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A Review on Power Quality in Ship's Electrical System

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Abstract

This paper reviews the electrical power system quality onboard specifically in vessels with All Electric Propulsion (AEP). Going through the conventional to the latest Medium Voltage Direct Current (MVDC) distribution systems, the major power quality issues that arise onboard are discussed. Also some important power quality standards that are adopted by onboard vessels are briefly mentioned. In order to mitigate these power quality problems, it needs to be estimated and measured. So some of the works that are already carried out in the assessment, estimation, measurement and finally the mitigation of power quality problems are reviewed.

Keywords: *All Electric Ship, MVDC Distribution, Harmonics, Power Quality.*

1. Introduction

The very first commercial use of electricity onboard was on SS Columbia in 1880 for merely lighting up of the lamps [1]. The technological development in machines and electric power system in land, realized the ac power generation and distribution onboard. Also the advancements in marine industry, increased the demand of electricity within the vessels. Initially ac power generated onboard were used only for supplying the electrical loads onboard alone and not for propulsion. Later the evolution of power semiconductor devices and power converters made the electric propulsion possible. The power electronics technology also enhanced the use of variable frequency drives and several other nonlinear loads onboard, which results in power quality issues such as harmonics, notching, modulation etc. Rise in power quality issues forced the designers to develop mitigation techniques, as the quality and continuity of power supply is essential onboard. Advanced power semiconductor devices even resulted in a new distribution topology onboard called MVDC distribution.

This review work goes through the different power generation and distribution systems adopted and focuses on the research efforts in the area of power quality concerns and the standards onboard. It details the research efforts in the power quality assessment, estimation and mitigation in AC distribution as well as DC distribution onboard.

2. Ship's Electrical System

Conventionally electricity generated onboard were used merely for lighting and some other electrical applications excluding propulsion and the propeller was driven by the main engine as shown in Fig 1. Two generators were enough to supply the required power demand, keeping one as auxiliary.

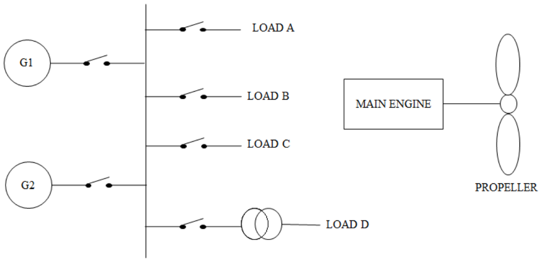

Figure 1: Conventional ship electric system

With the technology advancements, use of power semiconductor devices changed the conventional ship propulsion to electric propulsion. In so called All Electric Propulsion onboard as in Fig 2, the propeller is driven by motors, which are powered by the onboard generators through power converters. Thus generators have to provide power for propulsion as well as other electrical loads. In such a system the speed of the propulsion motor can be controlled by adjusting the frequency of the power converter.

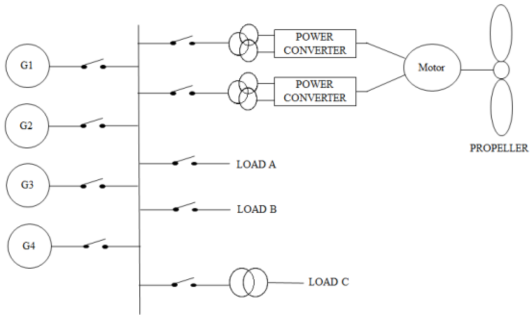

Figure 2: All Electric Propulsion onboard

2.1 Medium Voltage DC Distribution

In an All Electric Ship (AES), most of the loads are connected to the main bus through power converters. So to improve power density and system's efficiency a new distribution concept has been conceived called the MVDC distribution. Such a distribution system presents a Medium voltage (rated voltage higher than 1 kV) DC bus and it is based on the use of power electronic equipments, both on generator and load sides.

Ship's DC grid can be observed as an extension of multiple DC-links which are an integral part of frequency converters in propulsion and thruster drives of Integrated AEP vessels. Since those drives make up for more than 80% of the electrical power consumption on electric propulsion vessels, the idea was to unite all DC-links in a common DC bus. The concept of Onboard DC Grid has two configurations: multidrive approach and fully distributed approach. In the multidrive configuration [2], all converter modules are located within the same space layout as shown by the dotted rectangle in Fig 3. In such a configuration, the power cables that carry AC current are drawn from generators to the rectifiers and from inverters to the AC consumers.

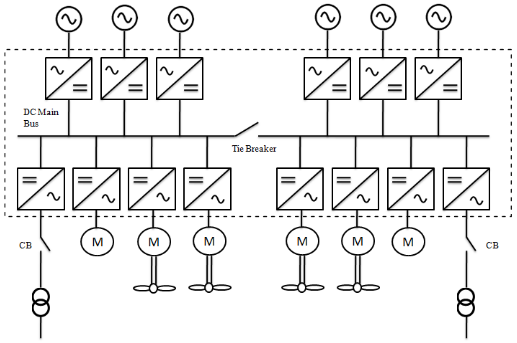

Figure 3: Onboard DC Grid: Multidrive approach

In the distributed configuration [3] as shown in Fig 4, each converter component is located as near as possible to the respective power source or load. In other words, each production unit has the possibility of an integrated rectifier mounted either directly on the unit itself or alternatively in a separate cabinet close by. Consequently, power cables carry DC current from generators' rectifiers to the DC bus. Also, the inverters are located near AC loads (mounted or in a separate cabinet close by) and power cables carry DC current from the DC bus to the AC consumers' inverters.

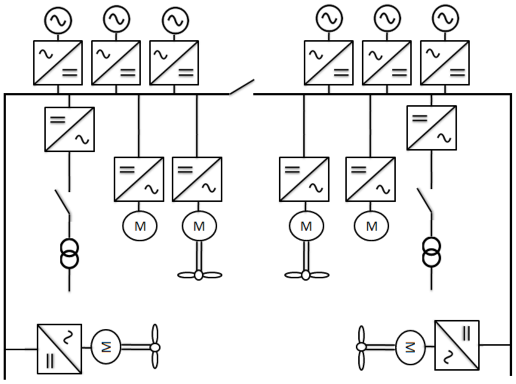

Figure 4: Onboard DC Grid: Distributed approach

Irrespective of the DC network configuration, electrical elements like the main AC switchboard and all thruster transformers are omitted in the new concept. Instead, voltages and currents of all the generators are rectified and the active power is sent into a common DC bus. That DC bus distributes the electrical energy towards the main consumers, and each of them is fed by a separate inverter unit. As a result, the volume of components that must be installed in the main switchboard room is drastically reduced, since there are no AC circuit breakers and their respective relays. The DC design enables upgrading of the system with energy storage or renewable energy sources (like photovoltaic panels), which can now be connected directly to the grid or via DC/DC converters. The main benefits [4] of this approach are space and weight savings and flexibility of placement of electrical equipment.

3. Power Quality Concerns Onboard in an AES

Even though it's a small scale power system, Ship's Electrical system include, generators, switch gear equipments, distribution system and other electrical equipments. Also in the case of AES, The Ship's Integrated Power system has to provide power for propulsion also. The technology advancements increased the use of power electronic devices onboard. The use of such nonlinear devices may tend to deteriorate the quality of power generated. Electric motors which are driven through power converters, used for propulsion is supposed to draw the major part of the generated electricity onboard. Also some electronic devices installed onboard ships like automation system, controllers and navigation system as well as dynamic positioning system are sensitive to power quality. The quality and continuity of power is utmost important onboard and power quality issues may lead to loss of power. Total loss of power means, loss of ship if it is in mid sea.

3.1 Power Quality Phenomena and Standards

Power System Quality phenomena onboard [5] can be classified into steady state and transient phenomena. Steady state phenomena include, harmonics, unbalance, notching and flickering. Variations in voltage and current waveforms for short durations such as spikes, dips and swells comes under transient-state phenomena.

Harmonics in power quality refers to the existence of distorted periodic voltage or current waveforms. Power electronic devices that are used to couple and control different operating voltage and frequency levels in shaft generator systems or in electric motor drives are the main source of harmonics. Some of the impacts of harmonic voltage and/or current distortion are extra heating losses in electric machinery and cable wiring, false tripping of protective switchgear, electromagnetic interference (EMI) problems with sensitive electronic equipments used in navigation, communication, control and automation. Two strong power quality issues related to harmonic distortion are the ‘notching’ and ‘noise’ phenomena, to which not much attention is paid by any ship Standard. More specifically, *notching* is a periodic voltage disturbance caused during the normal operation of power electronic devices due to commutation. As these kind of devices are been extensively used onboard in an AES either for AC/DC conversion or for electric motor driving, harmonic and notching problems are expected to significantly increase in such vessels.

Electric networks suffer from “short time duration non-periodical disturbances” of voltage and current caused by switching operations, short-circuits, fuse blowing- or even lightning strikes. These disturbances vary depending on certain characteristics of them and are named as transients, spikes, dips and swells. Voltage and Current spikes and transients have several adverse consequences like insulation breakdown, misfiring of semiconductor switches and false tripping of adjustable speed drives, resulting in equipment failure and improper operation of the entire system.

Periodic or quasi-periodic variations of voltage and frequency caused by regularly or randomly repeated loading with frequency less than nominal are referred in shipboard Standards (STANAG 1008, IEEE 45) as ‘*modulation*’. The future electric power system of naval warships in the context of the AES will supply energy to sophisticated systems for propulsion, electric guns, electric launchers, high power sensors and navigation. Some of new naval weapon systems, referred as ‘*pulsed loads*’, which require high power in the order of several Giga Watts for a very short interval (in the order of a few seconds and even milliseconds) are the main cause of voltage/frequency modulation.

Leakage capacitance phenomenon refers to capacitive leakage currents circulating between the main ship electric network and the ship's hull via stray equipment capacitances and/or their Electromagnetic Interference Compatibility (EMC) filter input capacitances.

Power quality indices in ship electrical system characterizes the process of power generation, distribution and utilization in all operation phases of the ship such as manoeuvring, sea voyage, stay in the port and its impact on the operation and safety of the ship as a whole. This set of indices cover the parameters of voltage and currents in all the points of the analyzed system and the parameters describing a risk of loss of power supply continuity. Parameters of the first group are mainly expressed by the coefficients of rms voltage value and its frequency deviations, coefficient of voltage asymmetry and coefficients characterizing the shape of voltage and current waveforms. Parameters of the second group are mainly related with correct distribution of active and reactive loads among generating sets working in parallel. These power quality indices have certain recommended limits set by the Classification Societies. A lists of most important standards concerning the issues of power quality assessment in the ship electrical networks, are shown in Table 1.

3.2 Research Efforts on Power Quality Assessment and Estimation Onboard

Process of the power quality assessment [6] fulfils a crucial role in the operation of the ship as a whole and is a basis for power quality improvement. The main components of this process are illustrated in Fig 5. Measurement methods of power quality indices are fundamentally based on signal processing, Fast Fourier Transform FFT, Wavelet Transform and digital signal processing. The commonly used instruments for power quality assessment are Fluke 435, Hioki 3196 and PowerVisaT.

Table 1: Important Standards Concerning the Issues of Electric Power Quality Assessment in Ship Networks

No	Symbol of the standard	Range of standard
1	IEEE Std. 45:2002	IEEE Recommended Practice for Electrical Installations on Shipboard
2	IEC 60092-101:2002	Electrical installations in ships. Definitions and general Requirements
3	STANAG 1008:2004	Characteristics of Shipboard Electrical Power Systems in Warships of the North Atlantic Treaty Navies, NATO, Edition 9, 2004
4	American Bureau of Shipping, ABS, 2008	Rules of building and classing steel vessels
5	Rules of international ship classification societies, e.g. PRS/25/P/2006	Technical Requirements for Shipboard Power Electronic Systems

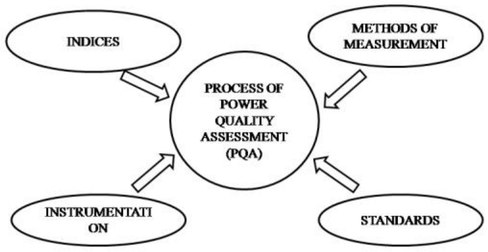

Figure 5: The main components of the process of power quality assessment in ship systems

Xiaoyan Xu *et al.* [7] listed the reasons for deterioration of power quality as: large amount of control and power electronic devices that are used for ship automation; increase in the number and power of electrical energy consumers onboard; appearance of harmonics during start-up of generators under parallel operation; low power factor of marine power plant under normal operation; impactive and fluctuant loads onboard which bring a large amount of harmonics to the system. With a mathematical model of Ship's Integrated Power system, N. F. Djagarov et al.[8] analysed the voltage and current distortions at different points of the power system through simulation under both static and dynamic operating modes. Result shows that that the presence of voltage harmonics reaches a level that disturbs the operation of loads as well as the control of frequency converter for propeller motor.

Janusz Mindykowski et al. [6] proposed a power quality estimation method based on complementary application of Fourier as well as wavelet transforms. The method is time consuming but an effective algorithm for analysis of signals in ship' system. Along with the estimation of power quality parameters, authors also point out some elements of risk assessment that should be taken into account, because of the synergy effect of different power quality disturbances. Certain solutions for power quality measurement onboard were proposed by Tomasz Tarasiuk et al. [9]. They have introduced more parameters for transient and notching evaluation, and finally implemented a complementary application of Discrete Wavelet Transform (DWT) and Discrete Fourier Transform (DFT) for time-efficient transient as well as harmonics detection and evaluation.

Philip Crapse et al. [10] proposed harmonic indices such as Harmonic Distance and Harmonic Similarity metrics. Harmonic Distance determines how much of a disturbance at one node is propagated to another node. Harmonic Similarity, is used concurrently with Harmonic Distance and provide a measure of similarity between the disturbances at various nodes based on the magnitudes and phases of their common frequency components. A DSP based power quality estimator–analyzer which has designed for operation under power frequency fluctuations was explained by Janusz Mindykowski et al. [11]. The device has a capability to determine active and reactive power distribution up to three generator sets working in parallel.

Frequency modulation is a major power quality phenomena caused by the operation of pulsed loads onboard. A design tool for the assessment of acceptable pulsed loading level onboard was expressed as frequency modulation in terms of parameters of the ship electric system by F.D. Kanellos et al. [12]. The method provides useful information on parameters such as frequency droop, pulsed load period and rotor inertia that affect frequency modulation which can be included in standards dealing with power system quality problems. Parameters that affect voltage modulation, such as AVR integral gain, pulsed load duty cycle and period, length of cables, generator loading before the occurrence of the pulsed load etc. were formulated by F.D. Kanellos *et al.* [13]. Chun-Lien Su *et al.* [14] presented a faster evaluation method for voltage sags due to motor starting, a common cause for modulation in ship electric power systems. The method was validated by the real time measurements from starting of several motors in ship electrical system by using Riemann summation principle based evaluation method.

A power quality monitoring system onboard ship in order to manage and optimize the power consumption of electric loads was introduced by S. E. Dallas *et al.* [15]. The system comprises measuring and recording of both voltage and current under the operation of three different motors. With the installation of variable frequency drives in such systems, there found a significant distortion in current waveform resulting a rise in current THD. LiMing Wang *et al.* [16] proposed an $\alpha\beta$ converter algorithm based on dq decomposition method to measure the voltage dip of warship power system. The improved $\alpha\beta$ converter algorithm, rectified the problem of phase delay in war ship power system. Ouyang Hua *et al.* [17] developed a power quality monitoring system using virtual instrument technology and configuration software. With the software LABVIEW and some real data picked by digital signal processors, certain power quality indexes were calculated, and the evaluation of power quality was done at monitoring station. The key data in the power quality monitoring station were sent to the ship energy management system (SEMS), for the unified energy management. A systematic power-quality assessment and monitoring methodology to calculate VFD contribution to voltage distortion at the point of common coupling (PCC), considering the source short-circuit capacity and the existing vessel's power system harmonics was introduced by Spyridon V. Giannoutsos *et al.* [18]. Julio Barros *et al.*[19] presented a virtual measurement instrument for detection and analysis of power quality disturbances in voltage supply using wavelets. Depending on the working mode selected as a function of the type of power quality disturbance to be detected and analyzed, the instrument implements in real time or off-line, different wavelet analysis on the input signal.

3.3 Research Efforts on Mitigation of Power Quality Issues Onboard

The majority of electrical nonlinear equipment, especially three-phase types, with larger powers will often cause the need for the addition of mitigation equipment in order to attenuate the harmonic currents and its associated voltage distortion to within the standards. The options available, depending on the application and desired level of attenuation are- Neutral current eliminators and phase shift systems (for four-wire systems), Standard AC line reactors, Wide spectrum (reactor/capacitor) filters, Passive L-C (inductance/capacitance) filters, Active filters and Active front ends (sinusoidal input rectifiers).

Xiaoyan Xu *et al.* [7] mentions some solutions to improve power quality of inland network. This include reactive power compensation for voltage deviation, static VAR compensators for fluctuation and flick off voltage, active and passive filters for harmonics suppression and automatization of electric power distribution to improve frequency deviation. Lixia Zhou *et al.* [20] put forward a phase-shifting reactor, a kind of passive device, which retains the advantages of passive filter to suppress the harmonics.

Y.Rajesh *et al.* [21] presented the application of DSTATCOM to improve the power quality in a ship power system during and after pulsed loads. An adaptive control strategy was also proposed for the DSTATCOM based on artificial immune system. The system was examined for pulsed loads of different magnitudes and durations show that the voltage regulation at the point of common coupling is much better with a DSTATCOM. Volker Staudt *et al.* [22] proposed pole-restraining controlled converter to guarantee the power quality within grids on board. The method is to introduce harmonic currents, which are selected in such a way that they are resistive (and, consequently, damping) with respect to already existing voltage harmonics into the local power grid in order to improve voltage quality. So if there is no voltage harmonics present, the converter current becomes purely sinusoidal, which verifies that the proposed methodology never generates harmonics of voltage or current on its own but always reacts to the voltage of the local power grid.

Janusz Mindykowski *et al.* [23] explained the measurement and control aspects of active power filtering in ship systems. The method is able to significantly reduce the response time of harmonic detection for the three-phase asymmetrical voltage. Chun-Lien Su *et al.* [24] designed a passive filter to reduce the voltage and current distortions in ship power systems. The on-board power system of a practical ship with a great number of VFDs were analyzed to illustrate the filter design. Tuned harmonic filters has improved the power quality and optimized utilization of the installed equipment.

Voltage sag is a major power quality issue in naval ships, due to the use of pulse power weapons. So-Yeon Kim *et al.* [25] proposed a method for the mitigation of voltage deviation in ship board power system by introducing a control strategy to the Active Front End rectifiers. The result shows that the voltage sag has been improved by 7.9% while 7.3% in the case of the line to line fault condition. Maciej Grabarek [26] introduced an onboard power surge compensator using the multilevel wavelet decomposition method. Jingnan Zhang *et al.* [27] compared the Wavelet and Fourier analysis for harmonic suppression in Electric Propulsion shipping system. Experimental result showed that wavelet analysis has high precision harmonic analysis ability which can be very suited to electric propulsive shipping system. Also a combination of Fourier and wavelet method can extract the time of the information and measure the harmonic values of the disturbance signal. Yong Li *et al.* [28] proposed a controllably inductive power filtering method to improve the power quality of ship-board power system (SPS). The topology contains a rectifier transformer integrated with linear filtering reactors, fully tuned branches and a voltage source inverter. The method can effectively dampen harmonic resonance caused by the varied short-circuit capacity or the harmonic voltage in SPS. Espen Skjong *et al.* [29] proposed a system-wide harmonic mitigation using Model Predictive Control (MPC) to generate the current reference for an Active Power Filter. Among the three cases of nonlinear load conditions, Total Harmonic Distortion (THD) obtained with system-oriented online optimization with the MPC are the lowest. The harmonic filter introduced by Spyridon V. Giannoutsos *et al.* [18] implemented onboard have maintained the total voltage harmonic distortion and individual voltage harmonics below 5% and 3%, respectively at PCC, showing that the design complies with relevant harmonic standards onboard in the worst operating case.

4 Research efforts on power quality concerns onboard vessels with MVDC distribution system

The power quality concerns of DC distribution systems are different in many ways from those in grid-connected AC distribution systems. Stephen Whaite *et al.* [30] identified the major power quality issues in DC distribution systems as: current harmonics and circulating currents that arise on a DC bus from nonlinear effects of the various power electronic converters, inrush current drawn by the filter capacitor at the load side, fault current through converters or from energy resources or capacitance directly on the DC bus.

Hasanzadeh *et al.* [31] addressed the analysis of pulsed load impact on active and passive rectification systems within an MVDC ship power generation unit. The work presented a diode-bridge rectifier integrated with a synchronous generator including an AVR which is fed from the three phase output voltage of the generator as first case and AVR fed from the DC output voltage of the rectifier as the second. In the first case generator is found to experience the rectifier’s harmful input current harmonics. The dynamic and transient performance of the input and output voltages of the three phase diode-bridge rectifier present better results when the AVR is fed back from the diode-bridge’s output DC voltage.

John P. Stubban *et al.* [32] reviewed the interaction of different loads and filter configurations on a shipboard microgrid with a medium voltage DC distribution bus. The study has shown that high power quality at the load can be achieved without high power quality at the generation source and MVDC transmission bus. T. Kourmpelis J. Prousalidis *et al.* [33] experimented on an MVDC distribution system to highlight the major power quality issues that arise from the prevalence of power electronic converters in an Integrated Power System (IPS). The system was simulated with an MVDC bus feeding a buck converter and a propulsion load to evaluate the harmonic distortion at both AC and DC sides. The result shows that the percentage of harmonic presence is very high and is a lot higher from the limits that the regulations define.

4.1 Standards on MVDC Distribution

The IEEE Std. 1709-2010 [34] recommends the functional MVDC block diagram assuming that all electrical power sources and loads are connected to the dc bus through power converters. Table 2 shows the IEEE recommended voltage variations in DC Distribution system.

Table 2: Voltage variations in DC Distribution

Parameters	Variations
Voltage tolerance (continuous)	±10%
Voltage cyclic variation	5%
Voltage ripple (RMS over steady dc voltage)	10%

5 Conclusion

Power quality problems are found to be serious onboard, especially in the case of AES, since the major electrical nonlinear load is the propeller. Technological developments in power electronics and power semiconductor devices and their wide application onboard are the main reason for this issue. Based on the power quality issues, some power quality indices are defined and there are certain limits set by the Classification Societies on these indices. In fact the base of power quality assessment onboard are these indices, standards, their measurements and instrumentation. Fundamental methods like digital signal processing, Fourier transform, or wavelet transform are usually used onboard for measurement of these indices, while some authors have used Fourier and wavelet transform together for measurement of these indices and some others have defined new indices like Harmonic Distance and Harmonic Similarity matrices. Normally instruments used for this purpose are Fluke 435, Hioki 3196 and PowerVisaT. Finally methods used onboard for mitigation of these power quality issues that are identified in literature are AC line reactors, active or passive filters and active front end rectifiers. The studies have shown that DSTATCOM and pole restraining controlled converters are also used for the mitigation. Some researchers have identified certain power quality issues in MVDC distribution system such as current harmonics and circulating currents that arise on DC bus, inrush current drawn by the filter capacitor and fault current through converters.

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