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A Comprehensive Review of Maritime Microgrids: System Architectures, Energy Efficiency, Power Quality, and Regulations

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ABSTRACT The recent trends to design more efficient and versatile maritime (both marine and offshore) vessels have attracted significant attention toward high penetration of power electronics systems in electric ship systems, which trigged a variety of power system architectures in civilian and naval ships. The availability of advanced power electronics converters further supported to improve maneuverability, efficiency, and compactness at reduced greenhouse gas emission in marine vessels. The fast-growing penetration of these power electronics converters adds a number of advantages to the ship power system. However, risk factors associated with the quality and reliability of the whole system should be considered. Power quality issues in marine networks have been reported from recent field accidents, therefore, the marine regulatory bodies need to revise and/or develop new power quality standards to ensure the reliability and scrutinize the safety of the whole ship system and crews. This paper presents 1) a classification of marine vessels and their power system architectures; 2) power electronics converters topologies and their non-linear characteristics; 3) control and protection architecture; 4) energy efficiency indicators; 5) a comprehensive case study to elaborate power quality in the marine system, and; 6) extensive discussion about power quality standards and highlights the urgency to update existing power quality standards.

INDEX TERMS Marine and ship networks, power system architectures, micro grids, distribution networks, power quality, energy efficiency, regulations, standardization, grid robustness.

I. INTRODUCTION

In recent years, energy and environmental issues become remarkably main concerns due to ever growing greenhouse gases (CO_2, NO_x and CH_4 etc.) emissions. If these emissions will continue with the same pace and no proactive measures are taken in timely manner, the greenhouse gas emissions could be projected to an increase from 50 to 250% by 2050 [1]. This is a major concern for environmental agencies, metrological institutions, which is gaining worldwide attention. Paris Convention is one such example, where numbers of recommendations have been made to achieve at least 2°C reduction in global warming. Today, shipping sector alone contributes around 15% of the global Nitrogen Oxide (NOX) emission, which is also projected to increase in the future, if no measure is taken on time. Therefore, the International Maritime Organization (IMO) enforces restriction on ship emission in their regulation of International Convention for the Prevention of Pollution from Ships (MARPOL) [1].

Diesel engine generators are most often source of power in a ship system, which also emits significant NO_x in the environment. Moreover, their optimum fuel utilization factor is just 40%, and rest of the stored energy in the fuel is dissipated through heat or the exhaust. Therefore, the propulsion power and generating plants of future ship have to reduce fuel consumption and emission overtime to meet the ship emission requirements imposed by MARPOL and other regulatory bodies.

The ship power system is continuously being improved through efficiency improvement and emission reduction; and at the same time, it should meet increasing power demand. For example, the propulsion system in a conventional

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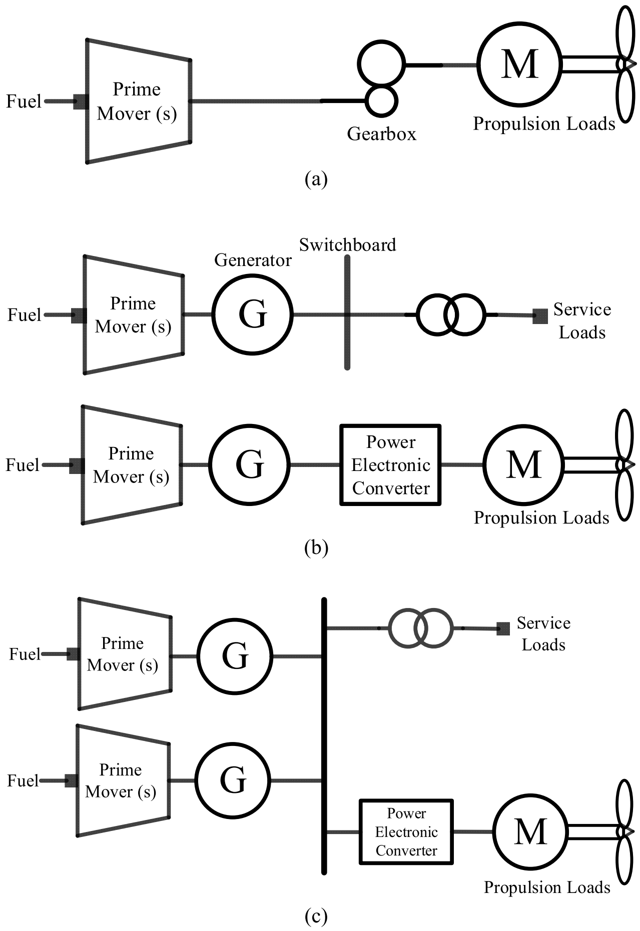


FIGURE 1. (a) Mechanical propulsion power system. (b) Conventional electric-drive power system. (c) Integrated power system (IPS).

power system was originally a mechanical-drive system with reduced gear connecting the prime movers to propeller shaft as illustrated in Figure 1(a) [2]. In order to gain faster response, many vessels were converted to electric propulsion with separate electric-drive power system which consists of two separate subsystems: one for propulsion and another for auxiliary service loads as shown in Figure 1(b) [3]. Due to separation between the subsystems, the engine of each subsystem is only utilized by their respective system. In some vessel designs, almost 90% of power is generated to the propulsion system and very small amount of power supplied to auxiliary service loads. However, it is still required a separate diesel generator in the system.

In order to optimize the conventional power system design, the Integrated Power System (IPS) was introduced as a solution, where all the generators are integrated to same power grid, which distributes the power to all consumer systems as shown in Figure 1(c) [3]. The power sharing ability of IPS improves power flexibility and availability of the system. At low and medium speed ranges, the IPS can generate same amount of power as conventional electric power system with a smaller number of running prime movers. This is desirable from both economic and environmental point of view, as fewer running generators will improve fuel efficiency and reduce greenhouse gas emission. Fuel/energy efficiency became an important factor among marine community. Recently, energy efficiency indicators have been proposed by IMO to set minimum efficiency requirements for ship. This paper includes brief description about energy efficiency indicators that can be taken into consideration from design to operating phase of a ship to improve energy efficiency.

Over the last decade, tremendous developments have been reported in electrical propulsion system design; especially in cruise vessels, icebreakers, Dynamic Positioning (DP) offshore vessels and Liquefied Natural Gas (LNG) carriers. Moreover, other kinds of vessels such as shuttle tankers, pipe and cable layers and fishing vessel are also gaining interest in utilizing full or partially electric propulsion system due to better fuel efficiency [4]. The architecture of electric propulsion systems today has many variants depending on vessel type, operational profile and the available technology at the time of construction.

Recent developments in marine vessels such as in information system, radar and military precision weapon, the use of electrical equipment is significantly increased and expected to continuously increase in future towards an All-Electric Ship (AES) concept, where all installed equipment and systems are based on electrical types. Most of these equipment and systems required different power conversion stages such as AC-DC, AC-AC, DC-DC or DC-AC. Power Electronics is an important part of any power conversion system, and therefore numerous power electronics devices are used in maritime power systems to supply power in a suitable form and level to different loads. However, these power electronics devices are of non-linear nature and generate harmonics and resonances in the grid side [5]. In maritime applications, the relatively high source impedance (typically 15-20%) of the supply generators is used, which can cause excessive level of voltage distortion together with current harmonics generated by power electronic devices. Recently, a couple of severe accidents have been reported due to higher voltage distortion in maritime network. For example, the Piper Alpha platform in the Scottish North Sea is the world's largest offshore oil field fire disaster in 1988, also caused by harmonics generated by large electrical submersible pumps and other variable speed drives [6]. Another such accident reported in 2006 in North Sea, where it took over four hours to extinguish the fire [6]. Later was been acknowledged that fire accident happened due to higher voltage distortion in the power system. In order to avoid such accident in the future and to ensure the reliability of equipment and the safety of crews, the marine regulating bodies have imposed strict limitations/requirements on power quality in marine power system. Various organizations (such as IEC, IEEE and ABS etc.) are working together to develop standards for implementing off-shore and on-shore power system to marine vessel. This paper reviewed various existing power quality standards and highlights the need of new requirements.

Power quality issues can be more complicated in some vessel such as container ships where a high number of containers with motor drives are connected. Nowadays, use of motor drive is very common in 'reefer container' to improve energy efficiency of compressors. In such application, continuous changing load profile makes it difficult to estimate the power quality at the Point of Common Coupling (PCC). Therefore, a comprehensive case study has been performed in this paper to understand power quality issues in the container ship.

The contents of this paper are presented as follow: in Section-II, the marine vessels are broadly classified into three categories and then electrical power systems of different vessel types are reviewed. Section-III presents the main components of marine electrical power system (generation, distribution and loads). Section-IV briefly describes energy efficiency indicators and discusses how to improve energy efficiency. In Section-V, highlights the power quality issues in electric ship network and a comprehensive power quality study is carried out. Section-VI reviews various available power quality standards and accentuate for new requirements. Finally, Section-VII draws the conclusions and future recommendations.

II. CLASSIFICATION OF MARINE TYPES

The maritime vessels can be classified broadly into the following three categories:

- Passenger Vessel
- Commercial Vessel
- Military Vessel

A. PASSENGER VESSEL

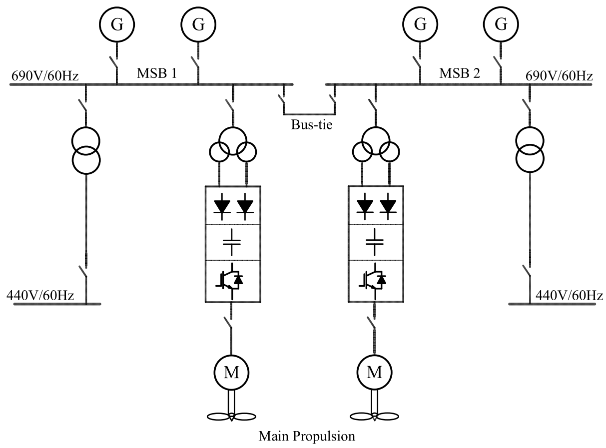
Passenger vessels are primarily used for carrying passengers. This includes ferries, cruise ships, ocean liners and yachts. Passenger ships have also been commissioned as navy ships on numerous occasions to deploy the naval forces. However, these navel passenger vessels have strict regulatory requirements; therefore, their electrical architectures are different than civilian passenger ships. Recent market trend shows that cruise and ferry travel is continuously growing with a steady pace. Therefore, discussion in this section is limited to ferries and cruise ships only.

1) PASSENGER FERRY

Modern passenger ferries often have two-split IPS designs for small and medium size vessels as shown in Figure 2. As can be seen, the power generating units are split into pairs, each pair is connected to a Main Switchboard (MSB 1 and 2), and the switchboards are connected through redundant bus-ties. Each switchboard supplies one propulsion system and the service loads.

Depending on the vessel type and its regulation, the IPS may include an emergency generator supplying vital loads, and in some cases part of the propulsion loads. The IPS is equipped with many breakers, which may be used to isolate faults from propagating through the grid and causing a complete blackout. This configuration is important for achieving the needed system reliability and safety as per regulatory requirements.

(a)



(b)

FIGURE 2. (a) Passenger ferry with electric propulsion [7]. (b) Electrical line diagram of passenger ferry.

The electrical and propulsion plant of a passenger ferry is designed with low voltage rated equipment, and a main electrical power distribution is supplied at 690V system. The Liquefied Natural Gas (LNG) or diesel generators are used to feed the main switchboard, as well as the propulsion drive system and service loads via propulsion transformer and service transformer. Propulsion converters are Voltage Source Inverter (VSI) type, and most of these vessels use synchronous motors as these are directly coupled to the propeller either in a pod or through a shaft-line.

2) CRUISE SHIP

Cruise ships are large passenger ships (in Figure 3(a)) having onboard facilities of restaurants, swimming pools, fitness centers and shops. Service loads are significant in cruise ship compare to ferry vessel. Therefore, the electrical power and propulsion plant in cruise ship are normally medium voltage rated equipment. The electrical line diagram of cruise ship is shown in Figure 3(b) [4], where a main electrical power distribution is supplied at 11 kV systems. Different numbers of diesel generators (4 to 6) feed the main switchboard, and from there the propulsion drive system of 3.3 kV (or other selected voltage rating) are fed via propulsion transformers. Service loads are fed via step-down transformer at low voltage (typically 440V/230V).

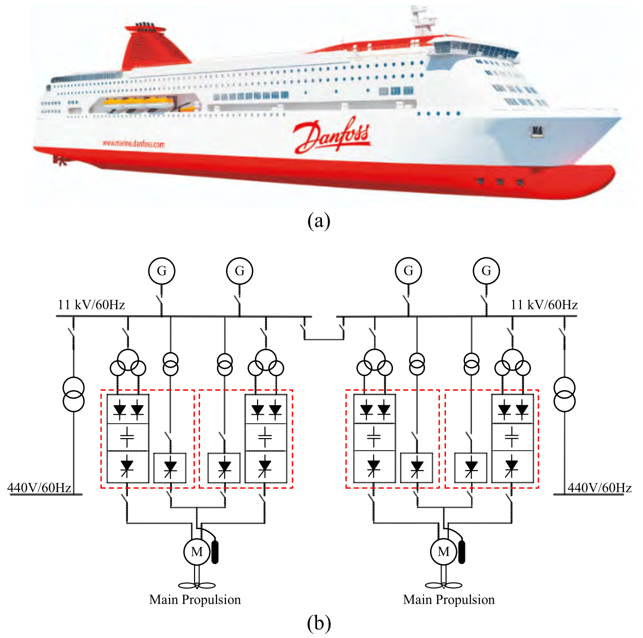


FIGURE 3. **(a) Cruise ship with electric propulsion [8]. (b) Electrical line diagram of cruise ship.**

Rated power of each propulsion line is typically around 20 MW and total installed generator power can reach 80 MW or more. For example, the largest cruise ship today "Allure of the Seas" has an installed power capacity of 97 MW divided on six engines, and 60 MW of propulsion divided on three propulsion lines [4].

B. COMMERCIAL VESSEL

The commercial vessels can be grouped into following categories:

- Offshore Vessel:
  - Oil and Gas: exploration, support, production and construction vessels
- Cargo Vessel:
  - Container vessel
  - Bulk carrier vessel
- Tanker vessel:
  - Crude oil tanker
  - Chemical tanker
  - Liquefied Natural Gas (LNG) tanker
- Specialty Vessels:
  - Ice breaker
  - Fish processing

1) OFFSHORE VESSELS

Offshore vessels are designed to perform a wide range of tasks associated with the offshore explorations and production of oil and gas. Offshore vessels are of different sizes, shapes and designs and are meant for specific roles or purposes. To be able to operate from remote locations, offshore drilling and production units need different types of support services that are provided by specialized vessels.

Offshore vessels can broadly include oil exploration platform (fixed or floating type) and some special service vessel such as drill ships, anchor handling ships, cable laying ships and transportation ships for moving equipment. Some of these offshore vessels are shown in Figure 4.

FIGURE 4. **Offshore vessels. (a) Drillship [9]. (b) Exploration platform [10]. (c) Pipeliner [11]. (d) Transportation vessel [12].**

The complexity and power size of offshore vessels depend on application requirements. Today majority of these vessels use diesel-electric systems, however still a certain amount of mechanical propulsion (or hybrid propulsion) is used in some standardized versions. The power generation and distribution of these types of vessels are commonly used 690V (low voltage) network. The VSI with synchronous motor is most common choice in the propulsion system of offshore vessels. The electrical line diagrams of few offshore vessels are shown in Figure 5 [4].

2) CARGO VESSELS

A cargo vessel carries goods and materials from one port to another. These vessels are specially designed for the task, often being equipped with cranes and other mechanical systems for loading and unloading operations. Based on goods packing, cargo vessels can be classified as bulk carrier and container vessel (Figure 6).

Bulk carriers are a type of ship which transport cargoes in bulk quantities without any specific packing to it and generally contain items such as food grains and coals. On the other hand, container ships hold a huge amount of cargo, compacted in different types of containers. Depending on the type of products to be shipped, container units may vary in structure, dimension and construction. For example, temperature regulated shipping containers are used for storages of fruits and vegetables over long distances. These refrigerated, or reefer container loads are significant in cargo ship and required special arrangement in electrical power system as shown in Figure 7.

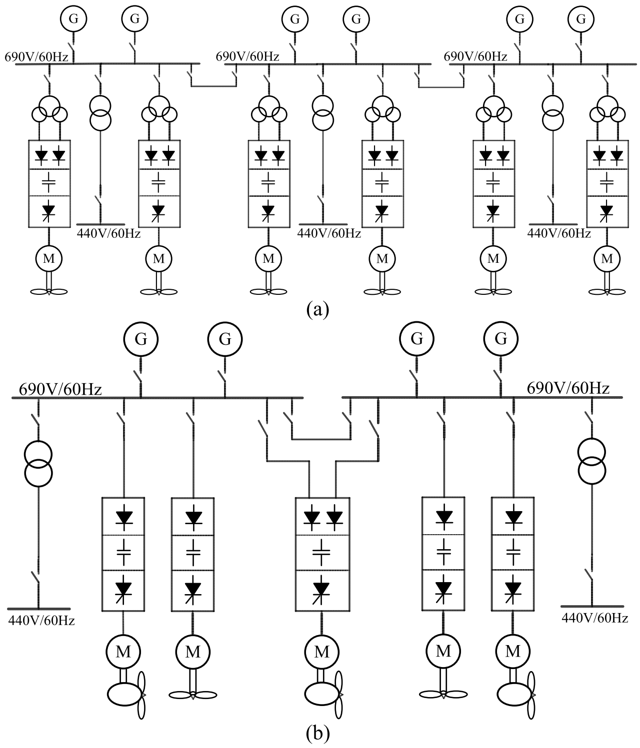


FIGURE 5. Electrical line diagram of (a) drillship and (b) construction vessel.

FIGURE 6. Cargo vessels, (a) Bulk carrier [13] and (b) Container vessel [14].

3) TANKER VESSELS

A tanker is a merchant vessel designed to transport bulk amount of liquids or gases. for example, oil tanker, chemical tanker and LNG tanker as shown in Figure 8.

Figure 9 shows a typical configuration of LNG carriers with electric propulsion - medium speed motors and gearbox. Recently, the medium voltage (3.3kV or 6.6kV) power plant is common in the tanker vessels. Due to increasing power demand, it is expected that voltage level will be increased up to 11kV in the near future. Standard diode rectifiers with 24-pulse solutions is used to minimize the harmonic distortions. The VSI with asynchronous motor is most common in these electric propulsion systems of LNG tanker vessels [17].

4) SPECIALTY VESSELS

Another important category of vessel is specialty vessels, which have specialized mission requirements that require

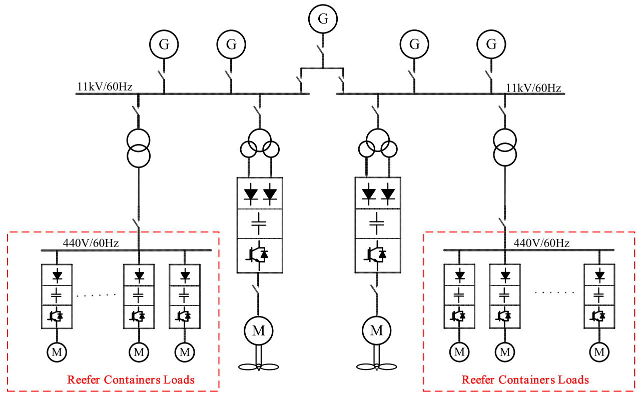


FIGURE 7. Electrical line diagram of reefer containers ship.

FIGURE 8. Tanker vessels, (a) LNG tanker [15] and (b) Crude oil tanker [16].

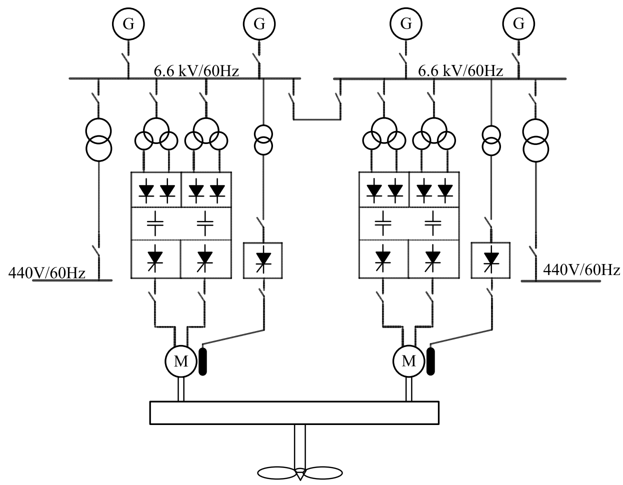


FIGURE 9. Electrical line diagram of LNG tanker.

more than just basic feature. Most common vessels in this category are ice-breaker and fish processing vessel as shown in Figure 10.

Fish processing vessel also known as factory ship, is a large ocean-going vessel with vast on-board facilities for processing and freezing of fishes. Together with propulsion loads, factory ship has significant processing and refrigeration loads. The typical configuration of factory ship with electric propulsion system and other processing and refrigeration loads are shown in Figure 11 [7].

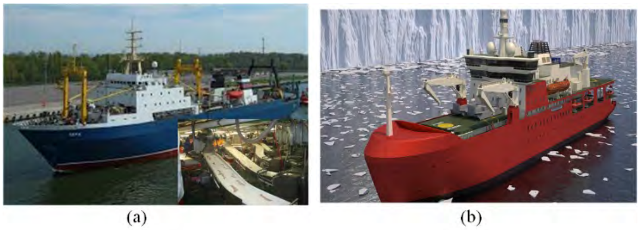


FIGURE 10. Specialty vessels: (a) factory vessel [18], [19] and (b) Icebreaker [20].

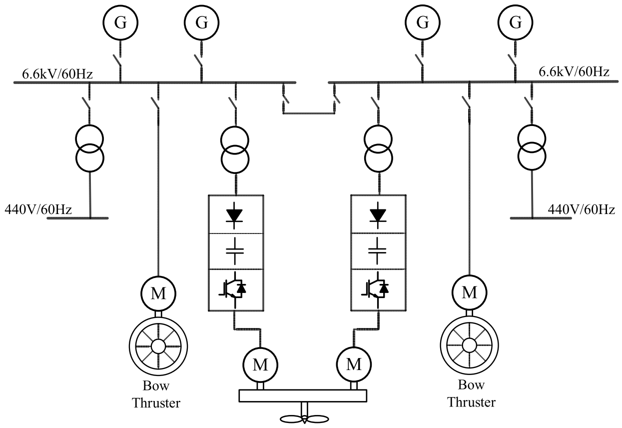


FIGURE 11. Electrical line diagram of factory ship.

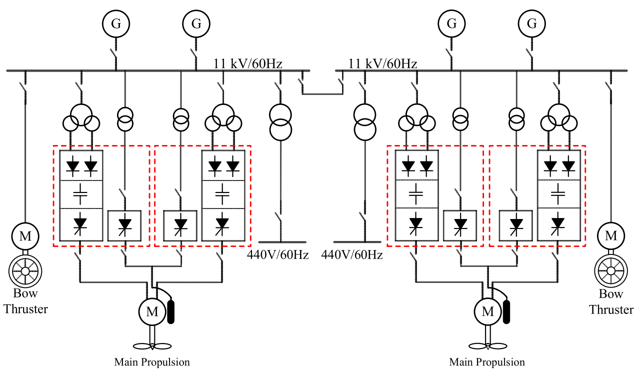


FIGURE 12. Electrical line diagram of icebreaker.

Icebreaker is a special designed ship to move and navigate through ice covered water, and to provide safe waterways to other boats and ships. As shown in Figure 12 [7], for icebreaking operation, electric propulsion system required high over torque capability and fast and accurate response of electric motor drives.

C. MILITARY VESSEL

Military vessels can be grouped into following categories:

- Navy vessel
  - Carriers: Aircraft and helicopter
  - Submarines: Ballistic missile
  - Surface warfare: Frigates, battleship
- Coast Guard

Military ships (such as warship) are normally smaller then commercial ships but are extraordinary dense with large engines and high technology system as shown in Figure 13. Warships are highly compact and equipped with complex sensors, weapons and communication and power distribution system (often in duplicate to provide redundancy). For example, a radar system is used for both commercial as well as in warship; however, in warship such system is not only for navigation but also for detecting threats and engaging them [25]. Moreover, military ships must also need to meet more demanding standards, because they operate in open seas as well as combat zones. Military ships normally have more strict customer requirements in the following areas compared to commercial ships [26]: i) Wide range of ship speed, ii) higher shock capability, iii) reduced noise, iv) infrared signature, v) cleaner emission, and vi) adaptable with change in operation requirements such as pulsed load.

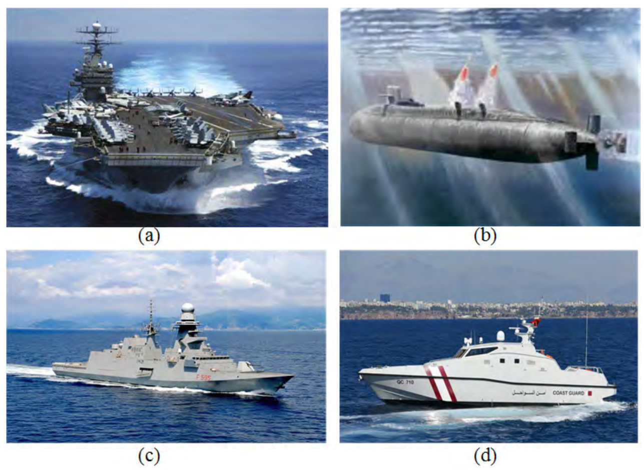


FIGURE 13. Military vessels, (a) Carrier [21], and (b) Ballistic Submarine [22], (c) Frigate [23], and (d) Cost Guard Vessel [24].

In order to meet special requirements in military ships, the electric power system is often different than commercial ships. A new hybrid (combined diesel-electric and gas) system attracted attention in military vessel due to its better fuel efficiency, flexibility and reliability. Figure 14 [27] shows a hybrid electric power system for frigate, where combined diesel and gas propulsion systems have been used. This hybrid system employs electric motor which is connected to the propeller shaft and powered by diesel generators. For higher speeds, gas turbines power the shafts via gearbox, but at lower speed ship service generator set to run at more efficient operating conditions and larger propulsion gas turbines to be shut down [27]. This arrangement helps to reduce fuel consumption and provide wide operating capability to ship.

III. AC POWER NETWORKS: GENERATION, DISTRIBUTION AND LOADS

The maritime power network is different than a traditional onshore power network. In contrast to the onshore power network, the ship network is an isolated system where loads

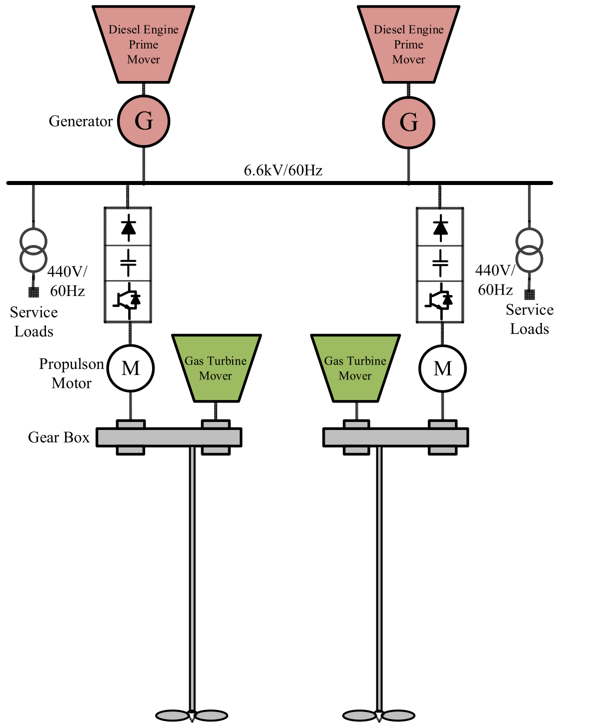


FIGURE 14. Electrical line diagram of hybrid electric power system for frigate.

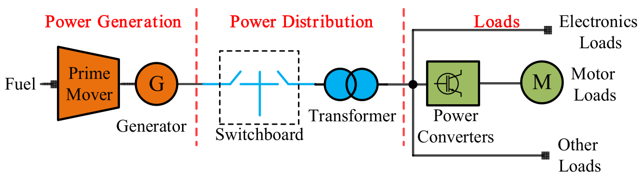


FIGURE 15. Typical line diagram of electric maritime power system.

are placed very close to power generation units with short feeders. Moreover, a centralized control electrical power system is used in a maritime network, whereas in an onshore network, it is totally decentralized and divided into several sub systems. Therefore, in the maritime network, high level of power is delivered locally to a number of loads in a small area, which can give special engineering challenges such as accuracy, safety, power quality and reliability.

The generalized line diagram of an electric maritime power system is illustrated in Figure 15 and its main components are listed as below:

- Power Generation
- Power Distribution: Switchboard and transformer
- Loads: Propulsion and service loads

A. POWER GENERATION

The power generation unit in the maritime network is mainly a synchronous generator set driven by a prime mover which is fueled with diesel or heavy oil. In some high-speed vessel, gas engine is sporadically used as a cheap energy source.

Diesel engine-generator is still cost- and size-effective option in many medium and high-speed vessels compare to similar rated low speed mechanical propulsion system. Availability of power generation is of high concern in maritime applications. Therefore, more than one power generation units (i.e. diesel engines) are used to improve overall system reliability, operating mode and efficiency.

B. POWER DISTRIBUTION

After the power generation, the power has to be distributed safely, efficiently and reliably to different parts of the ship. Unlike to shore based distribution system where the lengths of the conductors and feeders in distribution and transition networks as in the range of kilometer, in the shipboard electrical power distribution system, the length of feeders are very short. However, there are challenges to fulfill the safety and protection requirements in maritime system due to strict regulation.

A typical ship power distribution system divided into following main parts:

- Switchboard
- Transformer

1) SWITCHBOARD

The switchboard is integral part of a distribution system, which ensures safe and reliable supply to different parts of the vessel. The layout of vessel distribution system is very complex and normally split in different sections such as *Main Switchboard*, *Distribution Board* and *Emergency Switchboard* as shown in Figure 16.

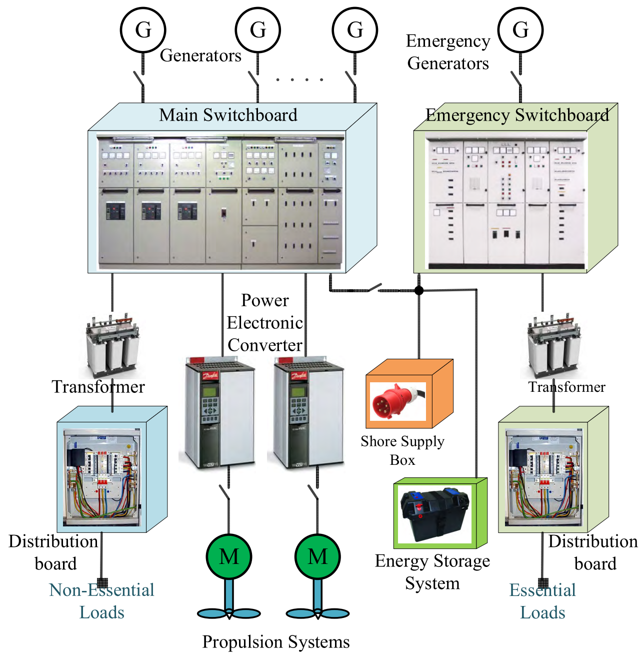


FIGURE 16. Layout of electric power system of a ship.

The main switchboard includes main bus bars, protection devices, measuring and monitoring devices. The main bus bar has three heavy, thick bars of conductors (usually copper), underlying and running horizontally throughout the length of the main switchboard. Each conductor insulated from each other. The main bus bar is normally split into two, three or more sections, in order to obtain the redundancy requirements of the vessel. The splits of bus bars are made through a change-over switch, which provide better flexibility during load transient (sharing of diesel generators) and fault condition (tolerate in the event of one section failure). A ship may contain many diesel generators connected to main bus bars, therefore various protection such as overload, reverse power and so on are implemented through circuit breakers such that the faulty generator is electrically isolated from the main bus bars. To monitor the performance of the ship network on continuously basis, the main switch board has various measuring and monitoring devices to measure power and power quality parameters.

The main switchboard gets its supply from main generators and then distributes to various loads. Normally high-power loads such as propulsions, pumps and compressors are directly connected to main switchboard. Some low power loads may not be connected directly to the main switchboard, such as small motors and other devices that consume very little amount of power and thus they may be grouped together. Instead of providing cable for every such individual motor, a single cable is taken from the main switchboard and then connected to distribution board which has a small bus bar. Advantages of these distribution boards are to save cable cost and to improve reliability of this system. Also, if any fault occurs in such small loads will not activate the protection devices on the main switchboard [52].

Loads are mainly grouped into two categories based on their importance from vessel and personnel safety view point: *Essential* and *Non-Essential loads* as listed in Table 1 During normal operation, both essential and non-essential loads get supply from main switchboard or distribution board (depending on power size), but during emergency situation such as fire or flooding, these essential loads can get supply from emergency board to continue their operation. Therefore, an emergency switchboard is connected with emergency generator. Another important aspect of this emergency switch board is that it is located above the load water line or uppermost deck. Thus, emergency services of a vessel are always supplied in order to maintain the safety of the vessel and personnel.

TABLE 1. **Essential and non-essential loads of a ship.**

Essential Loads	Non-Essential Loads
▪ Navigation lights and equipment	▪ Engine room pumps
▪ Alarm systems	▪ Air conditioning system
▪ Steering gear	▪ Gallery equipment's
▪ Other safety system	▪ Purifiers and other machines

In recent years, power demand is increasing in every kind of vessel. This will increase normal load and short circuit currents, which will require thicker bus bars and cable conductor to handle thermal and mechanical stresses. As weight and volume is major limitation in maritime applications, thus possible solution is to increase the system voltage and hence reduce the current levels. So, recent trend is to shift towards medium voltage to handle the increasing power demand in many applications. As per IEC voltage level, the most common alternative for main distribution system with application guideline is stated in NORSOK [53] as listed in Table 2.

TABLE 2. **Distribution voltage level and application guideline.**

Voltage (V)	Generator Capacity	Loads
▪ 11kV	Where total installed generator capacity exceeds 20MW	Motor from 400kW and above
▪ 6kV	Where total installed generator capacity between 4 - 20MW	Motor from 300 - 400kW
▪ 690V	Where total installed generator capacity is below 4MW	Used for consumers below 400kW
▪ 440V/230V		For lower distribution loads

FIGURE 17. **Power transformer for marine application [54].**

2) TRANSFORMER

Power transformer is another important part of a distribution system (as shown in Figure 17). The purpose of transformer is to isolate different parts of electric power system and provide suitable voltage level to loads. In some vessels, transformer also used as phase-shift transformer to cancel most dominating current harmonics generated by frequency converters used in different loads such as propulsion system. Reduction in current harmonics helps to reduce voltage distortion for generators and other connected loads at the same PCC.

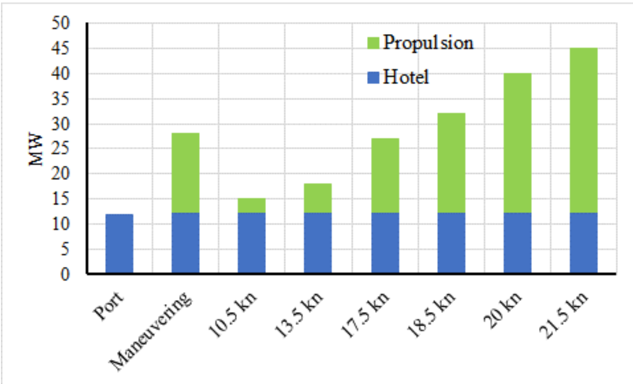


FIGURE 18. Electrical power distribution in a cruise ship.

The transformer normally provides a very good damping for high frequency noise, which helps to reduce high frequency emission to propagate within different parts of power system. The transformer can be classified into different categories based on their design, construction and electrical properties, although they all share the basic characteristics of transformer principles.

The selection of transformer depends on regulations, ambient conditions and connecting loads. Although, the selection of transformer rating became very critical due to increasing use of power electronics drive in propulsion and in other service loads. To facilitate the transformer manufacturers and customers, the IEEE developed standards IEEE Std C57.110-1998 and IEEE Std 519-1992 [55], [56] to give procedure for transformer design for nonlinear loads and requirements for harmonic control in electrical power system. In IEEE Std C57.110-1998, a rating system called K-FACTOR has been proposed to design a transformer which can withstand the effects of harmonic load currents. The significance of transformer K-factor discussed in Section VI of this paper.

C. LOADS

Marine loads can be classified into two categories based on their applications and power range: *Propulsion or Thrusters Loads* and *Service Loads*. The propulsion loads are most dominated loads in many vessels. For example, Figure 18 shows the electric power distribution in a cruise ship at different speeds [57]. The vessel speed is normally expressed in knot (kn), which is equal to 1.852 km/h.

1) PROPULSION LOADS

Varieties of propulsion designs are available, but their applications depend on specific vessel requirements. Discussion in this section is limited to some of the most commonly used propulsion system, such as *Shaft propulsion, Azimuth Propulsion* and *Podded Propulsion*.

***Shaft Propulsion*:** this is a conventional propulsion system and is normally driven by variable speed electric motors as shown in Figure 19. The horizontal motors may be directly connected to the shaft, which results a simple and mechanically robust solution. Disadvantage of direct diesel driven system (without frequency converter) is long shaft length, which can create balancing issue and also create high vibration and noise level. However, short shaft system can be possible by implementing frequency converter-based system. Maneuverability is another technical issue in shaft propulsion design, but this issue can be overcome by using rudder on each propeller. The shaft propulsion is available in wide power range and commonly used in shuttle tankers, research vessels, large anchor handler vessel and cable liners [28].

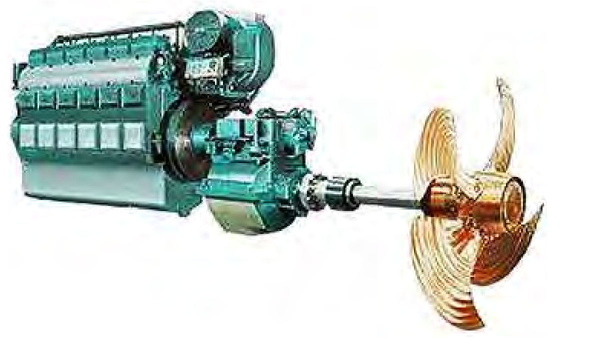
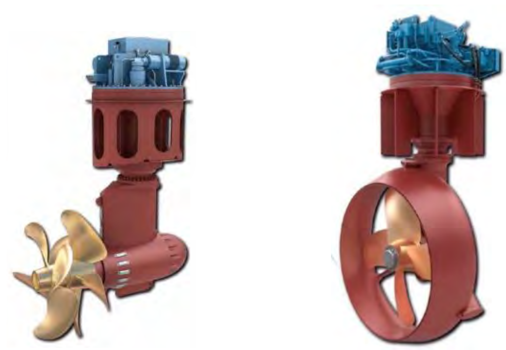


FIGURE 19. Shaft propulsion system [29].

Azimuth Propulsion: is used where better maneuverability is required. The Azimuth can freely rotate in order to produce thrust in any direction, thus this is also called Azimuth thruster. Azimuth thrusters are two types: *L-type* and *Z-type* depending on motor location. The Z-type applies when motor is horizontally mounted and L-type when motor is vertically mounted as shown in Figure 20. The azimuth thrusters are commercially available in the power range of up to *6-7 kW*. Main disadvantage of azimuth thruster is its limited capability to produce thrust at negative pitch because they are designed and optimized for unidirectional rotation only [28].



(a) (b)

FIGURE 20. Azimuth Propulsion: (a) L-type [30], and (b) Z-type [30].

Podded Propulsion: is type of azimuth thruster, the only difference is that an integrated motor/propeller unit is mounted on the same shaft inside a sealed pod unit as shown in Figure 21. The integrated approach helps to avoid gears and make construction much simpler and more efficient due

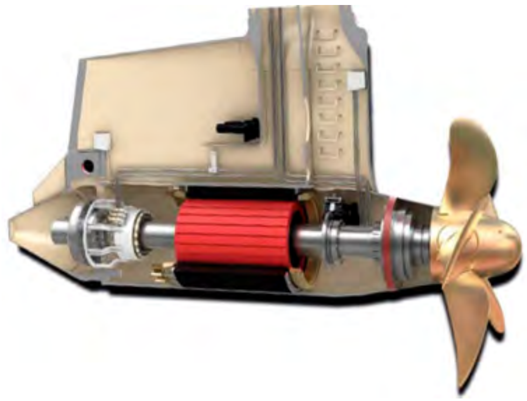


FIGURE 21. Podded propulsion system [30].

to absence of pitch control. The podded propulsion can also rotate freely and may produce thrust in any direction. With suitable thrust bearing, it is possible to rotate the propulsion in both directions. The propeller is normally optimized for one main direction, giving some reduced negative thrust capacities, but without any mechanical limitations [28]. The podded propulsion is available for the output power rating of *1-25 MW*.

2) SERVICE LOADS

Even though propulsion units are dominated loads in many vessels, but there are many other loads also used in different parts of the vessel, such as lighting systems, navigation, radar and control systems, air-conditionings and so on. These service loads are both three-phase and single-phase systems and their load profiles continuously vary over the day.

D. POWER CONVERTER TECHNOLOGIES USED IN SHIP LOADS

The advancement of power electronics devices and their decreasing price due to market demand have increased the use of Adjustable Speed Drive (ASD) systems as an effective energy saving solution in electric propulsion and other variable speed drive applications in maritime system.

The most commonly used power electronic converters in maritime application are as follows:

- Thyristor Rectifier (SCR) for DC motor drive
- Current Source Inverter (CSI)
- Cycloconverters and Matrix Converter
- Voltage Source Inverter (VSI)
- Active Front End (AFE)
- Multilevel Inverters
- Single phase systems

1) THYRISTOR RECTIFIERS (SCR) FOR DC MOTOR DRIVE

The rectification is the only step required in DC drive system. In most of high-power applications, the DC drive uses a full-bridge thyristor rectifier feeds the DC motor with a controlled armature current and a field winding is excited with a regulated field current as shown in Figure 22. The DC drive offers

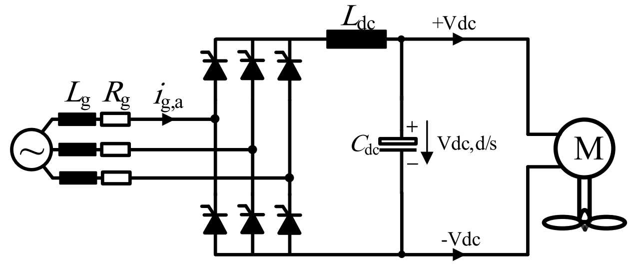


FIGURE 22. Three-phase thyristor rectifiers for DC motor drive.

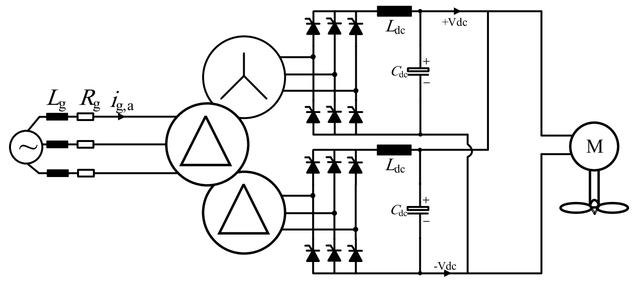


FIGURE 23. Three-phase thyristor rectifiers with pulse-shifting transformer for DC motor drive.

a wider speed range and higher starting torque, which are common requirements in drilling vessels.

In this topology, the DC voltage on motor armature winding is controlled by thyristor gate firing angle (α) as given below:

$$V_{dc} = \frac{3\sqrt{2}}{\pi} V_{L-L} \cos(\alpha) = 1.35 V_{L-L} \cos(\alpha) \qquad (1)$$

Based on above equation, the DC voltage (V_{dc}) on motor armature is related to the gate-firing angle. Theoretically, the gate-firing angle can be varied from 0 to 180°, but the minimum firing-angle of 15° is applied to ensure motor controllability and to avoid significant voltage drops in the network.

Since the motor rotational speed is proportional to the armature voltage, one can see that the rotational speed related to the gate-firing angle. As the phase-angle of the line current (I_g) is almost equal to the gate-firing angle (α), therefore the power factor also depends on the thyristor gate-firing angle. The maximum power factor which can be achieved is approximately 0.96 at 15° firing-angle.

For a six-pulse converter, the line current contains harmonics of the order 5, 7, 11, 13 and so on. The 5^{th} and 7^{th} are the most dominate harmonic components in the six-pulse converter. In order to reduce the harmonic distortion, it is common to use a multi-pulse configuration such as 12, 18 and 24-pulse to further reduce the distortion. A 12-pulse configuration (as shown in Figure 23) can be expected to eliminate approximately 90% of the 5^{th} and 7^{th} harmonics, which is normally enough to bring the distortion down to an acceptable limit.

The DC drives have an accurate torque control with low ripple, but other issues such as mechanical contact between the stator and rotor via brushes became a major source of failure which require regular maintenance. Also, the practical limits for the DC motor drive are *2-3MW*. Therefore, use of DC drives in propulsion system have been replaced by AC drives in the 1980s [28].

2) CURRENT SOURCE INVERTER (CSI)

The Current Source Inverter (CSI) is used for synchronous AC motors. In this configuration, three-phase thyristor-controlled rectifier with an inductor (L_{dc}) to smooth the DC-link is linked to a load commutated inverter as shown in Figure 24. The DC link current is passed through the motor phases by controlling the thyristors used in the inverter part. This results a six-step current waveform in motor phase, which contains significant harmonics and also results torque ripples. In order to perform thyristor commutation in inverter part, it requires a motor that can generate back electro-magnetic force (or back-EMF). Thus, it is mainly used in synchronous motor with a leading power factor. This can be an issue at lower speeds (below 5-10% of rated speed), the back-EMF is too low to perform natural commutation and the inverter runs in a pulsed mode operation, which leads higher torque ripple and shaft vibration in this speed range.

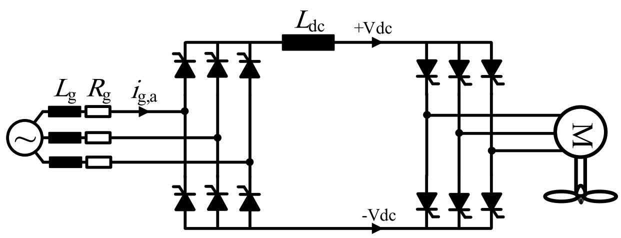


FIGURE 24. Current Source Inverter (CSI) type converter for AC motor.

In CSI configuration, line side performance is highly influence by the motor side non-characteristic (or non-integer) harmonics. The penetration of non-characteristic harmonics to the line side depends on the size of DC-link inductor. A complete set of frequency of the supply network current components can be generalized as [31]:

$$f_g = (nP_r \pm 1) f_s \pm P_i k f_m \tag{2}$$

where f_g is the frequency components of the input line current, n and k are integer number ($n = 0,1,2\ldots$, $k = 0,1,2,..$), P_r is number of pulse rectifier, f_s is the network supply frequency (i.e 50Hz/60Hz), P_i is the number of pulse inverter and f_m is the motor frequency.

The main disadvantage of the CSI configuration is large time constant in the DC link inductor, which degrades the dynamic performance of the drive. Moreover, this configuration generates non-characteristic harmonics in the network, which can be an issue to comply with future power quality standards. The power rating of CSI to utilize in large synchronous motor drives is up to *60MW* [58].

3) CYCLOCONVERTER AND MATRIX CONVERTER

The lower speed issue of CSI can be overcome by using cycloconverter (as shown in Figure 25), which can offer high torque at low speeds with low torque pulsations. The cycloconverter is a direct conversion (without DC link) and can be considered as a rectifier where the DC link voltage is slowly varying between minimum and maximum values. This fact limits the output frequency to about one-third of the input supply frequency. Thus, the cycloconverter applications are limited to low speed direct shaft drives without gears.

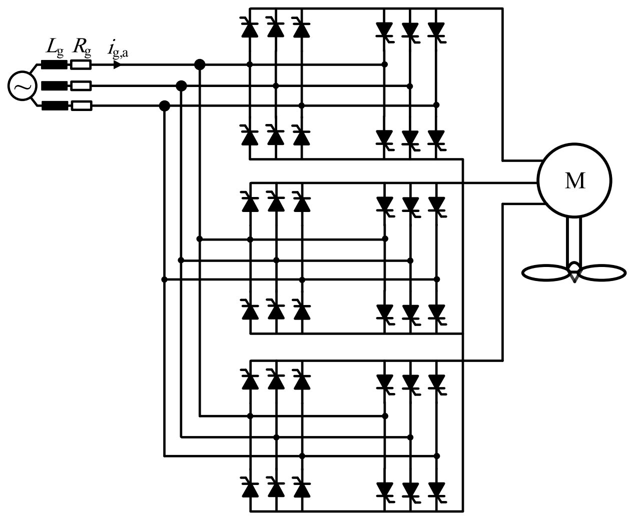


FIGURE 25. A 3-phase to 3-phase cycloconverter for an AC motor.

Cycloconverter can be used for synchronous or asynchronous motor. However, in marine applications, the cycloconverters have been used only for synchronous motors due to their output power factor characteristics. A cycloconverter can supply lagging, leading, or unity power factor while its input always lagging, and a synchronous motor can draw any power factor from the converter. Thus, these operational characteristics results a better match of cycloconverter with a synchronous motor.

The output voltage waveform of the cycloconverter has complex harmonics spectrum. Higher order harmonics are usually filtered by the motor inductance; therefore, the motor current has less harmonics. The remaining harmonics causes harmonic losses and torque pulsations. Moreover, there are no inductors or capacitors in the DC-link, consequently motor side harmonics (non-characteristics) pattern can be seen in input current waveform [59]. The amplitudes of the non-characteristic's harmonic are normally higher than CSI.

Application of the cycloconverter can be in modern ice-breaker vessels, where high torque performance at low speed can help to cut a block of ice with stalling the motor. The cycloconverter is available in a power range of *2-30MW* per drive [28].

However, cycloconverter limitations such as low speed and higher harmonic distortion can be overcome by using advanced AC-AC converter, also know known as Matrix

Converter [32], which can provide a wide range of output voltages and frequencies and also offer excellent steady-state performance and dynamic response [33]. The Matrix Converter topology is still immature and not yet fully analyzed for marine applications.

4) VOLTAGE SOURCE INVERTER (VSI)

A VSI requires a constant DC voltage input to the inverter and this is achieved with a LC filter in the DC-link. On other hand, CSI requires a constant current input, thus a series inductor is used in the DC-link as shown in Figure 24.

Modern AC drive configuration uses a VSI employing with Pulse Width Modulation (PWM) technique to control the switching elements in inverter stage to obtain the desired voltage output to the motor. The inverter uses either GTO or power transistor or IGBT. In PWM drives it is not necessary to vary rectifier output voltage to control motor speed. Therefore, it is possible to replace thyristors to diodes in rectifier stage as shown in Figure 26. The PWM drive has excellent dynamic performance and torque is smoothly controlled over wide speed range, including zero speed (e.g. in vector-controlled algorithm). Thus, the PWM drives can be best suited for high speed motor drive applications, such as propulsion system with stepdown gearbox – which offer cost and weight-effective solution.

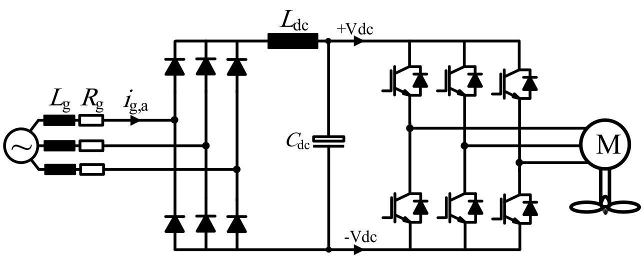


FIGURE 26. PWM-VSI converter for AC motor.

In the VSI, the DC link capacitor bank is used to smooth the DC-link voltage and to minimize the effect of harmonics distortion from the inverter to supply side.

In marine applications, the passive techniques such as AC and DC chokes are still preferred solutions due to their cost-effectiveness, simplicity, and reliability advantages [34]. In recent years, a reduced DC link capacitor used in a three-phase power converter named "Slim DC" link converter is also getting more attention as one of the harmonic mitigation techniques, but their performance is highly unpredictable at system level [35]–[37].

Today, the PWM-VSI type converter became a standard solution for all electric propeller marine vessels. It offers constant performance over wide speeds/loads range with low torque pulsations. This topology is capable to run AC motors in both directions. However due to the diode or controlled rectifier topology, the power regeneration from the AC motor cannot be feedback to the network.

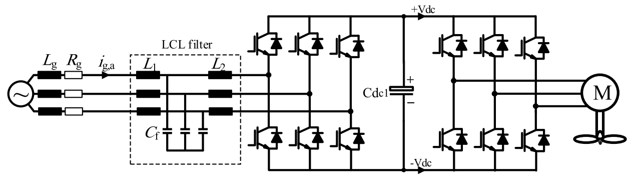


FIGURE 27. Three-phase Active Front End (AFE) for AC motor.

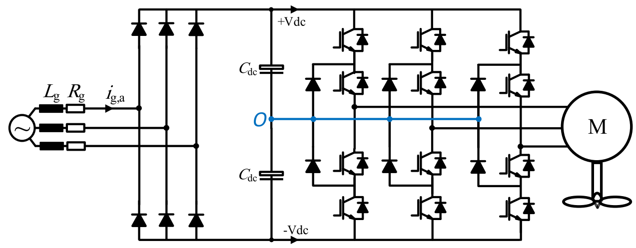


FIGURE 28. Three-level VSI for AC motor.

5) ACTIVE FRONT END (AFE)

The Active Front End (AFE) is a bidirectional power flow converter and also provides high quality sinusoidal line current waveform. The AFE is operated at higher switching frequency, which results better harmonic performance at low frequency (0-2kHz) but can generate high order harmonics and noise in 2-150 kHz range. The increasing use of AFE causes concern in this new frequency range, which attract attention of standardization organization to develop new standard in 2-150 kHz range as well. Section VI includes detail discussion on this topic.

The system has a six active power switches such as IGBT or MOSFET and are controlled based on a suitable PWM technique. In order to control the switching frequency ripple, a front side filter is required, which can be of L, LC or LCL type. The LCL filter is very common (in Figure 27) as it can remove high frequency noise and clean the line current at the grid side. Motor side performance is the same as PWM-VSI. The applications of AFE increased in recent years mainly in low power vessels such as passenger ferry.

6) OTHER CONVERTER TOPOLOGIES

In order to optimize weight and volume, trend is shifting towards medium voltage network in marine applications. Converters used in medium voltage are usually modified version of two-level converter shown in Figure 26. In order to accommodate increased DC-link voltage, more switches are connected in series in inverter part as shown in Figure 28 for three-level converter configuration. The rectifier part is normally supplied by phase-shifting transformer, which also reduce harmonic distortion in line current. The three-level converter also gives lower current distortion in motor currents at same switching frequency as a two-level converter.

7) SINGLE PHASE SYSTEMS

For low power such as lighting and other hotel loads, commonly used single-phase converter topologies in marine applications are: Diode/Thyristor Rectifier and Power Factor Correction (PFC).

Traditional single-phase diode/thyristor rectifier is still common in switch mode power supply and other low power applications, where input bridge is directly connected to the AC network, and then rectified voltage is smooth with LC filter in the DC-link as shown in Figure 29. The operation of single-phase rectifier results distorted line current with significant low order harmonics, mainly below 2kHz. Special characteristics of single-phase rectifiers are very high 3rd order harmonic contents in the line current. The 3rd harmonic current components are additive in the neutral of a three-phase system, thus increasing such loads can cause concern for overloading of neutral conductor. This is also concern for transformer overheating due to a combination of harmonic contents in current, stray flux and high neutral currents [60].

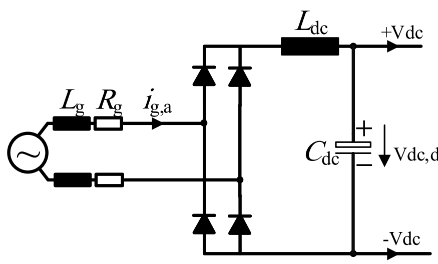


FIGURE 29. Single-phase diode rectifier for low power applications.

In recent years, the use Power Factor Corrector (PFC) circuit increased in a number of single-phase appliances, such as computer, television and modern lighting system (e.g. LED and compact fluorescent lamps). The main advantages of this topology are to improve the line current quality and power factor of the system due to use of active circuit in the DC-link system as shown in Figure 30. However, boost converter is operated at higher switching frequency, which can generate noise in 9-150 kHz range.

E. CONTROL ARCHITECTURE OF POWER ELECTRONIC SYSTEM

A generic control architecture of power electronic converter used in marine application is proposed in IEEE Std 1676-2010 [38], [39] as illustrated in Figure 31, where control architecture is divided into different layers.

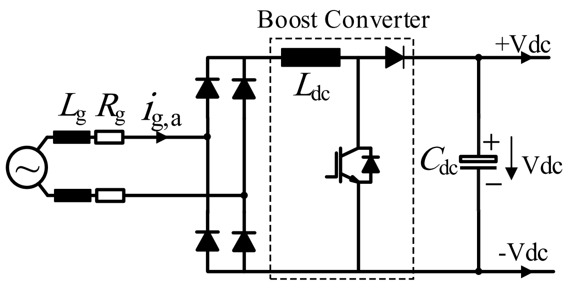


FIGURE 30. PFC for low power applications.

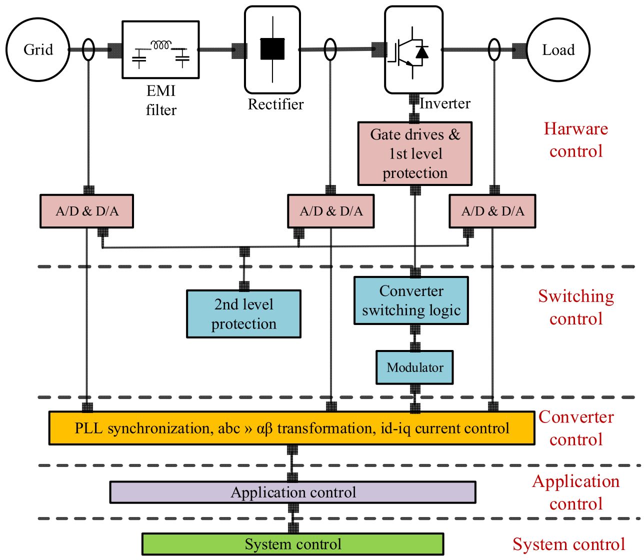


FIGURE 31. Control and protection architecture for power electronics.

1) SYSTEM CONTROL LAYER

System control layer includes all functions required to determine the system mission and the role of power electronics system required to execute this mission.

2) APPLICATION CONTROL LAYER

Application control involved in the operation of the power converter to meet the mission determined by the system control.

3) CONVERTER CONTROL LAYER

The converter control layer mainly includes the feedback control system. This involved many functions such as PLL, current and voltage measurement filtering and perform various calculation required for feedback control.

4) SWITCHING CONTROL LAYER

The switching control layer includes the modulation control and pulse generation to control switching operation of power converter.

5) HARDWARE CONTROL LAYER

This layer handles everything related to the power devices and execute different functions such as gating, isolation, commutation, protections and so on.

F. PROTECTION SYSTEM

An electric fault can have disastrous consequences in maritime application if it is not cleared by protection system. Any failure in protection system may leads to blackouts, fire, electric shocks to humans, collision with the cliff, transportation delay and so on [40]. To avoid such undesirable effects, the maritime system is normally well equipped with dedicated protection system.

1) PROTECTION REQUIREMENTS

To ensure the safe operation of maritime applications, any protection system needs to fulfill following basic requirements [40]–[42]:

- *Sensitivity:* protection system able to detect and react to the smallest unwanted fault
- *Selectivity:* protection system able to isolate any faulted part of the system
- *Operational speed:* protection system able to be cleared the electric faults as soon as possible to avoid any further damage to the equipment and system
- *Reliability:* protection system should be highly reliable to ensure system protection in the event of fault
- *Simplicity and economics:* simple protection system that offers the required functionalities at lower cost.

2) PROTECTION PRINCIPLE

Protection principle in maritime system is similar to many onshore applications, which is based on primary and backup protection strategy [42].

The primary protection is the first line defense which act quickly in the event of fault and clear fault. Primary protection is provided in each section of an electrical installation.

The backup protection is the second line of defense, which isolates the faulty section of the system in case of the primary protection fails to function properly. The backup protection may be provided either on same circuit breaker which would normally opened by the primary protection or in the different circuit breaker.

In most of existing maritime vessels, a centralized protection principle applied where a central control unit that monitors the entire power system, changes the relay settings or reconfigures the network [43]. However, to improve the reliability of the of the system, a zonal electric distribution system has been considered as preferred solution in maritime applications [44]. In zonal ship design concept, a decentralized protection system is recommended to meet the survivability conditions. Figure 32 illustrates the decentralized protection system concept for generic marine power system.

3) FUTURE CHALLENGES

Complexity of marine and offshore vessel is continuously increase, which introduces new challenges for power system protection design in such applications. Some of these challenges listed down:

- Increasing generation and load power
- Increasing voltage levels
- Higher power densities to optimize weight and volume
- More efficient use of generator sets
- Increasing penetration of power electronic based loads
- New upcoming system architectures such a DC onboard system

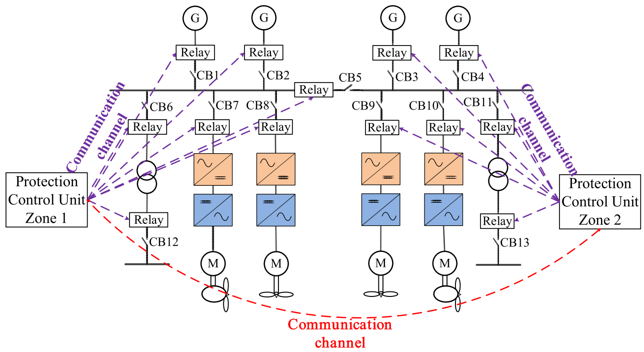


FIGURE 32. **Decentralized protection system.**

- Increasing use of cold ironing process in shipping industry to improve efficiency

To meet these challenges, new protection methods need to develop to ensure safe and reliable operation of maritime systems.

IV. SHIP ENERGY EFFICIENCY

The energy demand in marine application is increasing due to recent growth in global shipping business. Recent study shows that global shipping consumes about 300 million metric tons of fuel annually [75], mostly blends of heavy fuel oil and lighter fuels, also referred as heavy marine diesel oil. The combustion of such fuels emits greenhouse gases such as CO_2, NO_x and SO_2. Today shipping sector alone contributes about 3% and 15% of global CO_2 and NO_x emission respectively and likely to increase in future due to rapid growth in marine transportation. As increased energy/fuel efficiency and reduced greenhouse gases emission go hand in hand. Therefore, ship energy efficiency became an important factor for all stakeholders, such as ship builders, operators and regulators.

A. ENERGY EFFICIENCY INDICATORS

In order to reduce greenhouse gas emission, the IMO took a number of initiatives such as Energy Efficiency Design Index (EEDI) proposed in 2011, which sets minimum energy efficiency requirements for new ship built after 2013 [76].

The EEDI calculation basically reflects the theoretical design efficiency of a new ship and provides an estimation of CO_2 emission per capacity-mile. Its calculation is based on assumptions regarding the specific fuel consumption of the engines (in g/kWh) compared to the power installed on the ship [77]. Complete formula of the EEDI calculation is very complex and includes many adjustments and factors customized for a specific vessel class and operating conditions, as given in equation (3) [78], [79]:

$$EEDI = \frac{A + B + C - D}{E} \tag{3}$$

Parts of equation (3) described below to indicate the individual contribution of CO_2 emission from different components in any ship:

Main engine (s) CO_2 emission:

$$A = \left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right)$$

Auxiliary engine (s) CO_2 emission:

$$B = (P_{AE} \cdot C_{FAE} .S\ FC_{AE^*})$$

Shaft Generator/Motor (s) CO_2 emission:

$$C = \left(\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right)$$

The CO_2 emission reduction due to innovative technology (s):

$$D = \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} .S\ FC_{ME}$$

Transport work:

$$E = f_i \cdot \text{ Capacity. } V_{\text{ref}} \cdot f_w$$

Where, Engine Power (P) parameters are:

$P_{ME(i)}$: Individual power of main engine (kW)

P_{AE}: Combined installed power of auxiliary engines (kW)

$P_{PTI(i)}$: Power of individual shaft motors divided by the efficiency of shaft generators (kW)

$P_{AEeff(i)}$: Auxiliary engine power reduction due to individual technologies for electrical efficiency (kW)

$P_{eff(i)}$: Main engine power reduction due to individual technologies for mechanical efficiency (kW)

Fuel factors are:

$C_{FME(i)}$: Main engine individual fuel factors

C_{FME}: Main engine composite fuel factors

C_{FAE}: Auxiliary engine fuel factors

Specific Fuel Consumption (*SFC*) factors are:

$SFC_{ME(i)}$: Main engine individual factor

SFC_{ME}: Main engine composite factor

SFC_{AE}: Auxiliary engine factor

SFC_{AE*}: Auxiliary engine adjusted for shaft generators factor

Correction and Adjustment (f) factors are:

f_j: Correction factor for ship-specific design elements

f_i: Capacity adjustment factor for any technical/regulatory limitation on capacity (1.0 if none)

$f_{eff(i)}$: Availability factor of individual energy efficiency technologies (1.0 for waste energy recovery system)

f_w: Non-dimensional coefficient indicating the decrease in ship speed due to weather and environmental conditions

Ship Design parameters are:

V_{ref}: Ship reference speed (nm/hours)

Capacity: Deadweight Tonnage (*DWT*), which is measure of how much weight a ship can carry

To easy to understand, equation (3) can be simplified as below [80]:

$$EEDI = \frac{P_{\text{installed}} \times SPF \times CF}{DWT \times V_{\text{ref}}} \quad (4)$$

where, $P_{installed}$ is installed power of a ship in kW, *SFC* is specific fuel consumption in g/kWh, *CF* is carbon conversion factor, *DWT* is deadweight tonnage of ship and V_{ref} is ship reference speed.

The EEDI represents a measure of design efficiency of new ship, but it does not give any explanation of its operational efficiency. However, one can argue that two twin ships with the same EEDI may have different operational efficiencies due to their different operational profiles and sailing conditions [77]. This means the EEDI calculation is based on data available of specific engine type, power range and specific operating profile; it is not indicating actual fuel consumption of a ship. Also, the EEDI only applies to a new ship.

The IMO has also developed the Energy Efficiency Operation Indicator (EEOI) to indicate fuel consumption of a ship which is already in operation. This calculation is based on actual fuel consumption of a specific ship including detail information such as cargo mass and a number of passengers carried etc. as given in equation (5) and (6) for single and multiple vessel, respectively [81].

$$EEOI = \frac{\sum_j FC_j \times C_{Fj}}{m_{\text{cag}\,o} \times D} \quad (5)$$

$$EEOI_{\text{Avg}} = \frac{\sum_i \sum_j FC_{ij} \times C_{Fj}}{\sum_i (m_{c\,\text{arg}\,o,i} \times D_i)} \quad (6)$$

where, j and i are fuel type and vessel number respectively, $FCij$ is the mass of consumed fuel j at vessel i, C_{Fj} is the fuel mass to CO_2 mass conversion factor for fuel j, m_{cargo} is the mass (in tons) carried in a cargo and D is the distance covered by a cargo.

The EEOI can be used to calculate operational/real efficiency of a ship in operation and also give better idea if any improvement has been made by ship operator. However, EEOI calculation required detail information about ship activities such as load profile, distance sailed etc., which may be commercially sensitive. Therefore, application of EEOI remains non-mandatory.

The EEDI was formally adopted as efficiency matrix by the IMO in July 2011 and applies to new ships built from 2013 onwards.

B. MEASURES TO IMPROVE ENERGY EFFICIENCY

The energy efficiency of a ship depends on many factors, which can be considered from design phase to ship operation phase. This section includes a brief discussion of different parameters to improve energy efficiency of a ship.

1) SHIP DESIGN

The energy efficiency of a ship largely depends on main dimension of the ship such as length, breath, depth and displacement. Small changes in these parameters can results a big variation in energy efficiency. Recent study shows that it is very common for individual ships to consume more than 30% more fuel than required due to deficient design [77]. Ships have very long lifetime; therefore, a detail investigation should require at design phase to analyze all fuel-saving technical measure related to design and geometry of a ship based on their defined operational profile.

2) FUEL SUBSTITUTE

Heavy marine diesel oil is most common fuel type used for marine applications which contributes to increase carbon emission. Reduction in fuel consumption and carbon emission can be achieved by using alternative fuels option such as LNG, Methanol and Dimethyl Ether etc. [82]. There may be few issues to utilize these fuel alternatives in existing ship, such as need of modification of engine and requirements of additional storage space etc. The IMO forecasts that the use of alternative fuel will increase in new ship to fulfill EEDI requirements. It is expected that LNG will be dominated fuel option for costal shipping by 2050 [83].

3) OPERATIONAL PROFILE

Even through, the diesel engine technologies are continuously being advanced over the years to improve efficiency and reduced emissions, but still about 40% of fuel energy is actually utilized and the rest being removed in the form of exhaust fumes and heat dissipation. The fuel utilization factor or efficiency of diesel engine is load dependent as shown in Figure 33 [28].

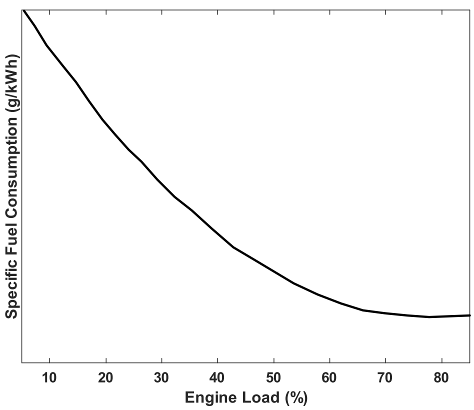


FIGURE 33. Specific fuel consumption of diesel engine at different load condition.

The efficiency of diesel engine mainly depends on its "air handling capacity". The excess air and higher compression ratio lead to increase its efficiency. At partial load condition, the fuel injection time has to increase to supply required amount of energy, which reduces the time of diesel droplets to complete the combustion. Therefore, the complete conversion of fuel chemical energy into mechanical energy does not take toward high efficiency operation.

The lower efficiency is not only the fuel consumption issue, but also environmental concerns. This enormous amount of

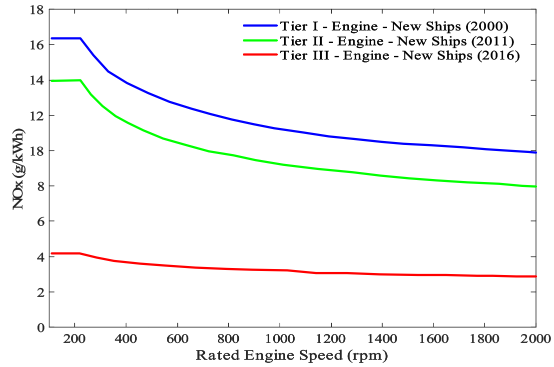


FIGURE 34. Annex VI of MARPOL 73/78 NOx emission limits.

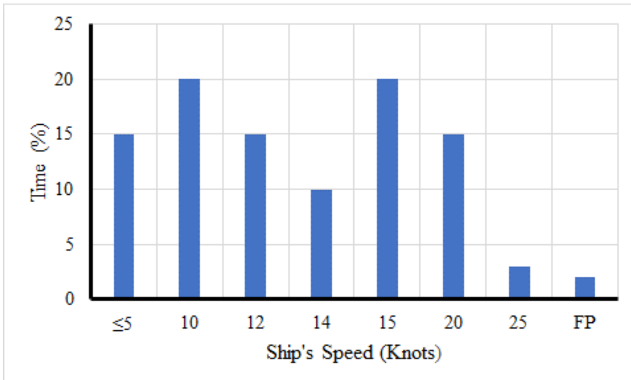


FIGURE 35. Typical operating profile of a ship.

exhaust fumes contains greenhouse gas (NO_x and SO_x), which is a big concern for environmental agencies such as IMO. Recently, IMO further tighten the emission regulation to limits the greenhouse gas emissions. For example, emission limits of NO_x are shown in Figure 34 as per Annex VI of MARPOL 73/78 [45].

From Figure 33, it is clear that diesel engine efficiency drops fast as the load becomes lower than 50% and similar observation has been seen for NO_x as shown in Figure 34. Based on the existing operating profile, a ship operates most of the time at partial load (or speed) conditions. For example, a typical operating profile of a ship is shown in Figure 35, notably this ship operated more than 80% of its annual hours at 15 knots or less [46]. Therefore, it is important to improve the diesel engine efficiency at partial load condition.

One possible solution is to operate diesel engine at variable speed. The fuel utilization of a diesel engine can be improved by adjusting the engine speed based on load profile as shown in Figure 36 [47]. At high engine speed, the fuel combustion is improved due to better mixing of fuel and air. Thus, a higher efficiency can be achieved at partial load condition by increasing engine speed. Though, this is not a practically viable solution in IPS based shipboard, where all generator sets must be synchronized at a fixed frequency to connect the same AC bus. Although, independent operation of engine could be possible by using back-to-back converters for each

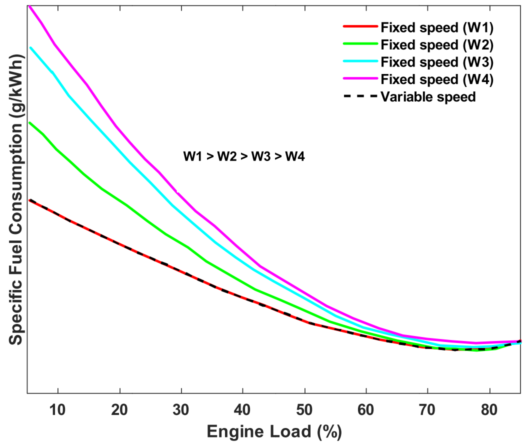


FIGURE 36. Specific fuel consumption of diesel engine at different load condition.

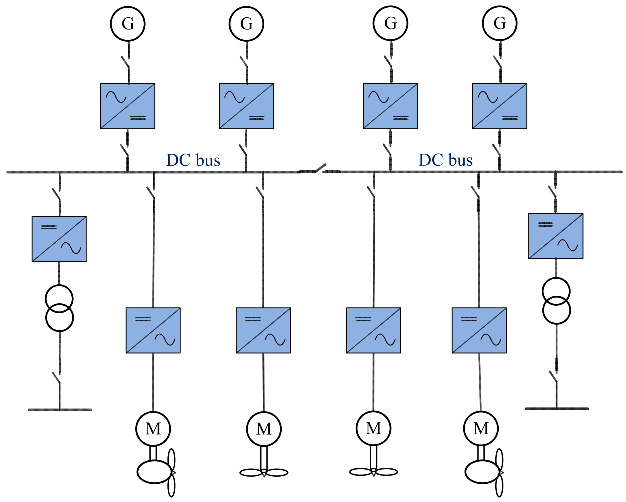


FIGURE 37. DC on-board system for a generic propulsion system.

generator, but this will add extra cost and complexity in the system [47].

Another possible solution to improve efficiency of diesel electric system is by implementing engine scheduling approach. Normally, a ship power system having several engines – it is possible to keep the diesel engines loaded at their optimum operating conditions by starting and stopping generator sets as per required load profile. The engine scheduling approach can create power quality issue in some vessels, such as navel application where pulsed loads can vary in wide kilowatts range in very short period. Practically, it is not possible to start and stop the diesel engines to follow such fast-varying load demand. This limitation can be overcome by enabling onboard Energy Storage System (ESS) to stored energy during lighter load and releasing stored energy during heavy load conditions. In this way, it would be possible for the diesel engines to always work with its maximum efficiency. At the same time power quality of onboard system might be enhanced.

4) NEW SYSTEM ARCHITECTURE

As discussed above, the engine efficiency can be increased by adjusting engine speed as per required load profile, although this is practically infeasible with conventional AC based IPS system. A DC power system (as in Figure 37), however, enables the engine to operate independently to achieve optimal speed adjustment at any load conditions [49], [50]. There are several other benefits of on-board DC system, such as:

- The main AC switchboards and transformers are no longer needed. This will result optimized and more flexible power and propulsion system. Also, with the DC on-board system, efficiency and reliability of the system will be increased due to less installed components.
- Power network is no longer fixed at 50Hz/60Hz. Therefore, variable speed diesel generators can operate at wider fuel-efficient loading ranges compare to the conventional fixed speed diesel generators [50].
- Even though the variable speed diesel generators can offer fuel-efficient system, but at the same time these generators can be more vulnerable during frequent load variations. In such condition, a DC grid system offers possibilities to integrate ESS, which can compensate the power variation during significant load variations. This will result to improve the dynamic performance of the propulsion system with less fuel consumption [51].
- A DC on-board system is simple "plug and play", which offers easy integration of future energy source and ESS without any significant change in the system.

5) COLD IRONING

Shutting down main engines at a port is a common practice. However, auxiliary generators are still in operation to continue provide electricity to cargo handling equipment and other ship services such as air conditioning, cooking and lighting. Big ferries and cruise ship required significant power at a port. As these auxiliary generators use heavy marine diesel oil, which generate harmful gas emission and noise pollution in ports and surrounding areas.

One possible solution is to use shore side electric power to a ship at a port while its main and auxiliary engines are turned off. This process is called *cold ironing* in shipping industry [84].

The reduction of CO_2 emission depends on how the electricity is produced to supply specific port. Growing interest in Renewable Energy Sources (RES) at the port will further help to minimize CO_2 emission.

6) OTHER MEASURES

Ship operators can achieve reasonable improvement in ship energy efficiency by taking some proactive measure without adding any extra cost, such as [85]:

- Reduction of speed under governor control during the period when there are head winds.

- Hull cleaning and paint technology to reduce resistance.
- Good fuel quality, proper adjustment of brakes and efficient gearing of pulleys.
- Good cooperation between the ship and the port, as this would reduce ships' turnaround time in port.
- Better business model helps to improve shipping efficiency, for example a bulk ship can be more efficient than cargo ship due to higher deadweight [86].

V. POWER QUALITY ANALYSIS OF SHIP NETWORK

A. POWER QUALITY ISSUES IN SHIP NETWORK

Increasing use of power electronics converters especially frequency converters for marine loads such as pumps, fans, bow thrusters, compressor units and propulsion systems, raise the power quality concerns in maritime microgrids. Three phase power converters with low cost diode rectifier are still widely used in aforementioned applications [67]. The diode rectifiers can achieve lower power losses compared to other Active Front End (AFE) topologies but may increase harmonics emissions – below 2 kHz - due to their non-linear effects. The current harmonics generated by these power converters can cause low power quality, resonances, and finally stability issues of distribution networks. These problems became further severe in maritime networks, where system impedance (generator and transformers) is typical 15-20% compare to 4-6% in many commercial and residential sectors [68]. These converters with such a high impedance system generate harmonic and the inter-harmonic distortions causing inadmissible disturbances in the power system. Distortions 15% to 20% and even above have been observed in onboard ships quite often [68].

Power quality issues in maritime microgrid, can result serious consequences due to utilization of these generators with limited capacity and distinct load profiles of high power non-linear and pulse loads. These special natures of maritime microgrids can result a number of power quality issues such as voltage and frequency variation, unbalanced, voltage and current harmonic distortion and commutation notches. There are very few papers addressing the power quality issues and their impacts on maritime power systems. Couple of these papers highlights maritime power quality issues in general [6] and [61]–[63] proposed a passive filter to meet harmonic requirements. Even though, all of these power quality issues lead to degrade performance and reliability of maritime power system, but voltage distortion and voltage unbalance phenomenon can lead severe consequence to generators and other electrical equipment connected to the same system [64]. Therefore, in this paper a case study has been performed to understand the impacts of voltage unbalanced in a typical ship network.

B. POWER QUALITY ANALYSIS OF SHIP NETWORK

For this study, a container ship example has been considered where a large number of power converter (motor drive) loads are connected via step-down transformers as shown in Figure 38. In a container ship, there are other kinds of loads which are also connected to the system such as propulsion and service loads. This study is mainly focused on container loads as highlighted in Figure 38 and further elaborate in Figure 39, where a number of power converters connected at the PCC. These power converters could be three-phase and single-phase systems. However, in this study only three-phase motor drives have been considered. The system inductance consists of the grid and the transformer inductances. The grid is modeled as an ideal three-phase voltage source (V_s) with a defined generator impedance. The transformer is modeled with no magnetic saturation and a defined series impedance. Therefore, the system impedance (Z_s) is a combination of the grid and the transformer impedances. The typical values of generator and transformer impedance are considered based on a short circuit ratio of approximately 230, which is very common in ship network. A 7.5 kW three-phase motor drive is investigated in this paper. It is a typical three-phase diode bridge rectifier with a DC side passive filter as shown in Figure 26. More information about the system parameters are provided in Table 3. In order to analyze the impacts of different load profiles and a number of drives at the PCC, different case studies have been considered as illustrated in Table 4. The three-phase motor drives operate at three different power levels: 1 kW, 3 kW and 6 kW.

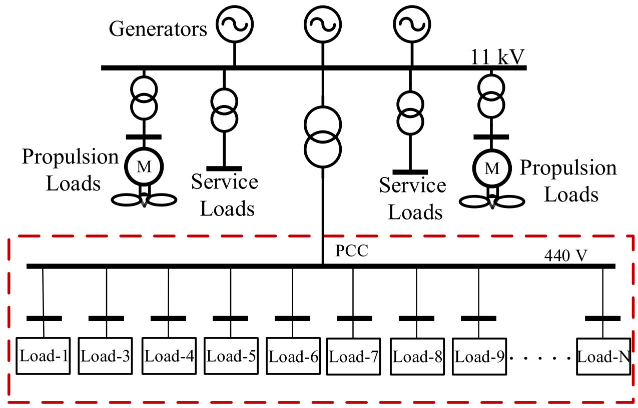


FIGURE 38. Simplified line diagram of a container ship.

TABLE 3. Parameters of the system.

	Grid phase voltage and frequency	DC-link Inductor	DC-link capacitor
3-phase Converter	U_{abc}, f_g, R_{sce}	L_{dc}	C_{dc}
	230 V_{rms}, 50 Hz, 230	2.5 mH	500 µF

In a typical ship network, numbers of single-phase loads are also connected at the PCC, which can easily create voltage unbalance due to unequal distribution on the three-phase system. Another reason for voltage unbalance in a ship network is due to asymmetrical feeders and transformer winding impedances [65]. In this study, the system is analyzed for

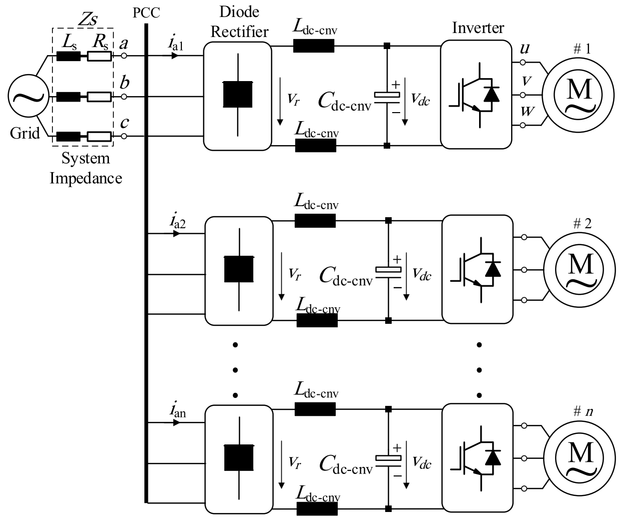


FIGURE 39. Several three-phase power converter units are connected in parallel at the PCC.

TABLE 4. Different load profile.

Number of drives at different power levels			
Case	1 kW	3 kW	6 kW
1	0	0	1
2	0	0	90
3	30	30	30

TABLE 5. Voltage unbalance case.

U_a	U_b	U_c	$U_{unbalanced}$
Balanced			
230∠0°	230∠-120°	230∠120°	0
Amplitude Unbalance (phase a)			
209.7∠0°	230∠-120°	230∠120°	5%

the balanced and unbalanced grid condition. Moreover, only three-phase non-linear loads have been considered and 5% voltage unbalance is created by reducing voltage in phase "a" as illustrated in Table 5. To simplify the simulation model and reduce the execution time, it has been assumed that all power converters are connected to the PCC through short cables in which their inductance values can be neglected.

1) BALANCED SYSTEM

In case-1, it is assumed that a single three-phase drive operated at 6 kW, whereas in case-2: 90 drives each operated at 6 kW are connected at PCC.

Figure 40 shows the simulation results for case-1, 2 and 3 with balanced grid supply. Line current and grid voltage harmonic distortion have been captured at the PCC as shown in Figure 41. To limit the data, only 13th harmonic values are shown in Figure 41. However, Total Harmonic Distortion (THD) for both line current and grid voltage mentioned in this figure are calculated up to the 40th harmonic. The phase angles of the 5th and the 7th harmonics are illustrated in Figure 42.

Figure 42 shows that the phase angle of the 5th current harmonics in three-phase system, where each phase changes approximately 47° from single unit (case-1) to 90 units (case-2). This is due to the system impedance (Z_s) effects on the 90 units. The total voltage drop across the grid impedance is approximately 90 times higher than a single unit – assuming that all operate at the same power. The effects of this grid impedance can be seen on THD_I and THD_V values changes from case-1 to case-2. With increasing grid impedance, THD_I will decrease but THD_V will increase. This fact has been verified by authors in another paper [66].

In case-3, 90 units are equally distributed into three groups (30 in each) and each unit in three groups are operated at 1 kW, 3 kW and 6 kW respectively as shown in Table 4. Here it is interesting to note that in case-2 and 3, the number of units is the same (i.e. 90), but still have different phase angle of the 5th and the 7th harmonic and also having different THD_I and THD_V values. This is due to differences in phase angles of three current harmonics from three groups. Total harmonic current at the PCC is vector summation of the current harmonics. Here it is important to note that each group of drive operate at different power level, which will result different phase angle at the PCC. This can be understood by equation (7), where 'i' numbers of drives are connected at the PCC and 'j' is harmonic order. The total harmonic current for any particular harmonic order can be calculated as below:

$$\sum_{h=1}^{n} i_{h(n)}(t) = \sqrt{\sum_{i=1}^{n}\left(\sum_{j=1}^{n} I_{h(i)}(t) I_{h(j)}(t)\cos\left(\phi_{h(i)} - \phi_{h(j)}\right)\right)} \tag{7}$$

This analysis shows that the voltage distortion of a ship network is highly depend on system impedance (including generator and transformer parameters), the number of power converters and their load profile. Normally it is assumed that harmonic performance of a power converter is same at unit (product) and at system and expected to solve power quality issue at PCC by incorporating harmonic mitigation technique at a unit level. This analysis confirms that it is not true without having complete information about system installation.

2) UNBALANCED SYSTEM

In order to analyze the performance of the container ship under the unbalanced supply grid, a number of simulations has been carried out as listed in Table 4 with 5% unbalance as per Table 5.

As can be seen from Figure 43, during the voltage unbalance (amplitude deviation in phase "a" (red color) in this study), in case-1 the three-phase rectifier enters into single phase operation and this result to significantly reduction of the current in phase "a" and increased in other

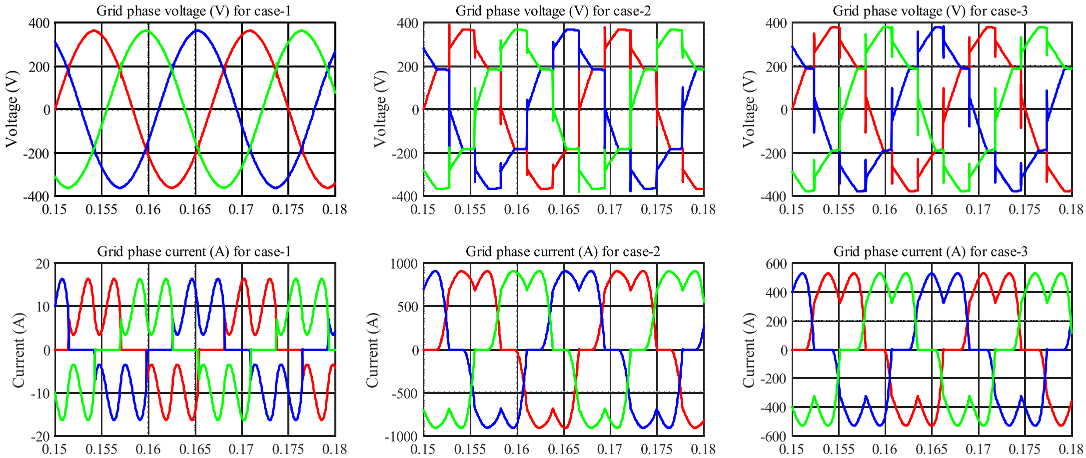


FIGURE 40. Waveform of three-phase supply voltage at the PCC and current under balanced supply voltage condition (where time(s) on x-axis).

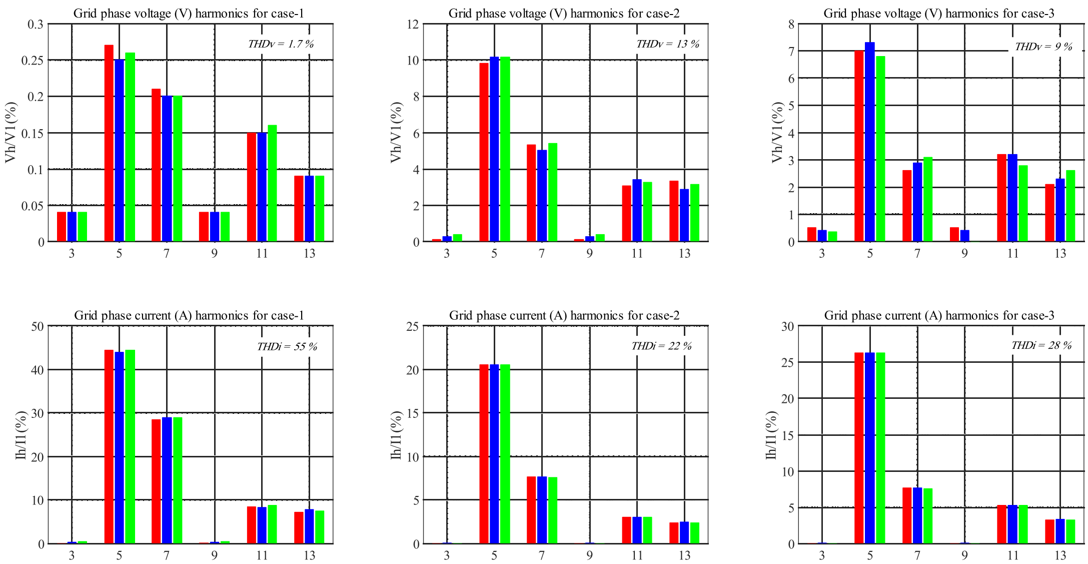


FIGURE 41. Harmonics of three-phase supply voltage and current under balanced supply voltage condition (where harmonics on x-axis).

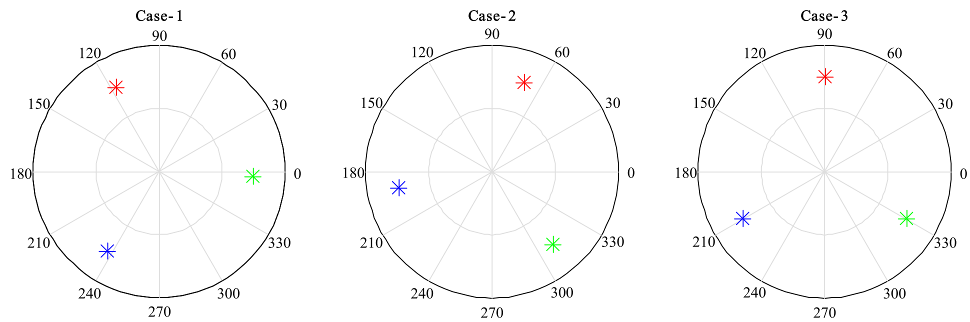


FIGURE 42. The 5 th harmonic phase angle of three-phase current under grid voltage balanced condition.

two phases due to asymmetric conduction of the diodes in the rectifier. The peak of current in other phases increases with respect to voltage unbalance level in the system. This excessive current can risk of overloading in these phases, which can trigger overload-protection circuits of the drive. During voltage unbalance, the input current harmonics are not restricted to the three-phase diode rectifier characteristic harmonics, but uncharacteristic triplen harmonics can also appear such as the 3rd and the 9th harmonics as shown in Figure 44.

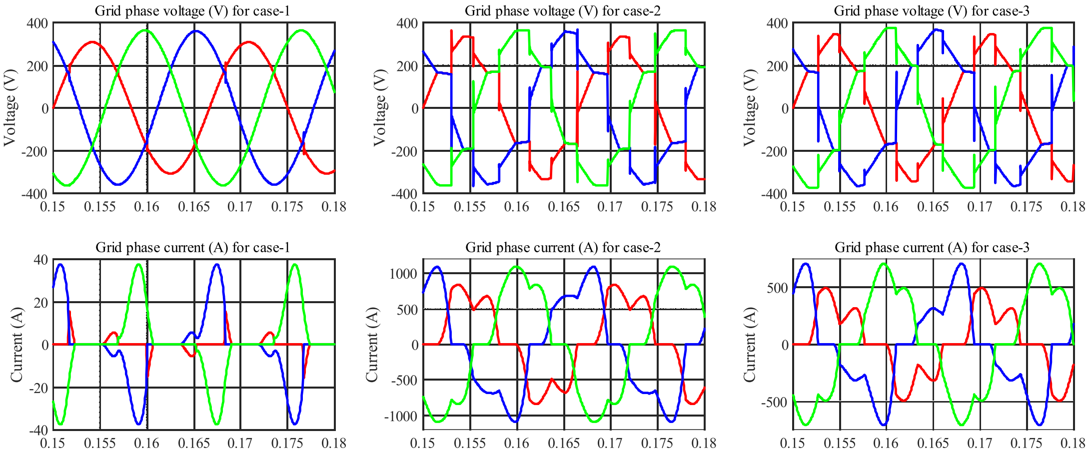


FIGURE 43. Waveform of three-phase supply voltage at the PCC and current under 5% unbalanced supply voltage condition (where time(s) on x-axis).

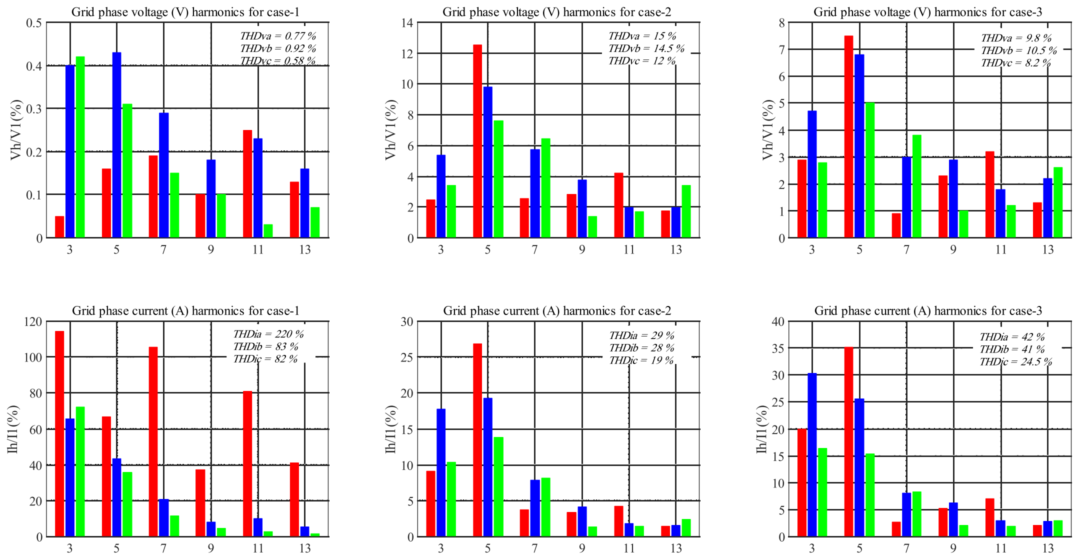


FIGURE 44. Harmonics of three-phase supply voltage and current under 5% unbalanced supply voltage condition (where harmonics on x-axis).

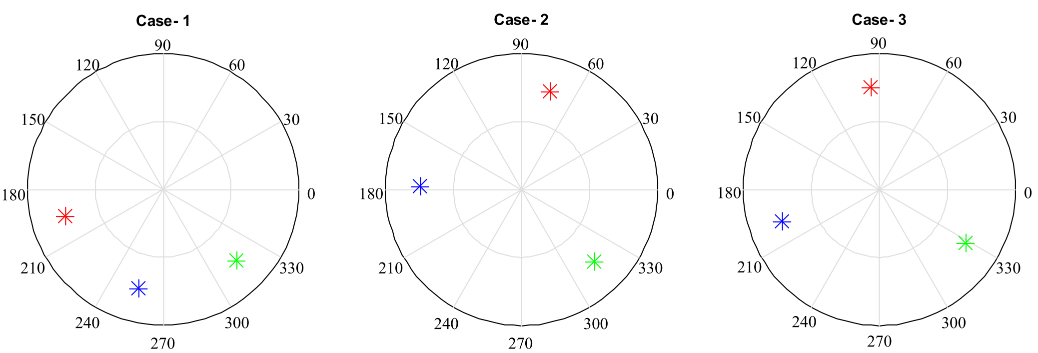


FIGURE 45. The 5 th harmonic phase angle of three-phase current under 5% unbalanced supply voltage condition.

Here it is important to note that in case-2 and case-3, the current waveforms at the PCC still show three-phase operation under 5% unbalanced (as shown in Figure 43), however, there is a magnitude reduction in the victim phase current. This effect can be seen on THD_I and THD_V values from case-1 to case-2. In unbalanced system due to asymmetry in three-phase current and voltage waveforms, the THD_I and THD_V values are given for each phase in Figure 44. In case-1, highly asymmetrical three-phase current waveform also affects the 5^{th} harmonic phase angle as shown in Figure 45 compare to the balanced case shown in Figure 42. On the other hand, there is not significant change in the phase angle for case-2 and 3 under unbalanced conditions compare to the balanced condition.

From this analysis it is clear that even under highly unbalanced grid, the power quality performance at the PCC depends on the system impedance, a number of parallel drives and their load profiles. The effects of unbalanced voltage are significantly reduced with increasing the number of parallel drives at PCC. Therefore, it is important to have better information about the system installation during the design phase of power electronic converters.

VI. POWER QUALITY REGULATIONS

To address power quality concerns associated with electric power system on ships, marine regulatory bodies have introduced specific standards. These standards define the acceptable level of different parameters. However, recent developments in marine vessel electrifications increase penetration of power electronic loads. Some of modern vessel start using emerging power electronic converter topologies (such as AFE), which results different concerns than conventional topologies. To accommodate new development in marine applications, it is important to either revised existing standards or set new standards and guidelines sooner than later. This section reviewed various existing ship power quality standards and highlights needs of new requirements in certain areas.

A. POWER QUALITY REGULATIONS AND STANDARDS

1) IEEE 1662-2008, GUIDE FOR THE DESIGN AND APPLICATION OF POWER ELECTRONICS IN ELECTRICAL POWER SYSTEMS ON SHIPS

This regulation is related to requirements for power quality and testings as well as parameters for specifications, performance characteristics, and analytical methods for power electronics equipment on commercial and military ships and similar applications [69]. The regulation covers a wide range of power electronics equipment with power ratings above 100 kW such as converters (DC to DC, DC to AC, AC to DC), power factor and reactive power control and motor drives.

The voltage level for AC systems is recommended at 1 kV or greater for equipment and systems of 5 MW or greater. However, IEEE P1709 Working group recommends the level of medium-voltage DC.

The frequency and voltage variations can be between $\pm5\%$ to $\pm10\%$ and $+6\%$ to $\pm20\%$, respectively. These variations are based on the permanent or transient phenomena.

There are three different types of grounds in ship networks: a) Safety, b) Electrical power system and c) Signal grounds which might be tied together in different applications. The following analyses are required to evaluate a power electronics system design:

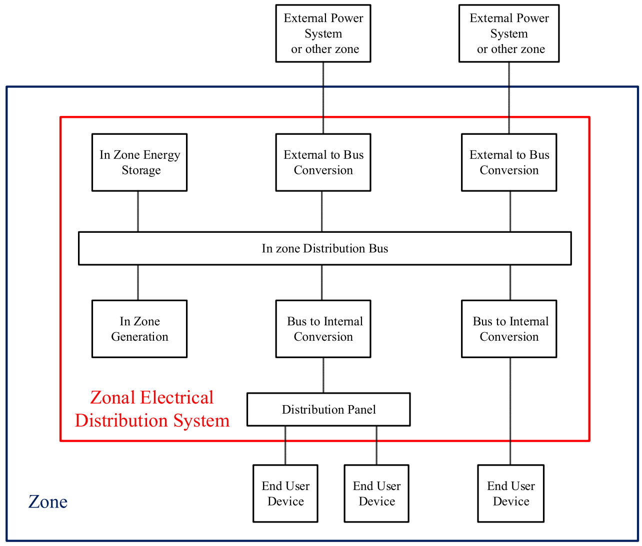


FIGURE 46. Zonal electrical distribution system.

- Basic power balance—rated and all operating conditions
- Power quality—harmonics, voltage sag, unbalanced conditions, Electromagnetic Interferences
- Dynamic performance—regulation, frequency ranges, and small-signal stability
- Transients—converter starting and stop, inrush current and dynamic braking, shut down

2) IEEE Standard 1826-2012 for Power Electronics Open System Interfaces in Zonal Electrical Distribution Systems Rated Above 100 kW

A zonal electrical distribution system (ZEDS) is part of a larger power system and consists of a group of loads which help to keep faults within the zone and are not outside the zonal boundaries.

Figure 46 shows the elements of a zonal power system and their power interfaces [70].

This standard can be used for open system concepts to zonal electric power systems controlled by power electronics. This means that each device attached to the power bus implement certain functionality that lets it "play well" with the other system components, conform to standard control and information interfaces. This document references and extends the application of IEEE Std 1662 and IEEE Std 1676.

3) IEEE 1709 2010, Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships

Medium Voltage DC (MVDC) power distribution systems with voltages above 3 kV have no specific standards. International Association of Classification Societies UR E11 covers mostly AC systems and very briefly DC systems. The recommended rated and withstand voltages are given in Table 6 and Table 7, respectively [71].

TABLE 6. Recommended MVDC voltage classes.

	MVDC Class kV	Nominal MVDC Class Rated Voltage (kV)	Maximum MVDC Class Rated Voltage (kV)
Already established Classes	1.5	1.5 or ± 0.75	2 or ± 1
	3	3 or ± 1.5	5 or ± 2.5
Future Design Classes	6	6 or ± 3	10 or ± 5
	12	12 or ± 6	16 or ± 8
	18	18 or ± 9	22 or ± 11
	24	24 or ± 12	28 or ± 14
	30	30 or ± 15	34 or ± 17

TABLE 7. Proposed rated withstand voltages for MVDC voltage classes.

MVDC Case	Rated short-duration withstand voltage to ground U_d kV for 1 min	Rated lightning impulse withstand voltage to ground U_p kV (peak value)
1	10	45
3	20	60
6	27	75
12	35	95
18	50	110
24	70	150
30	95	200

There are several DC sources but if the DC power is converted from an AC source through an AC-DC converter, the DC level is affected by the ripple voltage. This ripple magnitude depends on the rectifier (single or three phase system) and its filter. In some other applications, a bidirectional power flow converter (Active Front End) is utilized which is based on a pulse width modulated (PWM) rectifier. In this case, the DC voltage is affected by high-frequency waveform resulting from PWM switching and front side filter type and control. Noise also can come from the loads that are connected to the DC bus. The acceptable rms value of ripple and noise should not exceed 5% per unit.

Target users for this recommended practice cover a broad range of stakeholders such as evaluators and designers of electrical power systems for commercial marine and military applications, shipbuilders, port operators, classification societies, machinery and equipment manufacturers, research institutes, and universities. It can be used for analytical methods, preferred interconnection interfaces and performance characteristics for reliable integration of 1 kV to 35 kV MVDC distribution systems and electrical components into the ship electrical power systems.

4) IEC/ISO/IEEE 80005-1&2, High Voltage Shore Connection (HVSC) Systems – General Requirements, Data Communication for monitoring and Control

High Voltage (HV) shore supply has specific regulation in order to be connected to different ports. In this case, the HV shore connections shall be compatible with a nominal voltage of 6.6 kV AC and/or 11 kV AC with galvanic isolation from the shore distribution system; However, the galvanic separation on shore may be omitted if it is provided on board.

In addition, there are other regulations and restrictions for ship electrical equipment to be connected to shore supplies such as the distribution system voltage, frequency and total harmonic distortion characteristics given below [72].

- Under continuous conditions, a) the frequency tolerances should be within the continuous tolerances $+/-5$ % between no-load and nominal rating, b) the voltage at the point of the shore supply connection shall not exceed a voltage increase of 6 % of nominal voltage under no-load conditions and a voltage drop of -3.5 % of nominal voltage under loading conditions.
- Under transient conditions, a) the maximum step change in load and the response of the voltage and frequency at the shore connection shall be defined and documented, b) the voltage transients limits of voltage -15% and $+20$ % the frequency transients limits of $+/-10$ %, will be kept within these limits.
- voltage harmonic distortion limits under no-load condition is kept within 3 % for individual harmonic and 5 % for the total harmonic distortion.

In applications, where low voltage supply is required, a shield winding shall be provided between the high voltage and the low voltage windings in such a way that the neutral point of the transformer is connected to the main switchboard and according to the earthing method used for the main distribution system. However, galvanic separation should be considered between the shore and on-board systems.

5) IEEE 45-2002, Recommended Practice for Electrical Installations on Shipboard

Voltage levels given in Table 8 [73] with either 50 Hz or 60 Hz based on the following distribution systems are recognized as standard:

- Two-wire with single-phase AC or DC
- Three-wire with single-phase AC or DC
- Three-phase, three-wire AC
- Three-phase, four-wire AC

Small vessels with power apparatus up to 15 kW can have three-phase or single-phase generators at 120 V with 115-V for power and lighting. The next scale is intermediate-size vessels with power apparatus up to 100 kW. These systems have generators at 230V. For large vessels, a dual-voltage system might be used with two transformers operating at different voltages. The voltage levels of generators can be selected as 450 V, 480 V, 600 V, or 690 V.

TABLE 8. Standard voltages defined IEEE 45-2002.

Standard	AC (V)	DC (V)
Power utilization	115, 200, 220, 230, 350, 440, 460, 575, 660, 2300, 3150, 4000, 6000, 10600, 13200	115 and 130
Power generation	120, 208, 230, 240, 380, 450, 480, 600, 690, 2400, 3300, 4160, 6600, 11000, 13800	120 and 240

Higher voltage power generation is mainly used in very large ships at 13800 V, 11000 V, 6600 V, 4160 V, 3300 V, or 2400 V and transformers are utilized to supply lower voltage at load sides. If DC power generation is required in ship networks, either 120V or 240 DC generators are recommended depending on the power levels.

The frequency tolerances should be within $+/-3\%$ while frequency transient tolerance can be up to $+/-4\%$. Voltage tolerance based on the average of the three line-to-line voltages should be within $+/-5\%$.

Maximum total harmonic distortion and single harmonic voltage are 5% and 3%, respectively.

Line Voltage Unbalance Tolerance is define based on the ratio of a difference between (V_{maximum} and V_{minimum}) and V_{nominal}. This limit should be within $+/-7\%$.

Grounding of low-voltage (600 V or less) power distribution systems should be considered a) to reduce the potential for transient over -voltages, b) to allow for continuity of service under single line-to-ground fault conditions and c) to minimize the magnitude of ground fault currents flowing in the hull structure.

6) American Bureau of Shipping, ABS 2006, Guidance notes on Control of Harmonics in Electrical Power Systems

Power electronics-based loads and converters are utilized in ship networks and generate harmonics affecting power quality and efficiency of the ship electrical system. This technical guide line is developed in order to raise awareness among the potential risks associated with the harmonics in electrical power systems onboard ships or offshore installations.

K-rated transformers are usually preferred to de-rated transformers and they normally comply with Underwriters Laboratory (UL) and NEC requirements for transformers supplying nonlinear loads. The K-factor system is used to indicate the capability of transformers to handle harmonic loads and the ratings are described in UL1561. Essentially, the K-factor is a weighting of the harmonic current loads according to their effects on transformer heating as derived from ANSI/IEEE C57.110.

A K-factor of 1.0 indicates that loads have no harmonics and are linear loads while the higher value of the K-factor means the greater the heating effect on a given transformer [74].

$$K = \frac{P_1}{P_f} = \sum_{h=1}^{h=h_{\max}} I_h^2 h^2 \tag{8}$$

where, K is K-factor, P_1 is eddy current losses of liner load. P_f is eddy current losses on non-liner load, h is harmonic number and I_h is harmonic current (per unit).

In Europe with significantly more complicated calculations as given in BS 7821 Part 4, K factor is defined as:

$$K = \left[1 + \frac{e}{1+e}\left(\frac{I_1}{I}\right)^2 \sum_{n+2}^{n=N}\left(n^q\left(\frac{I_n}{I_1}\right)^2\right)\right]^{0.5} \tag{9}$$

where, e is eddy current loss at fundamental frequency divided by the loss due to DC current equal to the RMS value of the sinusoidal current at reference temperature, h is harmonic number, I is RMS value of the sinusoidal current including all harmonics given by:

$$I = \left[\sum_{n=1}^{n=N} (I_n)^2\right]^{0.5} \tag{10}$$

n is n-th harmonic and q is an exponential constant which is dependent on the type of winding and frequency. Typical values are 1.7 for transformers with round or rectangular cross sections in both windings and 1.5 for those with foil low voltage windings.

It is important to clarify a Power Factor (PF) of an electrical system which is defined as $= \lambda = \frac{|P|}{S}$, where P is the active power and S is the apparent power. Assuming that the voltage harmonics are negligible, the apparent power can be written as below:

$$S^2 = V_1^2 \cdot \left(I_1^2 + \sum_{i=2.n} I_i^2\right) \tag{11}$$

$$S = S_1 \cdot \sqrt{1 + THD_1^2} = \sqrt{\left(P_1^2 + Q_1^2\right) + Q_h^2} \tag{12}$$

where, S_1, V_1 and I_1 are the fundamental apparent power, line voltage and current, respectively. THD_I is the total harmonic distortion of the current. Also, P_1 and Q_1 are the fundamental active and reactive power and Q_h is the non-active power. Thus, the power factor of a system is defined as follows:

$$\lambda = \frac{|V_1 I_1 \cos\phi|}{V_1 I_1 \cdot \sqrt{1 + THD_1^2}} = \lambda_{\text{dit}} \cdot \lambda_{\text{dit}p} \tag{13}$$

where, λ_{disp} is displacement factor $\left(\lambda_{disp} = |cos\varphi_1|\right)$, and λ_{dist} is distortion factor, $\lambda_{dist} = \frac{1}{\sqrt{1+THD_I^2}}$.

Therefore, the power factor of the electrical system consists of two factors, λ_{disp} and λ_{dist} which have two completely different effects on grids. The reactive power (λ_{disp}) can affect the grid voltage level and line current at 50 Hz that may increase losses through cables and transformers. The current harmonic distortion (λ_{dist}) has an impact on power quality and energy efficiency of the grid. In fact, the loss models of magnetic elements significantly depend on the order of harmonics.

7) Some other key documents

- Converting equipment (transformers, rotating frequency convertors and/or semiconductor convertors) for connecting HV shore supplies to a ship electrical distribution system shall be constructed in accordance with IEC 60076 for transformers.
- IEC 60146-1 series for semiconductor convertors, as applicable.
- Rotating convertors shall be designed and tested in accordance with IEC 60034.
- Typical distribution systems used on shore are given in IEC 61936-1.
- Typical ship distribution systems are given in IEC 60092-503.
- IEC 60533:1999 Electrical installations in ships – Electromagnetic compatibility

B. FUTURE RECOMMENDATION

To encourage recent development in marine electric power system without compromise with quality and safety of marine vessel and crew onboards, authors address following areas to be address as soon as possible.

1) HIGH FREQUENCY (2-150 KHZ) HARMONICS

Recent developments towards All-Electric Ship (AES) concept have increased the use of power electronics equipment in almost all parts of ships from low power to high power loads such as navigation systems, radars, engine room pumps, energy efficient lights, cooking loads, heating and ventilation etc. Main drawbacks of these power electronic systems are generating low (below 2kHz) and high frequency (above 2kHz) harmonics.

As discussed in section IV, energy efficiency got high attention in recent years. Ship operators taking several measures to improve ship efficiency. For example, lighting system is a significant load in some vessels such as cruise ships, where use of high efficiency light such as LED lamps, compact fluorescent lamps and high-pressure sodium lamps with electronic ballast is increasing. Most of these high frequency lamps use Power Factor Correction (PFC) circuits. Similarly, other single-phase loads such as washing machines, televisions and computers have PFC circuit to improve line current quality and power factor. These PFC systems operate at very high switching frequency, which generate very low distortion below 2 kHz but can inject harmonics at high frequencies.

Due to stricken power quality standards, the use of Active Front End (AFE) is increasing in newly built ships, which operate at 3-5 kHz switching frequency to provide better current harmonics performance below 2 kHz but generate high frequency harmonics especially at a switching frequency and its multiples. However, amplitude of harmonics in high frequency range (above 2 kHz) is not significant, but noise in 2-150 kHz frequency range can easily disturb communication system and other low power devices connected at the same PCC. One such incident reported in the field, where low power equipment such as computers and Switched Mode Power Supplies (SMPS) stopping or tripping very often due to high noise above 2 kHz (as shown in Figure 47) due to AEF converters connected to the same PCC.

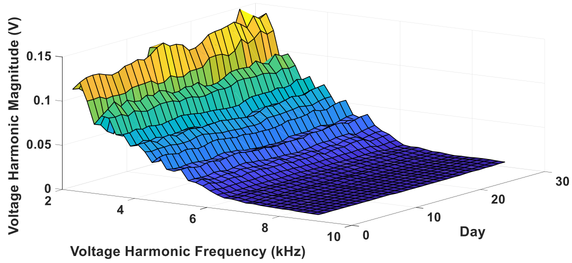


FIGURE 47. Field measurement of high frequency (above 2 kHz) due to Active Front End converters.

In order to further analyze 2-9 kHz harmonics in the power system, it is necessary to comprehend their peak level of distortion. For that purpose, Figure 48 demonstrates both peak and average values for one selected day and for the whole month with higher resolution measurement data. It can be seen from Figure 48(a) that the maximum value of harmonic occurred on the selected day is around 0.2 V, whereas the peak value for the whole month is around 0.3 V. These results present that even the peak values of voltage harmonics in 2-9 kHz range are not noticeable for the measurement data even when the resolution is high (1 second interval). Similarly, average values for the same periods have been demonstrated in Figure 48(b). The trend of different frequency components is quite similar to daily and monthly plots. This illustrates that, overall, behavior of 2-9 kHz remained the same and no major variation occurred over the whole measurement period.

At this moment, there is no general regulation and compatibility levels for harmonics within the frequency range of 2-150 kHz.

Advanced single-phase power electronics converters based on PFC are utilized in many electronics and lighting systems and operate at high switching frequency such as 30 kHz. Low power solar inverters utilized in residential areas operate at switching frequency range of 16-24 kHz. The field measurements show in Figure 49 that voltage harmonics are consistent with switching behavior of modern power electronics systems.

IEC-TC77A-WG1 and W8 experts have been working on the definition of compatibility levels for the frequency range of 2 – 150 kHz. This frequency range is divided into 2-9 kHz covered by WG1 and 9-150 kHz covered by WG8 experts. In 2015, the WG8 committee proposed a compatibility limit in the frequency range 2-30 kHz while a compromise for non-intentional emissions in the frequency range 30-150 kHz

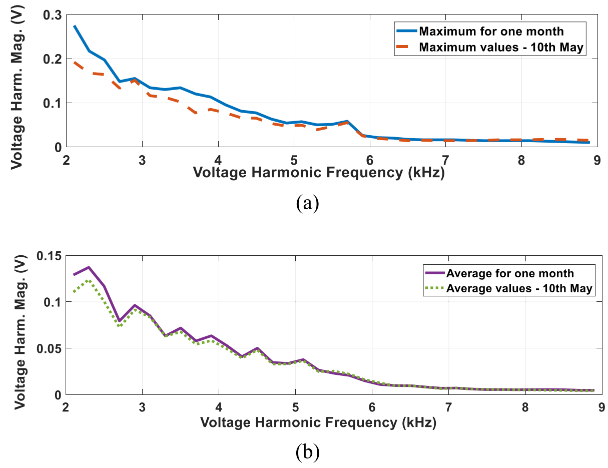


FIGURE 48. **2-9 kHz voltage harmonics: (a) maximum, and (b) average levels.**

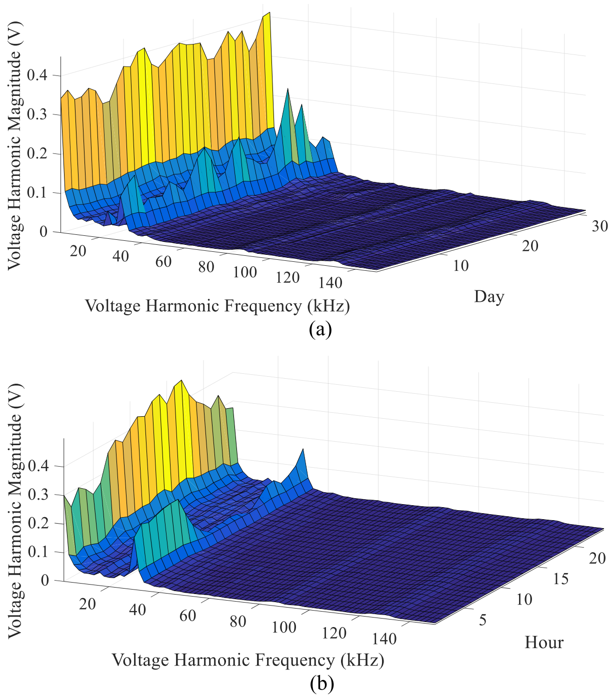


FIGURE 49. **(a) Daily and (b) hourly average values for 2-150 kHz voltage harmonics.**

had not been reached [93]. Finally, in 2016, both manufacturers and utility companies agreed on a new level to cover the whole frequency range of 9-150 kHz. According to the International Special Committee on Radio Interference (Comité International Spé cial des Perturbations Radioé lectriques), CISPR organization, there are specific standards CISPR14 & CISPR 15 for heating and lighting equipment to cover 9-150 kHz.

WG1 has been working on compatibility levels and harmonic emission limits for the frequency range of 2-9 kHz. One of the challenging issues related to this frequency range is to find a rational to select current or voltage measurement for the harmonic emission or immunity. In fact, for harmonics below 2 kHz, the measurement method is based on current harmonics (IEC 61000-3-2, and IEC 61000-3-12) while for harmonics above 9 kHz the measurement method is based on CISPR which is for voltage harmonics.

Figure 50 shows a broad range of frequency and existing future international regulations for each frequency range is addressed.

There are several other generic IEEE and IEC standards for grid connected electrical and electronics systems such as IEC 61000-3-2 & 3-12 and IEEE 519 which defines harmonic limits up to 2 kHz. These standards will cover a new frequency range of 2-9 kHz and the IEC TC 77A, WG1 technical group has been developing compatibility level and then test conditions for this frequency range.

IEC 61000-3-16 and IEEE 1547 main focus is on Active Front End technology with very low harmonic limits for the frequency range of 0-2 kHz. These two standards are developed based on unit tests where devices connected to a grid simulator and impacts of other equipment and grid conditions are not considered. However, new amendments will be developed to address interaction between devices.

2) INTERHARMONICS

Interharmonics are spectral components of voltages or currents, which are not multiple integer of the fundamental supply frequency [87], [88]. The interharmonic emission is usually less significant than harmonics, but their interference with the ripple control signals has recently became a more challenging issue, which has risen special concerns to pass limitations on their amplitudes and frequencies. Other important concerns caused by the interharmonic distortions are light flicker, sideband torques on the motor/generator shaft, interference with protection signals, dormant resonance excitations [89]–[92], [94]. Interharmonics issue is completely ignored in marine standards. In ship power networks, grid connected inverters based on AFE topology can generate interharmonics if the switching frequency of the inverter is variable such as hysteresis current control. In many industrial and marine applications, multi-pulse cycloconverters are commonly utilized in high power motor drives which can also generate interharmonics.

IEC TC77A, WG1 proposed a new grouping method based on 10 cycle data analysis to estimate interharmonics with 5Hz resolution for the 50 Hz grid frequency. The proposed method can detect interharmonics generated by many conventional power electronics converters such as controlled rectifiers for lighting systems or multi-cycle control systems for cooking home appliances. The proposed method can identify interharmonic energy distributed between harmonics. There are several methods proposed by IEC 61000-4-7 and 61000-4-30 for measurement methods.

3) ONBOARD DC GRID

Advantages of onboard DC grid as a new system architecture for marine application already discussed in Section IV, but

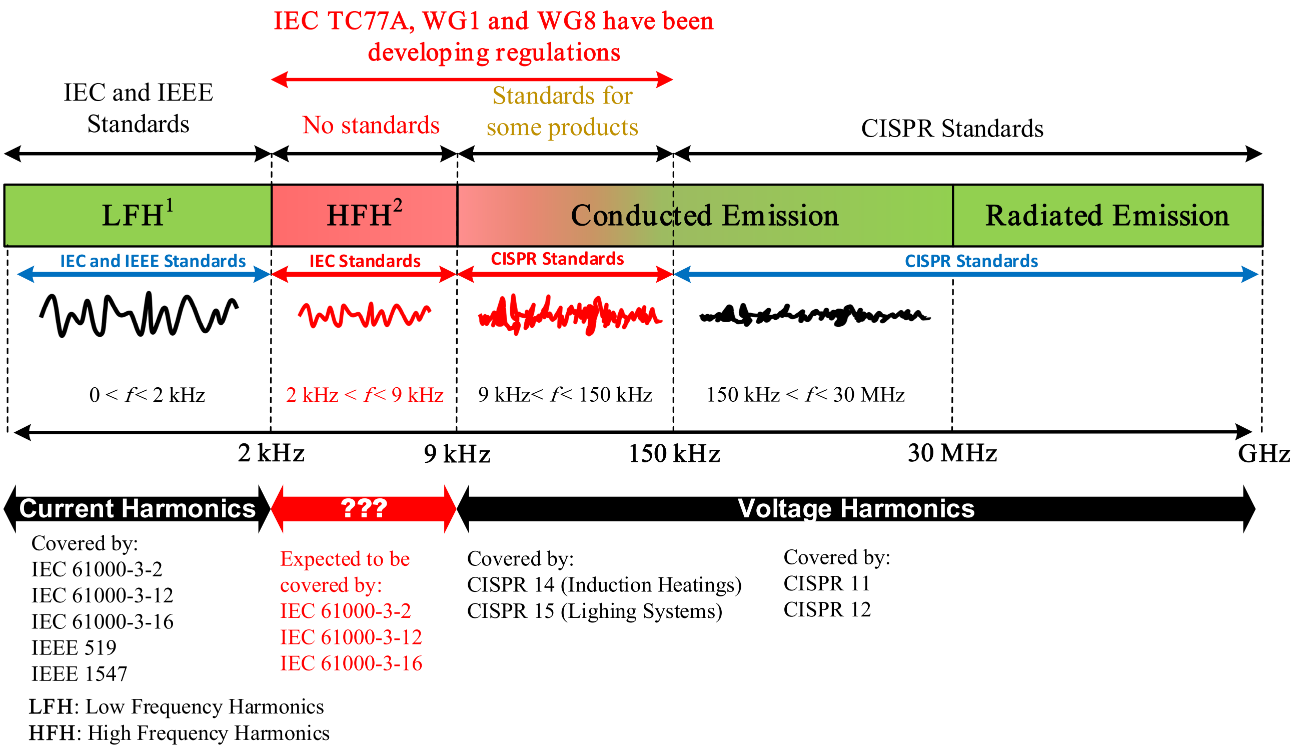


FIGURE 50. International regulations for low and high frequency harmonics.

biggest obstacle for onboard DC system is the requirements to standardize the voltage level, new safety regulations and suitable protection solution. However, there are some standards or guidelines available as listed below:

- IEC 63108-Electrical installations in ships-Primary DC distribution-System design architecture: 1st edition published in 2017
- IEC 61660- Short-circuit currents in d.c. auxiliary installations in power plants and substations, Part 1: Calculation of short-circuit currents
- IEC 60092-507 - Electrical installations in ships - Part 507: Small vessels (including some information about DC distribution system): 3rd edition published in 2014
- IEC 61892-1- Mobile and fixed offshore units – Electrical installations – Part 1: General requirements and conditions (including DC installations up to and including 1500V): 3rd edition published in 2015
- IEEE 1709- IEEE Recommended Practice for 1–35 kV Medium-Voltage DC Power Systems on Ships: 1st edition published in 2010

VII. CONCLUSION

This paper presents a classification of maritime vessels and their power system architectures including power electronics converters topologies utilized in many applications. Non-linear characteristics of power electronics-based converters, their energy efficiency indicators and a comprehensive case study to elaborate power quality issues in marine system are discussed in this paper. Extensive discussions about power quality standards, different frequency ranges and impact of power converter topologies on each frequency ranges are discussed.

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