



IEEE Guide for the Design and Application of Power Electronics in Electrical Power Systems on Ships

IEEE Industry Applications Society

Sponsored by the
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IEEE Guide for the Design and Application of Power Electronics in Electrical Power Systems on Ships

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IEEE Industry Applications Society

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Abstract: This guide applies to power electronics components and systems on ships and similar applications. It summarizes current electrical engineering methods and practices for applying power electronics in electrical power systems on ships and describes analytical methods, preferred parameters, and performance characteristics from a common frame of reference for reliable integrated marine electrical power systems.

Keywords: electric ships, integrated power systems, marine electrical power systems, power electronics, power electronic building blocks, propulsion

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Introduction

This introduction is not part of IEEE Std 1662-2008, IEEE Guide for the Design and Application of Power Electronics in Electrical Power Systems on Ships.

The IEEE Power Electronics Working Group was organized by the Marine Industries Subcommittee of the Petroleum and Chemical Industries Committee of Industrial Applications Society and later was cosponsored by the IAS Industrial Power Converters Committee and the Standards Committee of the Power Electronics Society.

The purpose of this new IEEE Std 1662™ is to recommend a methodology for analysis and specifications parameters of power electronics equipment for a ship's electrical power systems from a common frame of reference for reliable integrated marine electrical power systems. It evaluates the impact of such concepts as power electronic building blocks or integrated power systems on size, life cycle cost, weight, fuel efficiency, and risk reduction.

Stakeholders for this guide are evaluators and designers of power electronics systems for marine applications, marine end-users, shipbuilders, port operators, classification societies, machinery and equipment manufacturers, research institutes, and universities. It applies to all power electronics equipment rated above 100 kW. This guide is complimentary to IEEE Std 45™-2002^a and IEEE Std 1573™-2003.

This guide is not intended to specify a particular technology or procedures that should be followed.

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^aInformation on references can be found in Clause 2.

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1. Overview

This guide recommends parameters for specifications, performance characteristics, and analytical methods for power electronics equipment on commercial and military ships and similar applications. Requirements for power quality, construction, testing, and certification are also included.

Stakeholders for this guide are evaluators and designers of power electronics systems for marine applications, marine end-users, shipbuilders, port operators, classification societies, machinery and equipment manufacturers, research institutes, and universities. It applies to all power electronics equipment rated above 100 kW. This guide should be used together with IEEE Std 45™-2002 and IEEE Std 1573™-2003.

1.1 Scope

This document summarizes current electrical engineering methods and practices for applying power electronics in electrical power systems on ships. It describes analytical methods, preferred parameters, and performance characteristics from a common frame of reference for reliable integrated marine electrical power systems.

1.2 Purpose

The purpose of this document is to recommend a methodology for analysis and specifications parameters of power electronics equipment for marine electrical power systems. It analyzes the impact of such concepts

1.2 Purpose

The purpose of this document is to recommend a methodology for analysis and specifications parameters of power electronics equipment for marine electrical power systems. It analyzes the impact of such concepts as power electronics building blocks or integrated power systems on size, life cycle cost, weight, fuel efficiency, and risk reduction of implementation.

1.3 Limitations

This guide is applicable to a wide range of power electronics equipment designed for, and installed in, shipboard environments with power ratings above 100 kW.

1.4 Equipment covered by this guide

Some of the equipment is very specific to the power distribution system. Other equipment is the end-use equipment that uses electrical power to perform its function. Examples of equipment covered in this guide are as follows:

- Inverters
- Rectifiers
- Converters dc to dc, dc to ac, frequency, cyclo-, and others
- Power factor and reactive power [static or dynamic visual-aural range (VAR)] support
- Solid-state circuit breakers
- Current limiters
- Motor drives
- Active harmonic filters
- Uninterruptible power supply (UPS)
- High-power electric propulsion
- Energy storage and pulse load systems
- Other equipment with built-in power electronics that has the ship's service as the power source, such as auxiliary equipment, communication equipment, and radars

1.5 Guide for users

This guide is written to cover the needs of many different users of shipboard power electronics components, equipment, and systems. Examples of persons having a stake in this document are as follows:

- a) Systems integrator
- b) System designer
- c) Equipment designer
- d) Component designer
- e) Shipyard design and fabrication

- f) Testing, certification, nationally recognized testing laboratory (NRTL), and authority having jurisdiction
- g) End-user

This guide is organized into nine clauses and four annexes:

- Clause 1 is an overview of the scope, purpose, and organization of this guide.
- Clause 2 lists the references that should be consulted when using this guide.
- Clause 3 provides definitions, acronyms, and abbreviations used throughout the text of this guide.
- Clause 4 identifies major power electronics applications on ships.
- Clauses 5 and 6 identify general and design requirements for power electronics on ships.
- Clause 7 provides recommendations for technical information, data, and models to support the power system designers in order to achieve optimal power system designs.
- Clause 8 provides guidelines for analyzing and designing systems and subsystems for marine ships.
- Clause 9 provides guidelines for testing, inspection and certification of power electronics.
- Annex A is an informative bibliography of related publications.
- Annex B includes practical semiconductor's derating recommendations and stress limits.
- Annex C addresses marine systems grounding.
- Annex D describes various models for design and analysis.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so that each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEC 60146-1-1, Semiconductor Convertors—General Requirements and Line Commutated Convertors Part 1-1: Specifications of Basic Requirements.¹

IEEE Std 45™-2002, IEEE Recommended Practice for Electric Installations on Shipboard.^{2,3}

IEEE Std 1100™-2005 (Emerald Book), IEEE Recommended Practice for Powering and Grounding Electronic Equipment.

IEEE Std 1566™-2005, IEEE Standard for Performance of Adjustable Speed AC Drives Rated 375 kW and Larger.

¹IEC publications are available from the Sales Department of the International Electrotechnical Commission, 3, rue de Varembe, P.O. Box 131, CH-1211 Geneva 20, Switzerland (<http://www.iec.ch/>). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 25 West 43rd Street, 4th Floor, New York, NY 10036, USA (<http://www.ansi.org/>).

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IEEE Std 1573™-2003, IEEE Recommended Practice for Electronic Power Subsystems: Parameters, Interfaces, Elements, and Performance.

International Association of Classification Societies (IACS) Unified Requirement (UR) E11.⁴

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this guide, the following terms and definitions apply. *The Authoritative Dictionary of IEEE Standards Terms* [B23]⁵ should be referenced for terms not defined in this clause.

3.1.1 active filtering: Controlling power quality without primary control of system voltage.

3.1.2 agent technology: A tool for development of agent-based systems in which agents are capable of performing autonomous actions in order to meet system objectives.

3.1.3 catastrophic fault: A sudden and total failure from which recovery is impossible and from which immediate shutdown is warranted. Catastrophic faults often lead to cascading systems failure.

3.1.4 commissioning test: A test conducted when the equipment is installed to verify correct operation (also called installation testing, dock trials, and sea trials).

3.1.5 integrated power system (IPS): A power system where all prime movers produce electrical power that is shared among propulsion, mission, and ship service loads. Discriminating attributes of integrated power systems are flexibility of arrangements, mechanical decoupling between prime movers and propulsors, an increased level of energy conversion and transmission redundancy, and flexibility of redistributing available electrical power for future electrical weapons.

3.1.6 loading: Converting power and without primary control of system voltage.

3.1.7 medium voltage (MV): 1 kV to 35 kV.

3.1.8 power electronic building block (PEBB): A generic building-block concept for power electronics that incorporates standard modules that can be quickly configured to meet the specific hardware and software needs of particular applications. The PEBB concept includes power processor blocks (single phases or multiple phases), gate drives and sensor blocks, analog-to-digital converter blocks for sensor signals, switching or gate drive control blocks, and blocks for communication with higher level controllers. The exact requirements for the system protection depend on its mission and configuration of the system. Each PEBB includes built-in self-protection against voltage surges, overvoltage and undervoltage, fault currents, ground currents, internal faults, overloads, and overtemperature.

3.1.9 production test: A test conducted on every unit of equipment prior to shipment (also called factory acceptance test).

3.1.10 protecting: Mitigating effects from fault currents, overvoltages, or loss of power source.

3.1.11 sourcing: Converting power and providing primary control of system voltage.

⁴IACS publications are available from the IACS Limited, Permanent Secretariat, 6th Floor, 36 Broadway, London SW1H 0BH, United Kingdom.

⁵The numbers in brackets correspond to those of the bibliography in Annex A.

3.1.12 type test: Test of one or more devices made to a certain design to demonstrate that the design meets certain specifications (also called design test or first article test).

3.1.13 zonal distribution: Electrical power architecture structured along the geographic zones of a ship to improve survivability, reduce cost, and foster improved casualty control. Zones are usually aligned with primary damage control bulkheads. Zones may be single bus or dual bus and normally have in-zone conversion and distribution nodes.

3.2 Acronyms and abbreviations

2-D	two-dimensional
3-D	three-dimensional
ac	alternate current
AFE	active front end
dc	direct current
EMI	electromagnetic interference
EMC	electromagnetic compatibility
EMP	electromagnetic pulse
HMI	human machine interface
HRG	high resistance grounding
IGBT	insulated gate bipolar transistor
IPS	integrated power system
LAN	local area network
LRU	line replacement unit
LV	low voltage
MTBF	mean time between failures
MTTR	mean time between repairs
MV	medium voltage
PE	power electronic
PEBB	power electronic building block
PWM	pulse width modulation
SCR	silicon controlled rectifier, thyristor
SMES	superconducting magnetic energy storage
STBD	starboard
STS	solid state transistor switch
SWGR	switchgear
UPS	uninterruptible power supply
VAR	visual-aural range
VFD	variable frequency drive
VSC	voltage source converter
VSI	voltage source inverter

4. Power electronics equipment applications

4.1 Types of system-level functions

Four types of system-level functions may be assumed by any given power electronic (PE) equipment or subsystem as listed as follows:

a) Power conversion

- 1) Sourcing: The PE equipment may be viewed as a source at one or more of its terminals. As such, it converts power from one or more voltage or frequency levels while being in control of the output voltage or current [or phase angle in the case of alternate current (ac)] at its electrical output terminals. The PE may provide substantial energy storage capability. Examples for this application are active inverter connected to a high-speed generator, direct current (dc)/dc converter feeding a zone in a dc zonal distribution system, and dynamic voltage restorer.
- 2) Loading: The PE equipment may be viewed as a load at one or more of its terminals. As such, it is passive with respect to fundamental voltage or current control. Although normally it will be demanding power from the portion of the power system upstream of its terminals, it may also temporarily provide power. The PE may provide substantial energy storage capability. Examples for this application are a diode rectifier of a propulsion drive and a dc/dc converter fed from the dc lateral bus in a dc zonal distribution system.

b) Power conditioning

- 1) Protecting: The PE may protect equipment, conductive path, and continuity of power. As such, it does not convert power between voltage or frequency levels, nor does it provide any substantial energy storage capability. Examples for this application are transfer switch, fault current limiting circuit breaker, and crowbar.
- 2) Active filtering (shunt connected): The PE may actively control the power quality of the system voltage or current. It is passive with respect to fundamental voltage control but will actively control nonfundamental components of the system voltage or current, and it may control reactive power in ac systems.

The purpose of distinguishing these functions is to segregate specific PE equipment applications, converter functions, and converter topologies as discussed in 8.2 from their respective system-level functions.

The reason for defining the two basic functions “sourcing” and “loading” for power conversion is to acknowledge the importance of voltage control in converter fed systems. Although a converter that assumes the function of “sourcing” performs primary voltage control, the one that is “loading” behaves passively with respect to voltage control. Many converters can assume either function solely by applying different control algorithms. These two basic functions have nothing to do with the actual flow of power. In many applications, only one converter will assume the function of “sourcing” in order to maintain system stability. However, it is conceivable that in special cases, more than one converter can assume “sourcing” simultaneously. Three examples that shall illustrate the different combinations of power flow and function are as follows:

- The active front end of a variable speed motor drive may regenerate power into the system it is connected to without participating in system voltage control. Therefore, even during the regeneration phase, this front end converter still assumes the function of “loading.”
- The machine inverter of a flywheel energy storage system connected to a dc distribution system. During the charging of the flywheel, the inverter assumes the function of “loading” with respect to the dc system. However, if the upstream converter feeding the dc system shuts down and the dc system shall be powered from the flywheel energy storage system, its machine inverter will change its function to “sourcing” because it then controls the voltage in the dc system.
- Bidirectional rectifier connected to an ac distribution system and powering a dc system assumes the function “sourcing” on the dc side regardless of the actual power flow. Therefore, even if power flows from the dc system into the ac system, the rectifier is “sourcing” the dc system.

Whereas PE equipment that converts power between different frequencies or voltages may also participate in system-level protection functions, certain PE equipment only assumes the function of “protecting.” It specifically does NOT convert power between different frequencies or voltages and behaves passive with respect to voltage control. Therefore, this function is specifically called out in this guide. Examples are static transfer switches, solid-state fault current limiters, solid-state crowbar switches, and so on.

Finally, a fourth system level function exists called “active filtering.” This function only affects the quality of the voltage or current waveforms, although it does not actively control the magnitude of the fundamental waveform component. Only a static VAR compensator, which is also considered to assume the function of “active filtering,” affects the fundamental current waveform component in voltage-controlled systems. However, while performing the function of “active filtering,” it does not provide primary voltage control, and hence, it does not assume the function of “sourcing.”

Note that any specific PE equipment or subsystem normally assumes different functions at its various electrical terminals. In addition, it may assume different functions at any specific electrical port at different times (i.e., front end of an energy storage system). Therefore, because different functions result in different requirements, it is essential to specify clearly the functions that each of the electrical terminals assume at any given time.

4.2 Typical applications

Examples of equipment applications and their abbreviations are shown in Table 1. Examples of common electric ship topologies are shown in 4.2.1 through 4.2.6.

Table 1—Power electronics applications in shipboard system

Acronym	Description
ACFC	AC frequency converter
AC/DC	AC rectifier
DC/AC	AC inverter fed from dc source
DC/DC	DC converter fed from dc source
STS	Solid-state transfer switch
FIU	Fault interrupting or fault limiting equipment
STATVAR	Static reactive power (VAR) compensator
AHF	Active harmonic filter
VFD	Variable frequency drive, typically fed from fixed-frequency ac source
UPS	Typically fed from fixed-frequency ac source
HPSP	High-power ship propulsion
ES	Energy storage or pulsed power loads
Built-in power supplies	Any of the many power supplies built into other shipboard equipment

4.2.1 Single propulsor system fed from two main buses

The electrical power distribution system shown in Figure 1 is suitable for small commercial ship applications.

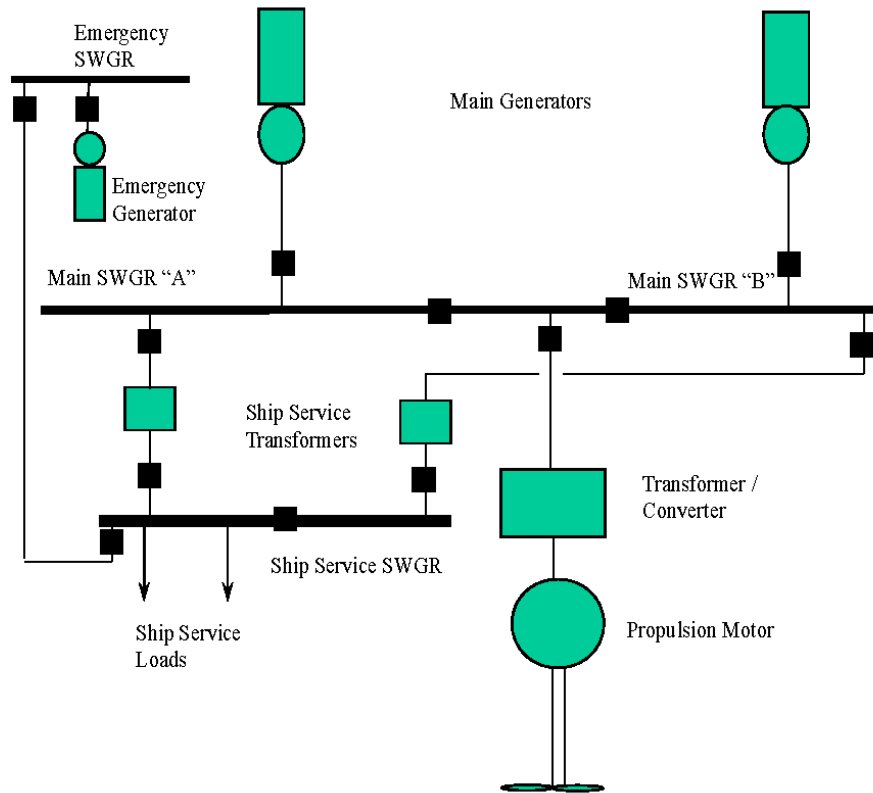


Figure 1—Single propulsor fed from two main buses

The system features dual redundant main bus and ship service bus arrangements. The main buses can be physically separated for greater survivability because they are equipped with their own tie circuit breakers. Ship service buses are fed from two ship service transformers. If the main power generation is blacked out, the emergency generator is started in order to help restore the main power plant.

A key disadvantage of the system shown in Figure 1 is its dependence on a single propulsor. Although the main buses can be placed in different noncontiguous compartments, the propulsion is fed from a single section of main bus that could also represent a single point of failure. The system redundancy is not sufficient for meeting the survivability requirements of modern naval ships (single screw).

4.2.2 Single propulsor system with a dual winding propulsion motor fed from two main buses

The electrical power distribution system shown in Figure 2 is also suitable for small commercial ship applications. The system features dual redundant main bus and ship service bus arrangements. However, the main buses cannot be physically separated for greater survivability because they are equipped with only one common tie circuit breaker (i.e., if one section of main bus is faulty and the tie breaker fails to open, the whole power system will be blacked out). Ship service buses are fed from two ship service transformers. When the main power generation is blacked out, the emergency generator is started in order to restore the main power plant. The dual winding propulsion motor runs with half power when one main bus is not available. The dual transformer/converter arrangement lends itself to the application of 12-pulse harmonic cancellation practice for lowering of main bus harmonic distortion. Also, the dual converter arrangement provides less torque pulsations.

A key disadvantage of the system shown in Figure 2 is its dependence on a single propeller shaft. Also, two tie breakers should be used for critical main bus arrangements that require survival of one half of the power system while the other half is faulty. The system does not provide sufficient redundancy in order to meet the survivability requirements of modern naval ships (single screw).

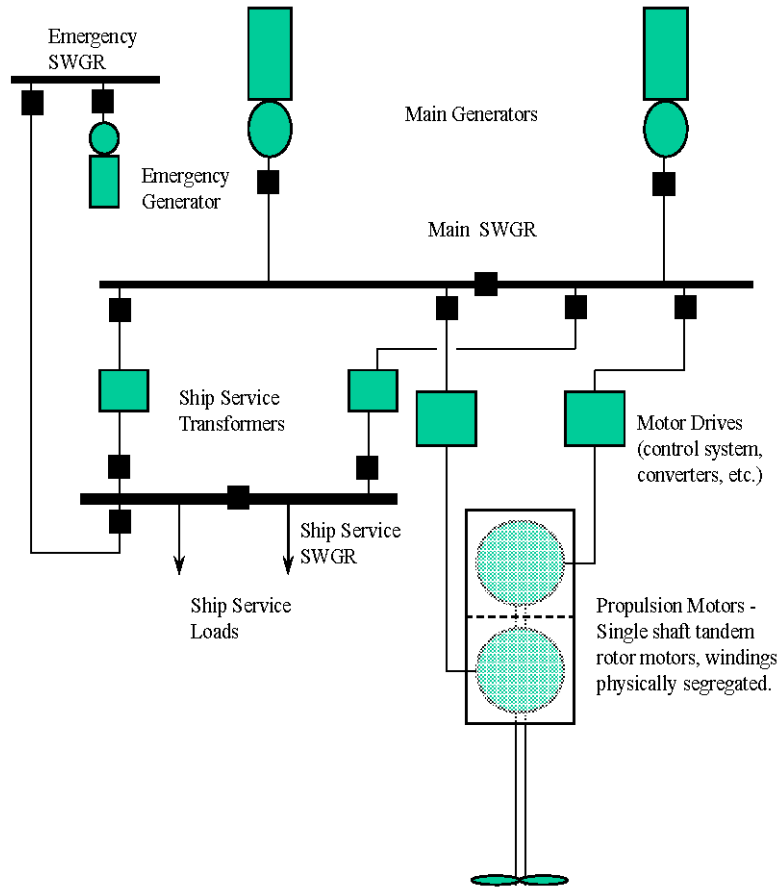


Figure 2—Single propulsor system with dual winding motor fed from two main buses

4.2.3 Dual propulsor system with propulsion motors fed from separate main buses

The electrical power distribution system shown in Figure 3 is suitable for naval ship applications. The system features dual redundant main bus and ship service bus arrangements that can be installed in noncontiguous compartments. The main buses can be physically separated for greater survivability because they are equipped with two tie circuit breakers. The whole power distribution system can be separated with a firewall. The ship service buses are fed from two ship service transformers. If the main power generation is blacked out, the emergency generator is started in order to restore the main power plant. If the number of generators on each main bus is greater than one, the emergency generator may become redundant. Two complete propulsion arrangements fed from separate power sources provide good survivability. A quasi 12-pulse harmonic cancellation scheme can be used for lowering of the main bus harmonic distortion (because the motors might not be loaded identically at all times).

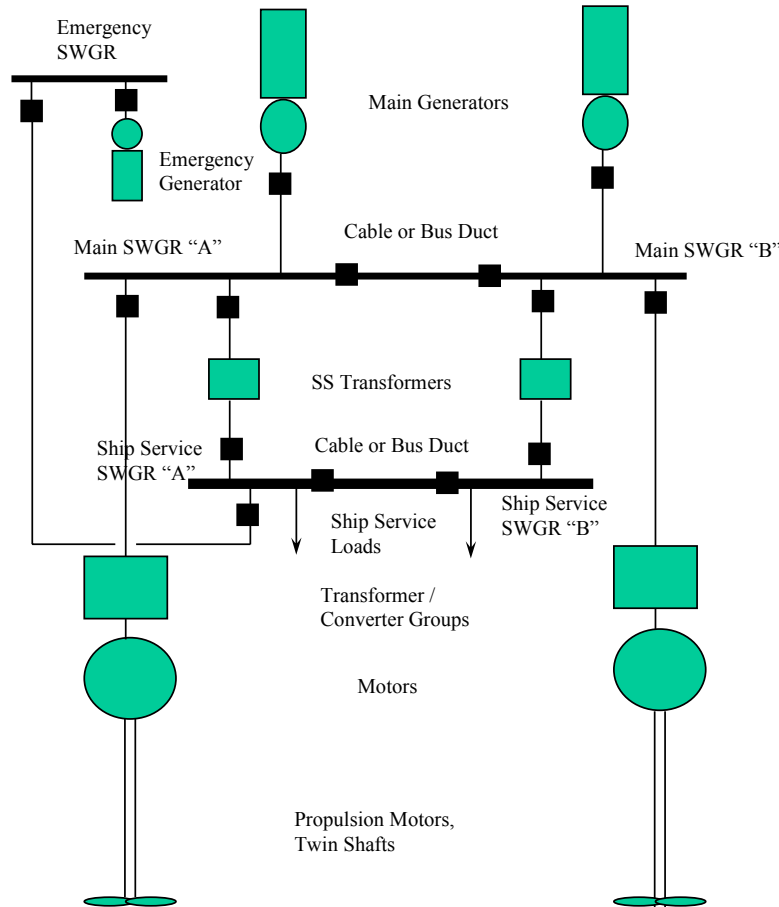


Figure 3—Dual propulsor system with motors fed from separate main buses

The system survivability can be further increased as follows:

- Optional cross feeding of the propulsion motors from the opposite buses
- Applying dual winding motors that are fed through pairs of transformers/converters
- Increasing the number of generators per each main bus (more than one per bus)
- Applying arc-resistant switchgear in order to limit the damage to the power distribution system in the event of an arcing fault in the main switchgear

The system shown in Figure 3 provides sufficient redundancy for meeting the survivability requirements of modern electric ships. The system shown in Figure 3 is representative of a system with total installed generation from 5 MW to 80 MW. Systems with installed power greater than 5 MW should use MV.

The system shown in Figure 3 uses conventional technology, and its problems are mostly associated with the size and weight of electrical equipment (i.e., motors, converters, transformers, switchgear, and filters) in relation to the ship size. The size and weight of electrical equipment might become a problem in cases when the total installed power required for propulsion and ship services becomes too high for the size of the ship (i.e., 40 MW for a frigate size vessel).