1

Overview – VFD Motor Controller

The variable frequency drive (VFD) motor controller has been proven to be suitable for shipboard low voltage and medium voltage application. The variable speed electric propulsion is very popular due to the full range of speed and torque controls. The medium voltage variable speed electric propulsion can achieve high propeller power a with full range of speed controls.

The VFD motor controller produces electrical noise. The standards recommend a wide range total harmonic distortion (THD) with limits of from 5% to 8%. The author recommends the shipboard power system THD should not be more than 5%. This 5% THD is allowed when all other design attributes are fully complied with.

There are situations when the THD can be up to 8%, but that distribution system must be isolated from the other system so that the electric noise is managed within the dedicated system.

The 5% harmonic contents can create a dangerous situation affecting other low voltage equipment and control circuits. The design engineers must understand the THD limits for the specific design and should consider these as a system level harmonic management approach.

It is highly recommended that one manufacturer VFD be used and the manufacturer guidelines for harmonic management, VFD cable selection and VFD cable termination should be followed. Otherwise the coordination with multiple VFD suppliers can be challenging.

The following requirements will be discussed as to the use of VFD:

1) The IEEE-45-2002 recommends an acceptable THD limit of 5%, which is in line with MIL-STD-1399. The IEEE-45-2002 also allows 8% THD only for a dedicated bus with dedicated VFD equipment suitable for 8% harmonic environment.
2) IEEE-519-1992 recommends an acceptable THD limit of 5%.

VFD Challenges for Shipboard Electrical Power System Design, First Edition.
Mohammed M. Islam.

Published 2020 by John Wiley & Sons, Inc.

3) IEEE-519-2014 recommends an acceptable THD limit of 8% with clarification that the IEEE-519 may not apply to the shipboard power system.
4) The IEEE-45.1-2017 recommends an acceptable THD limit of 8% for normal bus and dedicated bus.
5) ABS Steel Vessel rules 2017 have a THD limit of 8%.

For simplicity, voltage source inverters (VSI) will be presented. The VSI are fed with ship service constant voltage. The VFD electronics convert the AC to DC and then DC to AC voltage with adjustable magnitude and frequency.

The VSI drives use capacitive storage, with capacitors in their DC link, which both stores and smooths the DC voltage for the inverter input.

There are types of power switching devices used with variable frequency drives. We will discuss the use of IGBT which are semiconductor switches that are turned on and off, creating a pulse width modulated (PWM) output with regulated frequency.

For all shipboard ungrounded power generation and distribution systems, there is a possibility of a system level ground path, such as HRG, filter. These ground loops should be minimized and regulated, so that VFD generated noise such as common mode voltage and current can travel through the low resistance ground path.

System level capacitance monitoring and management is also recommended.

If there are HRGs used in an ungrounded system, total probable current path shall be monitored and managed to establish and maintain safe level.

All high frequency harmonics must be calculated and managed to establish a safe harmonic level. This may require harmonic calculation beyond the 49th harmonic of IEEE-519 requirements. The IEEE-519-2014 may not be applicable for establishing the shipboard harmonic level at the low frequency input site of the point of common coupling (PCC) due to the lack of ground reference in an ungrounded system. The IEEE-519 may not address the high frequency harmonics generated by the inverter side of the VFD. Therefore, the shipboard VFD application and inverter side high frequency noise must be managed, so that the high frequency EMI and RFI generated equipment malfunctional can be avoided.

In view of the high frequency noise propagation all over the shipboard power system, the cable between the VFD motor controller and the motor must be as recommended by the VFD manufacturer. The VFD cable usually has three-phase conductors, three drain wires and overall shield. The VFD cable must be terminated with drain wires and shielding, as recommended by the cable manufacturer and the VFD manufacturer. For additional details of VFD cable requirements and termination requirements refer to Chapter 6.

1.1 MIL-STD-1399 Shipboard Power System and Total Harmonic Requirements

The shipboard 60Hz power system is outlined in MIL-STD-1399-300 as follows:

a) The ship service electrical power distribution system supplied by the ship's generators is 440 Vrms, 60 Hz, three-phase, ungrounded.
b) Power for the ship's lighting system and other user equipment such as electronic equipment supplied from the ship power distribution system through transformers, is 115 Vrms, 60 Hz, three-phase, ungrounded.

Remarks: The MIL-STD-1399 does not address ungrounded 440 Vrms or 115 Vrms power generation and distribution. For an ungrounded distribution system (440 Vrms or 115 Vrms), engineering analysis should be performed to minimize the neutral current circulation in the distribution system by balancing single-phase and three-phase actual loads (See Table 1.1).

1.2 Shipboard Power System Design Fundamentals

Electrical power system detailed design and development for commercial ships, such as cruise ships, cargo ships, tankers, related support vessels, offshore industry related floating platforms, and all other support vessels is featured in this book. Some military ship designs are also included to establish differences in design fundamentals as to the requirements of redundancy requirements and zonal distributions. The design requirements and fundamentals are with the understanding of the following:

a) Regulatory requirements
b) Operational requirements
c) Redundancy requirements
d) Understanding of emergency requirements as to the power generation as well as the emergency load distribution.
e) Understanding the causes of blackout (Dead ship) situation. The blackout situation for all electric ship related power generation and distribution is more complex than the ship with non-electric propulsion.
f) Electric propulsion related power generation and distribution requirements have been taken in the design to adapt medium voltage power generation. Due to the fact that ample power is available to change the hydraulic system or mechanical system to electric system with variable drive operation.

Table 1.1 MIL-STD-1399 Shipboard Power System Characteristics.

MIL-STD-1399-300B

TABLE I. Characteristics of shipboard electric power systems. (NOTE: Characteristic percentages are defined in Section 3.)

Characteristics	Type I	Type II	Type III
Frequency			
1) Nominal frequency	60 Hz	400 Hz	400 Hz
2) Frequency tolerance	±3% (±5% for submarines)	±5%	±0.5%
3) Frequency modulation	0.5%	0.5%	0.5%
4) Frequency transient tolerance	±4%	±4%	±1%
5) Worst case frequency excursion from nominal resulting from items 2, 3, and 4 combined, except under emergency conditions	±5.5%	±6.5%	±1.5%
6) Recovery time from items 4 or 5	2 seconds	2 seconds	0.25 second
Voltage			
7) Nominal user voltage	440, 115, 115/200 Vrms	440, 115 Vrms	440, 115, 115/200 Vrms
8) Line-to-line voltage unbalance	3% (0.5% for 440 Vrms, 1% for 115 Vrms for submarines)	3%	2%
9) User voltage tolerance			
a) Average line-to-line voltage from nominal	±5%	±5%	±2%
b) Line-to-line voltage from nominal, including items 8 and 9a	±7%	±7%	±3%
10) Voltage modulation	2%	2%	1%
11) Maximum departure voltage from nominal resulting from items 8, 9a, 9b, and 10 combined, under transient or emergency conditions	±8%	±8%	±4%
12) Voltage transient tolerance	±10%	±10%	±5%
13) Worst case voltage excursion from nominal resulting from items 8, 9a, 9b, 10 and 12 combined, except tinder emergency conditions	±20%	±20%	±5.5%
14) Recovery time from item 12 or item 13	2 seconds	2 seconds	0.25 second
15) Voltage spike (± peak value)	2.5 kV (440 Vrms sys) 1.0 kV (115 Vrms sys)	2.5 kV (440 Vrms sys) 1.0 kV (115 Vrms sys)	2.5 kV (440 Vrms sys) 1.0 kV (115 Vrms sys)

g) The grounding requirements are different than the traditional low voltage distribution though both systems are three-wire ungrounded systems.
h) Vital auxiliary must be properly classified. There are regulatory requirements of vital auxiliary related redundant services and operational requirements which directly contributes to the design and development.

In general, shipboard electrical system is ungrounded. The ungrounded system has no dedicated neutral line in the distribution system. However, there is always a capacitive ground path. This phenomenon of capacitive ground path needs to be better understood in view of system level grounding and bonding.

For better understanding, the grounding and bonding will be called G and the neutral line will be called N.

The non-linear solid state power applications usually create rapid changes to voltage and current while transferring energy to the load. These changes cause high frequency current to flow to the ground. This is considered as electrical noise.

There are many good features of electric drive (VFD and ASD) related applications onboard ships and platforms. However, there are many features which may contribute as electric noise such as harmonics, transients, grounding at the equipment level and system level. The design engineer must understand those issues, so that the causes and effects are properly analyzed during concept design and detail design. Recent VFD-related failure reports warrant better understanding, better design, and then overall design management. Electrical propulsion and auxiliary service requirements for the use of VFD contributed to recent operational challenges due to critical operational issues.

There are sample designs in support with electrical one line (EOL) diagrams are presented in this book to explain operational requirements which are unique for each class of vessels leading to a customize design. The designs are presented with drawings and diagrams, so fundamental electrical design steps are discussed, and then compared with the service requirements. This includes ship service power requirements, power requirements, and emergency power requirements.

The design includes:

1) Shipboard electrical low voltage and medium voltage power generation, electrical propulsion and power distribution systems. The fundamental shipboard electrical design requirements, design details, verification of the design prior to equipment installation, and then verification of the test results to establish a design base for the ship.
2) Offshore floating platforms and offshore support vessels as applicable.

The shipboard power system ground detection system is provided to detect ground in the ungrounded system so that the ground lifted as soon as the ground occurs. Single-phase ground fault is detectable; however, the system will continue to operate on the other two healthy phases. However, a second ground fault, phase to phase will create arcing, which must be monitored and lifted as soon as possible. Then for a three-phase fault, which is also called bolted fault, which must be detected as fast as possible, then the protective system must isolate the bolted fault to avoid any kind of explosion:

i) The solid-state devices operate with some ground reference. The basic requirements of a shipboard ungrounded system may not be complied with.
ii) The resistance grounding system use delta-wye transformer with wye neutral connected to ground with resistor is also an established ground reference point in the ungrounded power system. The resistance grounded system and ungrounded low voltage distribution system create a ground loop in the entire power system.
iii) The ungrounded power system ground plane in ideal conditions is a zero-voltage reference point in ideal conditions only.
iv) The delta-wye configuration is not acceptable for shipboard installations as it can propagate electric noise with the wye distribution. The delta–delta configuration is recommended as both primary and secondary will help to circulate electric noise within the winding.
v) The delta–wye will circulate noise all over the distribution system due to the wye configuration. Again, it is very difficult to maintain zero ground reference in a wye distribution system. The grounded wye distribution system creates a ground plan coupled with an ungrounded zero reference point.

Remarks: There are some special cases where the grounded wye distribution system is allowed due to operator safety reasons, such as an electrical workshop where the operator may use hand-held electrical tools. These features will not be discussed to avoid any misrepresentation (See Figures 1.1 to 1.5).

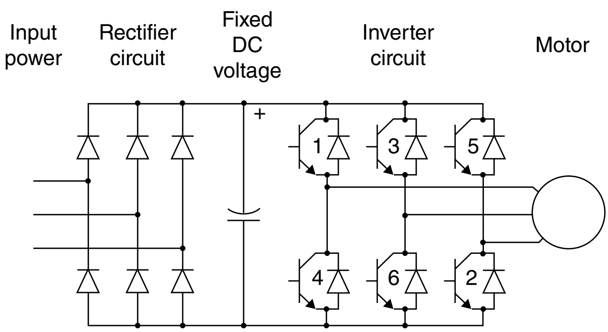


Figure 1.1 Typical VFD Power Circuit Topology With 6 Pulse Diode Rectifier, DC Link Filter and Voltage Source Inverter Showing Common Mode Voltage and Current.

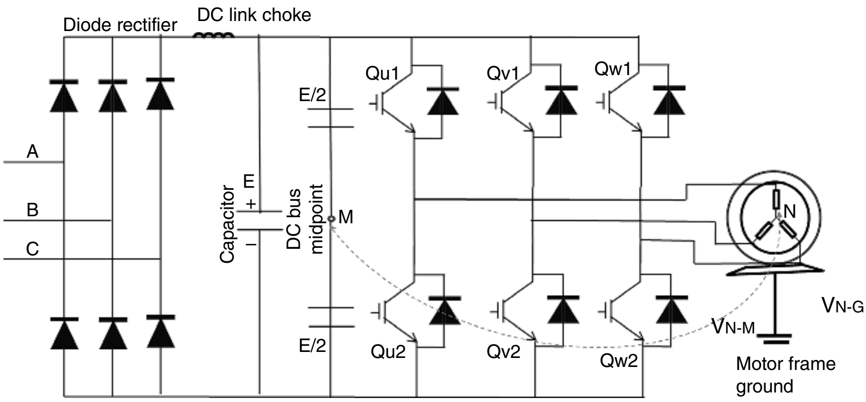


Figure 1.2 Typical VFD Power Circuit Topology With 6 Pulse Diode Rectifier, DC Link Filter, and Voltage Source Inverter Showing Common Mode Voltage and Current.

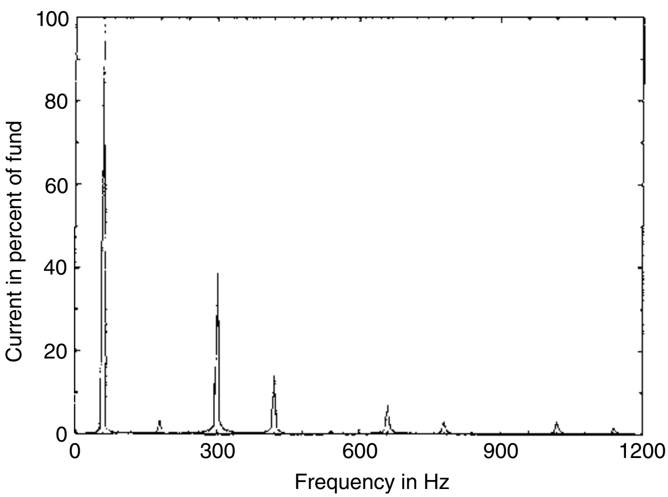


Figure 1.3 PWM Drive Harmonic Spectrum (Six Pulse Drive).

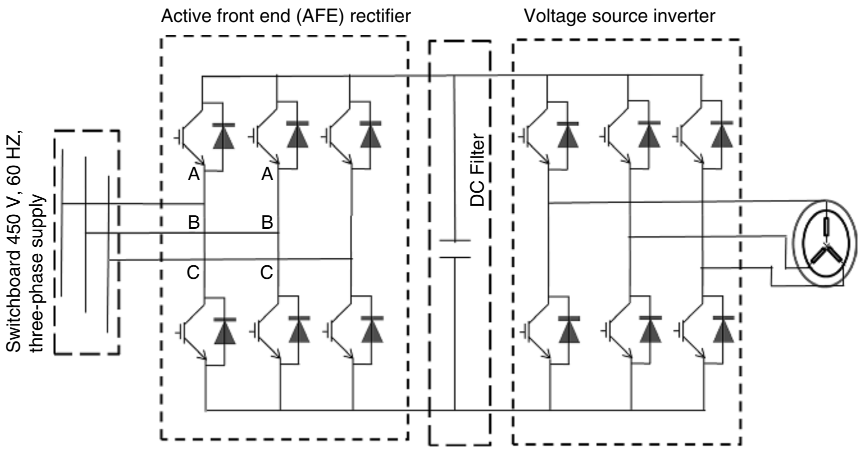
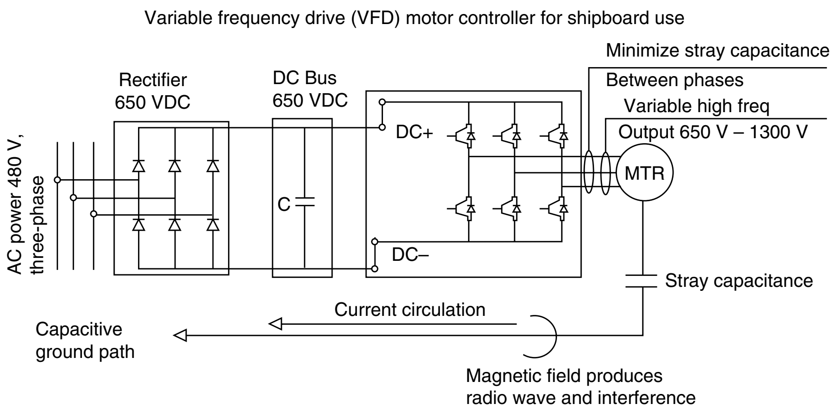


Figure 1.4 Typical VFD Power Circuit Topology With PWM Active Front End (AFE) DC Filter and Voltage Source Inverter.



Notes:

1. Do not anchor the VFD driven motor winding neutral point to the ground.
2. If the main supply line is grounded, the capacitive ground will circulate throughout the system ground and will contaminate the entire system. Shipboard power system is usually ungrounded, the shipboard ungrounded power supply will also be effected throughout through stray ground path.
3. Minimize stray system capacitance. Minimize stray capacitance between cable conductors.
4. Use VFD rated cable with proper voltage rating, drain wire and shielding.
5. Use short length VFD cable as recommended by the VFD supplier.

Figure 1.5 Typical VFD Power Circuit Topology With 6 Pulse Diode Rectifier, DC Link Filter, and Voltage Source. Inverter Showing Common Mode Voltage and Current.

1.3 Shipboard Low Voltage Power System Design Development With VFD and Verification

Refer to Figures 1.6 to 1.8 and Table 1.2.

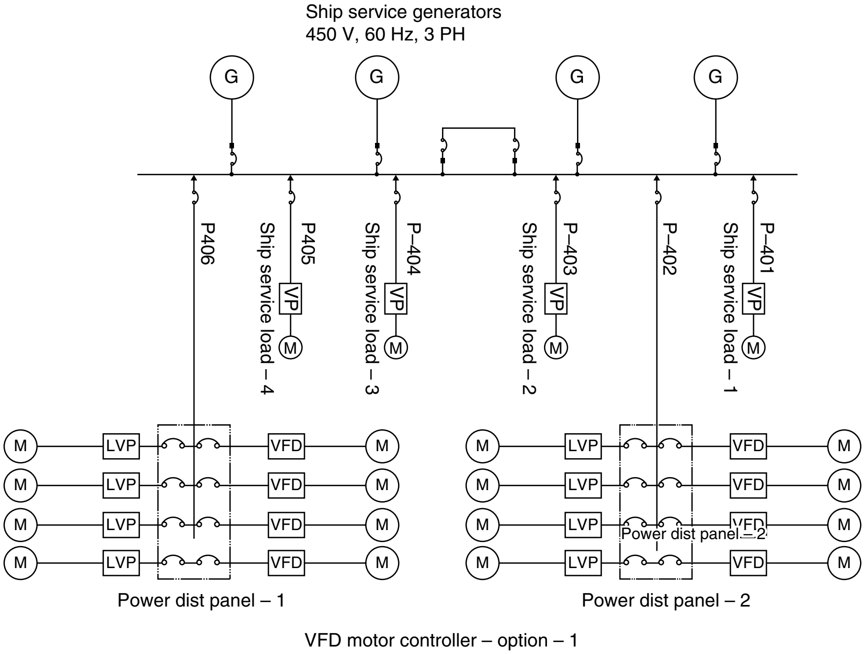


Figure 1.6 Typical EOL With Ship Service and Emergency Generator.

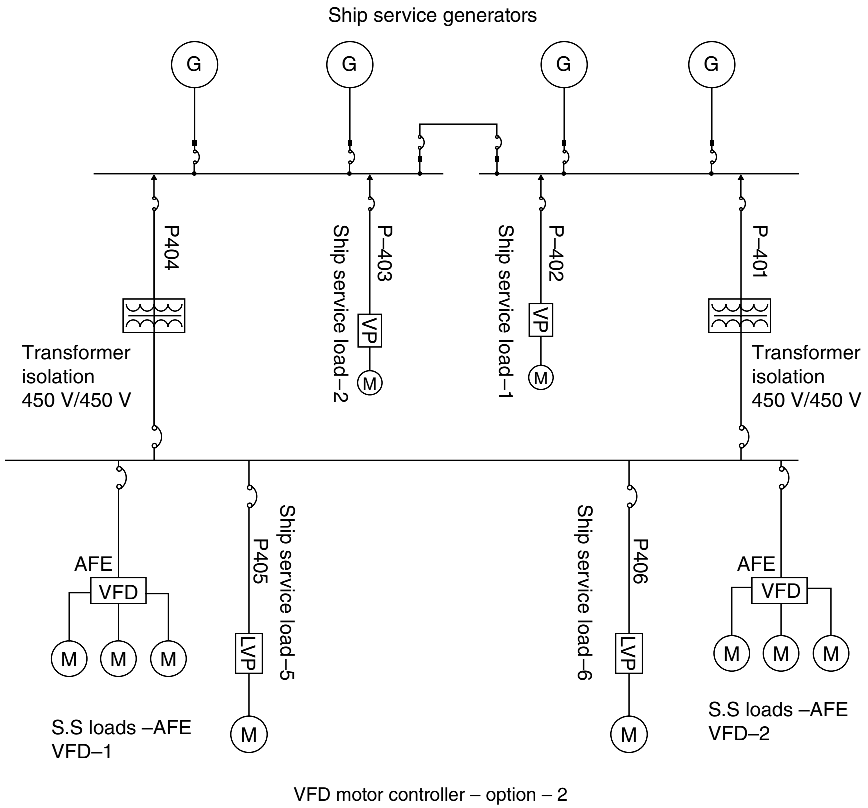


Figure 1.7 Typical EOL With Dedicated VFD Bus.

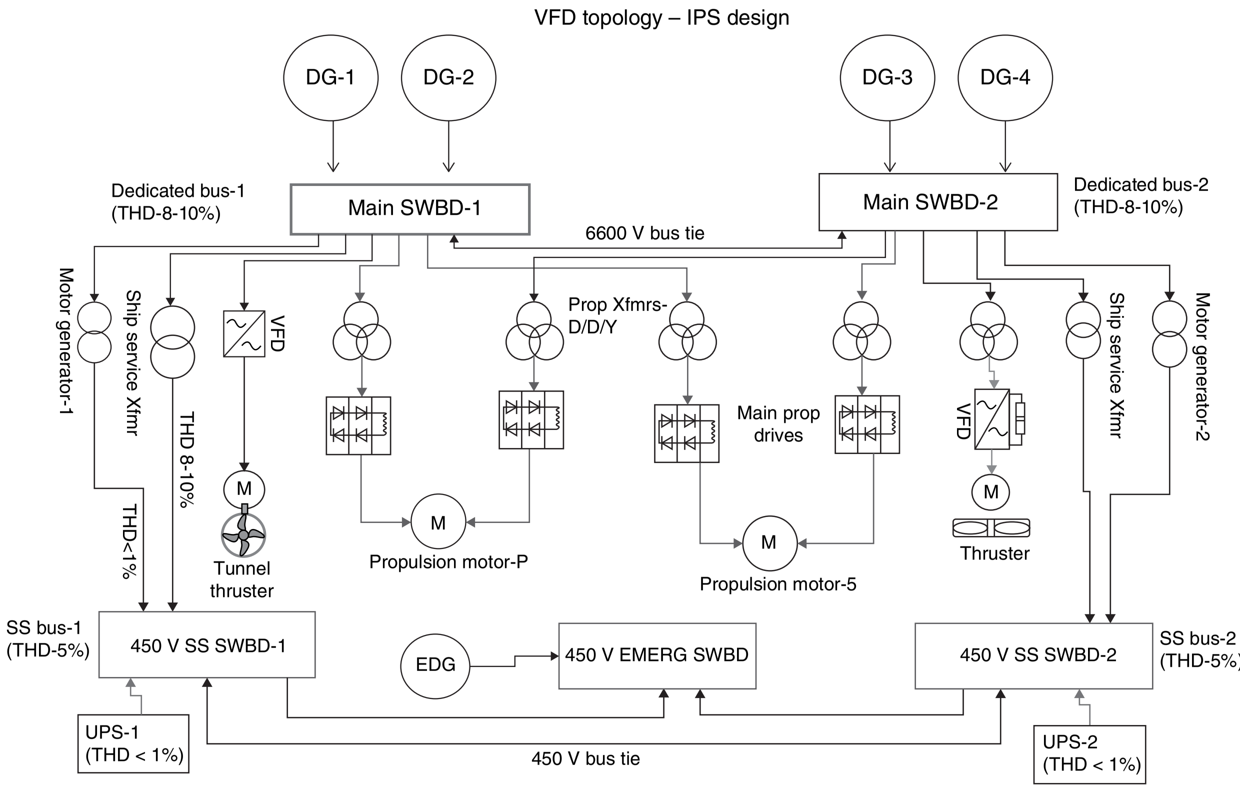


Figure 1.8 Typical Electrical One Line Diagram for Integrated Propulsion System With VFD, Ship Service Power Generation, and Emergency Generator and Distribution.

Table 1.2 Typical VFD Common Mode Voltage and Current.

COMMON MODE VOLTAGE IDENTIFICATION	
Balanced Three-phase System Motor Input	**VFD Driven Three-phase Output – Motor Input**
$V_{N\text{-}G}$ is zero	$V_{N\text{-}M}$ may not be zero (Common mode voltage) $V_{N\text{-}G}$ may not be zero (Common mode voltage)

Remarks: Icom is the common mode current flowing through the cable surface due to common mode voltage. This common mode current must be drained to the ground by a ground path such as the drain wire, cable shield, etc. Therefore, the VFD cable is identified as cable including drain wire and cable shield with higher insulation withstand capabilities.

1.4 Low Voltage Motor and Cable Insulation Stress Due to Variable Frequency Drive

The VFD output may is much higher than the input voltage. Per IEEE-45 the VFD motor cable voltage shall be 3.5 times the input voltage as shown in the Table 1.3.

Table 1.3 Low Voltage Motor and Cable Insulation Stress.

VAC RMS Voltage-Input	VAC Peak Voltage	Rectified VDC = VAC_{PK}	Inverted VAC_{PK}	VAC RMS Voltage-INV-Output	Voltage Swing-INV Out-Peak-Peak	VFD Cable Insulation
Rectifier Input-$VAC_{PK\ (RMS\text{-}IN)}$	Rectifier Input-VAC_{PK}	VDC $= VAC_{PK}$	$VDC = VAC_{PK}$ (Inverted)	$VDC = VAC_{RMS-OUT} = \frac{Vac\ pk}{\sqrt{2}}$		
120 $V_{RMS\text{-}IN}$	170 VAC_{PK}	170 VDC	340 VAC_{PK}	170 VDC	340 VAC_{PP}	600 V/1 kV
208 $V_{RMS\text{-}IN}$	294 VAC_{PK}	294 VDC	558 VAC_{PK}	294 VDC	558 VAC_{PP}	600 V/1 kV
460 $V_{RMS\text{-}IN}$	650 VAC_{PK}	650 VDC	1300 VAC_{PK}	650 VDC	1300 VAC_{PP}	2 kV
600 $V_{RMS\text{-}IN}$	849 VAC_{PK}	849 VDC	1698 VAC_{PK}	849 VDC	1698 VAC_{PP}	2 kV
690 $V_{RMS\text{-}IN}$	975 VAC_{PK}	975 VDC	1950 VAC_{PK}	975 VDC	1950 VAC_{PP}	2 kV
720 $V_{RMS\text{-}IN}$	1036 VAC_{PK}	1018 VDC	2036 VAC_{PK}	1018 VDC	2036 VAC_{PP}	2 kV
2000 $V_{RMS\text{-}IN}$	2828 VAC_{PK}	2828 VDC	5656 VAC_{PK}	2828 VDC	5656 VAC_{PP}	5 kV

1.5 Shipboard Power Quality and Harmonics Requirements

1.5.1 IEEE Std 45-2002, Clause 4.6, Power Quality and Harmonics

> Solid state devices such as motor controllers, computers, copiers, printers, and video display terminals produce harmonic currents. These harmonic currents may cause additional heating in motors, transformers, and cables. The sizing of protective devices should consider the harmonic current component. Harmonic currents in nonsensically current waveforms may also cause EMI and RFI. EMI and RFI may result in interference with sensitive electronics equipment throughout the vessel.
>
> Isolation, both physical and electrical, should be provided between electronic systems and power systems that supply large numbers of solid state devices, or significantly sized solid state motor controllers. Active or passive filters and shielded input isolation transformers should be used to minimize interference. Special care should be given to the application of isolation transformers or filtering, as the percentage of power consumed by solid state power devices compared with the system power available increases. Small units connected to large power systems exhibit less interference on the power source than do larger units connected to the same source. Solid state power devices of vastly different sizes should not share a common power circuit. Where kilowatt ratings differ by more than 5 to 1, the circuits should be isolated by a shielded distribution system transformer. Surge suppressers or filters should only be connected to power circuits on the secondary side of the equipment power input isolation transformers.

Notes:

1) To preclude radiated EMI, main power switchboards rated in excess of 1 kV and propulsion motor drives should not be installed in the same shipboard compartment as ship service switchboards or control consoles. (This is per IEEE 45-1998 Clause 4.6).
2) To reduce the effect of radiated EMI, special considerations on filtering and shielding should be exercised, when main power switchboards and propulsion motor drives are installed in the same shipboard compartment as ship service switchboards or the control console.
3) IEEE Std 519™-1992 provides additional recommendations regarding power quality. The IEEE-519-2014 is the latest edition which is widely different from the 1992 version. Reference to both standards will be necessary to establish the state of the requirement and apply as recommended.

1.5.2 Power Conversion Equipment Related Power Quality

1.5.2.1 IEEE Std 45-2002, Clause 31.8, Propulsion Power Conversion Equipment (Power Quality)

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

> Whenever power converters for propulsion are applied to integrated electric plants, the drive system should be designed to maintain and operate with the power quality of the electric plant. The effects of disturbances, both to the integrated power system and to other motor drive converters, should be regarded in the design. Attention should be paid to the power quality impact of the following:
>
> a) Multiple drives connected to the same main power system.
> b) Commutation reactance, which, if insufficient, may result in voltage distortion adversely affecting other power consumers on the distribution system. Unsuitable matching of the relation between the power generation system's sub-transient reactance and the propulsion drive commutation impedance may result in production of harmonic values beyond the power quality limits.
> c) Harmonic distortion can cause overheating of other elements of the distribution system and improper operation of other ship service power consumers.
> d) Adverse effects of voltage and frequency variations in regenerating mode.
> e) Conducted and radiated electromagnetic interference and the introduction of high-frequency noise to adjacent sensitive circuits and control devices. Special consideration should be given for the installation, filtering, and cabling to prevent electromagnetic interference.

1.6 Ship Smart System Design (S3D) for System Design With VFD (See Chapter 9)

The THD limits must be properly applied for specific distribution system to meet the operational requirements. For guide refer to Table 1.4.

Table 1.4 THD Limits for Various Applications.

Item	System	THD limits	Discussion
1	Dedicated bus-main switchboard	5 to 8%	Bus provides VFD power supply only
2	Sensitive bus- ship service switchboard	Less than 5%	Some critical equipment onboard
3	Non-Sensitive bus-ship service switchboard	Max 5%	
4	Emergency bus-Emergency switchboard	@ 1%	
5	UPS	Less than 1%	Guided by the system requirements

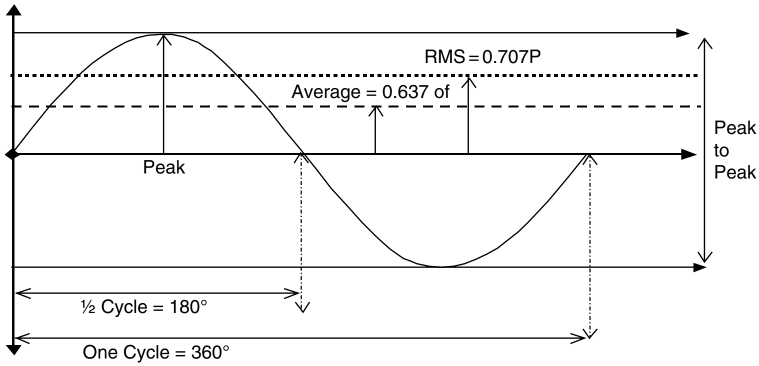


Figure 1.9 Typical EoI With Ship Service and Emergency Generator.

1.7 Carrier Frequency Ranges for Typical Solid State Devices

Refer to Table 1.5.

Table 1.5 Carrier Frequency for SCR, BJT and IGBT.

DEVICE TYPE	CARRIER FREQUENCY	EXPLANATION	REMARKS
SCR	250 Hz to 500 Hz	(a) 4 to 8 time the fundamentals	
BJT	I kHz to 2 kHz	(a) 8 to 16 times the fundamentals	
IGBT	2 kHZ to 20 kHz	(a) 16 to 160 times the fundamentals	

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

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

To reduce the effects of radiated EMI, special considerations on filtering and shielding should be exercised when main power switchboards and propulsion motor drives are installed in the same shipboard compartment as ship service switchboards or control consoles.

1.8 VFD Fundamentals

See Figures 1.10 to 1.14.

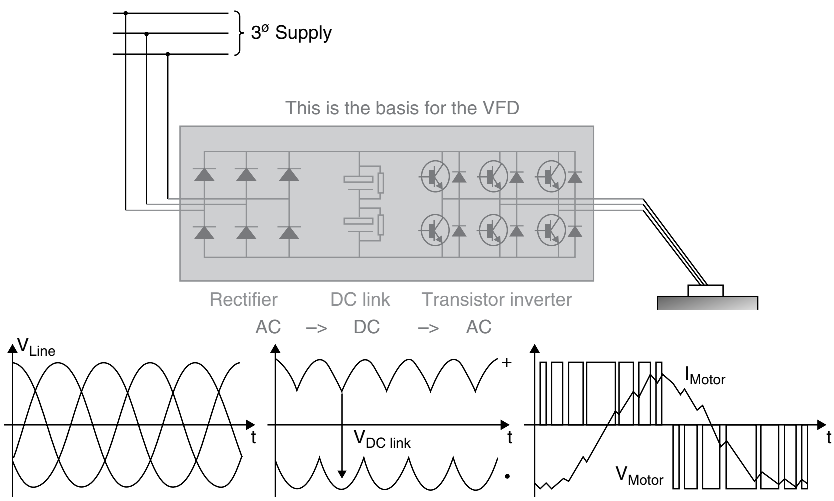


Figure 1.10 Frequency Spectrum for Input, Rectifier Output, and PWM Showing Uneven Current Output.

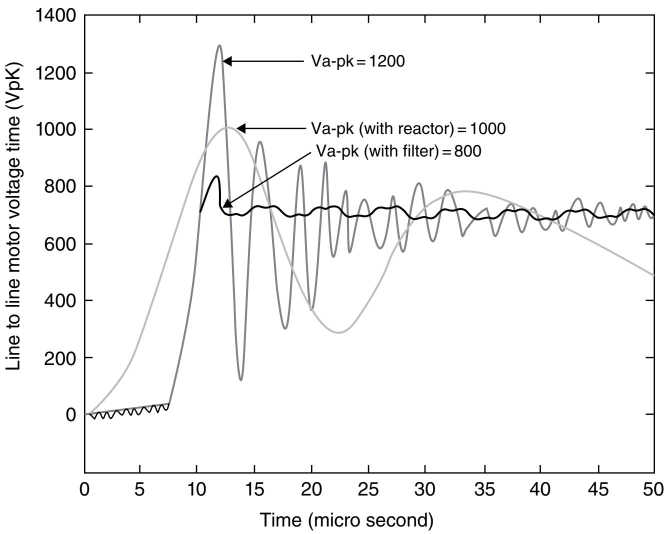


Figure 1.11 Frequency Spectrum for Input, Rectifier Output, and PWM Showing Uneven Current Output.

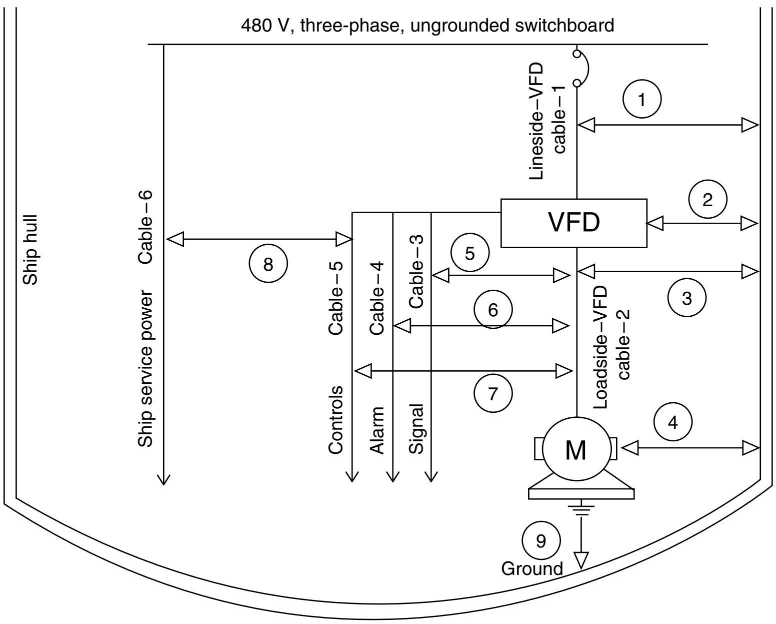


Figure 1.12 Recommended VFD and VFD Cable Separation.

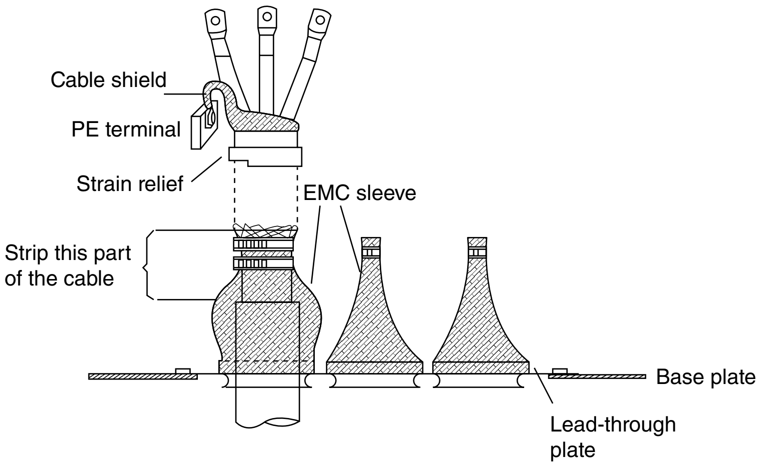


Figure 1.13 VFD Cable Shield 360 Degree High Frequency Termination With EMC Sleeve.

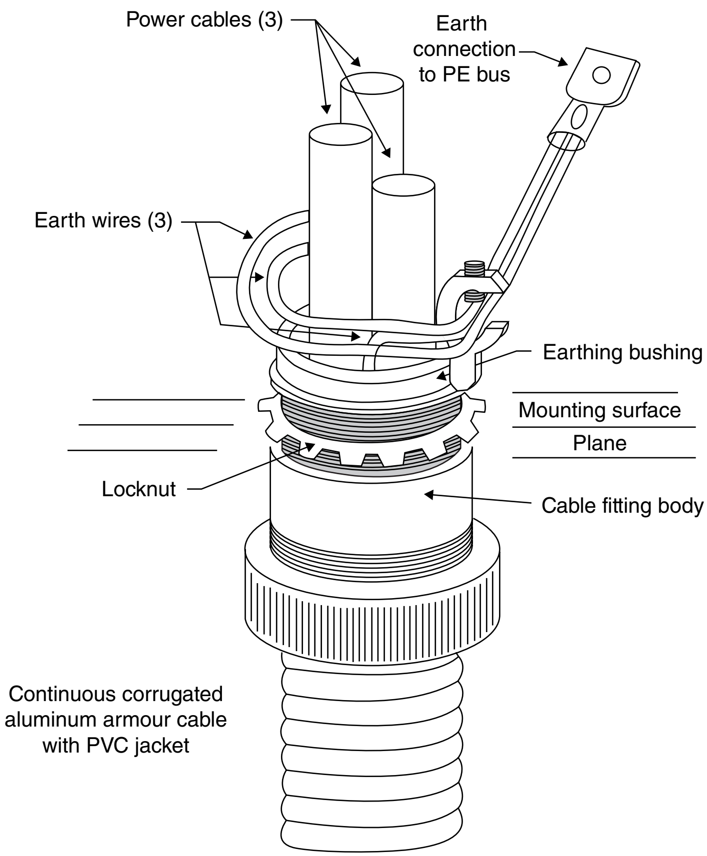


Figure 1.14 VFD Cable Drain Wire 360 Degree Termination.

1.9 Apparent Power for Linear and Non-linear Loads With and Without Harmonics

See Figures 1.15 and 1.16.

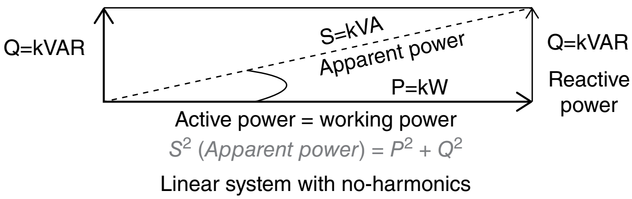


Figure 1.15 Power Vector for Linear System With No Harmonics.

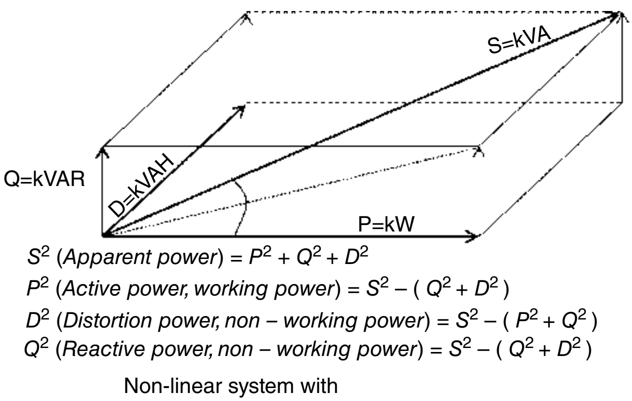


Figure 1.16 Power Vector for Non-Linear System with Harmonics.

1.10 Ship Smart System Design (S3D) – "Digital Twin"

The Smart ship system design (S3D) concept can be embodied in "digital twin" in view of low cost computing, powerful analytical platforms of data mining, machine learning, and data networking technology. Any complex ship design and development fidelity can be achieved by using "digital twin", so that there is no need for arbitrary simulation, costly hardware in the loop prototyping.