Shipboard
Installations & Design
Electrical Short Course

IEEE Format / Electric Equipment Design Considerations / Terminology / Theory

Power System Characteristics / Generation & Distribution / Electrical Studies

by

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Nomenclature[1]

ABS	American Bureau of Shipping	-
AC	Alternating Current	-
AFD	Adjustable Frequency Drive	-
ALF	Accuracy Limit Factor	-
API	American Petroleum Institute	-
ASD	Adjustable Speed Drive	-
ATS	Acceptance Testing Specifications	-
ANSI	American National Standards Institute	-
ASTM	American Society for Testing and Materials (International)	-
CFR	Code of Federal Regulations	-
COLREGS	International Regulations for Preventing Collisions at Sea	-
CONOPS	Concept of Operations	-
DAC	Damped Alternating Current	-
DAR	Dielectric Absorption Ratio	-
DC	Direct Current	-
ECS	Electrical Commissioning Specifications	-
EIA	Electronic Industries Alliance	-
EMC	Electromagnetic Compatibility	-
EMI	Electromagnetic Interference	-
EPLA	Electric Plant Load Analysis	-
EPS	Electric Power System	-
FMEA	Failure Mode and Effects Analysis	-
FS	Security Factor	%
HMI	Human Machine Interface	-
ICRP	International Commission on Radiological Protection	-
IEC	International Electrotechnical Commission	-
IEEE	Institute of Electrical and Electronics Engineers	-

[1] Not all the nomenclature, symbols, or subscripts may be used in this course—but they are related and may be found when reviewing the references listed for further information. Further, all the nomenclature, symbols, or subscripts will be found in of many electrical courses (on SunCam, PDH Academy, and also in many texts). For guidance on nomenclature, symbols, and electrical graphics: IEEE 280-2021. IEEE Standard Letter Symbols for Quantities Used in Electrical Science and Electrical Engineering. New York: IEEE; and IEEE 315-1975. Graphic Symbols for Electrical and Electronics Diagrams. New York: IEEE, approved 1975, reaffirmed 1993.

IMO	International Maritime Organization	-
IP	Internet Protocol	-
IPS	Integrated Power System	-
ISEA	International Safety Equipment Association	-
ISO	International Organization for Standardization	-
MAC	Magnetron Atmospheric Condition	-
MCC	Motor Control Center	-
MTS	Maintenance Testing Specifications	-
NEC	National Electrical Code	-
NECA	National Electrical Contractors Association	-
NETA	InterNational Electrical Testing Association	-
NIST	National Institute of Standards and Technology	-
NFPA	National Fire Protection Association	-
NIOSH	National Institute for Occupation Safety and Health	-
OEM	Original Equipment Manufacturer	-
OSHA	Occupational & Safety Health Administration	29CFR1910/1926
PI	Polarization Index	-
QoS	Quality of Service	-
RF	Rating Factor	-
RFI	Radio Frequency Interference	-
RTD	Resistance Temperature Detector	-
SCADA	Supervisory Control and Data Acquisition	-
SOLAS	International Convention for the Safety of Life at Sea	-
TCP	Transmission Control Protocol	-
THD	Total Harmonic Distortion	%
TDR	Time Domain Reflectometer	-
UDP	User Datagram Protocol	-
UL	Underwriters Laboratories, Inc.	-
UPS	Uninterruptible Power Supply	-
USNS	United States Naval Ship	-
VFD	Variable Frequency Drive	-
VLF	Very Low Frequency	-
VSD	Variable Speed Drive	-

Symbols

*	Optional Testing	-
C	Capacitance	F
Δ, δ	change (deviation)(delta)	-
ε,Δ	Deviation	%
η	Efficiency	%
E, *E*	Energy	J
f	frequency	Hz
I	Current	A
K	Remanence Factor	-
L	Inductance	H
LF	Load Factor	-
n	speed	rpm
P	Power	kW
p	poles	-
R	Resistance	Ω
T	Temperature	ºC
T	Time	hr
T	Tolerance	-
V	Voltage, Potential	V
X	Reactance	Ω

Subscripts

c	corrected	-
C	Capacitance	-
Gen	Generator	-
H	high	-
i	current	-
k	Knee Point	-
L	load	-
L	low	-
L	Inductance	-
max	maximum	-
min	minimum	-
m	meter	-
n	nominal (rated)	-
p	primary	-
r	remanence	-
R	Resistance	-
s	secondary	-
t	turns	-

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COURSE INTRODUCTION

The theoretical information is primarily from the author's books, Refs. [A] and [B]. The NESC Ref. [C] and NEC Ref. [D] though not covered in this course are useful sources for electrical engineers. Information useful in many aspects of electric engineering may be found in [E] and [F]. Reference [G] has detailed descriptions of analysis techniques. Reference [H] covers many terms in EE with excellent definitions and explanations. Reference [I] is the focus of this course. Reference [J], SOLAS, is part of the normative references. Reference [K], MARPOL, influences both the design and operation of ships. The appendices cover information useful in many engineering tasks.

CODE INFORMATION

Updates to the original IEEE 45 became too large for a single standard. So, around 2008 the standard was split into separate areas of focus. Today, those areas comprise the standards set shown in Fig. 1.

IEEE Std 45.1™-2016, IEEE Recommended Practice for Electrical Installations on Shipboard—Design

IEEE Std 45.2™-2011, IEEE Recommended Practice for Electrical Installations on Shipboard—Controls and Automation

IEEE Std 45.3™-2015, IEEE Recommended Practice for Shipboard Electrical Installations—Systems Engineering

IEEE P45.4™, Recommended Practice for Electrical Installations on Shipboard—Marine Sectors and Mission Systems

IEEE Std 45.5™-2014, IEEE Recommended Practice for Electrical Installations on Shipboard—Safety Considerations

IEEE Std 45.6™-2016, IEEE Recommended Practice for Electrical Installations on Shipboard—Electrical Testing

IEEE Std 45.7™-2012, IEEE Recommended Practice for Electrical Installations on Shipboard—AC Switchboards

IEEE Std 45.8™-2016, IEEE Recommended Practice for Electrical Installations on Shipboard—Cable Systems

Figure 1: IEEE 45 Series

The following is an excerpt from 45.1 Introduction, which is the focus of this course.

> The topics covered in this document should be considered from the beginning of the project and throughout the design and construction processes, and thereby should facilitate the integration of electrical systems at the shipyard level. Adherence to the IEEE 45.1 design process provides an effective set of integration requirements and identifies key issues and recommended solutions or options.

Since installations on a ship, especially military ones, seldom remain static, this course is meant to assist the electrical engineer during the modification, alteration, upgrade, or replacement of a system or piece of equipment in which this requirements may apply.[2] The overall structure follows.

- Overview
- Normative References
- Definitions, Acronyms, Abbreviations
- Systems Engineering
- Power System Characteristics
- Electrical Power System Elements
- Power System Design
- Electrical Power Generation
- Power Distribution
- Power Conversion
- Energy Storage
- Electrical Power System Control
- Motor and Motor Application
- Adjustable Speed Drive Applications
- Electric Propulsion and Maneuvering System
- Steering Systems
- Lighting Equipment
- Whistle and Siren Control Systems
- Heating Equipment
- Galley Equipment and Workshop Equipment
- Electrical Power System Protection
- System Studies, Analyses, and Reports
- EMI/EMC/RFI
- Materials
- Power System Grounding
- Arc Flash Management

[2] Admittedly, this will be skewed to the author's experience. The experience covers 2.5 decades of Navy service mostly on submarines but includes 3+ years as a material readiness inspector covering aircraft carriers, most of the submarine fleet at the time, USNS ships of the Military Sealift Command, and more. Each part of this structure are referred to as a "clause" with sub-paragraphs being "sub-clauses".

- Hazardous Locations, Installations, and Equipment
- Ship Construction and Outfitting
- System Operation and Maintenance
- Annex A: Bibliography
- Annex B: Electric Plant Load Analysis

1 OVERVIEW

This standard is considered "minimally acceptable guidelines" for equipment on both commercial marine vessels and Navy combatant ships. The focus is on electric power system and subsystem design. Changes made to shipboard systems, improvements, not covered should be equal in safety, reliability, and the general intent of this standard. The main purpose of the standard is to provide a consensus of design practices.

Mixing of standards being sometimes necessary is the choice of the user, the authority having jurisdiction, and/or the classification society.[3]

2 NORMATIVE REFERENCES

Normative references are considered part of this standard. As such they must be understood and used. How they related to this standard is explained in the text of the standard.

One such standard is IEC 60038 that specifies voltage ranges, including allowable voltage drops: 3% for lighting and 5% for everything else. See the IEC Voltage Range figure.

[3] Lloyd's Register is a well known classification society as is the American Bureau of Shipping (ABS).

IEC voltage range	AC RMS voltage (V)	DC voltage (V)
High voltage	**> 1,000**	**> 1,500**
Low voltage	50 to 1,000	120 to 1,500
Extra-low voltage	< 50	< 120

Figure 2: IEC Voltage Ranges

The list includes the National Electric Code® (NEC®), NFPA 70. See the entire list in Chapter 2 of IEEE 45.1.

3 DEFINITIONS, ACRONYMS, ABBREVIATIONS

A few of the definitions one doesn't encounter daily are given in this course.

For example, "amortisseur winding" is the permanently short-circuited winding used to inductively startup a synchronous motor. A "cargo vessel" is a vessel that carries bulk containerized, or roll-on/roll-off dry cargo *with no more than 12 passengers*. The term "electronics" indicates those devices in which conduction occurs by electrons moving in a vacuum, gas, or semiconductor.[4]

Capacitive reactance and inductive reactance are defined as follows. The capacitive reactance has a negative 90° phase angle and inductive reactance has a positive 90 ° phase angle.

Equation 1: Capacitive and Inductive Reactance.

$$X_C = \frac{1}{2pfC} = \frac{1}{wC}$$

$$X_L = 2pfL = wL$$

[4] So technically, florescent lights are "electronic"!

Though these are "common", they are mentioned because some texts include a negative sign in the capacitive reactance ($-1/wC$) while others expect one to know it's negative when combining the impedance elements of a circuit.

A "tank vessel" is one that carries liquid or gaseous cargo.

4 SYSTEM ENGINEERING

The relationship between systems engineering in IEEE 45.3 and IEEE 45.1 is shown in the figure below.

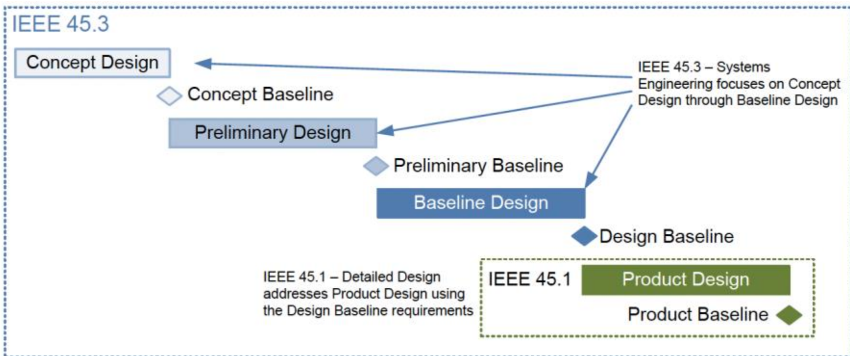

Figure 3: Design Process

The International Council on Systems Engineering (INCOSE) contains a great deal of explanatory material and the potential for certification. The Systems Engineering Guidebook is very useful for those working with the DoD (see Ref. [L]).

5 POWER SYSTEM CHARACTERISTICS

Standard three-phase systems include three-wire, three-phase (ungrounded, used on military ships) and three-phase, four-wire. Standard voltages are shown the table below.

Table 1: Standard Voltages

Standard	AC (V)	DC (V)
Power utilization	115, 200, 220, 230, 350, 440, 460, 575, 660, 2300, 3150, 4000, 6300, 10 600, 13 200	12, 24, 28, 115, 230, 270, 380 See IEEE Std 1709
Power generation	120, 208, 230, 240, 380, 450, 480, 600, 690, 2400, 3300, 4160, 6600, 11 000, 13 800	120, 240 See IEEE Std 1709

Standard frequencies are normally 60 Hz with 400 Hz used for ship mission equipment (which allows for greater accuracy).

Small vessels (≤ 15 kW) uses 120 V for generation, three-phase or single-phase. Single-phase loads should be balanced on a three-phase system. Intermediate vessels (≤100 kW) use 230 V or 240 V three-phase ass the generation voltage. Lighting is 120 V three-phase, three wire of 120/208 V three-phase, four-wire.[5] Large vessels use dual voltage systems at 450 V, 480 V, 600 V or 690 V for generation in the first consideration. Very large vessels the higher voltages in Table 1 may be used. DC, if required, is as specified in Table 1.

AC power characteristics are shown in Table 2.[6] All transient conditions are not listed.

Table 2: AC Power Characteristics

Characteristics	Limits
Frequency	
a) Nominal frequency	50/60 Hz
b) Frequency tolerances	± 3%
c) Frequency modulation	0.5%
d) Frequency transient:	
1) Tolerances	4%
2) Recovery time	2 s
e) The worst-case frequency excursion from nominal frequency resulting from item b), item c), and item d) 1) combined, except under emergency conditions.	5.5%
Voltage	
a) User voltage tolerance:	
1) Average of the three line-to-line voltages	± 5%
2) Any one line-to-line voltage, including item a) 1) and line voltage unbalances item b)	± 7%
b) Line voltage unbalance	3%

[5] Expect to see three-phase as 3ϕ and three- or four-wire as 3W/4W in some cases.
[6] DC power systems quality in the 28 V to 270 V are covered in MIL-STD-704F.

Example 1

What type of power system is expected for a small recreational sailboat with a 9.7 kW engine?

Solution

Small vessels (≤ 15 kW) generally use a 120 V single phase system.

Example 2

How should frequency be expected to deviate for a 60 Hz system?

Solution

The frequency tolerance from Table 2 is ±3%. So one should anticipate the following maximum excursion.

$$\begin{aligned} f_{\mathrm{D}} &= (f_{\mathrm{nominal}})(T) \\ &= (60\ \mathrm{Hz})(0.03) \\ &= 1.8\ \mathrm{Hz} \end{aligned}$$

Or, anywhere from 58.2 Hz to 61.8 Hz.

Frequency modulation is limited to 0.5% and is the periodic variation in frequency during normal operation that may be caused by repeated loading (e.g., air conditioning). For the purposes of this definition, the frequency modulation should not exceed 10 s.[7] In equation form, this modulation (in %) is as follows.

[7] Frequency modulation <10 s can result in tripping of protective features and interference with other operating equipment.

Equation 2: Frequency Modulation

$$M_{\% f} = \left[\frac{f_{\max} - f_{\min}}{2 f_{\text{nominal}}} \right] \times 100$$

5.9 Quality of Service (QoS)

First, QoS is a metric on the reliability of a system to provide power to the loads.[8] It is calculate and the mean time between service interruptions (MTBSI). Loads are separated into four categories: uninterruptible, short-term interrupt, long-term interrupt, and exempt.

An interruption is when power is outside acceptable parameters causing the parent system to be incapable of meeting requirements. Different loads are specified by two interrupt times: t1 and t2.

Uninterruptable load: A load that cannot tolerate service interruptions greater than t1.

Short-Term Loads: The term t1 indicates the maximum time to reconfigure the distribution system *without* bringing on additional generating capacity—measured in seconds. Common in naval vessels.

Long-Term Loads: The term t2 indicates the time it takes to bring on the slowest generation module. Time t2 is 1-5 minutes for naval vessels and <30 seconds for commercial vessels (or seek regulatory relief).[9]

Exempt Loads: These are loads that do not require restoration within t2, common on complex vessels such as naval combatants. The concept is limited to applications of sizing of the generating capacity of the ship.

5.10 Electric Power System Concept of Operation (EPS-CONOPS)

The concept of operations varies for a ship. For example, power requirements and priorities vary for in-port, transit, anchored, humanitarian relief, and combat. CONOPS is a focus on business

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[8] It was developed by the Navy in order to make reliability part of the system design. Anywhere power system reliability is a concern this requirement may be used.
[9] This may seem backwards, but commercial vessels don't have as much redundancy and operated often without the precautions Navy vessels make. Think of the Boston bridge collapse of 2024.

requirements and mission requirements. It includes margins for each operation and an allotment for future updates.

5.11 Marine Environmental Conditions

Normal conditions include moisture, salt atmosphere, waves and weather, high wind, and ice. Such condition must account for the temperature to which the ship is exposed and the temperature desired in the spaces. Vibration on equipment must withstand a frequency of 5 Hz to 50 Hz at a velocity amplified of 20 mm/s. Peak accelerations due to ship motion (see the figure below) for ships greater than 90 m is ± 5.9 m/s^2 and ± 9.8 m/s^2 smaller ships, with a duration of 5 s to 10 s. The figure below shows the six ship's motions. Roll (side to side, athwartships) and pitch (up and down, fore and aft) is given in the table below.

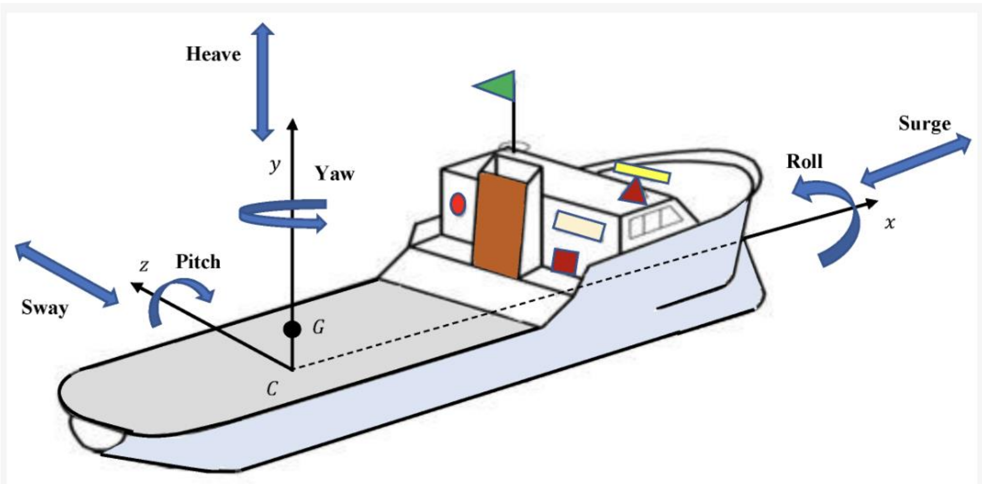

Figure 4: Ship Motion

[Source: *MDPI https://www.mdpi.com/1996-1944/15/2/674*]

Table 3: Roll and Pitch Requirement

[Source*: IEEE 45.1 Table 4*]

	Roll		Pitch	
	Static (°)	Dynamic (°)	Static (°)	Dynamic (°)
Ship service equipment	15	22.5	5	7.5
Emergency equipment [a]	22.5	22.5	10	10
Switchgear	45	45	45	45

[a] In vessels designed for carriage of liquefied gases and of chemicals, the emergency power installation is to remain operable with the vessel flooded to its permissible athwartship inclination up to a maximum of 30°.

Abnormal environmental conditions require special consideration—typically for complex vessels such as naval combatants.[10]

6 ELECTRIC POWER SYSTEM ELEMENTS

An electric power system (EPS) can be decomposed into the following elements: power generation; power distribution[11]; power conversion[12]; energy storage[13]; system supervisory control[14]; and loads.

Loads are broken into *uncontrolled loads* and *controlled loads*. Uncontrolled loads do NOT communicate the power system control while controlled loads do via a control interface. Controlled loads can be commanded to reduce loads or shut off in what is known as "shedding". A *large load* is defined as one that uses more than 20% of the online power generation capacity in any given operating condition.

7 POWER SYSTEM DESIGN

Though more meticulous, and complex in the explanation in the standard, when one generator is lost (the largest), the remaining generator capacity at 95% must supply all uninterruptible and short-term-interruptible loads.[15] The 95% is to allow for cycling loads.

Where an integrated power system (IPS) exists meaning electric power and propulsive are supplied from a common electrical plant when the largest generator is lost, the system must still allow for one half the design speed or 7 knots (whichever is less). The propulsion load is an exempt load.[16] Generator sets shall be designed for 110% continuous overloading though they should have the capacity to provide the end of service life electric load and the design propulsion load at 95% of capacity. Additionally, the IPS shall have the ability to prevent overloading the generators.

[10] Especially for submarines, which operate in two separate realms: surfaced and submerged.
[11] Shore power requirements are in IEC/ISO/IEEE 800005-1. Standard voltage simplify connecting to shore utility power.
[12] Power electronics requirements are in IEEE Std 1662.
[13] Energy storage requirements are found in IEEE Std 1826
[14] Sometimes listed as Supervisory Control and Data Acquisition or SCADA.
[15] This requirement is often called the "N-1" rule.
[16] This includes thrusters on large ships.

Emergency generators be sized to carry 100% of connected loads essential for safety of ship in an emergency situation. The emergency generators should start-up and be capable of carrying the full rated load within 45 s of loss of normal power. The start-up system shall be capable of at least six consecutive starts.

Emergency batteries should be capable of providing the emergency load without recharging while maintaining voltage within +5% to −12% of nominal.

The following are considered "final emergency circuits".

- one fire pump
- navigation lights
- emergency radio
- whistle and siren
- one sprinkler pump
- lifeboat flood lights
- navigation equipment
- emergency bilge pump
- daylight signaling lamp
- one steering gear system
- essential emergency communications

The time factor for supplying emergency power is given in the table below.[17]

Table 4: Minimum Time for Emergency Power

[Source: *IEEE 45.1 Table 5*]

Minimum time factor (hours)		
	Passenger vessels	**Cargo vessels**
Ocean and coastwise		
Under 1600 gross tons	12	12
1600 gross tons and over	36	18
Great Lakes		
Vessels navigating more than 4.8 km[a] offshore	8	8
Vessels navigating not more than 4.8 km[a] offshore	3	3
Ferries on runs over 1 h	2	
Ferries on runs under 1 h	1	
Great Lakes and rivers		
Ferries on runs over 1 h	2	
Ferries on runs less than 1 h	1	
Other vessels	3	3

[a] 3 statute mi

[17] A statute mile is 1,760 yards, which a sailor might call a "land mile". A nautical mile (M) is 1' (1 minute) of arc length of latitude or 1/60 of a degree at the equator—approximately 6,075 ft or 2025 yards. The Navy routinely rounds this to 2000 yards.

Harmonics, and frequencies not exactly the system frequency, tend to result in overheating of components. Additional information is in IEEE Std 519.

8 ELECTRIC POWER GENERATION

Diesel-fueled prime movers are the most practical driving ac or dc generators. Natural gas is also used, as are a variety of other sources. Steam generated from nuclear is used on military aircraft carriers and submarines. Gasoline engines are generally unacceptable because slow-speed diesels engines are more efficient and greater power capabilities—and when used to directly move the screw, they operate at or near the low-rpm required for propulsion.

All the material used must be protected against corrosion. Further, generating sets should have a minimum of 0.460 m [1.509 ft] between the generator sets and surrounding object for accessibility.[18]

Prime mover for rotating generators have a minimum continuous shaft power given by the equation below.

Equation 3: Generator Power

$$P_{\text{shaft min,kW}} = \frac{P_{\text{load}}}{h_{\text{Gen}}}$$

The minimum power does not include shaft powered auxiliary loads, nor allowances for cycling loads, nor future loads. Efficiencies of large electric generators can be 99% but is influenced by a variety of factors. For those 25 kW and larger, efficiency ranges from 88%–94%.

The number of poles is related to prime mover speed by the following equation.

Equation 4: Speed, Poles, Frequency

$$np = 120f$$

[18] Not generally used on military units, especially submarines. Those types of requirement will be defined by the Naval Sea Systems Command (NAVSEA).

The term n is the speed of the prime mover in rpm (revolutions per minute); p is the number of poles; f is the frequency in hertz; 120 is the conversion factor. Reciprocating engines for continuous operation are recommended to operate at 1200 rpm for increased life and reduced maintenance.

8.3.4.1 Gas Turbine Prime Mover

Gas turbine, though not as common on commercial vessels, offer the unique advantage on military ships in that it takes only minutes to startup and take all electrical (and propulsive) load. They are high speed (3600 rpm) and thus require a speed-reducing box (reduction gear) for propulsion.

Example 3

What is the number of poles in a generator that is to be coupled with a 3600 rpm gas turbine to produce a 60 Hz output?

Solution

Using the equation for speed, poles, and frequency along with the given data results in the following.

$$
\begin{aligned}
np &= 120f \\
p &= \frac{120f}{n} \\
&= \frac{(120)(60\ \text{Hz})}{3600\ \text{rpm}} \\
&= 2\ \text{poles}
\end{aligned}
$$

Note: Poles, cycles, and revolutions are not an acutal units, but merely numbers.

8.3.5 Steam Turbine Prime Mover

Though not as common as in the past, this is the prime mover for nuclear ships.

The steady state speed variation should not exceed 5% at rated speed under any load condition. When full load is removed, a speed limiter should limit the maximum speed to 110% or rated. The response times and speed deviations allowed are shown in the table below.

Table 5: Steam Turbine Response Time/Deviation for Load Changes

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

8.4 Generators

Generators are design per NEMA MG-1, IEEE Std C50 or IEC 60034, and IL-STD-1399 for naval ships. Air-cooled generators are normally rated for 0.8 power factor. The starting of large loads is a concern. Load analysis for voltage sag is recommended when motors capable of starting simultaneously exceeds 20% of generator nameplate capacity. (Provisions for soft-starting motor may alleviate this concern.)[19]

NEMA design class temperature ratings are shown in the table below. They are used, along with temperature ratings to determine the necessary insulation.

Table 6: NEMA Generator Design Class Temperature Rating

[Source*: IEEE 45.1 Table 8*]

NEMA design class	Total temperature rating (°C)
B	130
F	155
H	180

Heaters are used when temperatures inside the machine is lower than ambient to prevent condensation.

[19] This includes autotransformers, electronic starters, and variable speed devices.

Voltage regulators are to maintain voltage 97.5% to 102.5% of rated voltage. Transient condition apply as well.

9 POWER DISTRIBUTION

The ship's structure should NOT be used as a normal current-carrying conductor.

Feeder and branch circuit should be sized for 100% of connected load and derated for temperature, raceway configuration and so on. (See IEEE Std 45.8 and the NEC for additional information.) Conductors <15 AWG should NOT be used in any branch circuit.

Conductors for lighting, communication, and electronic circuits should be sized for the total connected load, but not less than 180 VA for each duplex receptacle, and should include 50% of the spare circuits on switchboards, load centers, and distribution panels.[20]

Conductor for galley equipment are sized based on 100% demand factor for the first 50 kW and 65% for all loads beyond 50 kW.

Example 4

What load should conductors be sized for a galley containing loads totaling 120 kW?

Solution

Per Section 9.4.3 of IEEE 45.1, the following demand is calculated.

$$
\begin{aligned}
P_{\text{Total}} &= P_{100\%,50\,\text{kW}} + P_{65\%,>50\,\text{kW}} \\
&= 50\ \text{kW} + (0.65)(120\ \text{kW} - 50\ \text{kW}) \\
&= 50\ \text{kW} + 45.5\ \text{kW} \\
&= 95.5\ \text{kW}
\end{aligned}
$$

---

[20] This means that one should not assume a new installation's load is covered. Research on past installations is necessary to ensure loading is within the capacity of the conductors.

Generally, conductors carrying motor circuits are sized for 125% of the nameplate motor rating.[21] This is the individual motor loading. See 9.4.4 for specific requirements for multiple motors and specific loads such as cargo winches, elevators, and cranes.

Conductors supplying emergency switchboard are sized at 115% of the emergency load or the emergency generator capacity, whichever is larger. Conductor from batteries are sized for the maximum continuous load, or discharge rate, whichever is greater. Although battery conductors for heavy duty applications (think diesel starting) are sized for 125% of maximum-rated discharge rate.

Power feeders for loads disconnected while underway (e.g., cargo elevators, winches and cranes) should not be used to supply loads required for ship's operation.

Steering gear motors are supplied by two separate circuits.

Arrangements should be made to stop all ventilation fans, fuel oil pumps, and lube oil transfer pumps from a single location in the event of a fire.

Separate branch circuits are required for electric heaters, motors with full-load current ratio of greater than or equal to 6 A. Lighting circuits have a variety of requirements in Sub-Clause 9.8.6.

9.9 Circuit Designation

Traditional designations for systems are shown in the table below.

Table 7: Traditional System Designations

[Source*: IEEE 45.1 Table 10*]

Type	Designation prefix
Ship service power	P
Emergency power	EP
Propulsion power	PP
Shore power	SP
Special frequency power	SFP
Lighting	L
Emergency lighting	EL
Degaussing	D
Cathodic protection	CPS
Interior communication	C
Control	K
Electronics	R

[21] Many of the ratings follow National Electrical Code requirements.

The next table shows a sampling of designations that should be used and may be modified by the traditional table designations. Some of the abbreviations are obvious others have a history. (For example C-2JV, the "C" is for communication; the "J" means "sound powered" and is designated as the first letter for battle telephone circuits while the "V" indicates a voice circuit. With the number "1" for ship control and "2" for engineering (machinery spaces), and so on.)

Table 8: System Designations

[Source*: IEEE 45.1 Table 11*]

SYSTEM	DESIGNATION
General Announcing	C-1MC
Call Bells	C-A
Electric Clocks	C-CE
Engine Order Telegraph	C-MB
Flooding Alarm	C-FD
General Alarm	C-G
Rudder Angle Indicator	C-N
Telephone: Sound-Powered (Electrical Engineers)	C-5JV
Telephone: Sound-Powered (Machinery Control Engineers)	C-2JV
Telephone: Sound-Powered (Ship Control & Maneuvering)	C-1JV
Underwater Log	C-Y

Distribution panels are limited to 18 for three-phase ac branches and 26 for single-phase ac or two-wire dc branches.

Shore power connections should be in accordance with IEC/ISO/IEEE 80005 series for medium voltage connections.

Receptacle, plugs and switches that are not watertight have numerous requirements, which can be found in Sub-Clause 9.10.10.

10 POWER CONVERSION

Power electronics used for power conversion is guided by IEEE Std 1662 and 1826.

Transformers that supply ship’s safety or propulsion loads should have the capacity to supply all loads with one transformer out of service. They are designed to operate in an ambient temperature of 50ºC (122ºF).

11 ENERGY STORAGE

Typical technologies include rechargeable storage batteries, flywheels, and capacitors. Additional requirements for energy storage systems are in IEEE Std 1826. Bulk energy storage is sized to ride-through a loss of all ac power generation.[22]

Primary batteries cannot be recharged easily and are discarded after use. Secondary batteries can be recharged by passing current “into” them in the opposite direction from which it is used. A vented battery freely gasses and contains replaceable electrolyte. Sealed batteries have vent valves to release gas only during overpressure conditions and whose electrolyte cannot be replaced. A sample of battery types is shown in the following table.

Table 9: Common Battery Types

Type/Use	Projected useful life (years)	Projected cycle life[a] (number of cycles)	Wet shelf life[b] (months)	Specific energy (W-h/kg)	Comments[c]
Primary	1–3	1	12		a) Least maintenance b) Periodic replacement c) Cannot be recharged
SLI (starting, lighting, and ignition) (automotive type Lead Acid)	0.5–2	50–100	2–3	30–40	a) High hydrogen emission b) High maintenance c) Not recommended for float service or deep discharge d) Low shock tolerance (flat plat design) e) Susceptible to damage from temperatures >27 °C
[redacted]					
Lithium Ion (Li-ion, LIB)		100 – 1200		100–250	a) Over double energy density compared to Ni-Cad and one-half self-discharge rate b) High cell voltage ~3.6V c) Low maintenance d) No “memory” and no scheduled cycling e) Requires battery management system to maintain voltage and current within the “safe operating envelope” f) Self-discharge rate ~1.5% – 2%/month

[22] Form experience, such a loss is quite concerning when one is thousands of miles from land.

Table Notes

[a] Cycle life is the number of cycles a battery can endure before it only retains 80% of its original ampere-hour capacity. One cycle is the removal of 80% of the battery capacity.

[b] Wet shelf life is the time a fully charged battery can be restored at 25ºC until permanent cell damage occurs.

[c] Float voltage is the voltage applied to a battery to maintain a constant state of charge.

A large battery is one with an output of more than 2 kW. A medium battery has a power output of 0.2 kW up to 2 kW. A small battery output is less than 0.2 kW.

Battery installation and clearance requirements are detailed in 11.3.5.3 through 11.3.6.3. Consult the standard for the multitude of requirements.

Except for batteries that stand idle for long periods of time, charging facilities should completely charge a battery in 8 hours without exceeding the charging rate.

Lithium-ion batteries have high energy densities making them desirable but failure modes must be accounted for before using them on ships. Specifically, Li-ion overheating or overcharging can result in thermal runaway leading to cell rupture and potential combustion. Li-ion fires are Class B fires because of the flammable electrolyte.[23] Numerous additional recommendations for use of such batteries on ships are Sub-Clause 11.3.11.

12 ELECTRICAL POWER SYSTEM CONTROL

The load-supervisory control system interface should be defined early in the design phase. Such networks should allow for 50% growth, and if EMI is an issue optical networks should be considered. Standard protocols in industry are TCP/IP and UDP/IP over Ethernet (IEEE Std 802.3 and IEEE Std 1815).[24]

At the application layer electrical power management include QoS, mission priority, and load shedding do not exist. However, one that comes close is ANSI/EIA 709.1 also call Lonworks.

A simple view of the integrated electrical system control is shown in the figure below.

[23] Li-ion does not contain metallic lithium, hence it's not a Class D fire.
[24] A summary layout of TCP/IP can be found in Ref [A].

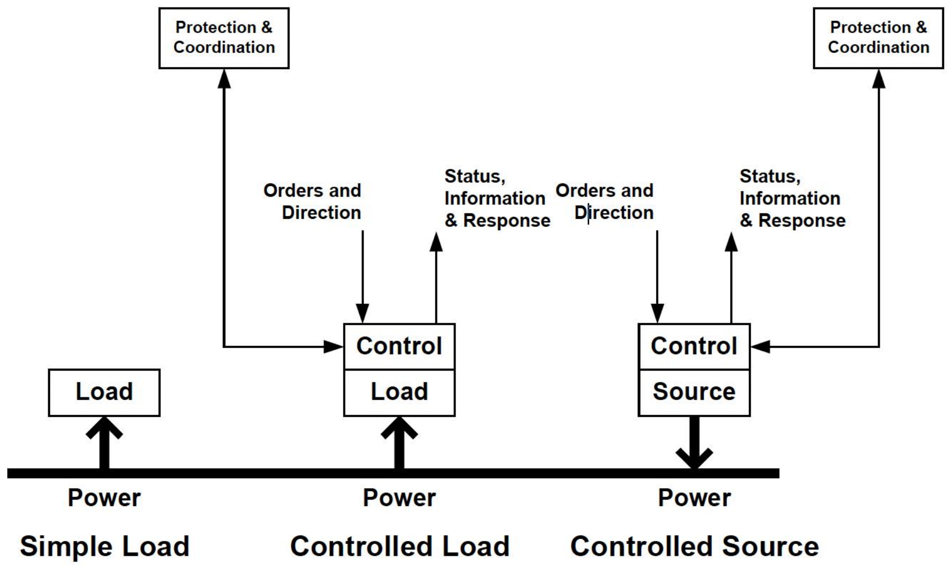

Figure 5: Sources and Loads Control/Management Overview
[Source*: IEEE 45.1 Figure 6*]

13 MOTOR & MOTOR APPLICATION

Motors are of varying types: wound-rotor induction, squirrel-cage induction, synchronous, or commutator type. All should be designed so the vibration or shock does not impair their operation.[25] Motors should not be located below the floor plates unless watertight.

Often motors are three-phase squirrel cage induction motors. For motors 7.5 kW (10 hp) to 373 kW (500 hp) see IEEE Std 841. For larger motors see API Std 541.

Supply voltage and frequency should be near the motor nameplate rating (*utilization*) and should not deviate by more than 10% in voltage and 5% in frequency not to exceed a sum of 10% (though frequency cannot be more than 5%).[26]

[25] Vibration is a repetitive oscillation motion, while shock is a sudden transient change in force or displacement. The second derivative represents acceleration for both, while the third derivative is called “jerk” and is important for analyzing shock and its rate of acceleration change.
[26] Standard *supply* (e.g., 480 V) and *utilization* (e.g., 460 V) voltages are usually much closer than the 10% nameplate rating deviation indicated/allowed. For single phase systems supply voltage is usually 120 V with utilization equipment rated for 115 V.

Motors should be installed, where possible, in the fore and aft direction. Insulating materials should be resistant to moisture, sea air, and oil vapor.

Three-phase motors are designed to handle five to six time the horsepower rating. This corresponds to NEMA locked rotor Codes F and G are suitable for most application.

NEMA Code Letter	kVA/HP with locked rotor	Approximate Mid-Range Value
A	0 - 3.14	1.6
B	3.15 - 3.55	3.3
C	3.55 - 3.99	3.8
D	4.0 - 4.49	4.3
E	4.5 - 4.99	4.7
F	5.0 - 5.59	5.3
G	5.6 - 6.29	5.9

Figure 6: NEMA Locked Rotor Codes

[Source*: https://www.engineeringtoolbox.com/locked-rotor-code-d_917.html*]

Motors should be designed for their ambient temperature conditions and designed temperature rise. See Sub-Clause 13.13 for details.

Motors are normally rated for continuous duty, which is defined by the NEC as "operation at a substantially constant load for an indefinitely long time". The duty rating for windlass, capstan, and winches vary with details in Sub-Clause 13.15.

14 ADJUSTABLE SPEED DRIVE (ASD) APPLICATIONS

Compliance with IEEE Std 1566 and 1662 for ASD is required. Advantages include lower maintenance and operating costs, energy savings, and less system vibrations. Filtering to avoid harmonics is an important design consideration.

15 ELECTRIC PROPULSION AND MANEUVERING SYSTEM

Classification societies and regulatory agencies provide detailed requirements. See Clause 15 for recommendations. The ASD's mentioned earlier are being widely used for electric propulsion with harmonics and redundancy being design considerations of import.

"Podded" propulsion is a term used to describe housing located under the hull. (These are used often for in-port maneuvering.) The requirements are in IEC 600092.

16 STEERING SYSTEMS

Very specific requirements apply, especially for control errors and alarms. See IEEE 45.1 for details.

17 LIGHTING EQUIPMENT

Lighting equipment is certified by various UL standards.[27] Lighting levels are governed by the *ABS Guide for Crew Habitability on Ships*, API RP 14FZ and API RP 14F, where applicable.

Lights in the normal line of vision of >60 W should have a diffusing shade to avoid excessive brightness. Berthing lights should not be able to be covered by bedding.

Emergency lights should have distinguishing marks, such as a red "E". Exit lights should have "EXIT" in red block letters. Solid-state lights may have restrictions *for use emergency lights*; check class and flag state rules.

Navigation lights and signals are specified by the International Regulations for Preventing Collisions at Sea (COLREGS) except as modified by the authority having jurisdiction.[28]

18 WHISTLE AND SIREN CONTROL SYSTEMS

There must be a mechanical system for operating ship's whistles from the bridge regardless of other installed systems. Electrical systems are powered from the emergency bus.

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[27] Specific lighting design methods are in Ref [B] and a SunCam course on Illumination.
[28] Should you be at sea and notice flashing amber light, you are looking at a surfaced submarine. [Three 1 s flashes, 3 s off.]

19 HEATING EQUIPMENT

Various requirements apply all guided by UL certification.

Electrical heat trace (EHT) for Artic Polar Marine Application can be large and loading impacts should be analyzed.

20 GALLEY EQUIPMENT AND WORKSHOP EQUIPMENT

Certification per UL 97. See IEEE Std 45.1 for details.

21 ELECTRICAL POWER SYSTEM PROTECTION

Faults are classified as either overcurrent, ground, line to line internal equipment, loss of phase, or other.[29]

A general thumb-rule is to isolate closest to the fault as possible first. On an unground system, with a single line-to-ground fault, fault isolation may be delayed as determined by the operator.[30] Medical spaces use segregated loads so that a loss of power will not put patients at risk.

A protection study is necessary to ensure coordination of devices. Prior to knowing the generator reactances,[31] the following thumb rules are provided for estimating short-circuit rms current:

- Maximum asymmetrical rms current: 10 times generator full-load current
- Average asymmetrical rms current: 8.5 times generator full-load current

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[29] Overcurrent definitions often encompasses overloads, short-circuits, and ground faults.
[30] Use on submarines and other naval ships to allow for consideration of maintaining power to equipment while finding the source of the fault. Used on commercial vessels to allow an operator to consider isolating the equipment against the safety of the vessel overall.
[31] Once the *X/R* ratio is known one can be more specific in the short-circuit study. A calculations known as the MVA method, which can be made by hand vice a computer software program, is described in Ref [B].

22 SYSTEM STUDIES, ANALYSES, AND REPORTS

Many if not most studies are accomplished with sophisticated and complex software. Nevertheless, one should know what the purpose of the study is, and ensure that the input is correct based on the design used. Most important, the ability to understand if the output makes sense is vital.

22.3 Load Flow Analysis and Voltage Drop Analysis

First, an electric plant load analysis (EPLA) is used to ensure the proper sizing of electrical equipment for the ship's loading. Information is in Annex B on the conduct of the study. The US Navy Design Data Sheet (DDS 310-1), *Electric Plant Load Analysis for Surface Ships*, which is available from the Naval Sea Systems Command and the Defense Technical Information Center (www.dtic.mil). Also, refer to IEEE Std 45.3.

The EPLA the normal steady-state operating condition. Multiple buses are defined. One is a swing bus, also known as a slack bus or reference bus. This bus is considered virtual where active (real) power and reactive power are emitted or absorbed and is set as the reference for the entire system.[32] The next is the generator buses (or PV buses) where the generators are connected.[33] Last are the load buses.

This study is the basis for defining the power system.

The study may include voltage drop analysis, loss analysis, power factor considerations, among others. This study is conducted at the first design iteration and must be repeated whenever major changes are made to the power and distribution system.

Once this analysis is defined software studies can calculate other scenarios: short-circuit fault analysis, dynamic stability (transient and steady state), protection device coordination, motor starting, arc flash, and harmonic analysis.

[32] Something to recall, especially for generators in parallel. Real power is controlled by the frequency; Reactive power is controlled by the voltage.
[33] The "PV" or "P V" is bus is where the generators are connected. Power is "P" and "V" is voltage.

22.4 Dynamic Analysis (Transient and Stability)

Shipboard electrical systems are non-linear, time varying complex systems that have large perturbations based on operations. Stability analysis is thus vital to ensure the system can handle the changes, stay within transient parameters, and return to steady-state conditions within the desired time frames.

22.5 Fault Current Analysis

This study commences once a one-line diagram is designed and load flow analysis is complete. It determines the short circuit current in different failure scenarios and ultimately if overcurrent devices are properly rated and set. This study provides input to the arc flash study.

22.6 Harmonic and Frequency Analysis

Harmonic distortion in modern power systems that incorporate non-linear loads: power electronic conversion and switching electronics. Results can be increased heat loss, vibrations, voltage distortion, and interference with communications, control systems, and other electronics. This may also result in “hunting” of generator governors.

The classification bodies (ABS, Lloyds) all set distortion limits.

Power electronics should be designed to IEC 61000 or MIL-STD-461E. Transformers use a K Factor to properly rate them for harmonics. (See IEEE Std C57.12.00, IEEE Std C57.12.90, or IEC 60076-1 for details.) Although IEEE Std 519 is a shore based standard, it too may be used for additional design guidance.

If not otherwise specified, total voltage harmonic distortion (VTHD) should not exceed 5% and no individual harmonic (IVHD) should not exceed 3%.

22.7 Failure Mode and Effects Analysis (FMEA)

A FMEA study determines every failure mode and effect from the lowest level of interest (part of module) up to the highest functional level that is impacted. The study is detailed and time consuming—and costly.

Variable speed devices are becoming more common. They often have their own filtering to limit harmonics. All variable speed device noise mitigation equipment (filters) should be considered vital and included in any FMEA report.

22.8 Electromagnetic Interference (EMI) Analysis

EMI uses the same tools harmonic and transient analysis, and thus is conducted after those studies. The results are important to complex vessels such as navy combatants.[34] Guidance is in MIL-STD-461 and IEC 61000 Series.

22.9 Thermal Analysis

On complex vessels electrical simulation tools calculate input for mechanical simulation tools, which then model thermal conditions on equipment.

22.12 Safe Return to Port/Survivability Analysis

This is a report, required for certain passenger ships, where the electric plant's ability to allow for a safe return to port following damage not exceeding the fire casualty threshold defined by SOLAS.

22.14 Protective Device Coordination Study

This study is accomplished after load fault and fault current analysis is complete. The goal is to isolate a fault, and the limit the energy from said fault, while maintaining a stable electrical system.

22.20 Incident Energy Analysis

This report documents the available arc-flash incident energy at all locations in the system where short-circuit current is calculated. This is completed after the fault analysis study.

23 EMI/EMC/RFI

The goal is limiting EMI and RFI. Standard include MIL-STD-461, IEC 61000, and IEEE Std C63.12.

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[34] A publicly acknowledged EMI disaster occurred on a carrier during landing resulting in the crash of the plane.

24 MATERIALS

Consideration here is on corrosion resistance, flame-retardant materials, fastening of brittle materials (e.g., fuses), and cable selection and use.

25 POWER SYSEM GROUNDING (EARTHING)

General guidance is in IEEE Std 142 and for power electronics IEEE Std 1100. The rest of IEEE 45.1 focuses on additional aspects of ground affecting shipboard systems.

The goal is to minimize hull current flow, minimizing arc fault damage and transient overvoltage, all while ensuring personnel safety.

Three types of grounding are applicable to ships:

- High-resistance grounding
- Solidly grounded
- Ungrounded

These types of grounding may be applied to four major classes of circuits with the following recommendations for each.[35]

- Medium voltage primary buses should be high-resistance grounded
- Primary low voltage buses and distribution buses should be high-resistance grounded or ungrounded
- Secondary low voltage buses should be solidly grounded
- Special circuits (hospital areas) may require special grounding treatment

This is visualized in the next figure.

[35] Navy ships tend to use ungrounded system to ensure that a single fault will NOT shutdown equipment when it might sorely be needed. Sophisticated ground monitoring allows personnel to find the fault and repair in a timely manner. All this is done for equipment reliability and not personnel safety, though such a system in not inherently unsafe when properly monitored. (The danger to personnel comes *after* the first fault occurs and before it is fixed.)

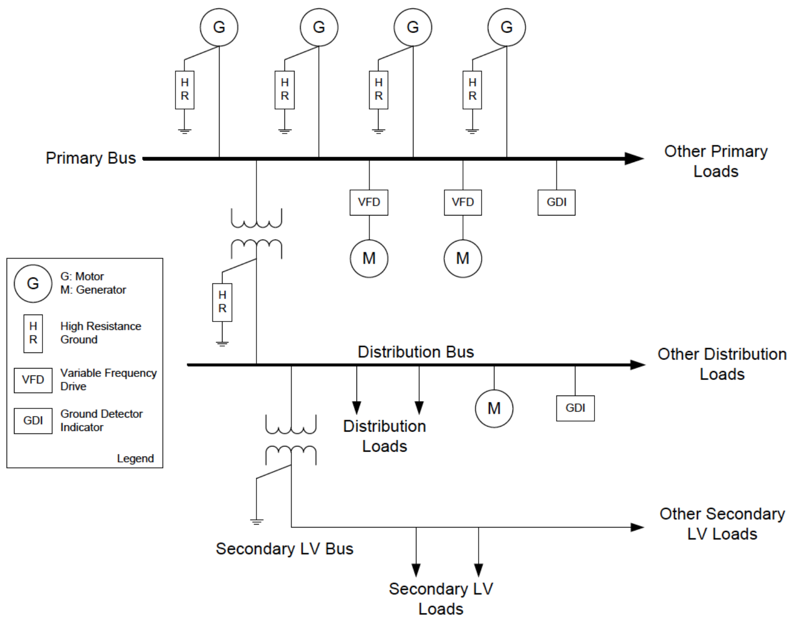

Figure 7: System Grounding
[Source: *IEEE 45.1 Figure 9*]

Grounding solutions must consider corrosion damage to structural components impacted by stray currents: aluminum, stainless steel, carbon fiber, high-performance steel, galvanized steel, and various coating systems.

Equipment grounding follows IEEE Std 142 or IEEE Std 3003.2 and Article 250 of the National Electrical Code.[36] The reading between the equipment enclosure and the structural attachment point should be ≤0.1 Ω. Nonmetallic ships use ground plates. Grounding poles are NOT required on portable appliances with double insulation and on equipment supplied at not more than 55 V.

Lightning protection follows NFPA 780, Chapter 10, "Protection for Watercraft" for wooden and composite vessels.

Ground fault detection system requirements are contained in 25.8.1, 25.8.2, and 25.8.3.

[36] This grounding is for personnel safety should equipment become grounded and metal casings become energized.

26 ARC FLASH MANAGEMENT

More electric propulsion is in use, limited space aboard ships, the marine environment, all make arc flash a challenge. Many accidents are attributed to arc flash situations.

The governing requirements used are OSHA 29 Code of Federal Regulations Part 1910 Subpart Sd; NFPA 70, the National Electrical Code[37]; NFPA 70E, Standard for Electrical Safety in the Workplace[38]; and IEEE Std 1584, Guide for Performing Arc-Flash Hazard Calculations.

27 HAZARDOUS LOCATIONS, INSTALLATIONS, AND EQUIPMENT

See the NEC Articles 500 through 504 for the Division classification system and Articles 505 and 506 for the Zone classification system.[39] Also of use, API RP 500 and 505.

Many details for various ship types are in this section and should be reviewed for details.

28 SHIP CONSTRUCTION AND OUTFITTING

This covers general guidance during construction such as storage of equipment, spare parts, and documentation required.

29 SYSTEM OPERATION AND MAINTENANCE

General guidance is provided on maintenance and safety operation (see IEEE Std 45.5). Cleanliness and safe operation (i.e., following proper procedures) and the main guidance.

Not included are the many types of maintenance systems available. Here is a list of types, from least expensive to most expensive, from least effective to most effective.

- Corrective (Reactive)
- Preventative
- Predictive (Condition Based)

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[37] Several courses are available on this topic.
[38] A separate course on 70E is available.
[39] See the course on NEC Special Occupancies for details.

- RCM (Reliability Centered Maintenance using Failure Mode Analysis with unique strategies for each piece of equipment)

Information on these maintenance strategies exist in numerous sources. Though equipment maintenance can be conducted individually, sometimes large vessels have *planned outages* (think drydock, maintenance availabilities, overhauls) where a great deal of maintenance is conducted over a set time period.

ANNEX A BIBLIOGRAPHY

This contains a list of informative references (for information only).

ANNEX B Normative Information

The various operating conditions of a ship are defined.

- In Port
- At Anchor
- Cruising (point A to B)
- Functional (underway performing its designed function)
- Emergency (main generator unavailable, on emergency power)
- Safe Return to Port (required for certain passenger ships and defined by SOLAS)

Load Factor guidance is provided for individual loads. Where load information is not available, the load factor is given by the following equation. [This may also use brake horse power (bhp) in place of kilowatts (kW).]

Equation 5: Load Factor

$$LF = \left(\frac{P_{\text{operating}}}{P_{\text{rated}}}\right)\left(\frac{T_{\text{hours per day}}}{24\text{ hours}}\right)$$

Individual loads may be grouped using the US Navy "Expanded Ship Work Breakdown Structure" (ESWBS). See the table below for the numbering scheme.

Table 10: Work Breakdown Structure

[Source: *NAVSEA Document S9040-AA-IDX-010/SWBS 5D*]

100 –Propulsion

200 –Batteries and Battery Chargers

300 –Power Conversion Equipment

400 –Lighting

500 –Electronics

600 –Navigation Systems

700 –Auxiliaries

800–Heating Ventilating and Air Conditioning Systems

900 –Deck Machinery

1000 –Food Services

1100 –Workshop/Laundry Equipment

Various table in Annex B provide examples of load analysis.

SUMMARY

This course is meant to provide an overview of the items of concern to the marine electrical engineer as well as to provide guidance as to where additional details may be sourced. I hope the task is accomplished. All the best.

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NOTE

Electrical refers to something related to electricity while "electric" refers to a device or machine that runs on electricity. Nevertheless, the NEC is sometimes referred to as the National Electric Code.

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Appendix A: Equivalent Units Of Derived And Common SI Units

Symbol	Equivalent Units			
A	C/s	W/V	V/Ω	$J/(s \cdot V)$
C	$A \cdot s$	J/V	$(N \cdot m)/V$	$V \cdot F$
F	C/V	C^2/J	s/Ω	$(A \cdot s)/V$
F/m	$C/(V \cdot m)$	$C^2/(J \cdot m)$	$C^2/(N \cdot m^2)$	$s/(\Omega \cdot m)$
H	W/A	$(V \cdot s)/A$	$\Omega \cdot s$	$(T \cdot m^2)/A$
Hz	1/s	s^{-1}	cycles/s	radians/$(2p \cdot s)$
J	$N \cdot m$	$V \cdot C$	$W \cdot s$	$(kg \cdot m^2)/s^2$
m^2/s^2	J/kg	$(N \cdot m)/kg$	$(V \cdot C)/kg$	$(C \cdot m^2)/(A \cdot s^3)$
N	J/m	$(V \cdot C)/m$	$(W \cdot C)/(A \cdot m)$	$(kg \cdot m)/s^2$
N/A^2	$Wb/(N \cdot m^2)$	$(V \cdot s)/(N \cdot m^2)$	T/N	$1/(A \cdot m)$
Pa	N/m^2	J/m^3	$(W \cdot s)/m^3$	$kg/(m \cdot s^2)$
W	V/A	W/A^2	V^2/W	$(kg \cdot m^2)/(A^2 \cdot s^3)$
S	A/V	1/Ω	A^2/W	$(A^2 \cdot s^3)/(kg \cdot m^2)$
T	Wb/m^2	$N/(A \cdot m)$	$(N \cdot s)/(C \cdot m)$	$kg/(A \cdot s^2)$
V	J/C	W/A	C/F	$(kg \cdot m^2)/(A \cdot s^3)$
V/m	N/C	$W/(A \cdot m)$	$J/(A \cdot m \cdot s)$	$(kg \cdot m)/(A \cdot s^3)$
W	J/s	$V \cdot A$	V^2/W	$(kg \cdot m^2)/s^3$
Wb	$V \cdot s$	$H \cdot A$	T/m^2	$(kg \cdot m^2)/(A \cdot s^2)$

Appendix B: Physical Constants

Table Note 1

Quantity	Symbol	US Customary	SI Units
Charge			
electron	e		-1.6022×10^{-19} C
proton	p		$+1.6022 \times 10^{-19}$ C
Density			
air [STP][32°F, (0°C)]		0.0805 lbm/ft^3	1.29 kg/m^3
air [70°F, (20°C), 1 atm]		0.0749 lbm/ft^3	1.20 kg/m^3
sea water		64 lbm/ft^3	1025 kg/m^3
water [mean]		62.4 lbm/ft^3	1000 kg/m^3
Distance			
Earth radius[2]	⊕	2.09×10^{7} ft	6.370×10^{6} m
Earth-Moon separation[2]	⊕☾	1.26×10^{9} ft	3.84×10^{8} m
Earth-Sun separtion[2]	⊕⊙	4.89×10^{11} ft	1.49×10^{11} m
Moon radius[2]	☾	5.71×10^{6} ft	1.74×10^{6} m
Sun radius[2]	⊙	2.28×10^{9} ft	6.96×10^{8} m
first Bohr radius	a_0	1.736×10^{-10} ft	5.292×10^{-11} m
Gravitational Acceleration			
Earth [mean]	g	32.174 (32.2) ft/sec^2	9.8067 (9.81) m/s^2
Mass			
atomic mass unit	μ or m_μ $\frac{1}{12}m\left({}^{12}C\right)$	3.66×10^{-27} lbm	1.6606×10^{27} kg or 10^{-3} kg mol^{-1} / N_A
Earth[2]	⊕	4.11×10^{23} slugs	6.00×10^{24} kg
Earth [customary U.S.][2]	⊕	1.32×10^{25} lbm	-
Moon[2]	☾	1.623×10^{23} lbm	7.36×10^{22} kg
Sun[2]	⊙	4.387×10^{30} lbm	1.99×10^{30} kg

electron rest mass	m_e	2.008´ 10^{-30} lbm	9.109´ 10^{-31} kg
neutron rest mass	m_n	3.693´ 10^{-27} lbm	1.675´ 10^{-27} kg
proton rest mass	m_p	3.688´ 10^{-27} lbm	1.672´ 10^{-27} kg
Pressure			
atmospheric		14.696 (14.7) lbf/in^2	1.0133´ 10^5 Pa
Temperature			
standard		32˚F (492˚R)	0˚C (273 K)
absolute zero		–459.67˚F (0˚R)	–273.16˚C (0 K)
Velocity[3]			
Earth escape		3.67´ 10^4 ft/sec	1.12´ 10^4 m/s
light (vacuum)	c, c_0	9.84´ 10^8 ft/sec	2.9979 (3.00) ´ 10^8 m/s
sound [air, STP]	a	1090 ft/sec	331 m/s
sound [air, 70°F, (20°C), 1 atm]		1130 ft/sec	344 ft/s
Volume			
Volume: molal ideal gas (STP)[4]		359 ft^3 / lbmol	22.41 m^3/kmol

Table 1 Notes

1. Units come from a variety of sources, but primarily from the Handbook of Chemistry and Physics, The Standard Handbook for Aeronautical and Astronautical Engineers, and the Electrical Engineering Reference Manual for the PE Exam. See also the NIST website at https://pml.nist.gov/cuu/Constants/.
2. Symbols shown for the solar system are those used by NASA. See https://science.nasa.gov/resource/solar-system-symbols/.
3. Velocity technically is a vector. It has direction.
4. The unit “lbmol” is an actual unit, not a misspelling.

Appendix C: Fundamental Constants

Quantity	Symbols	US Customary	SI Units
Avogadro's number	N_A, L		6.022×10^{23} mol^{-1}
Bohr magneton	μ_B		9.2732×10^{-24} J/T
Boltzmann constant	k	5.65×10^{-24} ft-lbf / R	1.3805×10^{-23} J/T
electron volt: $\left(\frac{e}{C}\right)$ J	eV		1.602×10^{-19} J
Faraday constant, $N_A e$	F		96485 C/mol
fine structure constant, inverse α^{-1}	α α^{-1}		7.297×10^{-3} (≈1/137) 137.035
gravitational constant	g_c	32.174 lbm-ft/lbf-sec^2	
Newtonian gravitational constant	G	3.44×10^{-8} ft^4 / lbf-sec^4	6.672×10^{-11} N·m^2 / kg^2
nuclear magneton	μ_N		5.050×10^{-27} J/T
permeability of a vacuum	μ_0		1.2566×10^{-6} N/A^2 (H/m)
permittivity of a vacuum, electric constant $1/\mu_0 c^2$	ϵ_0		8.854×10^{-12} C^2 / N·m^2 (F/m)
Planck's constant	h		6.6256×10^{-34} J·s
Planck's constant: h/2π			1.0546×10^{-34} J·s
Rydberg constant	R_∞		1.097×10^{7} m^{-1}
specific gas constant, air	R	53.3 ft-lbf/lbm- R	287 J/kg·K
Stefan-Boltzmann constant		1.71×10^{-9} BTU/ft^2-hr-°R^4	5.670×10^{-8} W/m^2·K^4
triple point, water		32.02 F, 0.0888 psia	0.01109 C, 0.6123 kPa
universal gas constant	R*	1545 ft-lbf/lbmol- R 1.986 BTU/lbmol- R	8314 J/kmol·K

Table Notes

1. Units come from a variety of sources, but primarily from the Handbook of Chemistry and Physics, The Standard Handbook for Aeronautical and Astronautical Engineers, and the Electrical Engineering Reference Manual for the PE Exam. See also the NIST website at https://pml.nist.gov/cuu/Constants/. The unit in Volume of "lbmol" is an actual unit, not a misspelling.

Appendix D: Mathematical Constants

Quantity	Symbol	Value
Archimedes' constant (pi)	p	3.1415926536
base of natural logs	*e*	2.7182818285
Euler's constant	*C* or t	0.5772156649

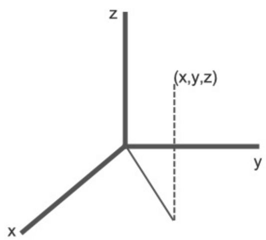
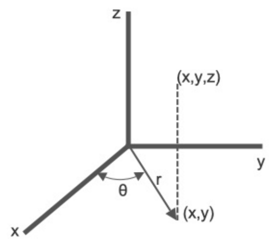
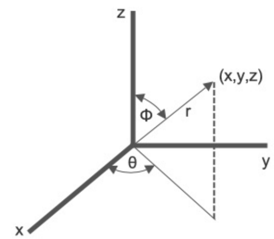
Appendix E: The Greek Alphabet

A	*a*	alpha	N	*u*	nu
B	*b*	beta	X	x	xi
G	*g*	gamma	O	*o*	omicron
D	*d*	delta	P	*p*	pi
E	*e*	epsilon	R	*r*	rho
Z	z	zeta	S	*s*	sigma
H	*h*	eta	T	*t*	tau
Q	*q*	theta	ϒ	*u*	upsilon
I	i	iota	F	*f*	phi
K	*k*	kappa	C	*c*	chi
L	*l*	lambda	Y	*y*	psi
M	*m*	mu	W	*w*	omega

Appendix F: SI Prefixes

symbol	prefix	value
a	atto	10^{-18}
f	femto	10^{-15}
p	pico	10^{-12}
n	nano	10^{-9}
m	micro	10^{-6}
m	milli	10^{-3}
c	centi	10^{-2}
d	deci	10^{-1}
da	deka	10
h	hecto	10^{2}
k	kilo	10^{3}
M	mega	10^{6}
G	giga	10^{9}
T	tera	10^{12}
R	peta	10^{15}
E	exa	10^{18}

Appendix G: Coordinate Systems & Related Operations

Mathematical Operations	Rectangular Coordinates	Cylindrical Coordinates	Spherical Coordinates
Conversion to Rectangular Coordinants	 $x = x$ $y = y$ $z = z$	 $x = r\cos\theta$ $y = r\sin\theta$ $z = z$	 $x = r\sin\phi\,\cos\theta$ $y = r\sin\phi\,\sin\theta$ $z = r\cos\phi$
Gradient	$\nabla f = \frac{\partial f}{\partial x}\mathbf{i} + \frac{\partial f}{\partial y}\mathbf{j} + \frac{\partial f}{\partial z}\mathbf{k}$	$\nabla f = \frac{\partial f}{\partial r}\mathbf{r} + \frac{1}{r}\frac{\partial f}{\partial \theta}\boldsymbol{\theta} + \frac{\partial f}{\partial z}\mathbf{k}$	$\nabla f = \frac{\partial f}{\partial r}\mathbf{r} + \frac{1}{r}\frac{\partial f}{\partial \phi}\boldsymbol{\phi} + \frac{1}{r\sin\theta}\frac{\partial f}{\partial \theta}\boldsymbol{\theta}$
Divergence	$\nabla \cdot \mathbf{A} = \frac{\partial A_x}{\partial x} + \frac{\partial A_y}{\partial y} + \frac{\partial A_z}{\partial z}$	$\nabla \cdot \mathbf{A} = \frac{1}{r}\frac{\partial (rA_r)}{\partial r} + \frac{1}{r}\frac{\partial A_\theta}{\partial \theta} + \frac{\partial A_z}{\partial z}$	$\nabla \cdot \mathbf{A} = \frac{1}{r^2}\frac{\partial (r^2 A_r)}{\partial r} + \frac{1}{r\sin\phi}\frac{\partial (A_\phi \sin\phi)}{\partial \phi} + \frac{1}{r\sin\phi}\frac{\partial A_\theta}{\partial \theta}$
Curl	$\nabla \times \mathbf{A} = \begin{vmatrix} \mathbf{i} & \mathbf{j} & \mathbf{k} \\ \frac{\partial}{\partial x} & \frac{\partial}{\partial y} & \frac{\partial}{\partial z} \\ A_x & A_y & A_z \end{vmatrix}$	$\nabla \times \mathbf{A} = \begin{vmatrix} \frac{1}{r}\mathbf{r} & \boldsymbol{\theta} & \frac{1}{r}\mathbf{k} \\ \frac{\partial}{\partial r} & \frac{\partial}{\partial \theta} & \frac{\partial}{\partial z} \\ A_r & A_\theta & A_z \end{vmatrix}$	$\nabla \times \mathbf{A} = \begin{vmatrix} \frac{1}{r^2\sin\theta}\mathbf{r} & \frac{1}{r^2\sin\theta}\boldsymbol{\phi} & \frac{1}{r}\boldsymbol{\theta} \\ \frac{\partial}{\partial r} & \frac{\partial}{\partial \phi} & \frac{\partial}{\partial \theta} \\ A_r & rA_\phi & rA\theta A_\phi \end{vmatrix}$
Laplacian	$\nabla^2 f = \frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} + \frac{\partial^2 f}{\partial z^2}$	$\nabla^2 f = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial f}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 f}{\partial \theta^2} + \frac{\partial^2 f}{\partial z^2}$	$\nabla^2 f = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial f}{\partial r}\right) + \frac{1}{r^2\sin\phi}\frac{\partial}{\partial \phi}\left(\sin\phi\frac{\partial f}{\partial \phi}\right) + \frac{1}{r^2\sin^2\phi}\left(\frac{\partial^2 f}{\partial \theta^2}\right)$

