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Tarasiuk, T, Jayasinghe, SG, Gorniak, M, Pilat, A, Shagar, V, Liu, W and Guerrero, JM (2021) Review of Power Quality Issues in Maritime Microgrids. IEEE Access, 9. pp. 81798-81817.

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Received May 22, 2021, accepted May 27, 2021, date of publication June 3, 2021, date of current version June 14, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3086000

Review of Power Quality Issues in Maritime Microgrids

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ABSTRACT This paper discusses contemporary problems concerning ship microgrids. It focuses on the role of power electronics and power quality issues, both conventional, such as voltage and frequency variations, and new issues, such as waveform distortions ensuing from the wide proliferation of power electronics in ship microgrids. The paper also contains a discussion on the provisions of the Unified Requirements of International Association of Classification Societies and other leading power quality standards in the industry, with an emphasis on Total Harmonic Distortion (THD) definition. An overview of power converters for high power applications in ships and their impact on ship networks is also given. Next, original results of various power quality phenomena recorded in ship microgrids are presented and commented on, followed by a review and recommendations for maritime microgrid modeling and signal processing methods for power quality assessment in the discussed systems. Finally, preliminary proposals for power quality control are presented.

INDEX TERMS Measurement, power electronics, power quality, power system modeling, ship microgrid.

I. INTRODUCTION

More electric technologies (METs) are becoming popular in the transportation sector as a promising solution to improve fuel efficiency and thereby reduce emissions. Maritime transportation, which accounts for more than 90% of goods transported globally, is not an exception to this trend [1]–[5]. As a result, more ships are now being fitted with variable speed drives (VSDs) for loads such as pumps, fans, thrusters and propellers. Out of these loads, thrusters and propellers constitute a large share of loads in ship microgrids, and thus, the maritime industry is experiencing extensive growth in the development of associated technologies. Even though electric propulsion has been under development for almost a century, broad proliferation, especially into cruise ships, began only after the 1980s with the development of power electronic converter technologies. Therefore, it is clear that

power electronics is the key enabling technology for METs in ships [6]–[9].

A typical electric propulsion or thruster system in an AC ship consists of a frequency converter, which is the power electronic converter system that generates variable voltage and variable frequency output from the fixed frequency fixed voltage supply. This conversion is achieved either using direct ac-ac converters such as cycloconverters or with an intermediate dc-link obtained through the rectifier-inverter combination such as a load commutated inverter (LCI). In dc ships, only an inverter stage is required to generate the required variable voltage variable frequency output [10]. In addition to their use in propulsion and thruster drive systems, power electronics enable matching new technologies, such as modern solutions for energy storage and generation, with older technologies, such as waste heat recovery systems or conventional drives [11]–[17]. Thus, solutions can be developed for pressing problems of energy efficiency and harmful emissions onboard, concurrently with safety in navigation, cargo, and human life on sea that can be solved with the aid of

The associate editor coordinating the review of this manuscript and approving it for publication was Derek Abbott¹.

power electronics. Therefore, the contemporary maritime industry heavily depends on power electronics and is becoming an inevitable technology.

Unfortunately, power electronics can create problems of its own in relation to power quality (PQ) in maritime microgrids, adding various kinds of waveform distortions to the notorious voltage and frequency variations [18]–[20]. This can lead to unwanted heat generation in generators and electric motors, unpredictable resonances, malfunction and failures of vital receivers. Coping with these issues is becoming increasingly pressing for the shipping industry. This requires a complex approach, starting from the ship design stage and is essential throughout the ship building process. This approach also consists of the entire lifecycle of exploitation and involves power quality assessment and management to achieve the main aim of the International Maritime Organization (IMO): “safe, secure and efficient shipping on clean oceans” [21].

The term “power quality” in ship electric power systems has a similar meaning as in other power systems. In the IEC standard 61000-4-30 [22], it can be defined as a “*characteristic of the electricity at a given point on an electrical system, evaluated against a set of reference technical parameters*”. However, the characteristics are hardly constant. They vary from ship to ship, depending on the power system configuration (e.g., number and power of nonlinear loads) or exploitation patterns. Nevertheless, it can be stated that the electrical characteristics of these systems match those of the other islanded microgrids [23], particularly those with extreme variation of loading conditions.

Finally, the power quality on a shipboard depends on many factors. In particular, the system behavior during varying operational conditions is of utmost importance. However, the resulting level of power quality also depends on the system’s key component features, such as the characteristics of generating sets, including their control and load characteristics. Nevertheless, it can be stated that the level of harmonic distortion in most cases depends on the topology and power of nonlinear loads and the subtransient reactances of synchronous generators. Moreover, this depends on the number of generators online and the power of linear loads working concurrently with nonlinear loads. In general, the higher the number of generators working in parallel with a larger load of linear receivers, the lower the level of resulting supply voltage distortions. Another power generation configuration is when the shaft generator is working via a power converter for frequency stabilization, where the distortions originate at the source itself. Similarly, the voltage and frequency variations as well as dips depend on the generator’s reactances and mechanical time constants, in addition to a significant impact caused by generating set control, such as automatic voltage regulators and governors. Voltage imbalance in maritime systems in most cases depends on load imbalance (usually related to load failure or malfunction), generator reactance and the number of generators working in parallel.

Therefore, dealing with power quality in maritime microgrids first requires answering the following three questions:

- What are the sources and resulting effects of various phenomena observed in marine electrical power systems, including their possible synergistic effects?
- how to assess the phenomena in marine systems?
- How can power quality in the systems be controlled and managed to ensure continuity of supply, to minimize the cost of energy generation and to improve fuel economy?

This paper aims to answer the above questions. Section II presents the extent of voltage and frequency fluctuations as power quality issues in marine power systems through case studies. It also describes the advent of power electronics and the resultant harmonic distortion phenomena as an impact on PQ. Section III reviews the power quality requirements from existing standards. Moreover, it presents the current legal framework related to the power quality issue in maritime microgrids. Section IV presents the assessment of PQ in ship power systems by modeling the system and subsequently through measurement techniques for further analysis. Section V presents a study done on improving power quality through modifying the power generation levels. Finally, Section VI presents the conclusions drawn from the work presented in the paper.

II. SOURCES OF POWER QUALITY PROBLEMS IN SHIP MICROGRIDS

The International Association of Classification Societies (IACS) power quality requirements have highlighted voltage fluctuation, frequency fluctuation and harmonic distortion as key power quality issues. Voltage and frequency variability in seagoing vessels has been widely acknowledged as a common phenomenon observed in marine electrical systems and has been widely documented and regulated. The ship power system is an isolated power grid and therefore more susceptible to any changes in the state of the network. Often, the essential loads onboard, such as thrusters, propulsion motors and pumps, are comparable to the capacity of the grid, and thus, their operation can cause power quality issues even during normal operation. This is compounded by the fact that sea conditions can be highly variable and major components of the power system have to be activated or deactivated with little notice resulting in unplanned volatility in system voltages, electrical frequency and harmonic levels.

The average load in the ship systems changes depending on the vessel operating conditions, e.g., normal sea going, cargo handling, harbor manoeuvring, etc. For instance, the average load of a particular dynamic positioning (DP) ship during sea-going (slow ahead) equals 400 kW, whereas during the stay at harbor, it equals merely 50 kW. Moreover, the load can change relatively fast, such as during ship maneuvering and mooring winches and/or thruster operation, when rapid load changes are the norm. Despite the fast controls, there are large fluctuations in voltage levels and frequency compared to commercial electrical power systems. To exemplify the phenomena, experiments were carried out in the all-electric ferry shown in Fig. 1(a) [24]. The single line diagram of the ferry power system is shown in Fig. 1(b).

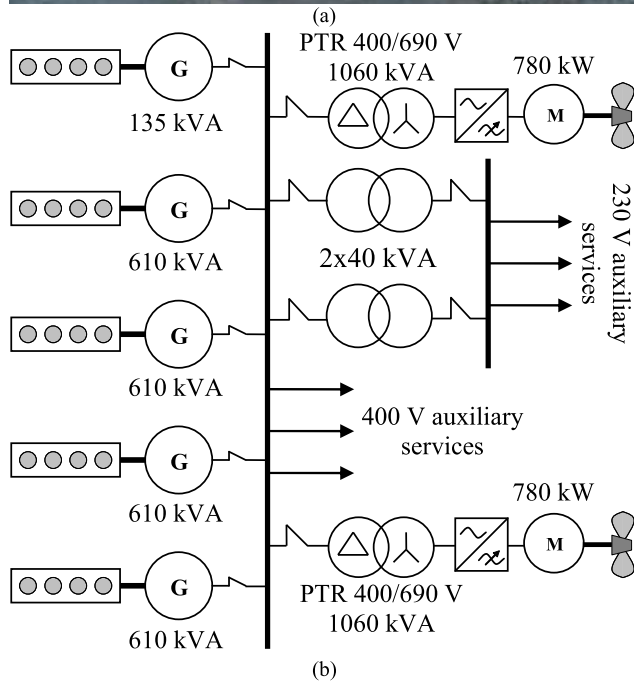


FIGURE 1. (a) All electric ferry, (b) single-line diagram of the ferry power system.

The results obtained for active load changes on the ferry during harbor manoeuvring are shown in Fig. 2. The corresponding voltage and frequency variations are shown in subsequent subsections (Fig. 3 for voltage and Fig. 4 for frequency). The changes in the average and momentary load highlight the necessity of matching the generating capacity to the actual load. This is due to the requirement for improvement of the fuel economy. As a result of the abovementioned phenomena, the system configuration (both power plant and load) and its characteristics change. This results in changes of power quality level. In particular, instantaneous frequency as well as voltage and current distortions can vary significantly. Illustrations of these phenomena are presented in the following subsections.

The implications of these events could result in hazardous current surges, overheating and malfunction of equipment endangering the safety of humans and machinery. The advent of all-electric ships, favored for their increased power generation capability and efficiency, in recent decades has

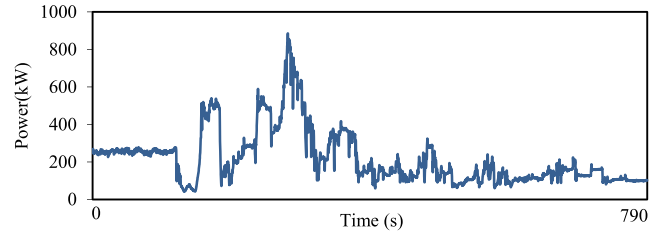


FIGURE 2. Active power of the ship power plant during harbor maneuvering.

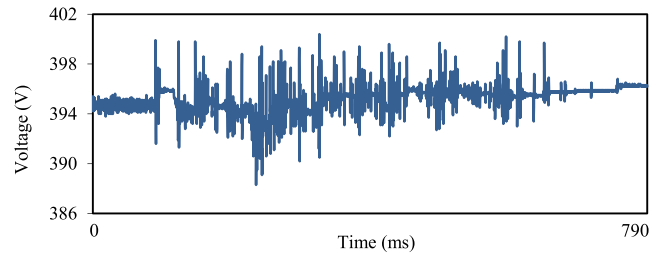


FIGURE 3. Changes in voltage during all-electric ferry harbor maneuvering.

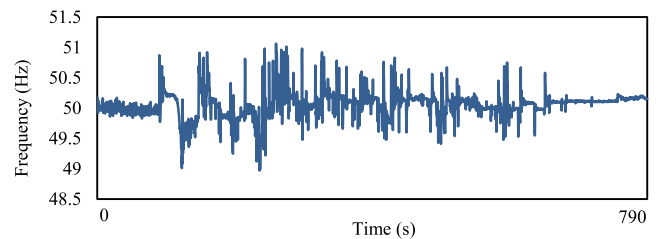


FIGURE 4. Changes in the instantaneous frequency of the voltage fundamental component during all-electric ferry harbor maneuvering.

exacerbated power quality issues for marine systems. This is due to an expansion of the power system through the introduction of multiple AC voltage levels, coupling between the electrical network and mechanical propulsion system and a more widespread use of a DC system onboard ships.

The startups of large motors, such as ballast pumps and thrusters, or simultaneous operation of different motors cause significant fluctuations in voltage levels due to the huge inrush currents. The adjustable speed drives for the motors consisting of controllers for the power electronic components add to the distortion of voltage profiles. Any fault that occurs at a particular voltage level of a system can propagate downstream to other sections of the network. This can create voltage sags in different parts of the system, and the subsequent fault clearing operation can induce a sharp voltage spike depending on the speed of protective action. Transformers can also contribute to voltage sags if they are energized during no-load or low-load operations. The sustained transformer inrush current can again cause a more prolonged transformer saturation voltage dip. Additional effects of this phenomenon can include harmonic distortion [25]–[28]. It is clear that electrical frequency will be proportionally affected when the power levels fluctuate, as is typical of ship power systems.

An extreme but not uncommon example of high impact power fluctuation would be the use of pulsed loads such as weapon launch systems and laser sensors. Power level fluctuations can even occur when the ship is at dock. The use of deck cranes has also been observed to cause considerable frequency deviations at the main busbars of ships. This is due to the nonlinear nature of the power consumption of the motor driving the pump of this equipment. However, these effects are not limited to electric ships. Hybrid electric ships have also been found to experience deterioration in power quality. The transfer of power between the main engine and the auxiliary genset allows propagation of fluctuations from the mechanical propulsion system to the electrical system of the ship. For instance, when the propulsion load is high, the main engine extracts power from the auxiliary engine. This greatly increases the power output of the latter, whose power output is already variable by nature due to fluctuating service load conditions in the ship. This combination of factors results in a frequency dip for the entire system. Frequency excursions such as these can contribute to blackouts onboard ships creating potentially hazardous conditions [29], [30].

Harmonic distortion is another power quality issue in marine applications that has become more widely documented and investigated in recent times. It originates from a range of sources, such as transformer saturation and parallel operation of multiple generators. However, the biggest factor is often the switching of power electronic devices found in most components of today's marine power system, ranging from navigational equipment to variable speed drives for motors [31].

The low power factor (PF) is another PQ problem encountered in ship power systems. It occurs when the generator is not able to meet the reactive power demands of the vast array of motor loads used onboard, mainly for propulsion but also including auxiliary services such as pumps and fans. Low PF leads to reduced energy efficiency. Additional installations are usually required for power factor correction (PFC). The simplest solution would be the addition of capacitor banks to the power system [32]. However, the capacitor banks have to be located close to the source of low PF. Other disadvantages of this method include huge switching transients, overheating and resonance due to harmonic distortion. Ships utilizing shaft generator configurations typically use synchronous condensers connected in parallel with electrical networks. This allows easy control of the PF through the exciter of the synchronous motor. The static var compensator (SVC) is a more sophisticated device that uses power electronic switches for faster action. It combines precise control of reactive power of the SVC with the simplicity of capacitor banks but with a higher cost for the owner [33]. Static synchronous compensators (STATCOMs) are another alternative for PFCs in ships. It consists of a voltage source inverter-based shunt device. In addition to compensating reactive power, it has been observed to offer other benefits, such as reduced voltage flicker and harmonic filtering abilities. Furthermore, STATCOM has been experimentally proven for use at

the AC-DC ship charging point with a DC-DC converter connection with a ship battery energy storage module [34]. Advanced semiconductor technology is another avenue to improve PF in ships. Wide bandgap semiconductor technology such as GaN, HEMT MOSFET, and SiC-SBD used in a boost converter within a PFC circuit has been shown to improve the PF by a larger extent, up to 0.99, compared to conventional silicon-type semiconductor materials [35]. It is clear from the literature that a low PF can also be addressed in conjunction with other PQ issues such as harmonic distortion simultaneously. In [36], a combined circuit is proposed that consists of an active power PFC (APPFC) circuit with a series active filter and a passive filter. The APPFC works well throughout a range of operating frequencies, as might be expected from a small isolated grid, while the shunt passive filter removes higher-order harmonics in high-power applications. This allows the series active filter to have a smaller rating just for the purposes of harmonic isolation, resulting in decreased harmonics while improving the PF.

The following subsections will illustrate in further detail voltage and frequency variations as PQ issues followed by an overview of the current state of the art in marine power electronics used in ships and the resulting harmonic distortion effect on power quality that this may bring about.

A. VOLTAGE VARIATIONS AND IMBALANCE

Voltage fluctuations occur in the shipboard power system during most ship operations, depending upon the load and sea conditions. For instance, the active power changes during the ferry maneuvering presented above and shown in Fig. 2 cause voltage fluctuations, which are shown in Fig. 3. Large variations in the voltage values may cause overheating of machines or insulations and present problems for proper operation of electronic equipment, speed drives and electrical contacts. Such variations can also occur due to the starting and stopping phases of large motors, such as those used for propulsion or thrusters used during maneuvering. This is illustrated in Fig. 5, where the voltage variation recorded onboard the ferry all-electric ferry is shown in Fig. 1. The process of starting of the bow thruster motor using stars/deltas switches is presented. The second voltage dip shown in Fig. 5 is approximately 23% of the rated bow thruster voltage of 6.6 kV. The voltage change due to this transient event is clearly in violation of the maximum allowed voltage magnitude fluctuation shown in Table 1.

Voltage imbalance is rarely reported for ship systems. The reason is that most of the high-power receivers are three-phase devices. Therefore, imbalance can usually be observed during failure of high power loads. However, if unbalanced phase voltages were to occur, it also caused a deterioration in power quality. Power electronic components such as rectifiers can produce unbalanced current surges that can trip out protective devices, leading to a partial blackout in the electrical network. Variable speed drives connected to crucial equipment, such as pumps and propulsion motors, have also been found to suffer from torque ripples.

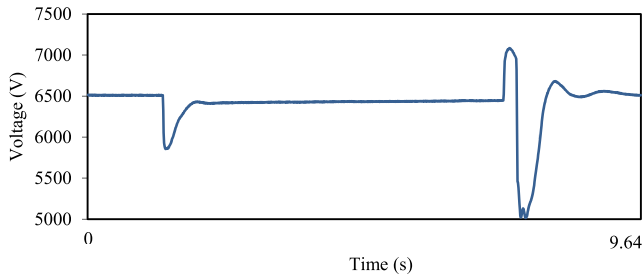


FIGURE 5. Measurement of bow thruster supply voltage behavior during bow thruster operation.

TABLE 1. Voltage and frequency variation requirements for AC distribution system.

Parameter	Permanent variation	Transient variation (recovery time)
Frequency	±5%	±10% (5 s)
Voltage	6%, -10%	±20% (1.5 s)

In addition, it can also result in other undesirable consequences, such as thermal aging of insulation, overheated bearings and reduced efficiency of equipment operation. An experimental study [37] where a single phase of a 3-ph heating load was disconnected to emulate an unbalanced load concluded that the harmonic distortion phenomenon during both steady state and transient operation phenomenon is more significant when voltage imbalance is present in the system. In the aforementioned experiment, the voltage THDs were in the range of 6.52%-6.73%, whereas for the unbalanced condition (imbalance factor $u_2=1.76\%$), the range of the THD changed to 6.15-7.38% depending on the line-to-line voltage [37].

In more severe cases, faults occurring in certain portions of shipboard power systems can also bring about voltage dips or spikes [25]. While these phenomena can be partly overcome by inherent protection mechanisms in the system, such as the automatic voltage regulator (AVR) in gensets or the uninterruptible power system (UPS) unit in the ship, their effect on the rest of the power system can still be significant [38]. Therefore, it is essential that transient or long-term voltage variations abide by the limits set by the relevant PQ standards. These will be discussed more extensively in the following section.

B. INSTANTANEOUS FREQUENCY VARIATIONS

The common feature of ship microgrids is instantaneous frequency variations of the fundamental voltage component [39] and harmonics accordingly. For the aim of this paper, the instantaneous frequency f_i can be defined as [40]:

$$f_i(t) = \frac{1}{2\pi} \frac{d\phi(t)}{dt} = f_p + \frac{1}{2\pi} \frac{d\theta(t)}{dt} \tag{1}$$

where:

$$\phi(t) = 2\pi f_m t + \theta(t) \tag{2}$$

where $\theta(t)$ represents the instantaneous phase, f_p is the nominal frequency and f_m is the actual power frequency.

Fluctuations of instantaneous frequency are due to significant load changes (in relation to generating capacity), e.g., during ship manoeuvring, as presented in Fig. 2. The corresponding changes in the instantaneous frequency of the voltage fundamental component for this process are presented in Fig. 5 (during all-electric ferry harbor maneuvering).

The instantaneous frequency changes presented below can adversely impact electric machine operation and commonly used measuring instrument performance. However, such a high level of variation should be expected during relatively short periods, as in ship manoeuvring. Additionally, minor load changes and/or minor changes in the generator rotational speed during relatively steady states should be considered. It leads to instantaneous frequency changes as well. Moreover, these changes can strongly depend on sea conditions. To exemplify the problem, a change in instantaneous frequency onboard the DP vessel during sea-going and when at harbor (berthing) are graphically compared in Fig. 6.

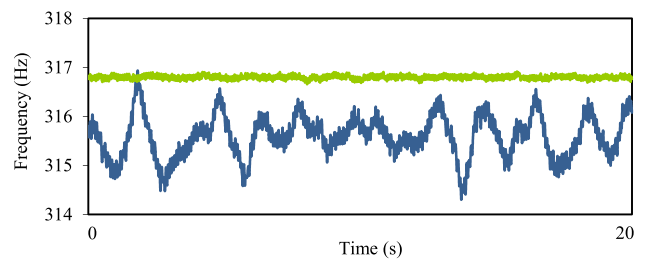


FIGURE 6. Changes in the instantaneous frequency of the fundamental voltage component of an all-electric DP vessel during sea-going (blue) and berthing (green).

The fluctuations of instantaneous frequency in the system of DP ship during sea-going is clearly related to changes in the electric plant load, which are shown in Fig. 7. The negative correlation between the instantaneous frequency fluctuations and the power fluctuation is clearly visible, i.e., a decrease in instantaneous frequency correlates to an increase in active power.

The instantaneous frequencies in both cases shown in Fig. 6 are not constant but show variation. One can distinguish variations with a frequency of approximately 12.5 Hz during both sea-going and mooring conditions. However, additionally, the instantaneous frequency is roughly modulated with a frequency of 0.5 Hz only during sea-going, which is related to sea conditions. The effect is a typical feature of ship microgrids, particularly with electric propulsion or ships equipped with shaft generators.

Ship classification societies do not deal with the problem of frequency or voltage modulation. Only IEEE Std 45-2002 *IEEE Recommended Practice for Electrical Installations on Shipboard* defines proper indices [41], as written in (3) and (4):

$$\delta_{mod} f = \frac{f_{max} - f_{min}}{2f_{nominal}} 100\% \tag{3}$$

$$\delta_{mod} U = \frac{U_{max} - U_{min}}{2U_{nominal}} 100\% \tag{4}$$

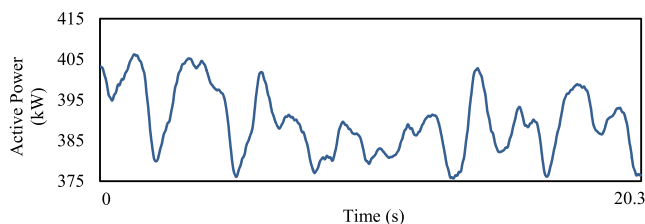


FIGURE 7. Changes in the active power of an all-electric DP vessel during sea-going.

The modulation can be understood as periodic variation in voltage or frequency during normal operation that might be caused by regularly and randomly repeated loading. The periodicity of voltage modulation is considered to be longer than 1 Hz and less than 10 s. For the purposes of definition, the periodicity of frequency modulation should be considered to not exceed 10 s. The recommended limit values of modulation were set as 0.5% for frequency and 5% for voltage [39]. It is clear that the recommended limit values for frequency modulation are sometimes hard to meet in ship systems, particularly during maneuvering or on ships on rough seas, as in the case shown above.

C. MARINE POWER ELECTRONICS

As mentioned, the more electric trend has now penetrated every corner of the transportation sector but at different levels. The automotive industry is the first to try and accommodate new technologies, mainly due to the technology demand from the large and fast-growing market and relatively lax regulations on reliability and safety. The marine industry, on the other hand, is strict, especially on the system availability for a given mission profile, reliability and the critical issue of safety and thus slow to accommodate new technologies. Compared to automotive and marine industries, regulations for the aerospace industry are more stringent depending on the mission profile, reliability and safety criticalness and thus are the most conservative in accommodating new technologies. Therefore, as shown in Fig. 8, despite having some commonalities, there are clear differences in the attributes that each sector expects from power electronic converter systems.

The most important attributes that the marine industry expects from power electronic converter systems are multimegawatt power levels (up to hundreds of MWs), high voltage operation (typically up to 11 kV) and availability during a given mission profile. The first two objectives can be achieved with high-power devices and converter technologies, while the third can be achieved with fault-tolerant and fault-accommodating technologies, which are out of the scope of this paper. Interested readers can refer to [42]–[44] for more information on the developments in this area.

As mentioned above, advancement of device technologies is the first approach towards achieving high-voltage and high-power converter systems. A comparison of currently available device technologies, in terms of their maximum operating voltage levels, current handling capacity and switching frequency, is shown in Fig. 9 [45]. It is evident from

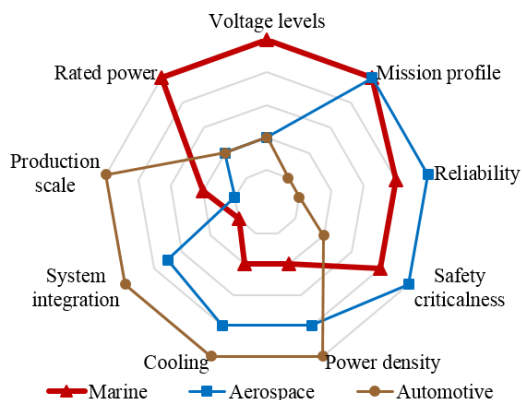


FIGURE 8. Attributes of power electronic converter systems sought by marine, aerospace and automotive industries.

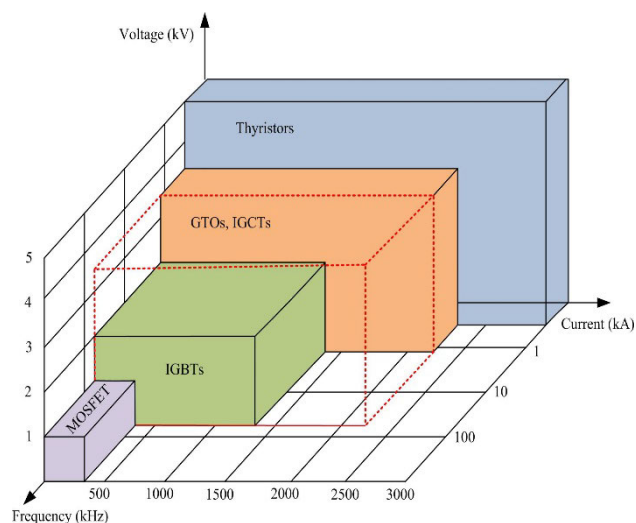


FIGURE 9. A comparison of power electronic device techniques.

this figure that, even with the recent development of metal oxide semiconductor field effector transistor (MOSFET) and insulated gate bipolar transistor (IGBT) device technologies, traditional thyristor devices (also known as silicon controlled rectifies (SCRs)) still play a major role in high-power applications. Therefore, the majority of very high-power electric propulsion systems use thyristors as switching devices. Their inherent limitation in switching frequency and the absence of turn-off control are the major causes of harmonics in ship power systems [46]. As a solution, gate turn-off (GTO) thyristors and integrated gate commutated thyristors (IGCTs) with turn-off control and increased switching frequency have been developed. GTOs are currently obsolete, and successors, IGCTs, are now increasingly being used in marine applications [29], [47]. Nevertheless, as the voltage and current levels of IGCTs are low compared to SCRs, series and/or parallel connections of multiple devices are required to achieve very high power levels. As shown in Fig. 9, IGBTs are fast switching devices that expect to reach the voltage and power levels of IGCTs and thus would become a popular choice in future marine applications.

The second approach for achieving high voltage and high power levels is the use of advanced converter topologies, which are shown in Fig. 10. These topologies can be broadly classified into direct ac-ac and indirect ac-dc-ac conversion systems. Direct AC converters do not employ energy storage elements such as capacitors or inductors and thus can be made compact and reliable. Cycloconverters are the most popular type of direct converter used in high-power applications. A schematic diagram of a typical cycloconverter is shown in Fig. 11, which uses SCRs as the switching element. This converter simply chooses suitable fractions of available three-phase supply to synthesize the required output, as shown in Fig. 12. As seen in the output, waveform distortion is quite high in the cycloconverter. In addition, the limited output frequency, for example, 24 Hz from a 50 Hz supply, is another drawback of the cycloconverter [46]. This, in turn, limits the speed of the motor and thus is not very popular in ship propulsion. The matrix converter, on the other hand, requires bidirectional switches, which increases the device count and thus results in more losses, cost and complexity. Therefore, matrix converters are not popular in ship microgrids [24], [25], [39], [46]–[53].

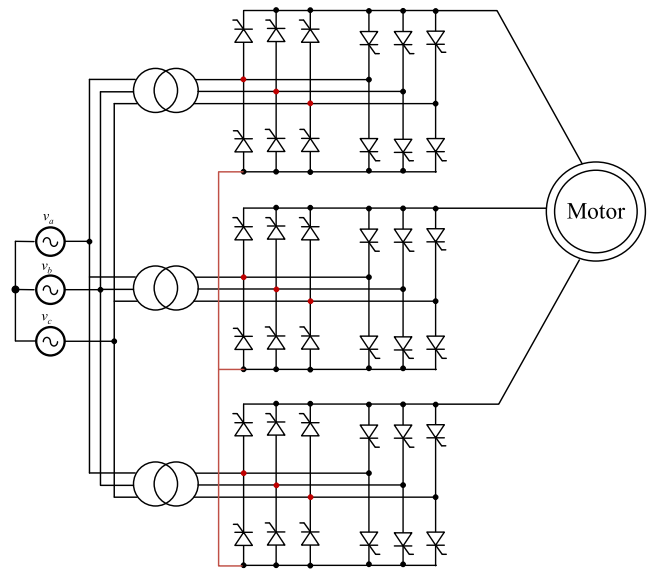


FIGURE 11. Cycloconverter.

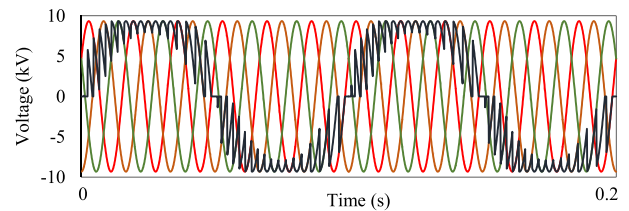


FIGURE 12. Desired output generation (black) in cycloconverters from the 3-phase supply (red, brown and green) waveforms.

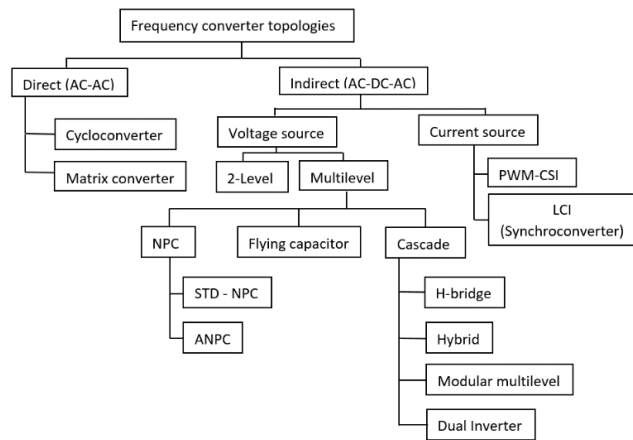


FIGURE 10. High power converter classification.

The indirect type of power electronic converter system consists of an intermediate DC link with an energy storage element. Depending on the type of energy storage element, indirect converter systems can be divided into voltage source-type and current source-type converters. As the name suggests, voltage source converters require a smooth dc-link voltage, and thus capacitors are used at the dc-link to smooth the voltage.

On the other hand, current source converters require a smooth current in the dc-link, and thus inductors are used at the dc-link. The two-level converter system and its current profile, shown in Fig. 13, is the simplest voltage source converter.

IGBTs are generally used in this converter, and thus pulse width modulation (PWM), at a relatively high switching frequency, can be employed to reduce waveform distortion [54].

The distortions in the converter input current are graphically presented in Fig. 13(b). Apart from that, the DC-link decouples the dynamics of the supply from that of the output and makes it possible to obtain higher frequencies at the output compared to the input. Despite having these advantages, the two-level converter suffers from limitations on operating voltage and current and is thus not suitable for high-power applications.

Multilevel converter topologies have emerged as a promising solution that uses a series connection of low voltage devices and clamping technologies to achieve high voltage capabilities and thereby achieve high power levels. The diode-clamped three-level converter, also known as the neutral point clamped (NPC) converter, shown in Fig. 14, is becoming popular due to the relatively low device count and the absence of phase shifting transformers [48]–[50]. As mentioned above, IGBTs are used in this topology for general applications, and thus, very low harmonic distortions can be achieved. Nevertheless, to achieve higher power levels, IGBTs have to be replaced with IGCTs that operate at lower switching frequencies, and thus, harmonic distortion increases. As a result, additional filtering stages are required to reduce the harmonic distortion.

Even though the abovementioned multilevel voltage source converter technologies are gradually being employed in high

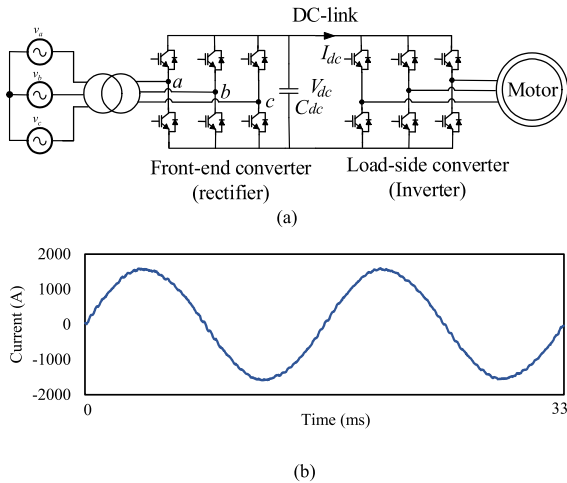


FIGURE 13. (a) Two-level PWM voltage source converter system with active front end (AFE), (b) current profile of voltage source converter with AFE.

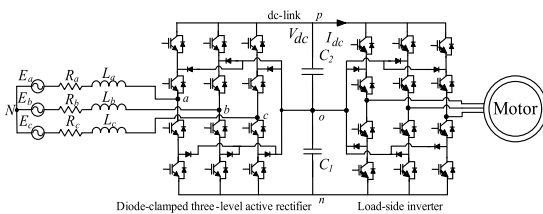


FIGURE 14. Diode-clamped three-level PWM voltage source converter.

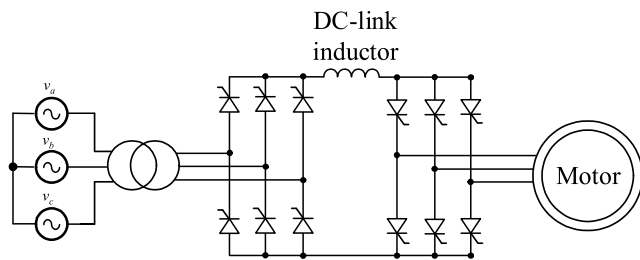


FIGURE 15. Synchroconverter.

power applications, the majority of existing systems use current source type converters (CSCs). Modern high-power PWM current source converters use symmetrical gate turn-off thyristors (SGTs) [46], [47]. Since PWM-CSCs use GCT devices, they cannot achieve very high power levels. The load commutated inverter (LCI), shown in Fig. 15, is the solution to achieve very high power levels. Therefore, even today, electric propulsion systems that require very high power use LCIs [50]. In addition to the very high-power levels, the main advantages of these LCIs are a simple converter structure, absence of issues related to ‘dv/dt’, transformerless topology and inherent overcurrent and short circuit protection [46].

As the name LCI suggests, the load should be able to commute SCRs in the load-side converter. Therefore, brushless synchronous motors are generally used in electric propulsion systems. As shown in Fig. 16, the back emf of the motor opposes the current in the previously conducting SCR, and

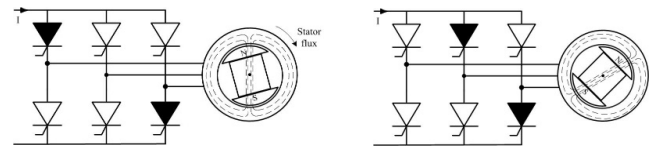


FIGURE 16. SCR commutation in the LCI.

thus, its current diminishes and is turned off while the next SCR picks up the load. The resultant converter operates in the six-step mode, and thus, the torque oscillation is very high. Therefore, instead of having one converter, generally two interleaved converters are used to obtain twelve-step operation and thereby reduce torque oscillations. Moreover, to ensure this commutation, the rotor speed should be above a certain limit, and thus, commutation will not occur at low speeds. As a solution to this issue, ‘dc chopping’ [51], which brings the rectifier current to zero, is used. The above-mentioned twelve-step operation, together with dc-chopping, results in severe waveform distortions, and thus filtering is essential for LCIs.

The Mermaid pod drive system in Queen Mary 2 (QM2) is a classic example of the use of LCIs in very high power electric propulsion systems. Studies have shown that if filters are not used, the total harmonic distortion in the bus voltage can increase up to 22% [52], [53]. This emphasizes the severity of the waveform distortion created by power electronics. Therefore, even though power electronics brings many advantages into ship microgrids, they introduce power quality issues as well, which require careful analysis and testing of appropriate solutions.

D. HARMONIC DISTORTION

Currently, the waveform distortions of voltage and currents are associated with the massive proliferation of power electronics onboard ships. Power electronics improve ship safety and/or fuel economy but create distortion problems. Similar to the instantaneous frequency, variations in the character and severity of the distortions depend on the electric power system configuration and load variation.

The use of power electronics to control the transfer of power to the squirrel cage motor in the 1950s marked the inception of the variable speed drive (VSD). Today, VSDs are a standard accompaniment to a vast array of modern machine applications because they enable efficient, cost effective and reliable speed and torque control of the myriad of motors used onboard vessels with minimum maintenance requirements. Their connection from the main power supply to the motor can introduce power quality problems into the power supply. They are one of the biggest causes of harmonic distortion in marine power systems because of their extensive use in power electronics. The VSD in its basic form consists of a rectifier to convert the AC supply to DC, followed by a power capacitor (DC bus) to store the DC power and finally an inverter to reconvert the DC power to AC with the desired frequency and voltage as per the operational requirements of the motor to which the VSD is connected. A standard configuration

for the VSD is the 6-pulse version, as shown in Fig. 17(a), with 6 diodes at the rectifier stage [54]. The diodes being passive devices are cost effective, and the VSD is compact and lightweight but produces high levels of harmonic distortion. To reduce the harmonics, 12 pulse rectifiers, as shown in Fig. 17(c), can be used for AC-DC conversion in VSD.

12-pulse rectification eliminates certain orders of harmonics due to the phase shift between the windings of the transformer, hence decreasing the THD [54]. This trend can be extended to 18 pulse rectifiers, 24 pulse rectifiers and so on to further reduce the harmonics produced [54]. However, the additional diodes required and the bulky transformer increase the total cost and the weight and space requirements onboard a ship. In recent times, the active front end (AFE) solution has been proposed for this problem, whereby the basic configuration of the VSD remains the same as in Fig. 17(a) with two changes. First, the diodes are replaced by IGBTs. These active devices switch on and off automatically to ensure that the waveform is more sinusoidal, thus decreasing the harmonics at the input side. Second, inductive filters at the input AC side of the VSD are added to decrease the higher-order harmonics caused by the switching action of the IGBTs. The benefits of AFE include a better power factor and lighter weight requirements [54]. Furthermore, AFE drives feature 4-quadrant speed-torque operation, thereby allowing backflow of power from the motor to the main supply. This increases energy efficiency during specific points of motor operation. However, interharmonics continue to cause harmonic distortion in AFE drives. VSD technology is predicted to improve in the near future to cope with demands on increased power ratings while employing more complex control algorithms for marine applications. This is expected to accelerate the penetration of power electronics into the complete setup of the modern motor [31]. It is therefore essential that the impact that these advancements in drive technology have on the harmonics being added to the system will continue to be monitored to ensure acceptable levels of power quality.

It was mentioned above that significant variations in the level of waveform distortions can occur rapidly aboard vessels. This is related mainly to VSD load variations. For instance, the changes in the voltage fifth, seventh and eleventh harmonic contents (in relation to the fundamental component) during all-electric ferry maneuvering are shown in Fig. 18. AFE drives were used for propulsion in this case. It is noted that harmonic content varies significantly with time. Moreover, the relationship between the respective harmonics changes noticeably depending on the actual load.

For the ferry ship, the overall level of voltage distortions is rather low (maximum observed THD value equalled to 4.2%), but for some cases, higher-order harmonics assume surprisingly high values. Exemplary registered voltage spectra are depicted in Fig. 19 for three various active loads of ship power plants.

As mentioned above, for the all-electric ferry, the level of voltage distortion remains low, but for the case depicted

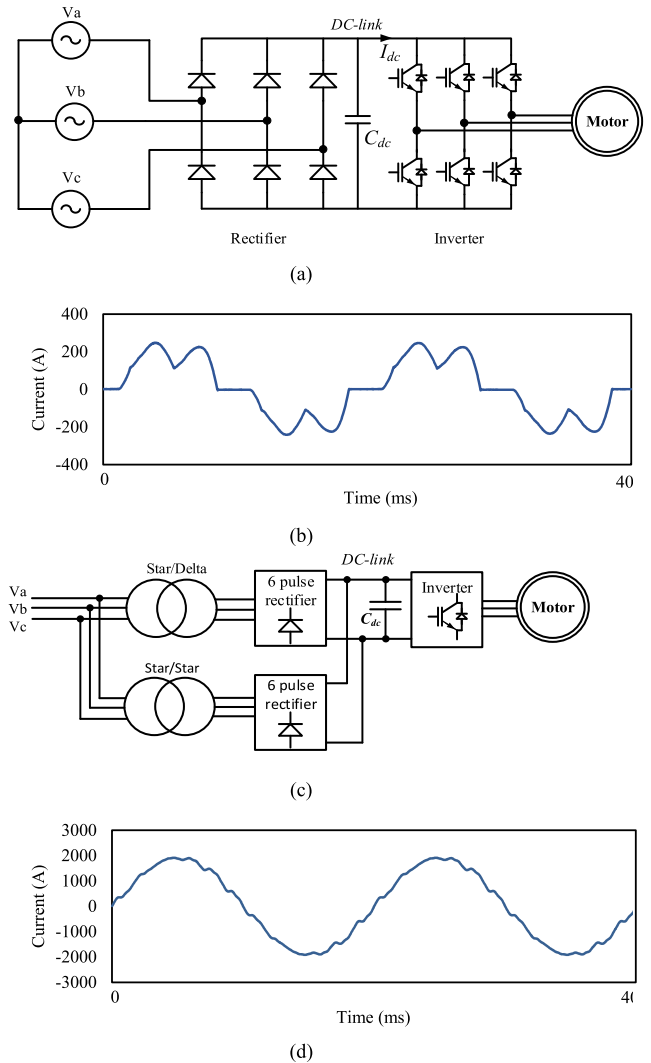


FIGURE 17. (a) VSD with a 6 pulse rectifier configuration, (b) current waveform for the 6 pulse rectifier configuration, (c) 12 pulse rectifier configuration, and (d) current waveform for the 12 pulse rectifier configuration.

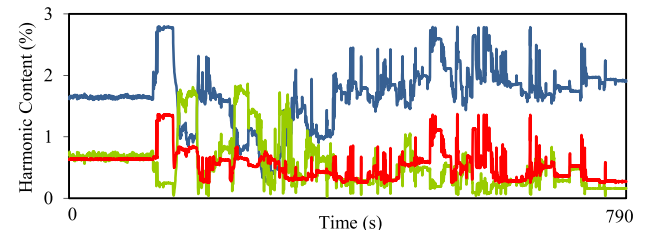


FIGURE 18. Changes in the fifth (blue), seventh (red) and eleventh (green) harmonic contents during electric ferry maneuvering.

in Fig. 19(a), significant values of higher-order harmonics should be pointed out. Both 35th- and 37th-order harmonics are above 0.5%.

It must be stressed that the voltage distortions on ships can sometimes attain very high values. During extensive research, a few cases with voltage THDs above 10% have been observed. As an example, voltage and current

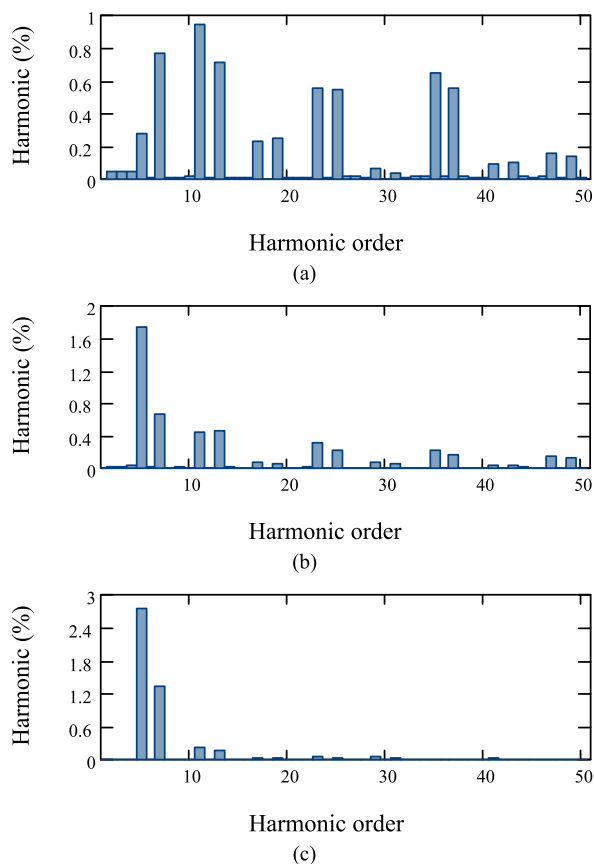


FIGURE 19. Voltage momentary spectra onboard an all-electric ferry during maneuvering: (a) active load 885 kW, (b) active load 202.9 kW, (c) active load 43.1 kW.

waveforms registered in the bow thruster subsystem are presented in Fig. 20. The subsystem contains an electric motor of a bow thruster with rated power 300 kW and a power converter and shaft generator with rated power 400 kVA (320 kW). The 6-pulse VSD was used.

The variety of power electronics technologies used today cause problems with proper THD definition and the required frequency bandwidth of a measuring device. To exemplify the problem of unifying the required frequency bandwidth for THD measurement, the distortion factor (including both harmonic and interharmonic) was determined for varying the frequency band from harmonic of the 50th order up to 10 kHz on boards of two ships. The results of the research are presented in Fig. 21 for a chemical tanker and in Fig. 22 for an all-electric DP ship. The first ship is an example of a vessel with a shaft generator working on the main busbars via a power converter with SCRs being used in the inverter stage. The second ship is a vessel with electrical propulsion (AFE drives with switching frequency 3.6 kHz).

It should be noted that for the two examples presented above, the determination of the THD in the frequency bandwidth up to a harmonic of the 50th order is insufficient, and the bandwidth must be extended. Moreover, in the case of the ship with electric propulsion, the THD determined for harmonics only up to the 100th order yields a result of 1.61% since

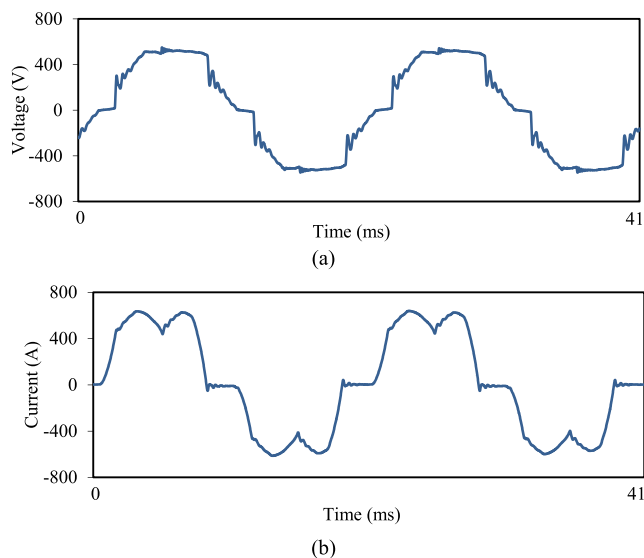


FIGURE 20. (a) Voltage waveform THD=12.6%, (b) and current waveform THD=24.4% in the subsystem of the bow thruster onboard the ship with mechanical propulsion.

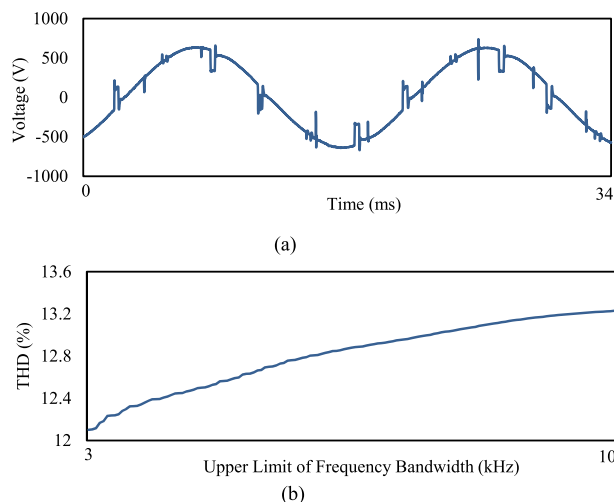


FIGURE 21. (a) Waveform of voltage on main busbars of chemical tanker ($U_{rat} = 440\text{ V}$, $f_{rat} = 60\text{ Hz}$) [49], (b) results of THD calculation including harmonics and interharmonics from fundamental component up to varying upper limit of considered frequency band.

the dominant components are interharmonics as opposed to harmonics.

III. POWER QUALITY REQUIREMENTS AND RECOMMENDATIONS BY SHIP CLASSIFICATION SOCIETIES AND MARINE ELECTRICAL STANDARDS

The growing importance of power quality issues on shipboards under normal and emergency conditions pressed ship classification societies to undertake uniform and, to some extent, coordinate action focused on minimizing the risk for ships, crews, cargo and seas. Some efforts have been undertaken under the auspices of International Association of Classification Societies (IACS). IACS is an association of twelve leading ship classification societies that verify the

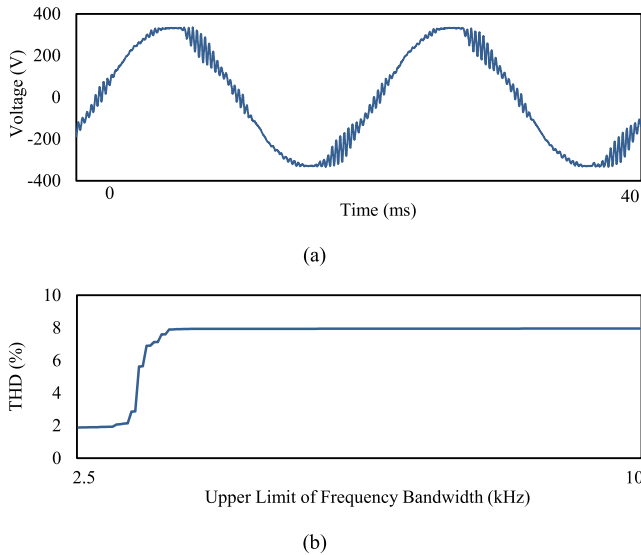


FIGURE 22. (a) Waveform of voltage on busbars of navigation equipment terminal of all-electric DP ship ($U_{rat} = 230\text{ V}$, $f_{rat} = 50\text{ Hz}$) [50], (b) results of THD calculation including harmonics and interharmonics from fundamental component up to varying upper limit of considered frequency band.

structural strength and integrity of the ship’s hull as well as “the reliability and functioning of the propulsion and steering systems, power generation and those other features and auxiliary systems which have been built into the ship in order to maintain essential services on board for the purpose of safe operation of a ship” [55]. To achieve this aim, each ship classification society issues its own rules related to all parts and functions of the ships, including electric power systems. However, the members of IACS also develop unified requirements (UR) accepted by all members. It is to unify the requirements and interpretations of IMO instruments to adopt and implement them uniformly.

Unfortunately, the exact term “power quality” does not appear in UR or specific rules of IACS members. Only Lloyd’s Register rules contain the term “Quality of power supplies”. Nevertheless, the parameters conventionally associated with commonly understood PQ are present in the UR or rules of ship classification societies, starting from voltage and frequency permanent and transient variations up to parameters of waveform distortions. For instance, the limits of voltage and frequency variations for AC ship distribution systems are stated in Table 1 [56]. On-board electrical equipment supplied from the main or emergency systems should be able to operate satisfactorily under these variations in voltage and frequency [56]. The values in Table 1 are unified and unchanged for many years. It is worth noting that ship classification societies part of IACS, such as the American Bureau of Shipping (ABS) and Lloyd’s Register, have identical requirements in this aspect of PQ. However, DNV, another member of IACS, has stipulated additional conditions for emergency distribution systems with slightly different requirements. The voltage and frequency parameters are shown in Table 2. Additionally, within 1.5 s and 5 s of a

TABLE 2. DNV voltage and frequency variation requirements for AC main switchboards of AC distribution systems.

Parameter	Permanent variation (%)	Transient variation (%)
Frequency	± 5	± 10
Main syst. Voltage	± 2.5	20, -15
Emergency syst. Voltage	± 3.5	-

transient event, the voltage fluctuation should not be more than 3% and 4% for the main and emergency distribution systems, respectively. It is also worth noting that Lloyd’s Register has a special requirement for cyclic frequency fluctuations where the rate of change of frequency should not exceed 1.5 Hz/s [57].

Ship classification systems such as ABS, Lloyd’s Register and DNV have also proposed similar voltage variation requirements at the main distribution board for DC battery powered systems and DC distribution systems, including instances where ship equipment is being charged and not charged by batteries. They are summarized as in Table 3 [58], [59].

TABLE 3. Voltage variation requirements for battery systems and DC distribution systems.

Parameter	Max. Variation (%)
Components being charged by battery system	± 5
Components not being charged by battery system	6, -10
Voltage cyclic variation	5
(AC) Voltage ripple over DC steady state voltage	10
Continuous voltage tolerance	10

Until recently, there were no unified requirements related to waveform distortion, and each classification society coped with this problem on its own. The situation changed after an accident onboard Queen Mary 2. The ship is an all-electric cruise vessel with an electric power plant containing four diesel engines ($4 \times 16.8\text{ MW}$) and two gas turbines ($2 \times 25\text{ MW}$). Her propulsion system consists of four pods, 21.5 MW each, supported during maneuvering by three thrusters 3.2 MW each. To suppress voltage distortions, two harmonic filters were installed [60].

The accident onboard the RMS Queen Mary 2 occurred in September 2010, caused by the catastrophic failure of a capacitor and explosion in the aft harmonic filter room. According to the report by the Marine Accident Investigation Branch, after several seconds, the vessel experienced a black-out. It was concluded that “most likely that the disruption within the aft HF at the time of the accident caused general instability in the electrical network which could not be contained and led to the generators shutting down” [60].

As a result of the accident, a discussion among IACS members ensued, and the IACS UR was amended. Chapter E24 “Harmonic Distortion for Ship Electrical Distribution

System including Harmonic Filters” was added [56]. According to the UR, the total harmonic distortion (THD) of electrical distribution systems does not exceed 8%” and “where the electrical distribution system onboard a ship includes harmonic filters, such ships are to be fitted with facilities to continuously monitor the levels of harmonic distortion experienced at the main busbar ...” [56]. The provisions are to be uniformly adopted by IACS members for ships contracted for construction on or after 1 July 2017. For existing ships, “as a minimum, harmonic distortion levels of the main bus bar on board such existing ships are to be measured annually under seagoing conditions” [56]. However, some classification societies, such as DNV [58] or ABS [59], added additional requirements related to single harmonic content, namely, any single-order harmonic shall not exceed 5%. Lloyd’s Register [57] has an additional stipulation limiting the 8% THD limit only up until the 50th harmonic level. Moreover, Lloyd’s Register requires that single-order harmonics above 25 times the supply frequency should not be above 1.5% of the fundamental voltage value.

Unfortunately, some ambiguities still exist. Most societies, except Lloyd’s Register [57] and Polish Register of Shipping (PRS), do not define THD or provide clues about the required frequency bandwidth for distortion monitoring. Next, the assumption of the same permissible limits for all harmonics independent of order seems at least disputable. Finally, none of the ship classification societies deal with the problem of interharmonics, except PRS, which requires determining THD including harmonics and interharmonics in the frequency band up to 10 kHz [61]. The PRS rules result from the fact that on some ships, components above the 50th order harmonic exist, sometimes with a dominant share of interharmonics [62].

On the other hand, apart from standards and rules aimed at civil or commercial ships, there are still rules concerning navy vessels. In particular, STANAG 1008, which refers to the electrical power plants in NATO naval vessels, has to be mentioned. According to STANAG 1008, the THD factor should be less than 5% (up to harmonic of 40th order), and any single-order harmonic should not exceed 3%. Moreover, the effect of the operation of user equipment and the resulting minimum harmonic distortion in the electrical power system is also defined. If rectifiers or power electronic converters are connected to the shipboard power system, the power of the largest single distorting load P_{distort} and the sum of the power of all loads $\sum P_{\text{distort}}$ that distort the current waveform should be determined and compared with the short circuit power of the generation capacity approximated as:

$$S_{sc} = 100S_n/x_d''\% \quad (5)$$

where S_{sc} represents the equivalent short circuit power of the supply system in KVA and S_n is the nominal apparent power of the feeding generators in KVA. $x_d''\%$ is the equivalent sub-transient reactance of the feeding generators in percent. The subsequent actions depend on the results of the comparison, as shown in Table 4.

TABLE 4. Stanag 1008 requirements for maximum power of distorting loads, which do not require further detailed analysis.

Harmonic Levels	Mitigation measure
$\begin{cases} \sum P_{\text{distort}} < 1\%S_{sc} \\ P_{\text{distort}} < 0.5\%S_{sc} \end{cases}$	No measures to be taken
$\begin{cases} \sum P_{\text{distort}} < 2\%S_{sc} \\ P_{\text{distort}} < 0.1\%S_{sc} \end{cases}$	No measures to be taken
$\begin{cases} P_{\text{distort}} \geq 0.5\%S_{sc} \text{ or} \\ \sum P_{\text{distort}} \geq 2\%S_{sc} \text{ or} \\ 1\%S_{sc} \leq \sum P_{\text{distort}} < 2\%S_{sc} \\ P_{\text{distort}} \geq 0.1\%S_{sc} \end{cases}$	Conduct analysis to ensure STANAG 1008 requirements are still valid

If harmonics levels are above the permitted values, mitigation measures would be necessary to reduce the current harmonics that may include installation of 12-pulse rectifiers, filters, etc. The STANAG 1008 requirements regarding the maximum power of distorting loads are beyond the scope of this paper.

Engineering professional organizations such as the IEEE have also recommended standards pertaining to PQ. The IEEE Std. 45. [41] describes the recommended practice for electrical installation for ship design, including recommended PQ characteristics for AC distribution systems onboard vessels. With the exception of permanent voltage variation limits, the voltage and frequency parameter limits are largely more stringent than those specified by IACS, especially with regard to the magnitudes of transient fluctuations. The IEEE standard also includes recommended limits on additional parameters such as 3-ph voltage imbalance, voltage spikes and further details on voltage and frequency excursion for emergency supplies. The recommendations are summarized in Table 5.

TABLE 5. IEEE STD.45.1 voltage and frequency variation recommendations for AC distribution and emergency systems.

Parameter	Permanent variation	Transient variation, (Recovery time)
Frequency	±3%	4%(2 s)
Average line to line voltage	±5%	16%(2 s)
Any one line to line voltage including aver. line to line voltage and voltage imbalance	±7%	16%(2s)
Voltage imbalance	3%	-
Voltage spike for 380-600 V system	-	2500 V
Voltage spike for 120-240 V system	-	1000 V
Emergency system frequency	-	-100 to 12%,(120 s)
Emergency system voltage	-	-100 to 35%,(120 s)

IV. POWER QUALITY ASSESSMENT IN SHIP SYSTEMS

A. POWER SYSTEMS MODELING

System modeling is a core component in the process of assessing a power system. The main objective is to develop

an almost identical virtual replication of the real system that behaves in a way that is as similar as possible to the physical system. The virtual system also has the ability to be tuned to match the existing behavior of the real system. This process of validation is a crucial part of maintaining reliable system operation. The validated model settings can then be modified as and when necessary to match real-time operation and predict future operation of the real system before significant resources are allocated for real system operation. Part of the analysis of the power system model includes determining essential information about key system parameters such as voltage, current, frequency and waveform distortion when different operating conditions are set for the model. These data can then be processed to assess and predict potential PQ issues that the real ship power system can encounter under similar operating conditions. For the model to be used for PQ analysis purposes, it must be able to predict crucial parameters such as frequency and voltage fluctuations as well as harmonic and interharmonic distortions that can occur during steady state or transient state ship operations. This is of special importance in marine power systems in view of the constantly varying loading conditions that seagoing vessels encounter that result in dynamic power system conditions onboard the ship. The results from model simulation are essential, as they can also be a useful predictive tool to modify ship operations to increase the efficiency of power system operation and reduce the risk of hazardous operating conditions for the physical system that may result in damage to equipment or injury to personnel onboard vessels.

In fact, the importance of ship electric system modeling and simulation results indirectly from the UR of IACS. The document states that “Where the electrical distribution system on board a ship includes harmonic filters the system integrator of the distribution system is to show, by calculation, the effect of a failure of a harmonic filter on the level of harmonic distortion experienced... The calculation results ... are to be verified by the surveyor during sea trials” [56].

Prior to system modeling and simulation, the process of system initial design takes place. This process ensures that the model to be built will include all the relevant components, subsystems and subsystem interconnections necessary to emulate the operation of the physical system. The design process of the subsystem or full system of power networks has been well documented for isolated power systems such as maritime microgrids [6], [63], [64]. Technical standards such as the IEEE 45.3 on Recommended practice for shipboard electrical installations [65] include guidelines on the design process of electrical systems from the initial concept design to the concluding product design involving integration of all subsystems and components of the full system. IEEE Std. 1826-2012 describes a baseline model for benchmarking the system performance of an MVDC network and an MVAC zone-based system. The control interfaces for hardware in the loop arrangement using FPGA-based solutions with appropriate communication protocols have been demonstrated. Data points were strategically placed throughout the system

for subsequent data analysis [66]. It has been noted that most of the literature on maritime microgrid models has made use of commercially available software such as PSCAD and MATLAB. The choice of the software to be used depends on user preference and needs, as each of them contains a different set of features with regard to mathematical models of the system elements, simulation modes and solver techniques. Reference [67] presents the characteristics of a number of the more common power system modeling software programs.

Individual components of a power system are largely built on the basis of mathematical models that mimic their behavior to their physical counterpart. Existing works [68], [69] have modeled these elements, such as the main engine, generators, propulsion motors and essential passive loads, in detail. These models are tested through the use of load changes and severe load disturbances such as short circuits. Maritime microgrid systems are broken down into subsystems containing individual system components for incremental testing and development during the modeling process. These could be the generation system consisting of the diesel engine/steam turbine, excitor and governor, as well as the synchronous generator. Conventional control techniques such as PID have been shown to be effective for speed control of prime movers and are advantageous for simple mathematical modeling. Each subsystem is tested separately using signals from the output of the nearest upstream subsystem in the initial stages before system-wide integration. Simulation control is an essential part of modeling [70] to determine the equation of motion of the vessel by setting predetermined acceleration and deceleration of the generators as well as a prime mover tripping condition. The propulsion subsystem is a unique part of the power system of maritime microgrids and has been extensively discussed [10], [71]. There are several approaches to modeling this subsystem. It is modeled with inverters and an induction motor with up to 15 phases. The propulsion system must be capable of absorbing constantly varying propulsion loads. A sinusoidally varying regenerating or motoring load with fixed service load levels is a proven possibility. Full and part loading with maneuvering operations under all or partial generator output are common testing scenarios for this model. The objectives of this model are to provide accurate shaft load and ramp torque commands to drive the simulation model while maintaining well-controlled prime mover output, system voltage and frequency parameters. Model testing is a crucial step before model validation with the physical system. The speed drives of the system form a major component and can be tested one at a time. The subcircuit of the drive can include the gas turbine-generator-VSD-motor model and can be repeated for all the drives individually under various load scenarios to satisfy incremental testing requirements. These could include on-off cases as well as crash back scenarios where motor speed changes directions. Determining the fault tolerance of the system is a crucial part of model testing, and this can include simulation of 3-ph, single phase, high impedance and variable duration faults with inbuilt fault clearing and circuit breaker reclosing

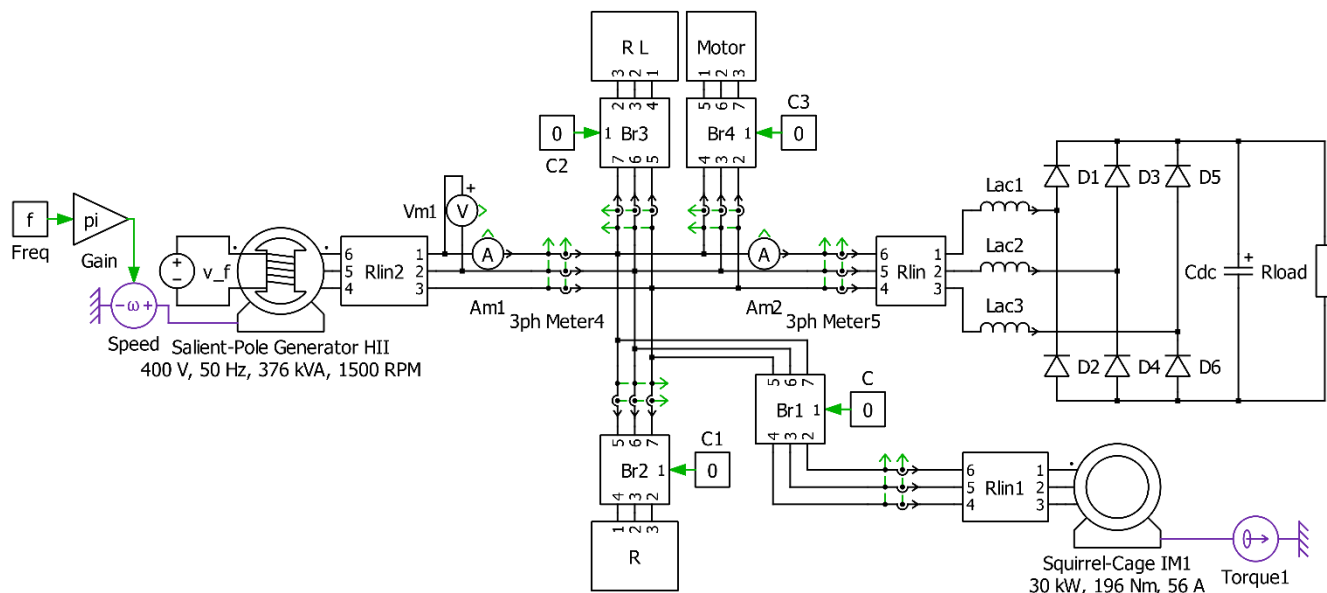


FIGURE 23. PLECS model of the ship electrical power system of the Horizont II ship.

operations [72]. Modern marine microgrids incorporate renewable energy sources such as solar power, and these sources have been integrated into the existing power system model of the vessel. Simple circuit models can be sufficient in the first instance to emulate changing environmental conditions, and they are well documented in the existing literature [73]. System simulators have more recently been used to model interactions between the different subsystems of the maritime microgrid. The time scale of the various system components is of critical importance in simulators, as they must accurately represent the reaction time of the physical system in response to changes in operating conditions. DP is a feature of modern maritime microgrid simulators. They must be flexible to test and validate any subsystem of the maritime microgrid. However, certain assumptions are being made in current simulators, such as a steady-state electrical system and variable speed thrusters with fixed pitch. The top-level view of a ship simulator includes the DP control system and the observer block to determine the position and velocity of the vessel. Other subsystems that can be added to the simulator are the thruster allocation system, electrical system and environmental model. Such a multidomain simulator is able to coordinate the decisions of the subsystems it contains and evaluate different aspects of microgrid operations, such as DP operating scenarios, electrical bus openings and closures, depending upon power requirements, energy storage operation and many others [73], [74].

Finally, to improve the results of the system modeling, hardware-in-the-loop technology has been used more extensively in the field of marine systems modeling [75]. This enables the use of physical devices that are hard to model or can be easily interconnected with the virtual part of the systems. Examples of such a device include electronic

governors and automatic voltage simulators or other controls.

To illustrate the process of marine power system modeling, a case study of the university training ship, Horyzont II, has current and voltage data collected from the ship during operation and has been used subsequently for modeling, sizing and verification of the main subsystems, namely, power generation, bow thruster and the remaining loads. In this model, the auxiliary loads have been represented as single entities because the current and voltage data of the total power generation as well as the bow thruster have been measured separately. For the scope of this paper, only the worst case scenario was analysed, namely, only one generator was connected to the main bus bars. These subsystems are subsequently integrated to form the whole system model and validated with real data. The PLECS software model of the power system considered is shown in Fig. 23.

The measured voltage and current data at the main electrical busbar of the ship were compared to the simulated results of the software model during steady-state operation, as shown in Fig. 24.

It is clear from the above voltage and current profiles that the difference between the measured and simulated models is minimal as a ratio of their absolute values and can be neglected. Furthermore, the voltage and current THD results gained from the model have also been compared with the measured values during actual ship operation. These have been displayed in Table 6.

The discrepancy of the parameter values gleaned from the simulation model for THD compared to the measured values are noted to be minimal at less than 3% compared to the measured values and can be safely ignored without significant loss of accuracy for further analysis using the model.

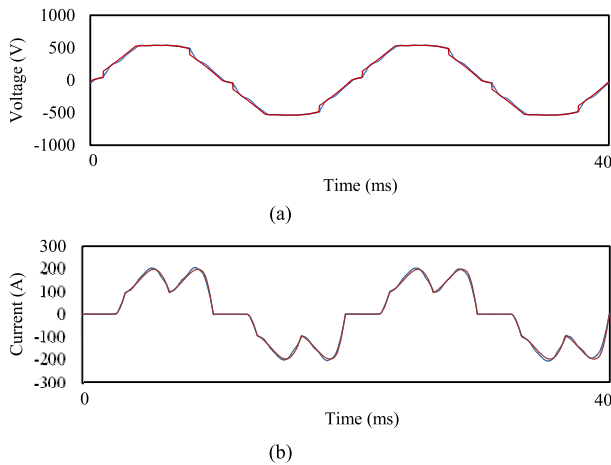


FIGURE 24. Comparison of the main busbar (a) voltage and (b) current waveforms from the measurement (blue) and simulation model (brown) onboard Horizon II.

TABLE 6. Voltage and current THD values from the measurement and simulation model.

Parameter	Value (%)
3-ph average voltage THD from simulation model	6.17
3-ph average voltage THD from measurement	6.36
Percentage difference of simulated voltage THD from measured value	2.99
3-ph average current THD from simulation model	33.67
3-ph average current THD from measurement	34.26
Percentage difference of simulated current THD from measured value	1.72

This process of using raw data for system modeling and verifying the simulation results allows a useful means of validation of the electrical simulation model of the bow thruster. Subsequently, this model can be incrementally extended by integrating more subsystems, or it can be used to predict and analyze the behavior of the real electrical system of the vessel with reasonable accuracy for a variety of operating scenarios.

The output of maritime microgrid design and modeling constitutes ship data in many cases in the form of a sample stream, such as in digital measurements. The following subsection reviews the different methods of analyzing these data to obtain meaningful findings and conclusions on the current state of the system with a focus on the determination and evaluation of potential PQ issues gleaned from these measurements.

B. POWER QUALITY MEASUREMENT

Measurement of power system parameters is an essential component to determining the power quality level of the system. Reliable and precise methods of PQ measurement can be used to determine the state of the system in various modes of operation as well as detect any deviation of the trajectory of system operation from the expected or desired

trajectory. A baseline for the measuring power quality parameters is laid out in the IEC Standard 61000-4-30 [22] and the IEC Standard 61000-4-7 [76]. These standards have been commonly accepted and implemented by the manufacturers of measuring instruments. According to these standards, the basic measurement window duration should be 10 periods for 50 Hz systems or 12 periods for 60 Hz systems. This is approximately 200 ms for both the systems. Next, the instrument for harmonic and interharmonics measurement should contain the following [77]:

- an input circuit with anti-aliasing filters
- sample-and-hold and an A/D converter
- synchronization and window-shaping unit, if necessary
- DFT processor providing the Fourier coefficients

Synchronization of the measurement time window with the actual input signal periods is necessary to avoid spectral leakage. The maximum permissible error of the measurement window synchronization with the actual duration of 10/12 periods should not exceed $\pm 0.03\%$. Synchronization with the required accuracy should be possible within a range of at least $\pm 5\%$ of the nominal system frequency [76]. A Hanning window can be applied only if there is a loss in synchronization.

Many manufacturers of related measuring devices implement synchronization of sampling frequency, e.g., by using the phase-locked loop (PLL) method to meet the abovementioned requirement. Unfortunately, synchronization of the sampling frequency always takes place after an interval of time after the actual power frequency changes [77], e.g., with a delay of approximately 200 ms. Therefore, for ship microgrids, the synchronization of sampling frequency with accuracy from the provision in the IEC 61000-4-7 standard is hard to obtain. Depending on the ship microgrid architecture and operation mode, proper synchronization cannot be obtained for 1.5-84% windows [39]. If one considers the previous example of sea going of DP ship (instantaneous frequency variations presented in Fig. 6 by blue line), proper synchronization would not be gotten for as many as 54.4% of windows with obvious consequences for measurement results.

The application of Hanning windows is no versatile solution. Let us consider quasiperiodic variations in voltage harmonics with corresponding instantaneous frequency variations onboard an exemplary chemical tanker with a shaft generator supplying the main bus bars via a power converter, as shown in Fig. 25. The shaft generator (1300 kVA) onboard the chemical tanker is directly coupled with the slow speed of the propulsion shaft (95-115 RPM), and the frequency on the shaft generator terminal is modulated at approximately 15 Hz depending on the actual propulsion shaft rotational speed and sea conditions. Therefore, the frequency must be separately regulated via the AC-DC-AC converter to maintain a rated frequency equal to 60 Hz. An additional synchronous machine driven by electric motors is used as a synchronous condenser. The resulting fluctuations of the voltage parameters are due to many factors, including the interaction between

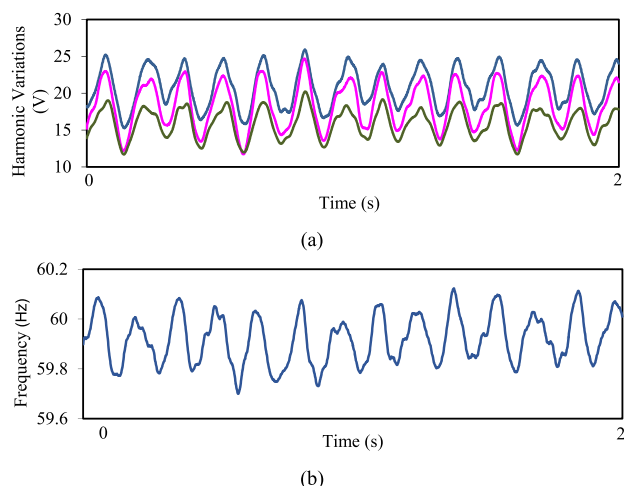


FIGURE 25. (a) Voltage harmonic variations onboard the chemical tanker: fifth harmonic U5 (blue), seventh harmonic U7 (pink) and eleventh harmonic U11 (green), (b) and instantaneous frequency variations.

the synchronous condenser, fluctuation load, inverter control and possibly, to a lesser extent, shaft generator rotational speed fluctuations.

Since the corresponding instantaneous frequency variations exclude the possibility of proper synchronization of the sampling frequency, a Hanning window should be used instead. Unfortunately, harmonic variations impact the method as well. The harmonic variations and two adjacent 200 ms Hanning windows are shown in Fig. 26.

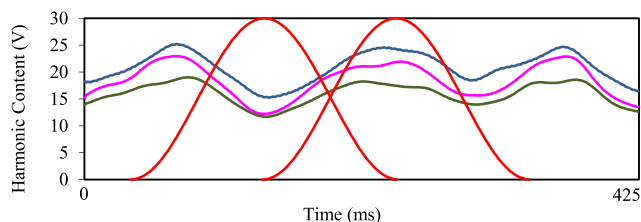


FIGURE 26. Two adjacent Hanning windows and variations in the 5th (blue), 7th (pink) and 11th (green) harmonic contents during the time interval.

It is obvious that determining the harmonic content for the two windows using a standard procedure would lead to completely different results not justified only by actual harmonic variation. To exemplify the problem, two methods of determining the fifth harmonic value have been used: rectangular window and classic DFT as reference and Hanning window and FFT. The maximum difference between the two methods for the singular window was 3.78 V or above 18% of the reference mean value (20.66 V).

Finally, the following signal processing methods for the measurement of power quality in ship microgrids are proposed and explained in Table 7:

- 1) sampling frequency – asynchronous and high enough to meet the abovementioned synchronization

TABLE 7. Proposed signal processing methods.

Method	Advantage(s)	Disadvantage(s)
Async. sampling frequency	Simple	Not recommended for direct FFT application, must be above 18 333.3 Hz
Window weighing – Rectangular	Narrow main lobe	Highest spectral leakage
DFT for offline measurement	Simple, arbitrary number of samples	Time consuming
CZT for online measurement	Arbitrary number of samples	More complex than FFT
FFT with interpolation in time domain for online measurement	Arbitrary number of samples	Trade-off needed between simplicity and necessity of oversampling and complexity of interpolation algorithms

requirements for ship system rated frequency $\pm 10\%$, with adjustment of number of the considered samples to the duration of 10/12 periods

- 2) Window weighting – rectangular
- 3) Signal processing tools:
 - discrete Fourier transform (DFT) for offline measurement.
 - chirp z-transform (CZT) or fast Fourier transform (FFT) with interpolation in the time domain for online measurement.

V. IMPROVEMENTS OF POWER QUALITY IN SHIP SYSTEMS

The chief aims of PQ control in integrated marine electric power systems are as follows:

- 1) Securing the continuity of the supply of vital receivers entails the necessity of controlling the power component distribution and distorting the voltage and currents.
- 2) Ensuring a sufficient level of supply voltage quality for minimizing the risk of malfunction or failure of electrical receivers and limiting broadly understood losses entails the necessity of voltage and frequency control, asymmetry, and waveform distortions.

To achieve the abovementioned goals, one must ensure a proper level of broadly understood PQ in all zones of the ship electric power system. It requires assessment of power quality and improvement if necessary. The assessment of power quality must be carried out during the ship design and exploitation stages. The former means PQ assessment by the considered system modeling (including overhauling of the design if needed, e.g., by adding filters, changing ship power plant or intended loads characteristics, separation of distur-

bance or susceptible loads) and subsequent measurement of power quality indices during carefully planned sea trials.

The latter stage, namely, ship exploitation, requires measurement of power quality indices for PQ management in ship systems, e.g., control of load disturbance and re-configuration of ship power plants. For instance, the improvement of voltage quality can be obtained by increasing the generating capacity (adding additional generators to work in parallel) for particular cases. The exemplary voltage waveforms recorded for bow thruster full load and various power plant configurations onboard the research-training ship are depicted in Fig. 27 [78].

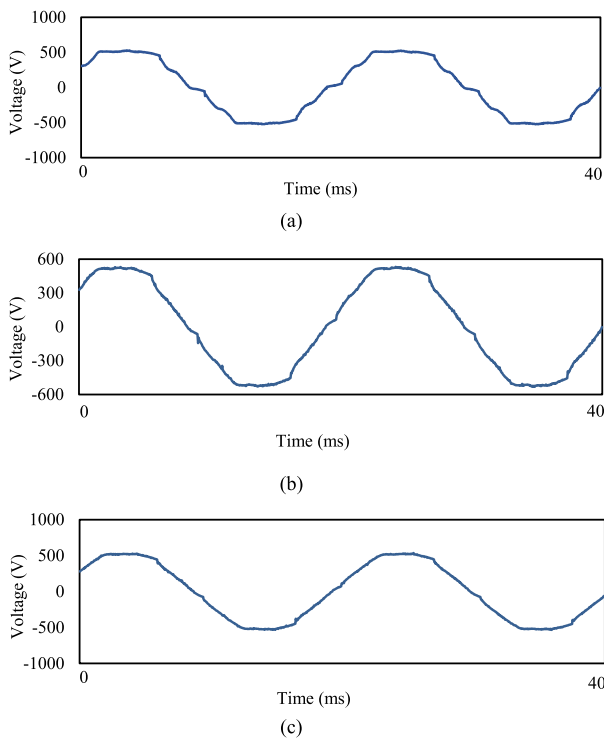


FIGURE 27. Exemplary voltage waveforms recorded on bus bars of main switchboard during bow thruster operation for (a) one generator working, (b) two generators working in parallel, (c) three generators working in parallel.

The resultant maximum, mean and minimum values of THD for the cases shown in Fig. 27 are displayed in Table 8 [78].

The voltage THD measured on the bus bars of the main switchboard during bow thruster full load onboard the research-training ship (designations: μ - mean value, min – minimum registered value, max – maximum registered value)

The results from Table 8 prove that increasing the generating capacity is a viable solution for power quality improvement in ship systems. However, it can be considered only for short periods or in emergency situations since it leads to an increase in specific fuel consumption. Alternatively, harmonic filters have to be considered.

TABLE 8. Harmonic distortion for different numbers of working generators.

		Number of working generators		
		1	2	3
THD (%)	max	8.08	4.85	3.77
	μ	7.91	4.77	3.70
	min	7.68	4.70	3.58

Finally, power quality monitoring can be a part of a more unified ship power management system with higher efficiency. The propagation of large power disturbances from one node of the power system to another can influence the strategic placement of equipment installation such as filters and power system operating decisions [10], [71]. However, it will require the proper design of power management control algorithms for concurrent management and integration of power quality information in the said systems.

VI. CONCLUSION

The PQ issue in ship microgrids is still an open question. This is a multidimensional problem that includes issues such as the design of power converters, their interactions with other sections of the ship power system and the system as a whole, PQ assessment methods and procedures and finally PQ control and management in a well-defined legal framework. Nevertheless, the hitherto research allows formulation of some final remarks:

- 1) Current rules of ship classification societies regarding power quality are insufficient in ensuring ship safety due to existing ambiguities in definitions of basic quantities.
- 2) Standard methods of power quality assessment and tools of signal processing are inappropriate for ship usage.
- 3) Real-time PQ monitoring capabilities integrated into power management systems can lead to better operating efficiency for the shipboard power system.
- 4) Properly developed models of future ship systems will be invaluable tools during the ship design, trial and exploitation stage.
- 5) The impact of environmental conditions and the system’s real characteristics should be taken into account when modeling ship systems or developing measurement methods.

ACKNOWLEDGMENT

The authors would like to thank Mariusz Szweda for providing the samples of chemical tanker voltage.

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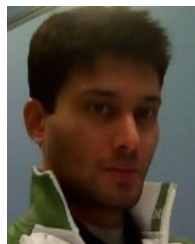
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