Std 45-2002, 7.3.4, Governors (Propulsion and Ship Service Generator Engines)

The prime-mover governor performance is critical to satisfactory electric power generation in terms of constant frequency, response to load changes, and the ability to operate in parallel with other generators.

The steady state speed variation should not exceed 5% (e.g., 3 Hz for a 60 Hz machine) of rated speed at any load condition.

Each prime mover should be under control of a governor capable of limiting the speed, when full load is suddenly removed, to a maximum of 110% of the rated speed. It is recommended that the speed variation be limited to 5% or less of the over-speed trip setting.

The prime mover and regulating governor should also limit the momentary speed variation to the values indicated in this sub-clause. The speed should return within 1% of the final steady state speed in a maximum of 5 seconds or as set by the limits specified in Table 7 IEEE Std 45-2002.

For emergency generators, the prime mover and regulating governor shall be capable of assuming the sum total of all emergency loads upon closure to the emergency bus. The response time and speed deviation shall be within the tolerances indicated in the Table 7 IEEE Std 45-2002.

Table 7— Response time and speed deviation requirements

Load (%)	Response time (s)	Speed deviation (%)
0 to 50, 50 to 0	5.0	10
50 to 100, 100 to 50	5.0	10

Generator sets should be capable of operating successfully in parallel when defined as follows: If at any load between 50% and 100% of the sum of the rated loads on all generators, the load (kW) on the largest generator does not differ from the other by more than $\pm 15\%$ of the rated output or $+25\%$ of the rated output of any individual generator, whichever is less, from its proportionate share. The starting point for the determination of the successful load distribution requirements is to be at 75% load with each generator carrying its proportionate load.

2.2.6 IEEE Std 45-2002, 7.4.7, Voltage Regulation (Propulsion and Ship Service Generator)

At least one voltage regulator should be provided for each generator. Voltage regulation should be automatic and should function under steady state load conditions between 0% and 100% load at all power factors that can occur in normal use. Voltage regulators should be capable of maintaining the voltage within the range of 97.5% to 102.5% of the rated voltage. A means of adjustment should be provided for the voltage regulator circuit. Voltage regulators should be capable of withstanding shipboard conditions and should be designed to be unaffected by normal machinery space vibration.

Solid-state voltage regulators are recommended for high reliability, long life, fast response, and stable regulation. Regulator systems should be protected from under-frequency conditions. It is recommended that voltage regulators for machines rated in excess of 150 kW be provided with under-frequency and over-voltage sensors for protection of the voltage regulators.

Under motor starting or short-circuit conditions, the generator and voltage regulator together with the prime mover and excitation system should be capable of maintaining short-circuit current of such magnitude and duration as required to properly actuate the associated electrical protective devices. This shall be achieved with a value of not less than 300% of generator full-load current for a duration of 2 seconds, or of such additional magnitude and duration as required to properly actuate the associated protective devices.

For single-generator operation (no reactive droop compensation), the steady state voltage for any increasing or decreasing load between zero and full load at rated power factor under steady state operation should not vary at any point more than $\pm 2.5\%$ of rated generator voltage. For multiple units in parallel, a means should be provided to automatically and proportionately divide the reactive power between the units in operation.

Under transient conditions, when the generator is driven at rated speed at its rated voltage, and is subjected to a sudden change of symmetrical load within the limits of specified current and power factor, the voltage should not fall below 80% nor exceed 120% of the rated voltage. The voltage should then be restored to within $\pm 2.5\%$ of the rated voltage in not more than 1.5 s.

In the absence of precise information concerning the maximum values of the sudden loads, the following conditions should be assumed: 150% of rated current with a power factor of between 0.4 lagging and zero to be applied with the generator running at no-load, and then removed after steady state conditions have been reached.

For two or more generators with reactive droop compensation, the reactive droop compensation should be adjusted for a voltage droop of no more than 4% of rated voltage for a generator. The system performance should then be such that the average curve drawn through a plot of the steady state voltage vs. load for any increasing or decreasing load between zero and full load at rated power factor droops no more than 4% of rated voltage. No recorded point varies more than $\pm 1\%$ of rated generator voltage from the average curve.

Isochronous operation of a single generator operating alone is acceptable. However, where two or more generators are arranged to operate in parallel, it is recommended that isochronous kilowatt load sharing governors and voltage regulation with reactive differential compensation capabilities be provided. Care should be taken if operating machines in parallel to ensure that the system minimum load does not decrease and cause a reverse power condition.

If voltage regulators for two or more generators are installed in the switchboard and located in the same section, a physical barrier should be installed to isolate the regulators and their auxiliary devices.

Where power electronic devices (such as variable frequency drives, soft starters, and switching power supplies) create measurable waveform distortions (harmonics), means should be taken to avoid malfunction of the voltage regulator, e.g., by conditioning of measurement inputs by means of effective passive filters.

Power supplies and voltage sensing leads for voltage regulators should be taken from the "generator side" of the generator circuit breaker. Normally, voltage-sensing leads should not be protected by an over-current protection device. If short-circuit protection is provided for the voltage sensing leads, this short-circuit protection should be set at no less than 500% of the transformer rating or interconnecting wiring ampacity, whichever is less. It is recommended that a means be provided to disconnect the voltage regulator from its source of power.

2.3 Additional details of sizing ship service generators

Detailed electrical load analysis should be made to select the size of ship service generators. The radial electrical system generator sizing requirement is different from the ring distribution. The radial system in general consists of ship service generators and emergency

generator. The ring bus distribution system often consists of multiple generators and may not have a dedicated emergency generator. The ship service generator sizing requirement is as follows (For additional details refer to Section 6, Electrical load analysis for determination of generator rating):

- a) Ship Service Generator for radial distribution: (Refer to Figure 5-1 for typical radial bus power distribution)
 - The generator size must be equal to or bigger than the maximum steady state worst-case load requirement of the system.
 - The generator must be able to sustain the largest direct on line (DOL) motor starting load (Starting current and transient voltage dip) of the system. If the DOL starting requirement leads to bigger size generator and engine, detail calculation must be performed to replace the DOL starting system with Wye-Delta starting, with open transition or closed transition, auto-transformer starting, soft starting, or variable frequency drive. The calculation must be accompanied by trade study for service requirement, space requirement and cost impact. Always remember, the radial distribution system may not have additional generator to support the loading requirements.
 - The generator must be able to sustain the harmonic distortion effect of the system contributed by non-linear loads in the system
- b) Ship Service Generator for ring bus distribution system (Refer to Figure 5-8 for typical ring bus power distribution)
 - The ring bus distribution is usually set-up with multiple generators in the system so that generators can be connected in parallel to support steady state loading under automatic or manual power management system. In this configuration, the sizing of generators is not as complex as the radial configuration. However, in radial configuration, there is no dedicated emergency generator, where the redundant power feeder requirement can get complicated.

2.4 Engine governor characteristics

Governors for engine generator sets used in parallel operation should be of the electronic load sharing type. Such governors are specifically designed for isochronous operation at any load from zero to 100% load. These governors cause their respective prime movers or engines to share load proportional to their horsepower or kilowatt rating and as a function of direct measurement of the electrical load (in kilowatt) on a specific engine governor set. Proportional division is accomplished via feedback through a load share loop, which connects all governors to all generator sets on-line at any given time. Such governors provide the following functions:

- a) Rapid response to load changes
- b) Stable system operation
- c) Paralleling dissimilar sized engine generator sets
- d) Speed regulation of .25%

2.5 Generator voltage regulator characteristics

It is the function of the voltage regulator to control the excitation of the generator so as to maintain constant generator terminal voltage, within defined limit e.g. +6%, to -10%. Since most engine generator sets used in today's power systems are brushless type generators, relatively inexpensive solid-state voltage regulator can be furnished to provide steady state regulation of 1 to 2% under any load condition from zero to 100% load. These solid-state controls are also capable of rapid response to load changes and of boost excitation to provide current magnitude capable of achieving selective coordination with the over-current protective devices in the power system. As with the governors, voltage regulators are also available with droop characteristics. The purpose of a droop characteristic in a voltage regulator is to enable the generator to share reactive component of the load in proportion to the kilovolt ampere rating of the generator.

The amount of reactive load is also an important design factor. For example, if an engine is delivering 800 kW at .8pf, then the engine is delivering 1000 kVA. The reactive power, kilovar, equals the square root of kilovoltampere squared minus kilowatt squared. So for this example, the generator would be delivering 600 kvar reactive power. When generator sets are operating in parallel, allowing voltage to drop or droop, as the current out of the machine increases, it causes the generators to share load almost proportionately. Why "almost proportionately"? It stems from dissimilarities in current-transformer-to-full-load-rating ratio discrepancies. Because the electrical loads driven by to-days power systems require precise frequency and voltage levels, droop compensation in the voltage levels, droop compensation in the voltage control for kilovar sharing is as objectionable as speed droop is for kilowatt sharing between the engines. Modern voltage regulators for both brushless and brush-type generators are readily available and provide constant voltage from no load to full load while achieving proportionate kilovar sharing between the generators.

In most cases, the same regulator that would be used for droop compensation can also be used for cross current compensation. The only difference lies in the connections of the regulator in the power system. Cross current compensation for proportionate reactive load division (kilovar sharing) is highly desirable design feature for paralleling systems employing automatic unattended operation. The designer should also specify cross-current compensation for the voltage regulation of these systems.

2.6 Droop characteristics – generator set

When selecting engine generator sets for parallel operation, the size of the sets is determined by analyzing the voltage and frequency requirements in term of the load, transient response, stability, and droop.

Droop is a function of the difference between no-load and full-load operation. It is the percent difference in the values based on the no-load value. For instance a machine with 3% droop and a no-load frequency of 61.8 Hz, the full load frequency will be 97% of the no-load frequency of 60 Hz. The frequency droop for this set-up is therefore 1.8 Hz. Similarly, if the voltage droop is 5% on a nominal system voltage of 480 V AC, the voltage droop is 24 V AC.

However, today's engine generator sets can be furnished with relatively simple and reliable electronic governors and voltage regulators, which make these sets suitable for unattended automatic paralleling and load sharing. This is a basic key to paralleling engine generators for emergency power systems. The electronic governor provides isochronous operation, and automatic proportionate load division which make possible the automatic paralleling of dissimilar size sets. The electronic governor provides a more adaptable engine generator set because it will permit paralleling at any time without necessitating adjustment or requiring droop. Similarly, voltage regulators are available to achieve automatic reactive load division to provide constant voltage systems. These devices help to make automatic unattended emergency power paralleling system highly practical.

2.7 Typical generator prime mover set-ups

Figures 2-2, 2-3, and 2-4 show typical generator prime mover set-ups. These drawings are presented with minimum explanation and not intended to show a complete or proven design.

2.7.1 Ship service electric generator for 460 V generation and 450 V distribution (Handbook Figure 2-2)

Figure 2-2 shows the ship service power generation with two ship service diesel generators supplying power to the 450 V AC, three phase, 60 Hz ship service switchboard. Two generators are installed for redundancy consideration.

Typical Ship Service Generator Characteristics:
2000 kVA, 1600 kW, 3-Phase,
460 V,
3-phase, 0.8 Power Factor

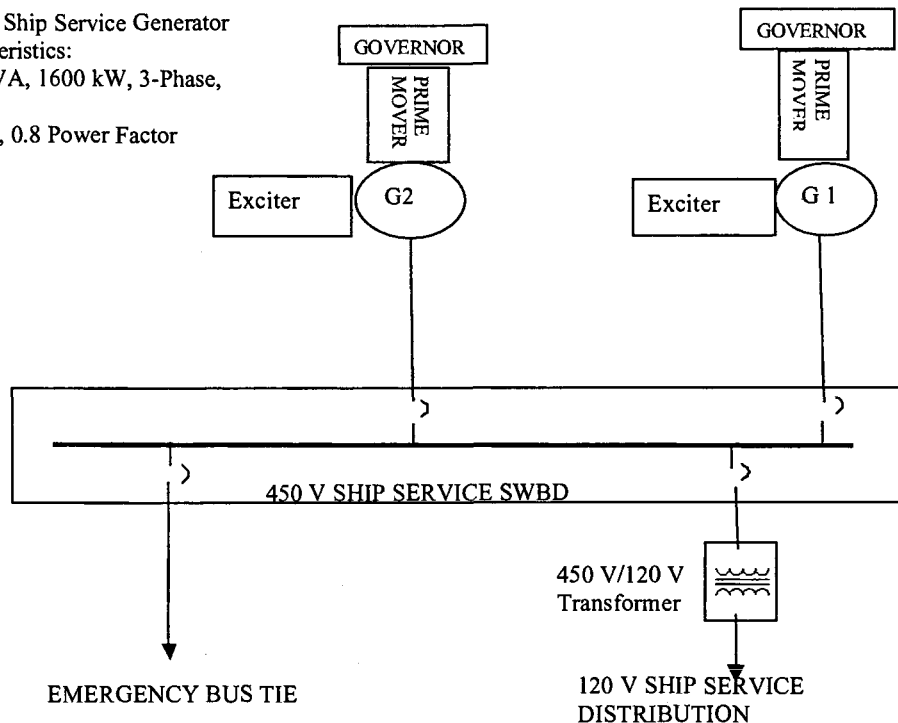


Figure 2-2: Electrical One-Line Diagram-Ship Service Electric Generator for 460 V Generation and 450 V Utilization

2.7.2 Electric propulsion system (ABS R2 redundancy)

Figure 2-3 below shows electric propulsion configuration with four prime movers, two high-voltage switchboards, two sets of propulsion motors with their drives. This configuration is in compliance with ABS R2-S notation for redundant propulsion system. In this configuration there is no requirement of physical separation by watertight and fireproof bulkhead in the machinery space, that means four engines and propulsion drives can be in the same machinery space.

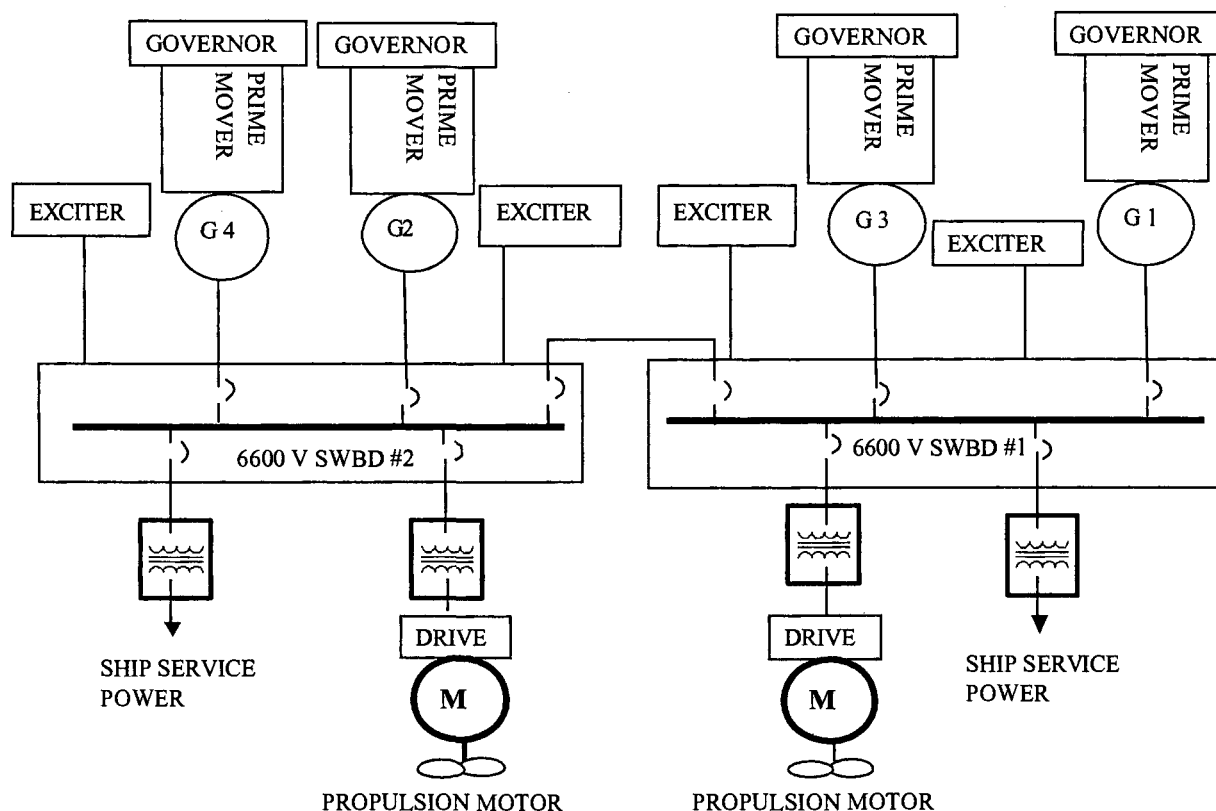


Figure 2-3: Electrical One-Line Diagram, Electrical Propulsion System (R2 Redundancy)

2.7.3 Electric propulsion system (Redundancy)

Figure 2-4 shows an electric propulsion configuration with four prime movers. Two high-voltage switchboards, two sets of propulsion motors with their drives. This configuration is an extension of Figure 2-3, with the additional requirement to meet ABS R2-S+ notation, which means there is a separation between two machinery spaces with a watertight centerline bulkhead.

Refer to Sections 14 and 21 for additional explanation for redundancy.

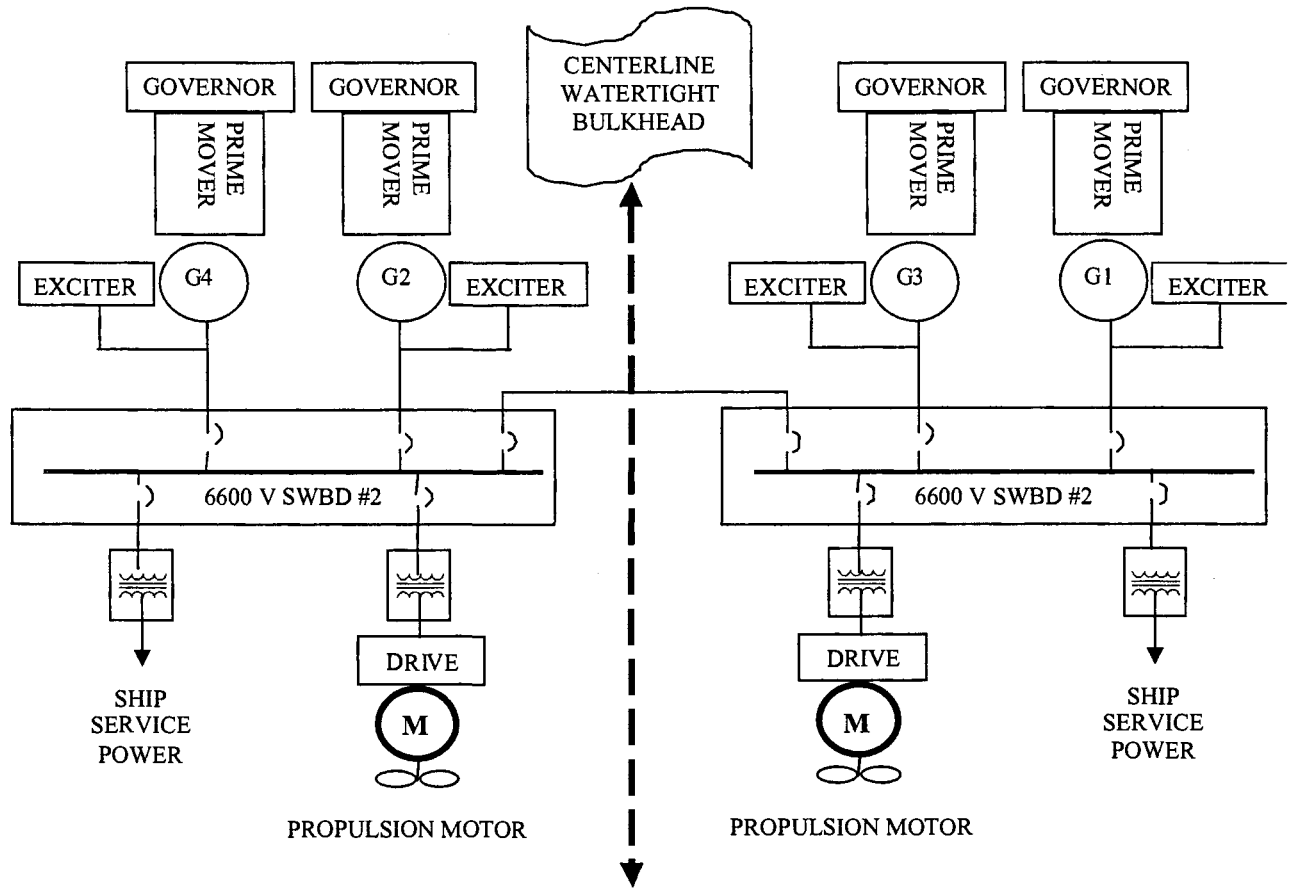


Figure 2-4: Electrical One-Line Diagram-Electrical Propulsion System (Redundancy)

Section 3: Emergency power generation and distribution—shipboard (SWBS 310)**3 Emergency power generation and distribution—shipboard (SWBS 310)****3.1 General**

The provision of emergency power generation and distribution is a requirement by the regulatory bodies so that, in a shipboard electrical black-out situation, the emergency generator starts automatically after a predetermined interval and supplies power to dedicated emergency electric loads. The location of emergency generator and associated switchboard is also predetermined so that in case of damage of the engine room by flood or fire or electrical fault, the emergency generator room is not affected. The starting system of the emergency generator is also required to have multiple starting system, making sure that the emergency generator will start in black out situation.

3.2 IEEE Std 45-2002 Recommendations

Section 6 of IEEE Std 45-2002 refers to emergency power generation. Some of the most relevant comments are extracted below.

3.2.1 IEEE Std 45-2002, 6.1, General (extract)

... Every vessel should be provided with a self-contained emergency source of electric power, generally a diesel-engine generator, gas turbine-driven generator, or storage batteries. These emergency sources of power and an emergency switchboard should be located in a space separate and remote from the main switchboard, that is above the uppermost continuous deck, aft of the collision bulkhead, outside the main machinery compartment, and readily accessible from the open deck. The emergency switchboard should be located in the same space as the emergency power source, in an adjacent space, or as close as practical....

3.2.2 IEEE Std 45-2002, 6.2, Emergency Generators (extract)

Each emergency generator should be equipped with starting devices with an energy storage capability of at least six consecutive starts. A single source of stored energy, with the capacity for six starts, should be protected to preclude depletion by the automatic starting system, or a second source of energy should be provided for an additional three starts within 30 min. If, after three attempts, the generator set has failed to start, an audible and visual start failure alarm should be activated in the main machinery space control station and on the navigation bridge. The starting sequence should be automatically locked-out until an operator can initiate the final three starting attempts from the emergency generator space.

3.2.3 IEEE Std 45-2002, 6.4, Emergency Power Distribution System (extract)

The emergency switchboard should be supplied during normal operation from the main switchboard by an interconnecting feeder. This interconnecting feeder should be protected against short-circuit and overload at the main switchboard and, where arranged for feedback, protected for short-circuit at the emergency switchboard. The interconnecting feeder should be disconnected automatically at the emergency switchboard upon failure of the main source of electrical power. Means shall be provided to prevent auto closing of the emergency generator circuit breaker should a fault occur on the emergency switchboard....

Upon interruption of normal power, the prime mover driving the emergency power source should start automatically. When the voltage of the emergency source reaches 85% to 95% of nominal value, the emergency loads should transfer automatically to the emergency power source. The transfer to emergency power should be accomplished within 45 seconds after failure of the normal power source. If the system is arranged for automatic retransfer, the return to normal supply should be accomplished when the available voltage is 85% to 95% of the nominal value and the expiration of an appropriate time delay. The emergency generator should continue to run without load until shut down either manually or automatically by use of a timing device....

The emergency switchboard should be arranged to prevent parallel operation of an emergency power source with any other source of electrical power (i.e. main power), except where suitable means are taken for safeguarding independent emergency operation under all circumstances. This will allow for the emergency generator to be used to supply non-emergency loads. This is useful when exercising and testing the emergency generator(s).



3.2.4 Emergency shipboard electrical equipment roll and pitch withstanding requirement

IEEE Std 45-2002, 1.5.1, Table-1, Roll and pitch requirements extract to show emergency shipboard equipment only

Table -1: Roll and pitch requirement [emergency equipment] (Extract only)

Equipment	Roll		Pitch	
	Static (°)	Dynamic (°)	Static (°)	Dynamic (°)
Emergency equipment	22.5	22.5	10	10

3.3 Emergency Source of Electrical Power – ABS 2002 Requirement

ABS Section 4-8-2 refers to system design and also has several requirements for emergency power generation and distribution, from which we have quoted below.

3.3.1 ABS-2002, 4-8-2, 5.1.3 – Requirements by the Governmental Authority

Attention is directed to the requirements of governmental authority of the country, whose flag the vessel flies, for emergency services and accumulator batteries required in various types of vessels.

3.3.2 ABS-2002, 4-8-2, 5.3.3 – Separation from Other Spaces

Spaces containing the emergency sources of electrical power are to be separated from spaces other than machinery space of category A by fire rated bulkheads and decks in accordance with Part 3, Chapter 4 of ABS Rules or Chapter II-2 of SOLAS.

3.4 SOLAS (Safety of Life at Sea) Requirements

The SOLAS convention also sets requirements for emergency power generation and distribution, from which we have quoted.

3.4.1 Bulkhead and Deck Class “A” divisions (refer to SOLAS Chapter II-2)

- a) They shall be constructed of steel or other equivalent material
- b) They shall be suitably stiffened
- c) They shall be so constructed as to be capable of preventing the passage of smoke and flame to the end of the one-hour standard fire test approved non-combustible materials such that the average temperature of the unexposed side will not rise more than 139 °C above the original temperature, nor will the temperature, at any point, including any joint, rise more than 180 °C above the original temperature, within the time listed below:

— Class “A-60”	60 min
— Class “A-30”	30 min
— Class “A-15”	15 min
— Class “A-0”	0 min

3.4.2 SOLAS requirements (Part D—Chapter II-1, Regulation 42) (extract only)

- a) Emergency lighting for a period of 36 hours
- b) Navigational lights and external Communication, for a period of 36 hours
- c) Internal Communications for 36 hours (Refer to SOLAS for further details)
- d) Fire fighting and emergency bilge for 36 hours
- e) Steering gear as required by SOLAS Chapter II-1 Regulation 29
- f) Watertight doors for 30 minutes

3.5 List of Emergency Loads (USCG CFR 46)

By regulation, the following emergency loads must be fed from the emergency switchboard. For emergency generator rating calculation the connecting loads must be calculated for 100 percent load factor: (Refer to USCG 46 CFR Chapter 1 Subpart 112.15 for details)

- Emergency fire pump (At least one fire pump with all auxiliaries must be fed from the emergency switchboard)
- Steering gear (For 1 steering gear system the power must be provided from ship service as well as emergency through automatic bus transfer switch)
- Watertight door closure (all)
- Emergency lighting
- Navigation and communication system—Emergency power supply with UPS back up
- Emergency power supply for the automation with UPS support
- Emergency bilge (1)

3.6 Use of Emergency Generator in port (ABS-2002, 4-8-2-5.17) (extract only)

In accordance with ABS rules the emergency generator can be used in port with the following provisions:

- Special fuel tank with level alarm for harbour operation with a change over feature
- Continuous rated prime mover with special features
- Special electrical system fault protection
- Safeguard from overload with automatic load sharing

(For details refer to ABS rules.)

3.7 Emergency generator and emergency transformer rating—load analysis (sample calculation)

Table 3-1 is a sample electrical load analysis in support of selecting the emergency generator kilowatt rating and emergency transformer kVA rating. Items 1 through 7 are required to be powered from the emergency generator. The load factor for these loads is required to be 100 percent.

1	2	3	4	5	6	7	8
Item	Service	Qty	kW - Each	kW- Connected	Load factor	Total -kW Generator	Total-kW transformer
1	Emergency Fire Pump System	1	125.0	125.0	1.0	125.0	
2	Steering Gear	1	98.0	98.0	1.0	98.0	
3	Watertight Dr Closure	5	3.0	15.0	1.0	15.0	

1	2	3	4	5	6	7	8
Item	Service	Qty	kW - Each	kW- Connected	Load factor	Total -kW Generator	Total-kW transformer
4	Emergency Lighting	all		50.0	1.0	50.0	50.0
5	Navigation & Communications System			15.0	1.0	15.0	15.0
6	UPS	2	5.0	10.0	1.0	10.0	10.0
7	Emergency Bilge	1	5.0	5.0	1.0	5.0	
	Grand total—generator					317.0	
	Grand total—transformer						75.0

NOTES

1—Emergency generator rating: (example only)

- Emergency generator load analysis load factor is 100 (1.0) percent for all loads as shown in column 7
- As shown in the calculation the generator output rating must be at least 317 kW.
- The engine output must be $317/0.95 = 333.68$ kW [Considering (95 percent) 0.95 generator efficiency]
- The engine output rating should be equal to or greater than the calculated load 333.68 kW, or equivalent 447 Horsepower (HP)
- Additionally, large motor starting transient load on the generator must be considered. The engine must be able to start the largest load such as emergency fire pump, 125 kW.
- Sometimes the engine increase is necessary to support large motor starting transient.

2—Emergency transformer rating:

- Emergency transformer rating in kilovoltampere (kVA) = $75 \text{ kW}/0.8 = 93.45$ kVA (0.8 is the system power factor)
- The transformer nameplate rating 100 kVA

Table 3-1: Sample Load Analysis for Emergency Generator and Transformer Rating

3.8 Emergency power generation and distribution with ship service power and distribution system

Shipboard emergency generation and distribution consists of a dedicated emergency switchboard for a dedicated emergency generator. The emergency switchboard is tied to the ship service switchboard through a bus tie. The emergency switchboard feeds the 120 V section of the emergency switchboard through 450 V/120 V transformer. The 450 V section of the emergency switchboard provides power to all 450 V emergency loads. The 120 V section of the emergency switchboard provides power to all 120 V loads.

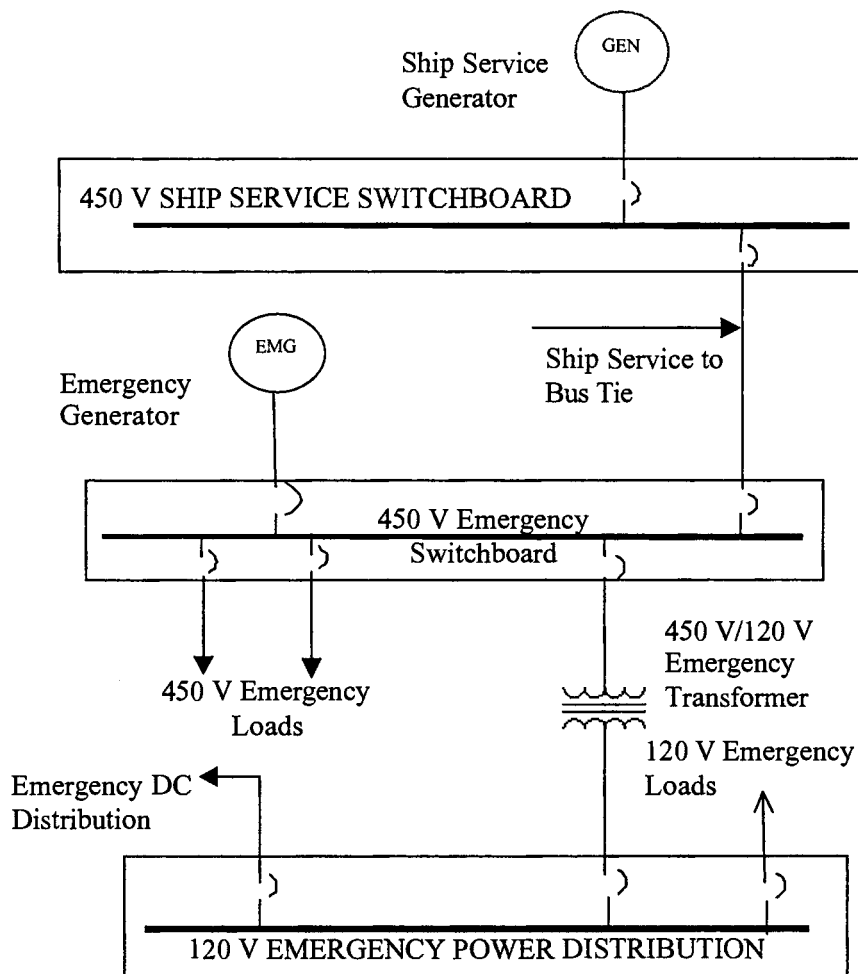


Figure 3-1: Electrical One-Line Diagram-Emergency Power Generation and Distribution with Ship Service Power

3.9 Emergency power generation and distribution with ABT bus tie

Shipboard power generation in a radial configuration and with an emergency generator generally configured such away that automatic bus transfer system is incorporated in the ship service and emergency generation control scheme. Figure 3-2 provides additional redundancy with a dedicated automatic bus transfer (ABT) function provided between two ship service generators and the emergency switchboard.

The emergency switchboard is tied to two ship service switchboards through a bus tie and automatic bus transfer switch (ABT), as shown in Figure 3-2.

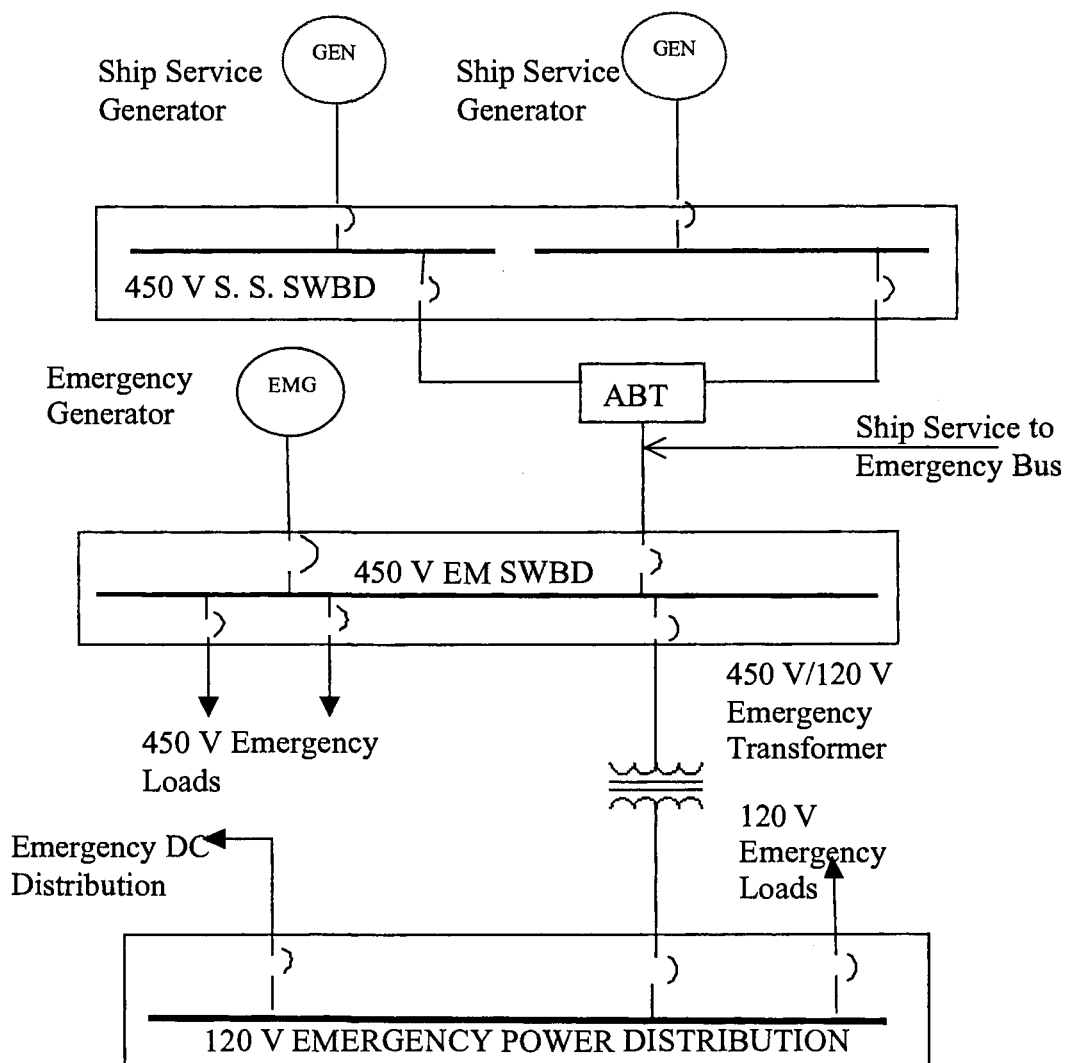


Figure 3-2: Electrical One-Line Diagram-Emergency Power Generation and Distribution with Ship Service Power Generation and Distribution with ABT Bus-Tie

3.10 Emergency Transformer 450 V/120 V (Per ABS 2002-4-8-5, Section 3.7.5)

In place of one three-winding transformer or three single-winding transformers in one enclosure with one primary breaker requirement, the ABS rules recommend the use of three separate single-phase transformers with dedicated circuit breakers, as shown in Figure 3-3.

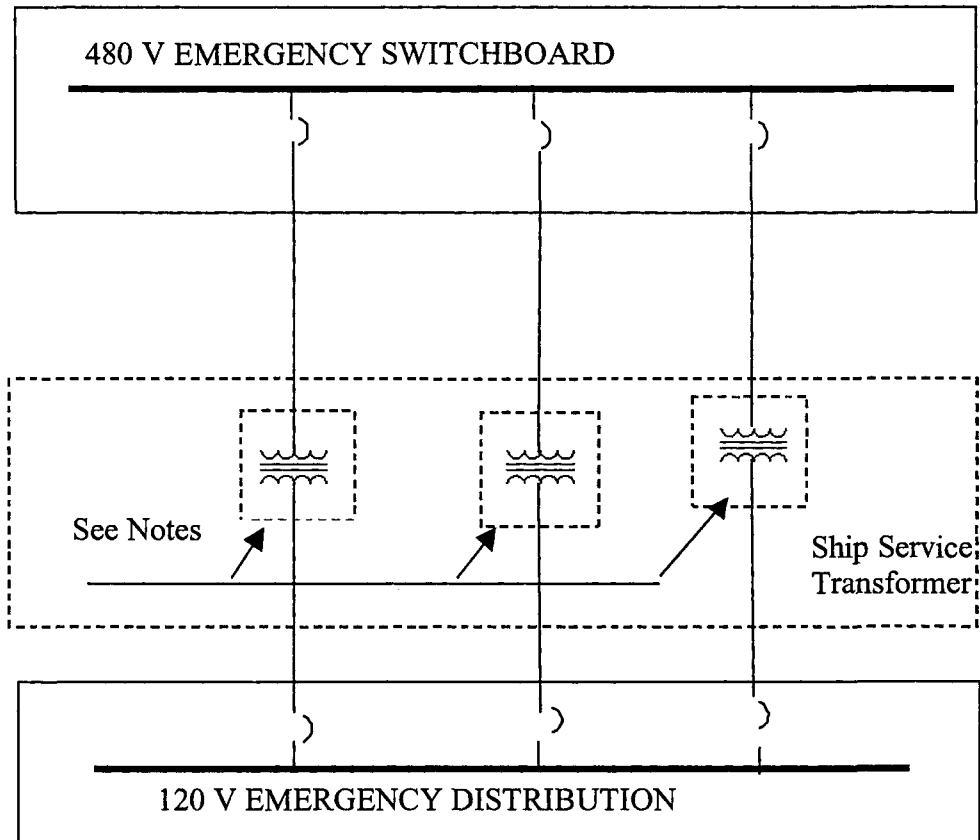


Figure 3-3: Emergency Transformer 480 V/120 V (Per ABS 2002- 4-8-5, Section 3.7.5)

NOTES:

1. Three single phase 480 V/120 V transformers, forming 120 V three-phase distribution. Each transformer is installed separately and each transformer is protected separately by dedicated circuit breaker. (ABS -2002, 4-8-5 Section 3.7.5)
2. One three phase transformer 480 V/120 V with appropriate protection

3.11 Emergency Generator Starting Block Diagram

The starting system of the emergency generator engine is required to have redundant engine starting capabilities, ensuring that the engine is ready, get started, and take over emergency loads within 45 seconds of the failure of the normal ship service power, by detecting zero voltage at the switchboard bus. The starting systems are usually combination of compressed air, hydraulic, and electrical UPS.

Figure 3-4 is a typical starting system with one hydraulic and two electrical systems. The second electrical starting system is additional capability to ensure redundancy if and when the criticality of the ship's performance is ship owner's requirement.

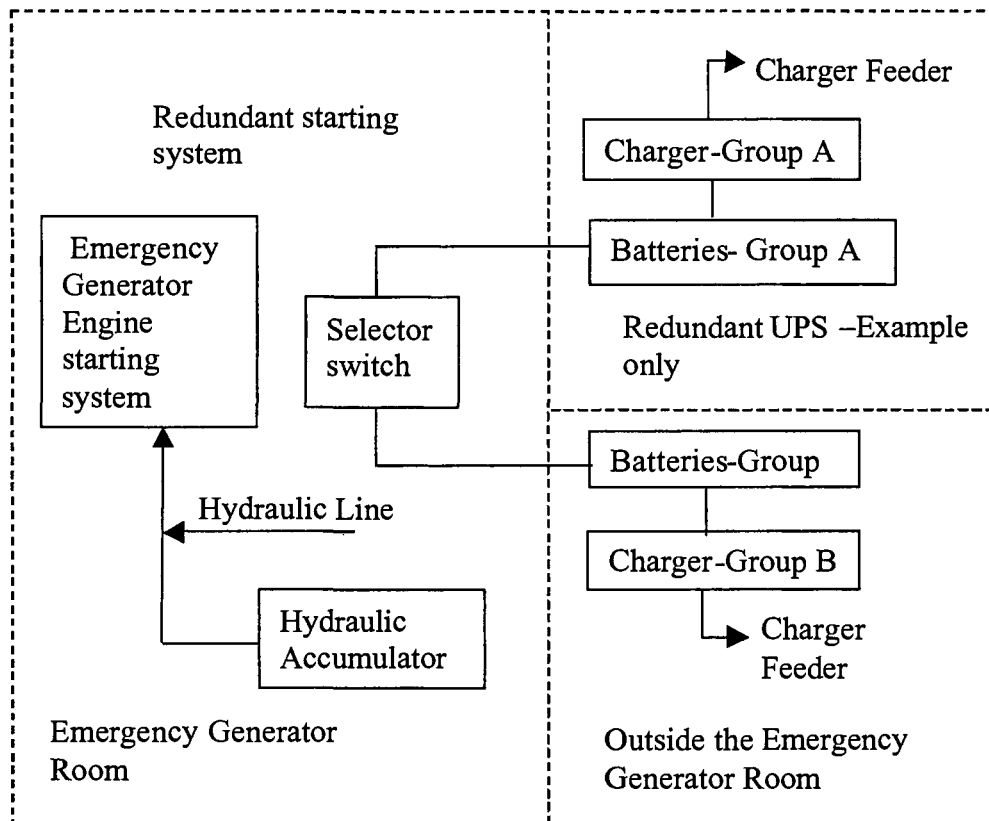


Figure 3-4: Emergency Generator Starting Block Diagram

4 Shipboard electrical system power quality

4.1 General

Shipboard AC power generation and distribution is theoretically perfect three-phase, 60 Hz or 50 Hz sinusoidal. In practice, the sinusoidal waveform gets distorted for reasons such as voltage transients, frequency transients, and harmonic distortion. The harmonic frequencies are multiples of fundamental frequencies such as 3rd, 5th, 7th, which are 180 Hz, 300 Hz, and 420 Hz for a 60 Hz system. The non-linear loads also contribute to the harmonic effects. Non-linear loads include:

- power electronics driven adjustable frequency drive AC motor for ship's propulsion system
- switching power supplies such as UPS
- microprocessor based controllers, computers, etc.

The non-linear loads produce electromagnetic interference (EMI) effects, electromagnetic susceptibility (EMS) effects, and radio frequency interference (RFI). These three effects together fall under the heading of electromagnetic compatibility (EMC). The EMI effect is exacerbated by reflected waves related to capacitive coupling, galvanic coupling, inductive coupling, and radiated coupling. EMS effects are increased by conducted susceptibility and radiated susceptibility. The non-linear loads also produce common-mode voltage and common mode current, which relates to EMI and EMC. These are the electrical noises produced and propagated in the system by high rate of dv/dt in the power electronic switching circuits.

For further detail on EMC, refer to Section 18.10.1 and Figure 18-4.

The effects of harmonic content in the distribution may include:

- Torque pulsation during motor application
- Overheating of transformer and rotating machines
- Nuisance tripping of protective devices
- Signal transmission interference
- Computer malfunction

The power supplies to the microprocessor-based equipment are non-linear, non-sinusoidal and they are also harmonic generators.

Variable frequency power electronic drives generate harmonics. The variable frequency drives, such as cycloconverter, load commutating inverter, and pulse width modulation (PWM) also produce harmonics. The harmonic distortion of these drives affects quality of power. Total harmonic distortion of each application should be calculated and then appropriate measures must be taken to minimize and manage harmonic contents within acceptable levels.

There are many different ways shipboard power system harmonics can be reduced, such as the use of transformer with shielding between primary and secondary winding, phase shift transformer for harmonic cancellation, 6-pulse, 12-pulse, 24-pulse configuration for harmonic cancellation, and harmonic filters. If these measures are not sufficient to reduce the harmonics to an acceptable level, motor generator installation is recommended. Sample electrical distribution system one-line diagrams are shown with different configurations in this section and other sections. These one-line diagrams are for guidance only. Electrical power distribution for each class of ship is to be set up to meet all operational requirements. It is the responsibility of the design engineer to design a system meeting such requirements and in compliance with applicable regulatory body requirements.

IEEE Std 519™-1992 provides required standards for harmonic measurements and acceptable harmonic levels in general. IEEE Std 45-2002, 4.5, Table 4 provided the same information for shipboard application, which is similar to Mil-Std-1399.

The EMI and EMS related noise propagation can be reduced by appropriate cable application with proper insulation, cable shielding, and cable grounding features. For additional details refer to the cable chapter 18.10 (Cable requirements for non-linear power equipment).

4.2 Total harmonic distortion calculation

Equations for calculating total harmonic distortion are given below.

$$\text{Total Harmonic Distortion (THD)} = THD_{\%Fundamentals} = \left(\frac{I_{rms(distortion)}}{I_{Fundamentals}} \right) \times 100 \quad (a)$$

$$I_{RMS} = \sqrt{I_1^2 + I_2^2 + I_3^2 + \dots + I_n^2} \quad (b)$$

$$I_{RMS} = \sqrt{I_{1(Fundamental-60Hz)}^2 + I_{2(5th)}^2 + I_{3(7th)}^2 + \dots + I_n^2} \quad (c)$$

4.2.1 Current—harmonic distortion (sample calculation)

Figure 4-1 and Table 4-1 show a sample diagram and harmonic current calculation. Figure 4-2 is provided showing fundamental, 3rd harmonic, 5th harmonic wave forms, and resultant wave form of those wave forms.

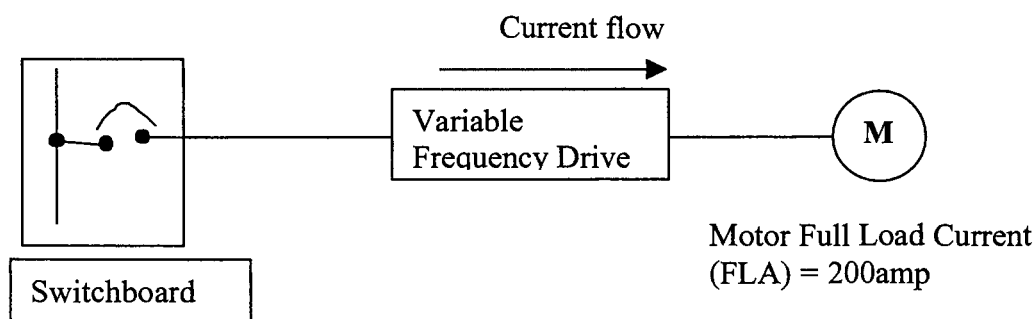


Figure 4-1: Harmonic Distortion Current – Simple Diagram

1 st harmonic	200 A
5 th harmonic	27 A
7 th harmonic	18 A
11 th harmonic	10 A
Distortion rms	33.9 A
Rms	202.86 A
Total harmonic distortion (THD)	16.98%

Table 4-1: Current Distortion Calculations (typical)

The harmonic current does not flow through the system; however it directly contributes to transformer winding heating, causing heating effects. The transformer should be oversized to prevent premature winding failure due to harmonic-related overheating

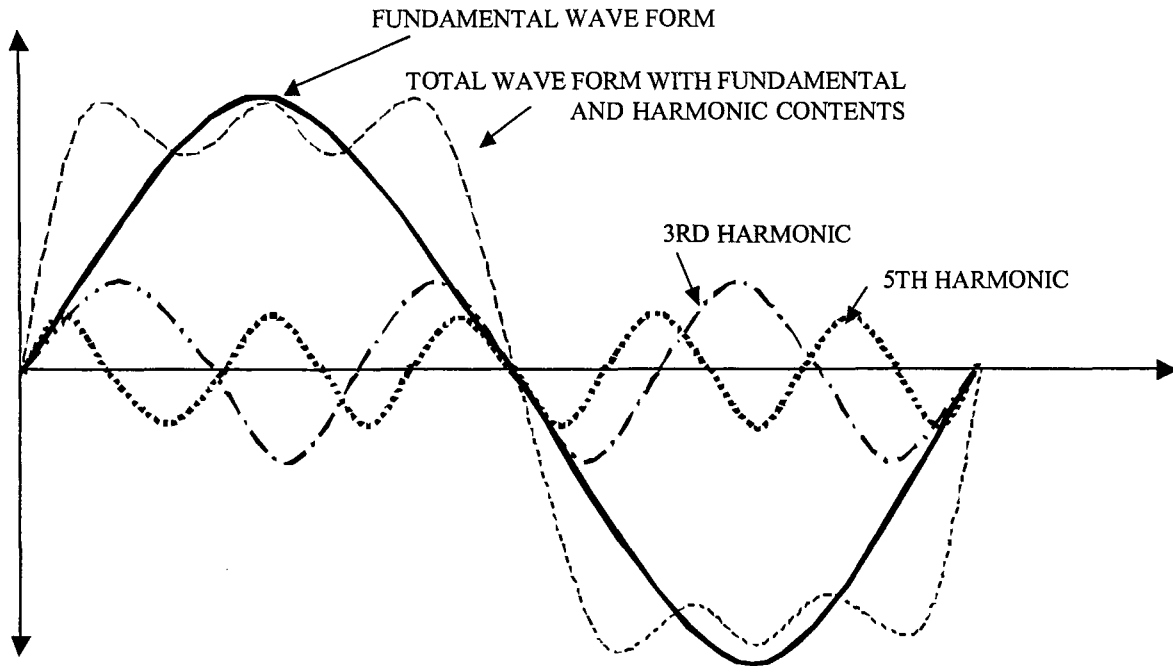


Figure 4-2: Sinusoidal Waves with Harmonic Contents

4.2.2 Voltage harmonic distortion (sample calculation)

Figure 4-3 and Table 4-2 show the result of voltage harmonic distortion calculations for the sample diagram shown.

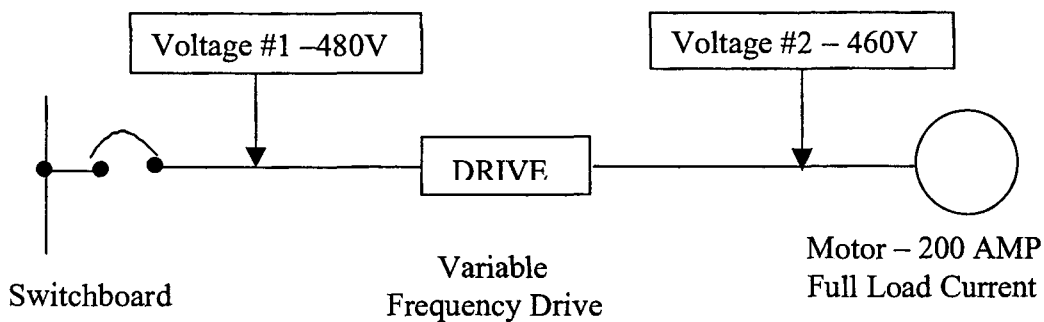


Figure 4-3: Harmonic Distortion Voltage – Diagram

1 st harmonic	480 V	
5 th harmonic	9.5V	
7 th harmonic	6.5V	
11 th harmonic	5.5V	
Distortion rms	12.76V	
rms	480.17V	
Total harmonic distortion (THD)	2.6%	

Table 4-2: Voltage Distortion Calculations (typical)

4.3 Power quality requirements

When considering power quality, the designer should be aware of what other standards-making bodies have had to say on the matter. The sections below discuss the most relevant standards in this area.

4.3.1 MIL-STD-1399, Type I power requirements (extract)

For shipboard application, power quality requirements are given in MIL-STD-1399. Type I power is 440 V or 115 V, 60 Hz ungrounded and is the standard shipboard electric power source. See Table 4-3 below for details.

Characteristics	Type I	
FREQUENCY		
a. Normal Frequency	60 Hz	
b. Frequency Tolerance	Plus or minus 3%	
c. Frequency Modulation	½ percent	
d. Frequency Transient		
1. Tolerance	Plus or minus 4%	
2. Recovery time	2 seconds	
e. Worst case, frequency excursion from nominal frequency	Plus or minus 5-1/2 %	
Resulting from b, c, and d(1) combined except under		
Emergency Cond		
VOLTAGE		
f. Normal user voltage	440, 115v	
g. User voltage tolerance		
1. Average of three line to line voltage	Plus or minus 5%	
2. Any one-line to line voltage including g(1) and	Plus or minus 7%	
Line voltage unbalance (h)		
h. Line voltage unbalance	3%	
i. Voltage modulation	2%	
j. Voltage transient		
(1) Voltage transient tolerance	Plus or minus 16%	
(2) Voltage transient recovery time	2 seconds	

k. Voltage spikes (peak value, includes fundamental)	Plus minus 2.500 V for 440 V sys and 1000 V for 115 V	
l. Maximum departure voltage resulting from g(1), g(2), (h), and (I) combined, except under transient or emergency conditions	Plus or minus 6 percent	
m. The worst case voltage excursion from nominal user voltage resulting from (g)(1), (g)(2), (h), (I), and j(1) combined except under emergency conditions.	Plus or minus 20 percent	
n. Insulation resistance test		
(a) surface ships	500 vdc	
WAVEFORM (VOLTAGE)		
(o) Maximum total harmonic distortion	5 percent	
(p) Maximum single harmonic	3 percent	
(q) Maximum deviation factor	5 percent	
EMERGENCY CONDITION		
(r) Frequency excursion	Minus 100 to plus 12 percent	
(s) Duration of frequency excursion	Up to 2 minutes	
(t) Voltage excursion	Minus 100 to plus 35percent	
(u) Duration of voltage excursion		
(1) lower limit (minus 100 percent)	Up to 2 minutes	
(2) upper limit (plus 35 percent)	2 minutes	

Table 4-3: Type I Power Requirement per MIL-STD-1399

4.3.2 IEEE Std 45-2002, 4.5, AC Power system characteristics

Power distribution systems should maintain the system characteristics described in Table 4 under all operating conditions. Power-consuming equipment should operate satisfactorily under the conditions described in Table 4, and it should be designed to withstand the power interruption, transient, electromagnetic interference (EMI), radio frequency interference (RFI), and insulation resistance test conditions inherent in the system. Power-consuming equipment requiring a nonstandard voltage or frequency for successful operation should have integral power conversion capability. Power-consuming equipment should not have inherent characteristics that degrade the power quality of the supply system described in Table 4-4.

Table 4-4, Alternating current (AC) power characteristics

Characteristics	Limits
Frequency a) Nominal frequency b) Frequency tolerances c) Frequency modulation d) Frequency transient: 1) Tolerance 2) Recovery time e) The worst-case frequency excursion from nominal frequency resulting from item b), item c), and item d) 1) combined, except under emergency conditions.	50/60 Hz ± 3% ½% ± 4% 2 s ± 5½%
Voltage a) User voltage tolerance: 1) Average of the three line-to-line voltages 2) Any one line-to-line voltage, including item a) 1) and line voltage unbalances item b) b) Line voltage unbalance c) Voltage modulation d) Voltage transient: 1) Voltage transient tolerances 2) Voltage transient recovery time e) Voltage spike (peak value includes fundamental) f) The maximum departure voltage resulting from item a) 1) and item d) combined, except under transient or emergency conditions. g) The worst case voltage excursion from nominal user voltage resulting from item a) 1), item a) 2), and item d) 1) combined, except under emergency conditions.	± 5% ± 7% 3% 5% ± 16% 2 s ± 2500 V (380–600 V) system; 1000 V (120–240 V) system ± 6% ± 20%
Waveform voltage distortion^a a) Maximum total harmonic distortion b) Maximum single harmonic c) Maximum deviation factor	5% 3% 5%

Emergency conditions

a) Frequency excursion	–100 to +12%
b) Duration of frequency excursion	Up to 2 min
c) Voltage excursion	–100 to +35%
d) Duration of voltage excursion:	
1) Lower limits (–100%)	Up to 2 min
2) Upper limit (+35%)	2 min

Definitions:

a) Frequency

- 1) Nominal frequency: The designated frequency in hertz.
- 2) Frequency tolerance: The maximum permitted departure from nominal frequency during normal operation, excluding transient and cyclic frequency variations. It includes variations caused by load changes, environment (temperature, humidity, vibration, inclination), switchboard meter error, and drift. Tolerances are expressed in percentage of nominal frequency.
- 3) Frequency modulation: The permitted periodic variation in frequency during normal operation that might be caused by regularly and randomly repeated loading. For purposes of definition, the periodicity of frequency modulation should be considered as not exceeding 10 s.

$$\text{Frequency Modulation (\%)} = \frac{\{f_{\text{maximum}} - f_{\text{minimum}}\}}{\{2 \times f_{\text{nominal}}\}} \times 100$$

- 4) Frequency transient tolerance: A sudden change in frequency that goes outside the frequency tolerance limits, returns to, and remains inside these limits within a specified recovery time after initiation of the disturbance. Frequency transient tolerance is in addition to frequency tolerance limits.
- 5) Frequency transient recovery time: The time period from the start of the disturbance until the frequency recovers and remains within frequency tolerance limits.

b) Voltage

- 1) User voltage tolerance: The maximum permitted departure from nominal user voltage during normal operation, excluding transient and cyclic voltage variations. It includes variations such as those caused by load changes, environment (temperature, humidity, vibration, inclination), switchboard meter error, and drift.
- 2) Line voltage unbalance tolerance (three-phase system): The difference between the highest and lowest line-to-line voltages.

$$\text{Line Voltage Unbalance Tolerance (\%)} = \frac{\{E_{\text{maximum}} - E_{\text{minimum}}\}}{\{E_{\text{nominal}}\}} \times 100$$

- 3) Voltage modulation (amplitude): The periodic voltage variation (peak to valley) or the user voltage that might be caused by regularly or randomly repeated pulsed loading. The periodicity or voltage modulation is considered to be longer than 1 Hz and less than 10 s. Voltages used in the following equation shall be all-peak or all-rms:

$$\text{Voltage Modulation (\%)} = \frac{\{E_{\text{maximum}} - E_{\text{minimum}}\}}{\{2 \times E_{\text{nominal}}\}} \times 100$$

- 4) Voltage transient
 - i) Voltage transient tolerance: A sudden change (excluding spikes) in voltage that goes outside the user voltage tolerance limits and returns to and remains within these limits within a specified recovery time longer than 1 ms after the initiation of the disturbance. The voltage transient tolerance is in addition to the user voltage tolerance limits.
 - ii) Voltage transient recovery time: The time elapsed from initiation of the disturbance until the voltage recovers and remains within the user voltage tolerance limits.
- 5) Voltage spike: A voltage change of very short duration (less than 1 ms).

c) Waveform

- 1) Total Harmonic Distortion (THD)(of a sine wave): The ratio in percentage of the rms value of the residue (after elimination of the fundamental) to the rms value of the fundamental.
- 2) Single Harmonic (of a sine wave): The ratio in percentage of the rms value of that harmonic to the rms value of the fundamental.
- 3) Deviation Factor (of a sine wave): The ratio of the maximum difference between corresponding ordinates of the wave and of the equivalent sine wave to the maximum ordinate of the equivalent sine wave when the waves are superimposed in such a way that they make the maximum difference as

$$\text{Deviation factor (\%)} = \frac{\{\text{maximum deviation}\}}{\{\text{maximum ordinate of the equivalent sine wave}\}} \times 100$$

small as possible.

d) Emergency conditions

- 1) A situation or occurrence of a serious nature that may result in electrical power system interruptions or deviations, such as the occurrence of ship service generator failure and the emergency generator coming on line.

^aFor ships with electric propulsion or other adjustable speed drive loads, higher voltage distortion can be accepted on a dedicated power bus if the equipment connected to the dedicated power bus is designed and tested for the actual conditions.

4.3.3 IEEE Std 45-2002, 4.6, Power quality and harmonics

Solid state devices such as motor controllers, computers, copiers, printers, and video display terminals produce harmonic currents. These harmonic currents may cause additional heating in motors, transformers, and cables. The sizing of protective devices should consider the harmonic current component. Harmonic currents in nonsensical current waveforms may also cause EMI and RFI. EMI and RFI may result in interference with sensitive electronics equipment throughout the vessel.

Isolation, both physical and electrical, should be provided between electronic systems and power systems that supply large numbers of solid state devices, or significantly sized solid state motor controllers. Active or passive filters and shielded input isolation transformers should be used to minimize interference. Special care should be given to the application of isolation transformers or filtering as the percentage of power consumed by solid state power devices compared with the system power available increases. Small units connected to large power systems exhibit less interference on the power source than do larger units connected to the same source. Solid state power devices of vastly different sizes should not share a common power circuit. Where kilowatt ratings differ by more than 5 to 1, the circuits should be isolated by a shielded distribution system transformer. Surge suppressors or filters should only be connected to power circuits on the secondary side of the equipment power input isolation transformers.

Notes:

1. To preclude radiated EMI, main power switchboards rated in excess of 1 kV and propulsion motor drives should not be installed in the same shipboard compartment as ship service switchboards or control consoles. (This is per IEEE Std 45-1998, 4.6).
2. To reduce the effect of radiated EMI, special considerations on filtering and shielding should be exercised when main power switchboards and propulsion motor drives are installed in the same shipboard compartment as ship service switchboards or control console.
3. IEEE Std 519™-1992 provides additional recommendations regarding power quality.

4.4 IEEE Std 45-2002, 31.8, Propulsion power conversion equipment (power quality)

The following quote is an extract referring only to the power quality portion of this clause.

Whenever power converters for propulsion are applied to integrated electric plants, the drive system should be designed to maintain and operate with the power quality of the electric plant. The effects of disturbances, both to the integrated power system and to other motor drive converters, should be regarded in the design. Attention should be paid to the power quality impact of the following:

- a) Multiple drives connected to the same main power system.
- b) Commutation reactance, which, if insufficient, may result in voltage distortion adversely affecting other power consumers on the distribution system. Unsuitable matching of the relation between the power generation system's sub-transient reactance and the propulsion drive commutation impedance may result in production of harmonic values beyond the power quality limits.
- c) Harmonic distortion can cause overheating of other elements of the distribution system and improper operation of other ship service power consumers.
- d) Adverse effects of voltage and frequency variations in regenerating mode.
- e) Conducted and radiated electromagnetic interference and the introduction of high-frequency noise to adjacent sensitive circuits and control devices. Special consideration should be given for the installation, filtering, and cabling to prevent electromagnetic interference....

4.5 Typical system design with harmonic management

Figure 4-4 is a simple power generation and distribution diagram with non-linear loads. A harmonic filter is used to reduce the harmonic level within the required limits.

Figure 4-5 shows power system distribution with non-sensitive and sensitive loads. The sensitive loads are usually the loads that cannot tolerate harmonic effects. The sensitive bus is powered by a motor generator set to ensure quality power for the sensitive loads.

Figure 4-6 is a typical power distribution for a ship's central control system. The central control system requires redundant clean power with battery backup to ensure power at the console under all normal and emergency situations.