

IEEE Recommended Practice for the Design and Application of Power Electronics in Electrical Power Systems

IEEE Industry Applications Society

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IEEE
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IEEE Std 1662-2008)

IEEE Recommended Practice for the Design and Application of Power Electronics in Electrical Power Systems

Sponsors

Petroleum and Chemical Industry Committee
of the
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IEEE Power Electronics Society

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IEEE-SA Standards Board

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Abstract: Recommendations and requirements for the design and applications of power electronics in land-based (onshore) and marine (offshore) electrical power systems are provided in this standard. A wide range of power electronics equipment with aggregated power ratings at and above 100 kW with voltages equal or less than 52 kV (ac) or (dc) is covered. Existing engineering practices, analytical methods, and performance characteristics are described. Applicable international and local standards are referenced with appropriate guidance to provide users of the standard with correct criteria for design, testing, and maintenance necessary for reliable operation of integrated power systems.

Keywords: IEEE 1662™, integrated power systems, PEBB, power electronic building blocks, power electronics

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William Lockey
Earl MacDonald
Allan Mantoosh
David Mills
T. W. Olsen

Lorraine Padden
Julian Profir
Daniel Sabin
Michael Steurer
Giorgio Sulligoi
Albert Tucker
John Vergis
James Wilson

Technical comments from the following individuals have been implemented in this recommended practice:

Paul Barnhart
Paul Bishop
Dushan Boroyevich
Charles Brown
David Cartes

Narain Hingorani
Matti Lehti
Mirko Maksimcev
George Robinson
Timothy Robirds

James H. Rockot
Robert Schuerger
Peter Steimer
Eric Vaughn
Fred Wang

The following members of the individual balloting committee voted on this recommended practice. Balloters may have voted for approval, disapproval, or abstention.

David Aho
Ali AlAwazi
Dwight Alexander
Roy Alexander
Saleman Alibhay
John Amy
Paul Barnhart
Frank Basciano
Michael Basler
Thomas Basso
William Bloethe
Dennis Bogh
Frederick Brockhurst
Bill Brown
Gustavo Brunello
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Paul Cardinal
Leo Casey
Arvind Chaudhary
Robert Christman
Larry Conrad
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Matthew Davis

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Mamadou Diong
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Gary Donner
Neal Dowling
Ernest Duckworth
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Gary Fox
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Paul Giorsetto
Alexander Glaninger-
Katschnig
Mietek Glinkowski
Jalal Gohari
J. Travis Griffith
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Paul Hamer
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John Houdek
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Hermann Koch
Gerald Kolbe
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Hua Liu
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 Michael Roberts
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Joseph Rostron
 Daniel Sabin
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 Eric Udren
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 Eric Vaughn
 John Vergis
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Introduction

This introduction is not part of IEEE Std 1662-2016, IEEE Recommended Practice for the Design and Application of Power Electronics in Electrical Power Systems.

This revision of IEEE Std 1662-2008 provides recommendations and requirements for the design and applications of power electronics in land-based and marine electrical power systems. It covers a wide range of power electronics equipment with aggregated power ratings at and above 100 kW with voltages equal or less than 52 kV (ac) or (dc). It describes existing engineering practices, analytical methods, and performance characteristics. Applicable international and local standards are referenced with guidance to provide users of this standard with correct criteria for analysis, design, testing, and maintenance of power electronics and reliable integration of power electronics in electrical power systems.

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

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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 45TM-2002 and IEEE Std 1573TM-2003.~~

1.1 Scope

This document summarizes current electrical engineering methods and design practices for applying power electronics (PE) in electrical power distribution and conversion 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. It recommends PE equipment requirements, necessary power system analytical studies, PE design analysis and testing, and certification and inspection procedures.

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~~ PE equipment for ~~marine~~ electrical power systems. It analyzes the impact of ~~such concepts as~~ power electronics building blocks (PEBBs) or integrated power systems (IPSSs) on size, life cycle cost, weight, fuel efficiency, and risk reduction of implementation.

1.3 Limitations

This ~~guide~~ standard is applicable to ~~a wide range~~ design and applications of ~~power electronics~~ PE equipment ~~designed for, and installed in, shipboard environments~~ with aggregated power ratings at and above 100 kW in land-based and marine electrical power systems with voltages equal or less than 52 kV (ac) or (dc).

1.4 Equipment covered by this ~~guide~~ standard

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~~ standard 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~~ volt-ampere reactive (VAR)] support
- Solid-state circuit breakers, solid-state transfer switches, and solid-state soft starters
- Current limiters
- Motor drives
- Active harmonic filters
- Uninterruptible power supply (UPS)
- ~~High-power electric propulsion~~
- Energy storage and pulse load systems static VAR compensator (SVARC)
- Traction power-diode rectifier (TPR)
- Energy storage and pulse load systems
- Other equipment with built-in ~~power-electronics~~ PE that has ~~the ship's~~ a utility or microgrid service as the power source, such as auxiliary equipment, communication equipment, and radars

1.5 Guide for users

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

- Systems integrator
- System designer
- Equipment designer
- Component designer
- Equipment installer or repairman

~~e) Shipyard design and fabrication~~

~~f) Testing, certification, nationally recognized testing laboratory (NRTL), and authority having jurisdiction~~

- 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.

[CSA C22.1, Canadian Electrical Code.](#)²

[IACS UR E11, Unified requirements for systems with voltages above 1 kV up to 15 kV.](#)

[IEC 60068-2-2, Environmental Testing—Part 2-2: Dry Heat.](#)³

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³IEC publications are available from the International Electrotechnical Commission (<http://www.iec.ch/>). IEC publications are also available from the American National Standards Institute (<http://www.ansi.org/>).

[IEC 60068-2-6, Environmental Testing—Part 2-6: Vibration \(Sinusoidal\).](#)

[IEC 60068-2-30, Environmental Testing—Part 2-30: Damp Heat.](#)

[IEC 60146-2:1999, Semiconductor converters—Part 2: Self-commutated semiconductor converters including direct d.c. converters.](#)

[IEC 61439 \(all parts\), Low-voltage switchgear and controlgear assemblies.](#)

[IEC 62271-200, High-voltage switchgear and controlgear—Part 200: AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV.](#)

[IEEE Std 519™, IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems.^{4,5}](#)

[IEEE Std 1012™, IEEE Standard for System, Software and Hardware Verification and Validation.](#)

~~IEC 60146-1-1, Semiconductor Converters General Requirements and Line Commutated Converters 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~~ IEEE Recommended Practice for Powering and Grounding Electronic Equipment ([IEEE Emerald Book™](#)).

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[IEEE Std 1250™, IEEE Guide for Identifying and Improving Voltage Quality in Power Systems.](#)

[IEEE Std 1409™, IEEE Guide for Application of Power Electronics for Power Quality Improvement on Distribution Systems Rated 1 kV Through 38 kV.](#)

[IEEE Std 1547.1™, IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems.](#)

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

[IEEE Std 1676™, IEEE Guide for Control Architecture for High Power Electronics \(1 MW and Greater\) Used in Electric Power Transmission and Distribution Systems.](#)

[IEEE Std 1676™-2010, IEEE Guide for Control Architecture for High Power Electronics \(1 MW and Greater\) Used in Electric Power Transmission and Distribution Systems \(Figure 1\).](#)

[IEEE Std 1688™, IEEE Standard Requirements for the Control of Electromagnetic Interference Characteristics of Replaceable Electronic Modules.](#)

[IEEE Std 3003.2™, IEEE Recommended Practice for Equipment Grounding and Bonding in Industrial and Commercial Power Systems.](#)

[IEEE Std 3007.2™-2010, IEEE Recommended Practice for the Maintenance of Industrial and Commercial Power Systems.](#)

[IEEE Std C37.20.1™, IEEE Standard for Metal-Enclosed Low-Voltage \(1000 Vac and below, 3200 Vdc and below\) Power Circuit Breaker Switchgear.](#)

[IEEE Std C37.20.7™, IEEE Guide for Testing Switchgear Rated up to 38kV for Internal Arcing Faults.](#)

[IEEE Std C37.90.1™, IEEE Standard for Surge Withstand Capability \(SWC\) Tests for Relays and Relay Systems Associated with Electric Power Apparatus.](#)

[IEEE Std C57.18.10™, IEEE Standard for Practices and Requirements for Semiconductor Power Rectifier Transformers.](#)

[IEEE Std C62.92.1™, IEEE Guide for the Application of Neutral Grounding in Electrical Utility Systems—Part 1: Introduction.](#)

[ISO 9001, Quality management systems: Requirements.](#)⁶

[NEMA ICS 1.1, Safety Guidelines for the Application, Installation, and Maintenance of Solid State Control.](#)⁷

[NEMA ICS 10, AC Transfer Equipment, Part 2: Static AC Transfer Equipment. NFPA 70®, National Electrical Code® \(NEC®\).](#)^{8,9}

[UL 347A, Medium Voltage Power Conversion Equipment.](#)¹⁰

[UL 508C-2008, Standard for Power Conversion Equipment. UL 1008S, Standard for Solid-State Transfer Switches.](#)

[UL 1066, Standard for Low-Voltage AC and DC Power Circuit Breakers Used in Enclosures.](#)

[UL 61800-5-2, Standard for Adjustable Speed Electrical Power Drive Systems—Part 5-2: Safety Requirements.](#)

⁶ISO publications are available from the International Organization for Standardization (<http://www.iso.org/>). ISO publications are also available from the American National Standards Institute (<http://www.ansi.org/>).

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IEEE Std 1573TM-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~~ [document](#), the following terms and definitions apply. The ~~Authoritative Dictionary of IEEE Standards Terms~~ [B23]⁵ [Dictionary Online](#) should be ~~referenced~~ [consulted](#) for terms not defined in this clause.¹¹

active filtering: Controlling power quality without [impacting](#) primary control of system voltage.

[energy storage system \(ESS\):](#) [System that is capable of absorbing energy, storing it, and dispatching the energy back into the power system.](#)

~~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.~~

~~catastrophic~~ fault: ~~A sudden and total failure from which recovery is impossible~~ [An abnormal condition exceeding designated limits](#) and ~~from~~ which [warrants](#) immediate shutdown ~~is warranted.~~ [Catastrophic of the entire system.](#) Faults often lead to cascading systems failure [if not addressed correctly.](#)

~~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).~~

¹¹[IEEE Standards Dictionary Online](#) is available at: <http://dictionary.ieee.org/>.

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

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

integrated power system (IPS): A power system where all prime movers are used to produce electrical power that is shared among propulsion, mission, ~~and ship~~ microgrids, or service loads. Discriminating attributes of ~~integrated power systems~~ IPSs 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~~ loads.

land-based (offshore) power systems: Power systems installed on the land as distinguished from being in deep or open waters.

line replaceable unit (LRU): A modular component designed to be replaced quickly at location.

low voltage: Rated 1000 V (ac) or 1500 V (dc) and below.

marine (offshore) power systems: Power systems with multiple power sources installed on ships, boats, mobile, and fixed offshore units.

medium voltage (MV): ~~1 kV to 35 kV.~~ Rated above 1000 V (ac) or 1500 V (dc) and less than or equal to 52 kV.

per unit (PU): The reference unit, established as a calculating convenience, for expressing all power system electrical parameters on a common reference base. One PU is 100% of the base chosen.

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

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.-

power electronics (PE): Single device or system utilizing power semiconductors for conversion, switching, protection, and distribution of electrical power.

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

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

resistance grounded: Grounded through impedance, the principal element of which is resistance, to limit current to the ground.

solidly grounded: Connected directly to ground through an adequate ground connection in which no impedance has been inserted intentionally.

sourcing: Converting power ~~and providing primary~~ from one or more voltage or frequency levels while being in control of system the output voltage or current (or phase angle in the case of alternating current) at its electrical output terminals.

ungrounded: A system, circuit, or apparatus without an intentional connection to ground, except through voltage-indicating or measuring devices, or other very high impedance devices.

~~**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).~~

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.~~ by zones where a zone is a logical and physical grouping of generation, storage, or consumption assets arranged in a common neighborhood. Zones with generation or storage may be operated for periods of time independently from the power system. A zone is the smallest logical and physical grouping of assets.

3.2 Acronyms and abbreviations

2-D	two-dimensional
3-D	three-dimensional
ac	~~-alternate~~ <u>alternating</u> current
AFE	active front end

[BSES](#) [backup stored energy system](#)

dc direct current

EMC electromagnetic compatibility

EMI electromagnetic interference

EMP electromagnetic pulse

[ESS](#) [energy storage system](#)

HMI human machine interface

HRG high resistance grounding

[HSSB](#) [hybrid solid-state breaker](#)

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~~ [to repair](#)

MV medium voltage

[MVDC](#) [medium voltage direct current](#)

[NEC](#) [National Electric Code[®] \(NEC[®]\) \(NFPA 70\)](#)

PE power electronics

PEBB	power electronic building block
PU	per unit
PWM	pulse width modulation
QOS	quality of service
SCR	silicon controlled rectifier, thyristor
SMES	superconducting magnetic energy storage
SSCB	solid-state circuit breaker
SSSS	solid-state soft starter
~~STBD~~	~~starboard~~
STS	solid-state ~~transistor~~ transfer switch
SVARC	static VAR compensator
TCR	thyristor controlled rectifier
TPDR	traction power diode rectifier
TRD	total rated-current distortion
~~SWGR~~	~~switchgear~~
UPS	uninterruptible power supply
VAR	~~visual-aural range~~ volt-amp reactive
VFD	variable frequency drive
VSC	voltage source converter
VSI	voltage source inverter

4. Power electronics (PE) 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~~. They are listed as follows:

a) Power conversion

- 1) Sourcing: The PE ~~equipment may~~ could 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~~ alternating current (ac)] at its electrical output terminals. The PE may ~~provide~~ include substantial energy storage ~~capability~~. capacity. 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~~ should protect equipment, conductive path, and continuity of power. As such, it does not convert power between voltage or frequency levels, nor does it ~~provide~~ include any substantial energy storage ~~capability~~ capacity. Examples for this application are transfer switch, fault current limiting circuit breaker, and crowbar switches.
- 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~~ later 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 to which it is connected 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 (ESS) 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~~ should be powered from the flywheel ~~energy storage system~~ ESS, its machine inverter will change its function to *sourcing* because it then controls the voltage in the dc system.
- Bi-directional 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 protective function is specifically called out in this guide. Examples ~~are~~ include static transfer switches, solid-state fault current limiters, and solid-state crowbar switches~~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 wave-form component. Only ~~a static VAR compensator~~ an SVARC, 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 Recommended PEBB architecture for PE 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 over temperature. [From IEEE Std 1676-2010,¹² recommended PEBB architecture for PE applications is shown in Figure 1.](#)

4.3 Typical applications

[Examples of typical and future applications of PE in electrical power systems described by Wheeler and Bozhko \[B53\], Nii and Makato \[B48\], Dragicevic et al. \[B2\], and Khersonsky \[B34\] are shown in Figure 2.](#)

~~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**~~

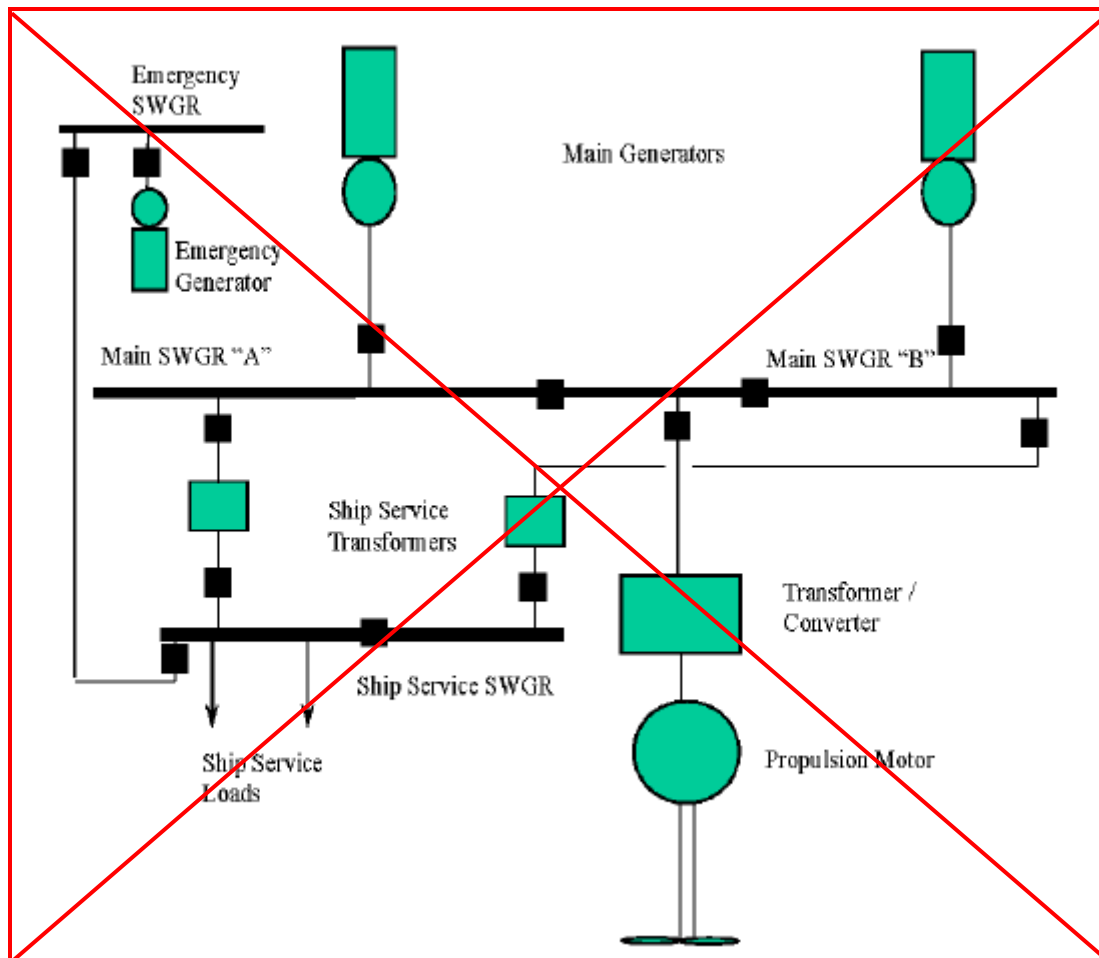
Acronym	Description
ACFC	AC frequency converter
AC/DC	AC rectifier
DC/AC	AC inverter fed from dc source
DC/DC	DC converter fed from dc source
STS	Solid-state transfer switch
FIU	Fault interrupting or fault limiting equipment
STATVAR	Static reactive power (VAR) compensator
AHF	Active harmonic filter
VFD	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

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¹²[Information on references can be found in Clause 2.](#)

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.



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~~Figure 1 Single propulsor fed from two main buses~~

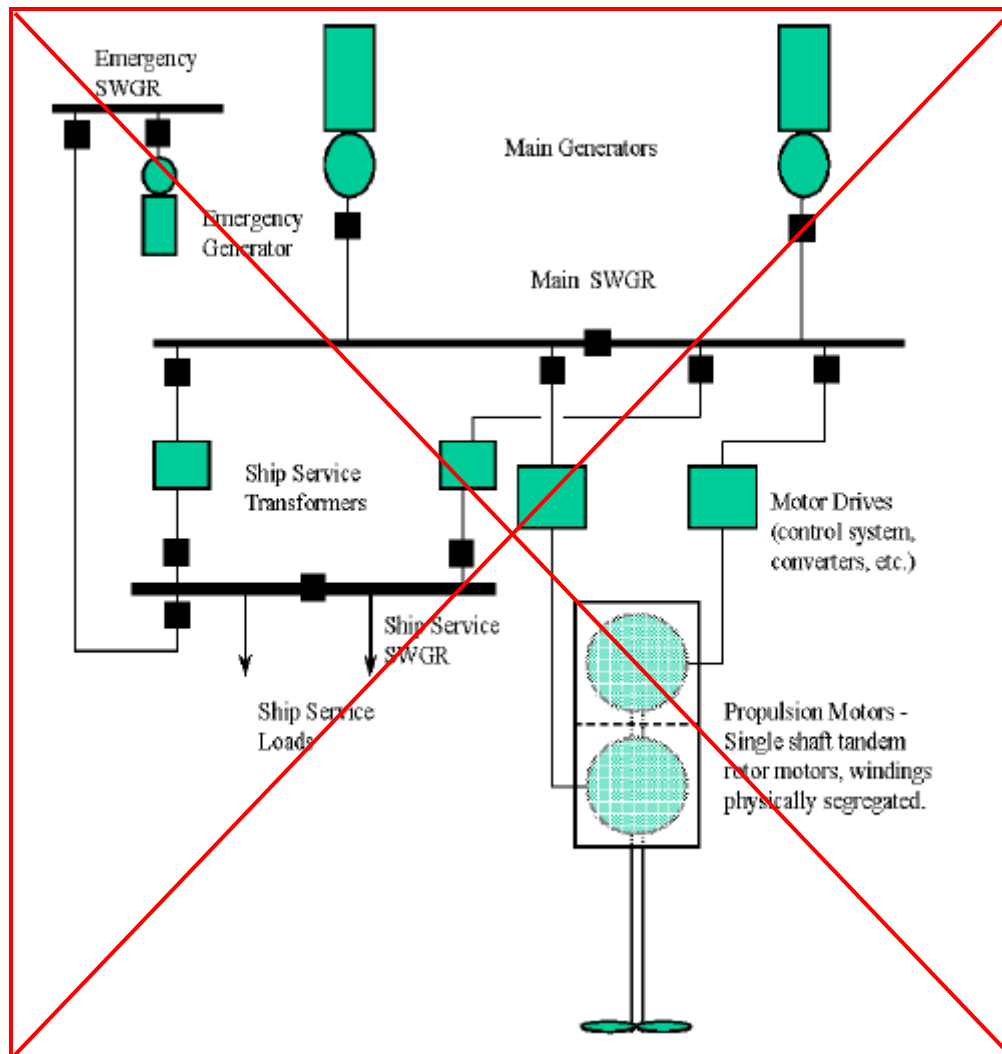
The system features dual redundant main bus and ship service bus arrangements. The main buses can be physically separated for greater survivability because they are equipped with their own tie circuit breakers. Ship service buses are fed from two ship service transformers. If the main power generation 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).

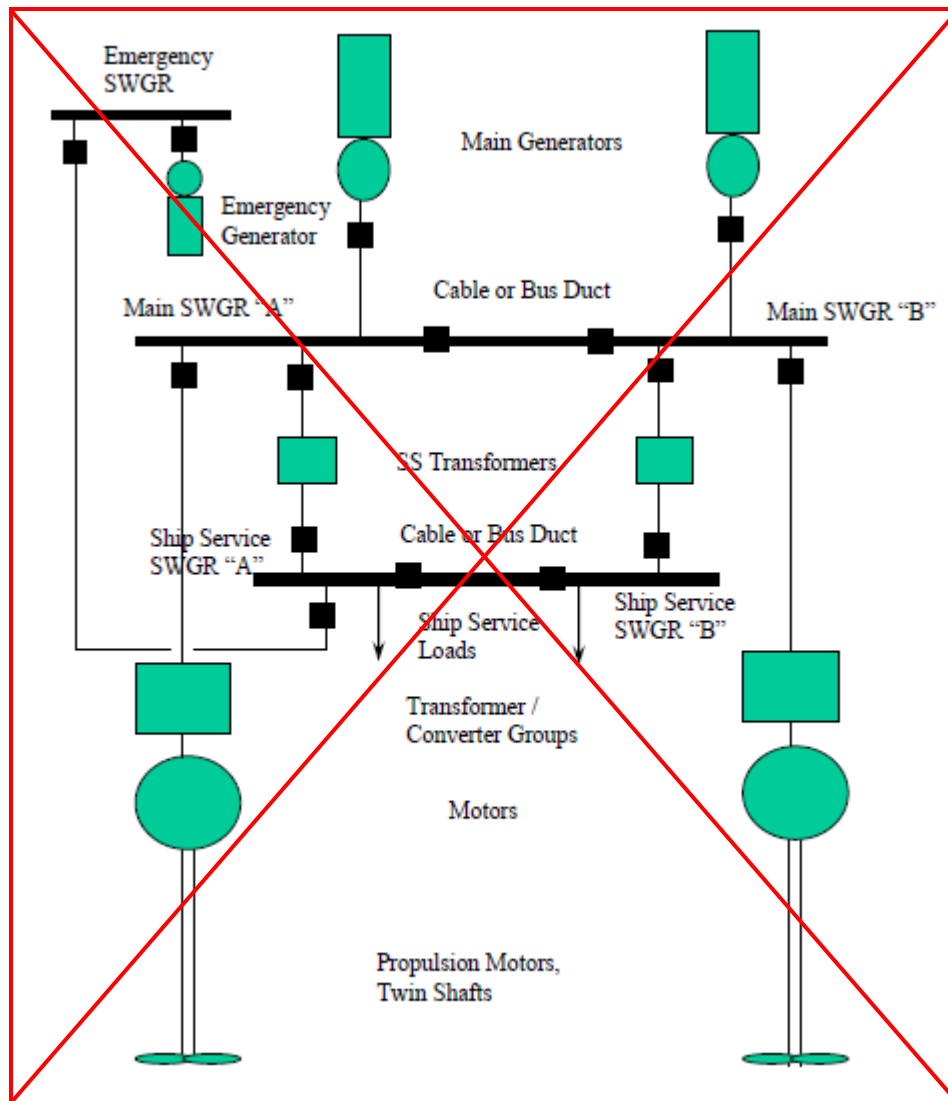


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~~Figure 2—Single-propulsor system with dual winding motor fed from two main buses~~

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).



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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).

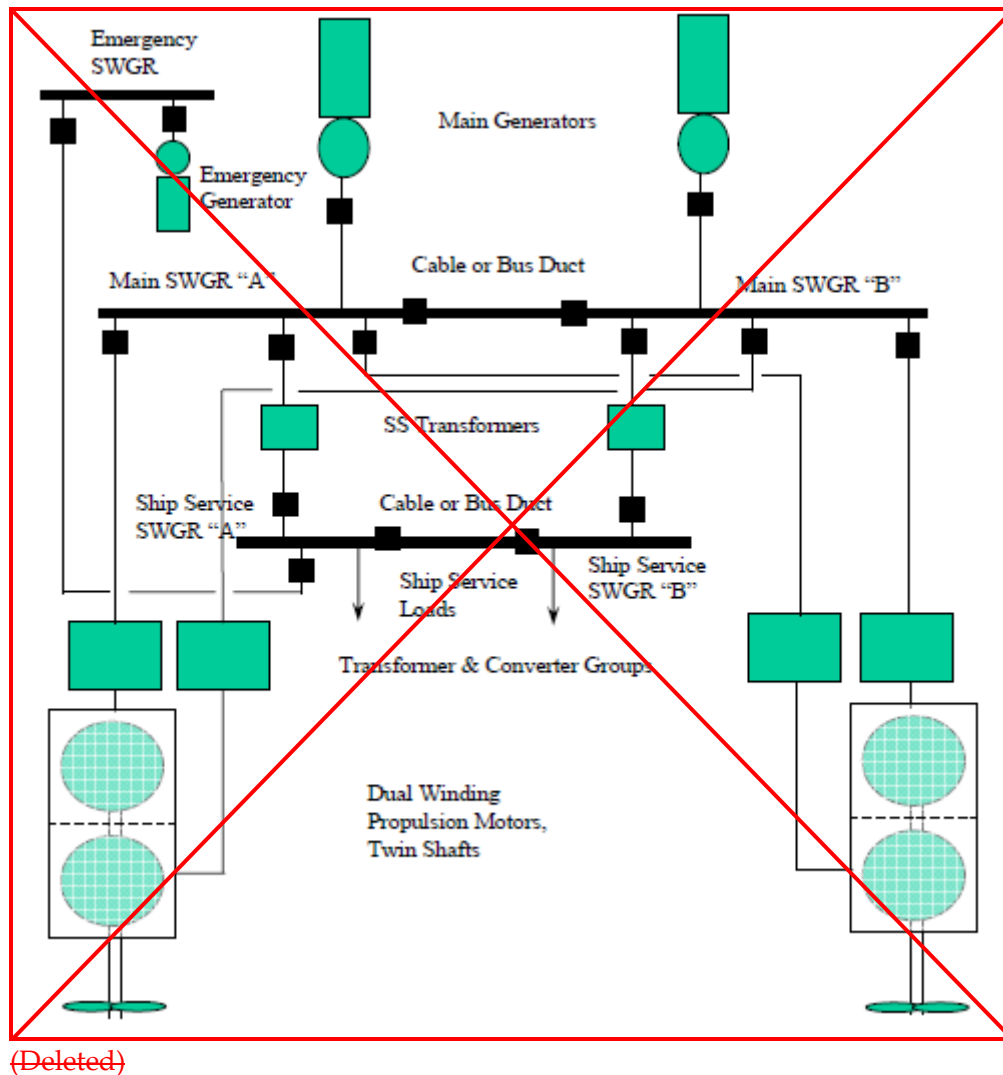
4.2.4 Dual-propulsor system with dual-winding propulsion motors (one motor winding can be cross fed)

The electrical power distribution system shown in Figure 4 is essentially an “improved Figure 3” system. The system is more than dual-redundant and less than triple-redundant. The system survivability is increased as follows:

- a)—— Optional cross-feeding of the propulsion motors from the opposite bus
- b)—— Applying dual-winding motors that are fed from pairs of transformers/converters

Continued survivability improvement can be achieved as follows:

- Increasing the number of generators on 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



**~~Figure 4—Dual propulsor system with dual winding propulsor motors
(one winding can be cross fed)~~**

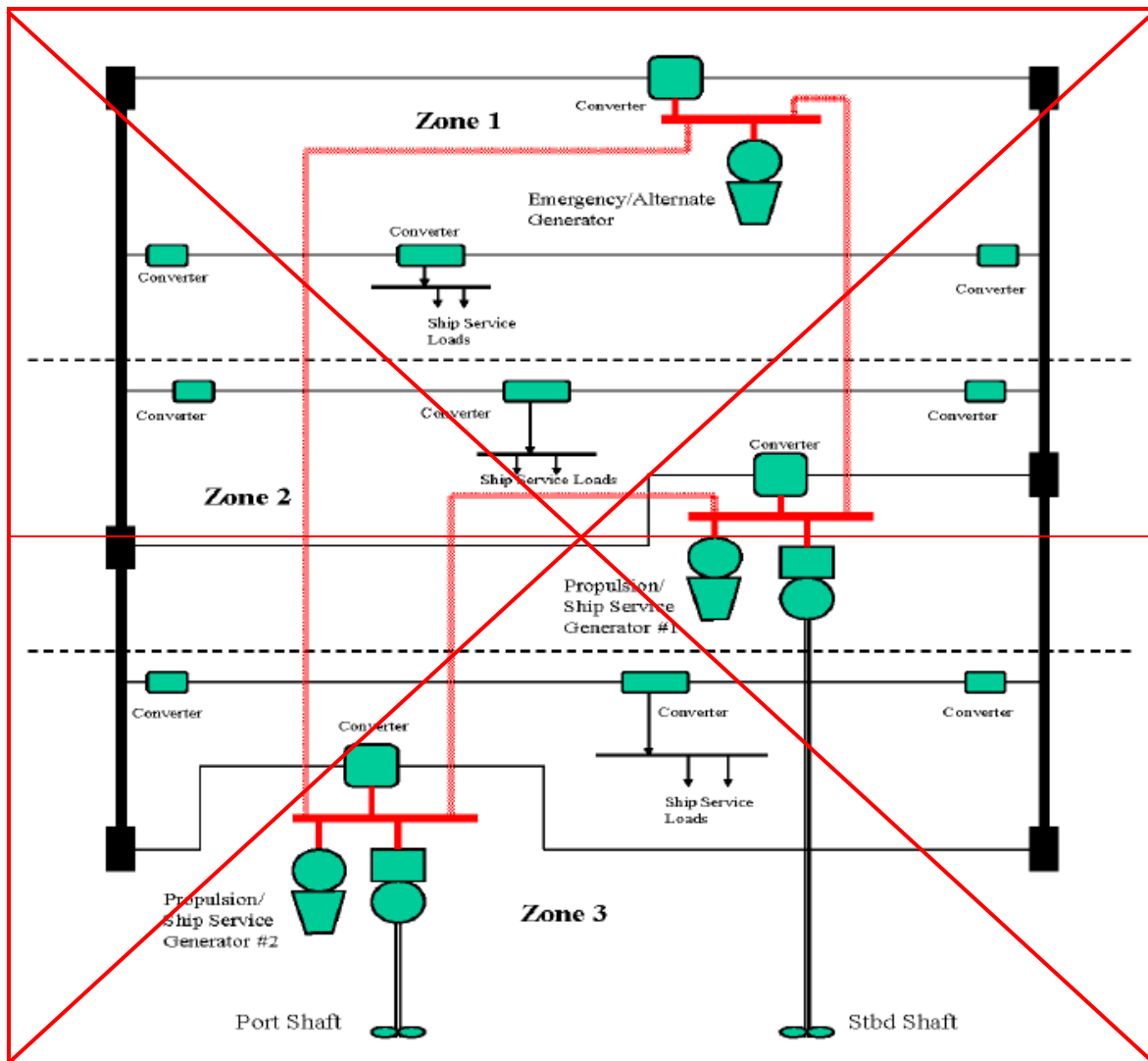
~~The system provides sufficient redundancy for meeting the survivability requirements of modern electric ships. All technology required for building of this type of electric ship is currently available. Future developments in the areas of superconductivity can greatly improve the system. Future component replacement (insertions) is possible (i.e., high temperature superconductor motors and generators, fault current limiter, and so on). The potential problems are the same as for Figure 3.~~

4.2.5 Zonal distribution with conventional propulsors

The system shown in Figure 5 is representative of an electric ship system with zonal distribution. This notional system has two main gas turbine generator sets and an auxiliary turbine generator. The main bus shown is MV ac. The system has two propulsors. Each propulsion motor is supplied by two transformers, and each transformer can be fed from a separate main bus source. The ship's service power is derived from the same bus, and loads are categorized as critical and noncritical. Noncritical loads are fed from load centers directly from step down transformers. Critical loads are fed from either port or starboard power distribution buses through the semiconductor transfer switches. Ultra fast static switches are utilized for disconnection of faulted loads. The zonal system contains feeder cables, including port and starboard power distribution buses, local feed and equipment power feed buses, as well as loads in each zone.

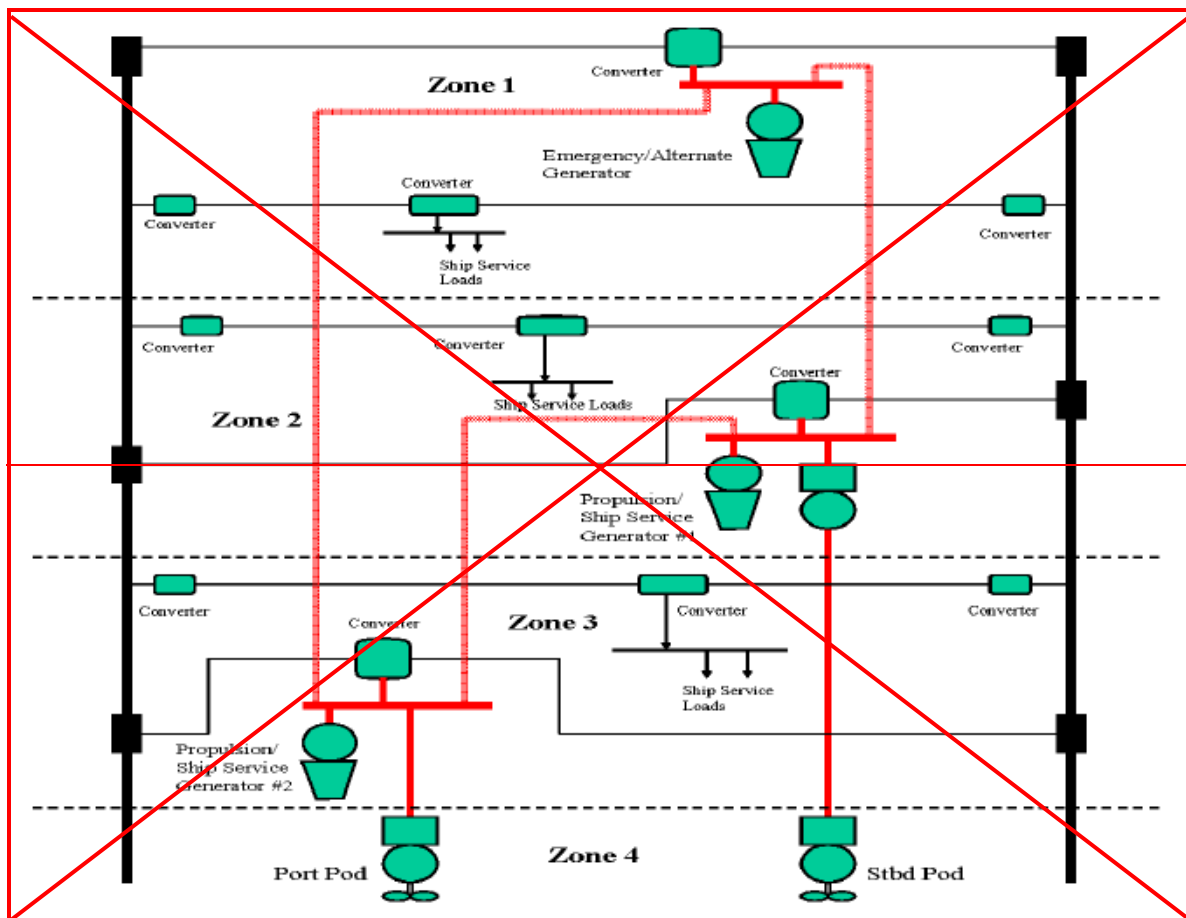
The power distribution system is redundant; in case of an electrical fault in either the PORT or starboard (STBD) feeders, the power to the loads is provided by the alternative feeder. Power is transferred by semiconductor transfer switches. As soon as a fault in the PORT or STBD power distribution buses is detected, the electric power is disconnected from the affected zone by circuit breakers or disconnect switches, whereas power to the loads is rerouted by the transfer switches through unaffected alternative feeders. The described system is still under development, and most of its key building blocks either are not commercially available or, if available, they are very expensive.

The configuration shown in Figure 6 is essentially identical to the one from Figure 5 with one exception, in that the propulsion motors are located within the pod structures. The podded propulsion benefits are well explained and documented elsewhere. They mostly relate to better ship maneuvering capability, better propulsion motor cooling, and lower fuel consumption. However, the system described in Figure 6 is characterized by the same problems as the one shown in Figure 5. The survivability is perceived to be lower because both propulsion motors are located outside of the hull and are therefore susceptible to damage from underwater shock.



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Figure 5—Zonal distribution with conventional propulsors



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Figure 6—Zonal distribution with podded propulsors

4.2.6 Integrated power system

The systems shown in Figure 6 are also known as integrated power systems (IPs), where all prime movers produce electrical power that is shared among propulsion and ship service loads. The 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, as well as flexibility of redistributing available electrical power for future electrical weapons. These attributes permit the lower IPS propulsion transmission efficiency to be offset by improvements in the fuel efficiency of the prime movers, improvements in the efficiency of the propulsor, and reductions in hull drag. Mechanically decoupling prime movers from propulsors enables segregation and separation of ship propulsor components.

5. General requirements

5.1 Introduction

PE should comply with the IEEE, IEC, and UL standards applicable to the specific type of PE equipment, standards listed as normative in Clause 2, as well as with all requirements in this standard.

~~Cross references to performance requirements are shown in Table 2.~~

Table 2—References for power electronics equipment requirements

Performance evaluation requirements	Clause in this document
System voltages	5.1
Power rating	5.2
Duty cycle	5.4
Efficiency	5.5
No-load losses	5.6
Overload	5.7
Stress limits and derating factors	5.8
Power quality requirements	5.9
Grounding	5.3
Protection requirements	5.10
Protection for regenerated power	6.17
Inrush current protection	5.10.5
Overvoltage protection	5.10.1
Protection against moisture and condensation	6.14.2
Surge voltage withstanding capability	5.11
Dynamic requirements	6.3
Size and weight	6.1
Reliability requirements	6.2
Maintainability requirements	6.2
Selection of parts	6.2.1
Isolating means	6.6
Fuses	6.7
Solid state power switches	6.8
Heat dissipation	6.9
Environmental	6.10
Ambient temperature	6.10.1
Cooling	6.10.2
Airborne noise	6.10.3
Structure-borne noise	6.10.4
Vibration	6.10.5
Electromagnetic interference (EMI)	6.11
Data communication	6.12
Control circuits	6.13
Software	6.5
Enclosures	6.14
Clearance and creepages	6.19
Power cables terminations	6.20
Network and control cable terminations	6.21
Quality assurance requirements	6.22

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5.1 System voltages

The system voltage selection should be performed by a system designer and will correspond to the power level, with consideration of cable size and protection. For example, the voltage of 1 kV or greater is recommended for systems of 5 MW or greater. Nominal voltages for ac and low voltage dc are well established in active IEEE standards. Nominal voltages for medium voltage dc are being developed by the IEEE P1709 Working Group. The power electronics system's nominal output voltage ratings should be selected from the IEEE standard voltages.

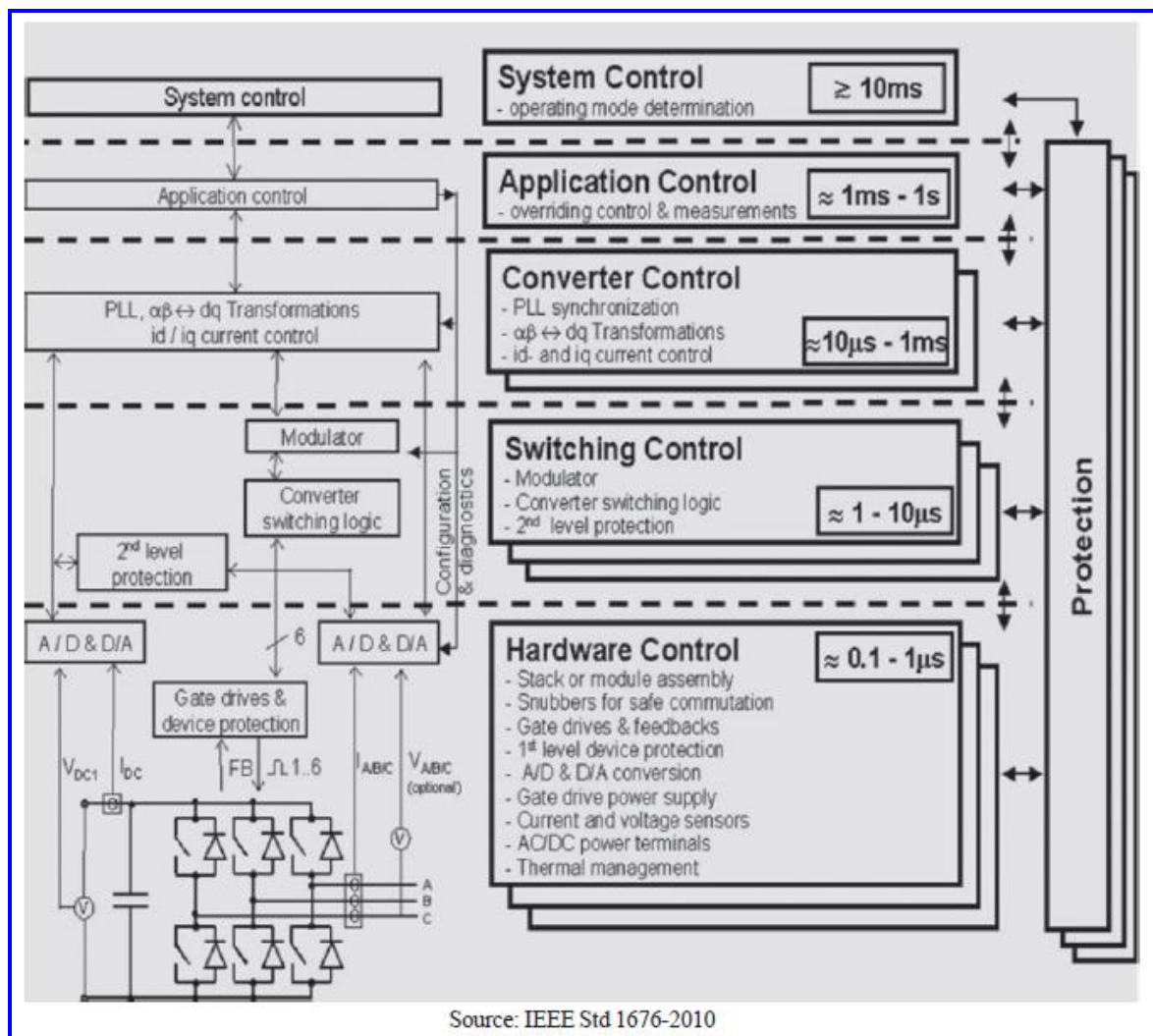
Power electronics equipment supplied from the electrical distribution systems should be capable of being operated satisfactorily under normally occurring variations in voltage, frequency, and power quality requirements, as stated herein.

The electrical equipment supplied from the main or emergency systems are to be capable of being operated satisfactorily under normally occurring variations in voltage and frequency. Unless otherwise specified in national or international standards, the variations in Table 3 through Table 5 from the rated value as defined in IACS UR E5-2005 [B41] should be assumed.

5.2 Power rating

The [PE](#) power rating can be impacted by environmentally specific requirements, overload conditions, and protection equipment. The [nominal](#) power rating of ~~power electronics~~ [PE](#) equipment is the rated load at which the equipment can continuously operate without exceeding the steady-state temperature rise as specified by the manufacturer. The nominal rating ~~is~~ [should be stated on](#) the nameplate ~~rating~~.

Power converters often have constant power load and also are subject to voltage and current limits; therefore, the power ratings are often functions of the source and load conditions. For example, high and low line voltage conditions often result in different power capabilities from those of the nominal conditions, and therefore, the requirements specified should consider these conditions. Dynamic operating conditions such as start-up inrush, ride through, switching transients, and faults can also impact the converter power rating characteristics. ~~These operating conditions require system level analysis.~~



(New)

Figure 1—Recommended architecture for PE applications

These operating conditions require system-level analysis. In addition, efficiency and power factor are two important converter parameters. Note that the displacement factor is often used in place of power factor, although strictly speaking, the displacement factor only refers to the ~~fundament~~ fundamental frequency, voltage, and current relationship.

~~Power electronics equipment~~ PE should be designed for continuous operation at 110% ~~(as defined in~~ of rated power (IEEE Std 1566TM-2005) within the maximum ambient and cooling water or air temperature (if water or air cooled) without reduction of the equipment's ~~rated performance criteria.~~

~~Power electronics equipment should be used in preference to electromechanical equipment to supply electric power having characteristics that differ from those of the power furnished by the ship service distribution.~~

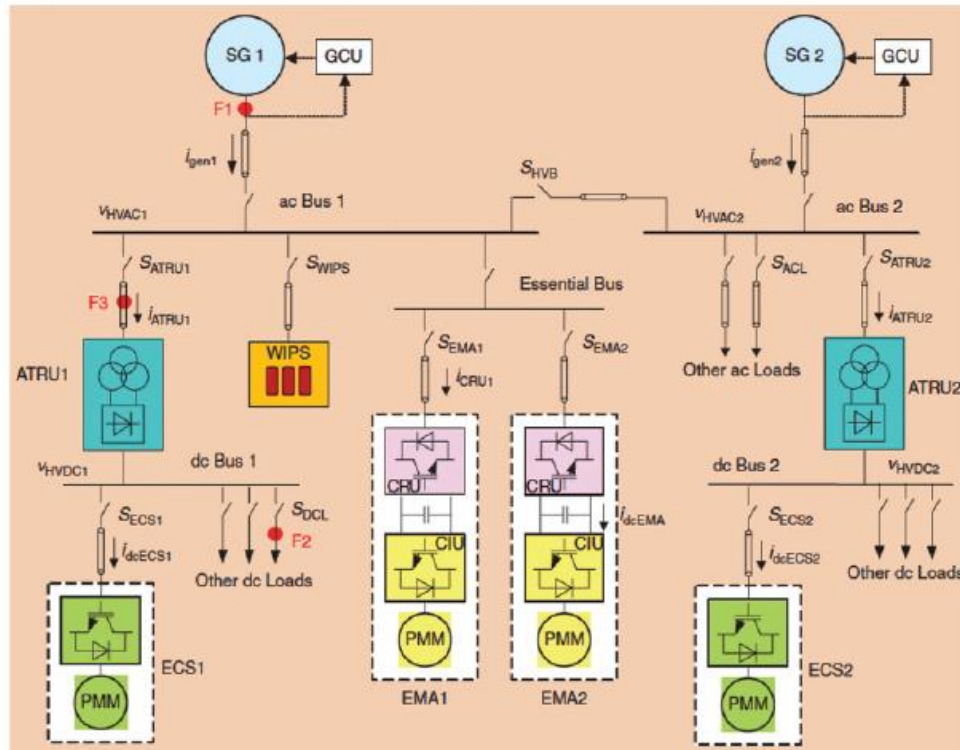
~~Where practical, power electronics equipment having similar power characteristics should be of identical ratings. It is desirable to minimize the number of distinct sizes and ratings.~~

The number and type of ~~power electronics~~ PE equipment and the capacity for a specific application should be determined as follows:

~~——Power electronics equipment should be selected to have standard ratings.~~

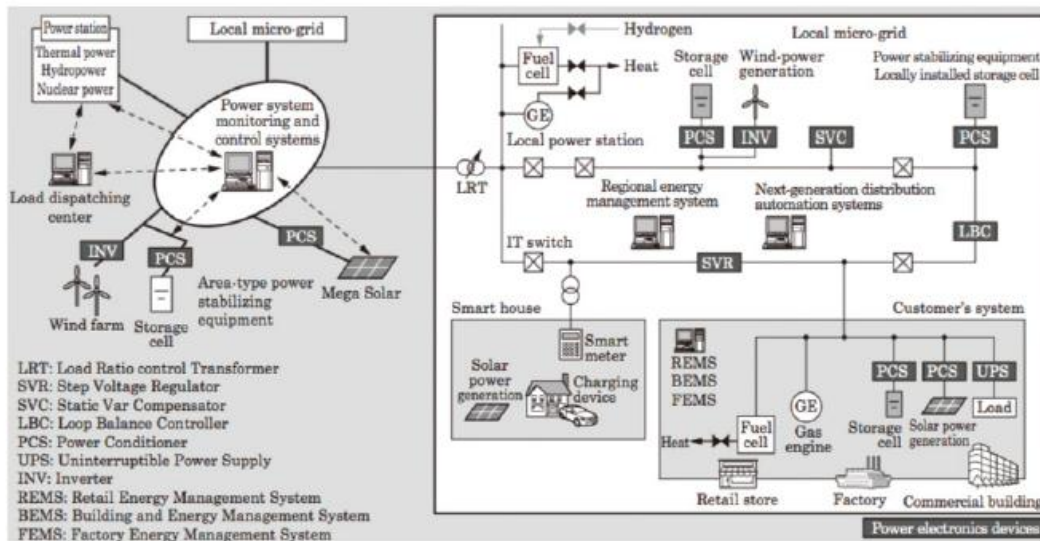
- The selection of capacity for ~~power electronics~~ PE equipment supplying groups of loads should be based on the normal operating load under the specified ~~ship~~ operating conditions ~~(shore, anchor, cruising, battle, or functional),~~ as determined by the load analysis. The reserve capacity to support the microgrid or ship service load and future growth should be provided as specified in the acquisition specification. The selection of capacity for ~~power electronics~~ PE equipment supplying individual loads should be based on normal connected load unless otherwise specified.

⁶~~Notes in text, tables, and figures are given for information only and do not contain requirements needed to implement the standard.~~



a) Electric aircraft

Source: Wheeler and Bozhko, "The More Electric Aircraft," *IEEE Electrification Magazine* [B35] © 2014.



b) Smart grid

Reprinted with permission from Fuji Electric, "Power Electronics Technology that Supports Smart Grid" [B49] © 2011.

(New)

Figure 2—PE applications in power systems

5.3 Voltage requirements

5.3.1 Rated voltages

The system voltage selection should be performed by a system designer and is driven by the power level, with consideration of cable size and protection devices limitations. Nominal voltages for ac systems are defined in IEEE Std C37.20 and the IEEE C37.100 series of standards for switchgear assemblies. Nominal voltages for medium-voltage direct current (MVDC) in IEEE Std 1709 [B22] could be applied.

PE supplied from the electrical distribution systems should be capable of being operated satisfactorily under occurring variations in voltage, frequency, and power quality conditions, as stated herein. The electrical equipment supplied from the main or emergency systems are to be capable of being operated satisfactorily under occurring variations in voltage and frequency. Unless otherwise specified in national or international standards, the variations in Table 1, Table 2,¹³ and Table 3 apply.

Table 1— Voltage and frequency variations for ac distribution systems

Quantity in operation	Permanent variation	Transient variation (recovery time)
Frequency	±5%	±10% (5 s)
Voltage	+6%, -10%	±20% (1.5 s)

¹³Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.