Power Quality Analysis for the Highly-Electric Asset with DC Power Distribution

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***Abstract*—The purpose of this work is to highlight the major power quality issues that arise from the prevalence of power electronic converters in an Integrated Power System (IPS) of a ship with Medium Voltage Direct Current (MVDC) distribution. In the first part of the paper the indexes of power quality as a means of reliable operation of shipboard power systems, as defined from classification societies and other (mainly military) standards, are discussed. In the second part, the vessel's electrical grid is modeled and a detailed power quality assessment is performed. Finally, the analysis results are validated through detailed simulation.**

***Index Terms*—All-Electric Ship, DC Power Distribution, Power Electronics, Power Quality, Harmonic Analysis**

I. INTRODUCTION

The amount and nature of electrical power usage on-board has grown exponentially over the last years. This fact, led researchers to consider new versatile and more efficient power distribution architectures that support the operational needs of these new loads. Future assets will enjoy the flexibility of optimal placement, connection and configuration of electrical production and consumption to the electrical network. Electrical power is envisioned to be supplied from a variety of power generation and energy storage modules utilizing a variety of technologies to propulsion, mission and ship service with maximum efficiency and reliability. The widespread electrification of systems that have been coupled to AC electric network via frequency converters has evolved to the recognition of the favorable characteristics of the Direct Current (DC) grid. As technology continues to advance, there is a need for a detailed simulation of the "highly electric asset" in order to investigate the effect of integrating the appealing DC into the Power Distribution subsystem of the ship grid and on its overall performance.

In this paper an Integrated Power System (IPS) with Medium Voltage Direct Current (MVDC) distribution is modeled and simulated. The model consists of the power generation module, the power conversion modules, the DC distribution line, the several distribution loads and the propulsion motor. Also, the major power quality issues that arise from the prevalence of power electronics in a highly integrated DC power system are discussed regarding the regulations of classification societies and the military standards for electrical systems power quality. The lack of quality power has an adverse impact upon the reliable operation of the entire grid. More specifically, poor Power Quality levels can result to loss of production, damage of equipment or appliances or can even be detrimental to personnel health. It is therefore imperative that a high standard is maintained and a detailed power quality assessment is performed.

The discussion and analysis presented is further enriched and validated through detailed simulation. The software that was used for the simulations is the PowerSystems Toolbox of Mathwork's Matlab/Simulink.

II. POWER QUALITY FOR SHIPOBOARD POWER SYSTEMS

a. Background

During the recent years, a major increase in the installation and use of power electronic converters onboard ships has taken place. This growing application of power electronic devices in the generation, distribution and utilization of systems has been accompanied by a corresponding growth in power system harmonic problems. The increased harmonic components had caused a significant degradation to the vessel's electrical power quality to such an extent that measures have to be implemented in order to minimize the resultant adverse effects on the electrical plant and equipment.

Thus, Power Systems Harmonic Analysis had become an essential part of system planning and design. All classification societies are actively engaged in producing guidelines to facilitate the task of assessing the levels of harmonic distortion. Also, guidelines for the presence of harmonic components appear at all the recently revised military standards for shipboard power installations [1].

b. Power System Harmonics

The presence of voltage and current waveform distortion is often expressed in terms of harmonic frequencies which are integer multiples of the main generator's frequency. The main sources of harmonic distortion can be divided into three categories: (1) Large number of distributed non-linear components of small rating (2) Large and continuously randomly varying non-linear loads and (3) Large static power converters. The first category consists mainly of single-phase diode-bridge rectifiers, the power supply of most low voltage appliances. Gas discharge lamps are also included in this category. Although the individual ratings, compared to the vessels power rating are insignificant their accumulated effect can be substantial, considering their large numbers and lack of phase diversity. The second category refers to the loads like arc furnace, with power ratings in megawatts, connected directly to the medium or high voltage distribution network and usually without adequate filtering. The impedance of this load type is randomly variable and extremely asymmetrical. Finally, as far as analysis is concerned, it is the third category that causes considerable difficulty. This is partly due to the size of the converter plants in shipboard applications, and partly to their sophisticated point on wave switching control systems. The operation of the converter is highly dependent on the quality of the power supply which is itself heavily influenced by the converter plant. Thus, special attention has to be paid in power system harmonic analysis and simulation of the process of power conversion. For that reason, this work focuses on the harmonics caused by the power electronic converters in a power system with DC distribution.

c. Regulations and Standards for Shiboard Power Quality

A number of professional societies and committees have issued standards documents for shipboard power installations and for electrical power quality onboard. For the electric ship cases (and the electric warships, in particular), IEEE, IEC, NEMA, ASTM, SAE and API are likely to be the sources of most commercial standards used. The Naval Sea Systems Command is currently reviewing and updating the many military specifications, standards, and handbooks under its responsibility. Where possible, the Navy employs commercial standards and specifications in an effort to reduce cost while maintaining military effectiveness.

The ABS Guidance Notes for Control of Harmonics in Electrical Power Systems [18] has been developed in order to raise awareness among electrical system designers of the potential risks associated with the harmonics in electrical power systems onboard ships or offshore installations. These Guidance Notes encompass topics from the fundamental physics of harmonics to available means of mitigation to practical testing methods. They are intended to aid designers to plan an appropriate means of harmonics mitigation early at the design stage of the electrical power distribution systems to make the system more reliable, more robust and more easily controllable. On Table 1 the ABS regulations for the allowed levels of harmonic components are summarized.

The IEEE Std 45 [15] is a standard (a set of recommendations and specifications) relating to to shipboard electrical installations. This standard, is not a regulatory body requirement for shipbuilding however it provides vital guidelines for the safe operation of the electrical equipment, for proper equipment selection, and for system coordination. The IEEE Std 45 recommendations are a supplement to American Bureau of Shipping (ABS) rules and regulations for commercial vessels. But also, provide to military users a proper understanding of the requirements and be able to correlate Military Specifications with IEEE 45 recommendations. The guidelines for harmonic distortion and management are provided in section 4.3.3 of the standard and summarized at table 1 below.

For naval vessels, the applicable standards for electrical installations are MIL-STD-1399 [17] and STANAG-1008. MIL‑STD‑1399_300_Revision B defines the electrical interface power requirements for shipboard and submarine equipment. Thus, current harmonic control limits for single phase and three phase equipment operating at 60 Hz and 400 Hz services are dictated. The measurement and control of current harmonics, especially for power electronics equipment, is essential for both on and off shore defense platforms and is also covered under the electromagnetic interference control for subsystems and equipment requirements provided by MIL‑STD‑461F test method CE101. In many instances, the measurement techniques and limits are leveraged and shared between the two standards. However, differences do exist which can lead to errors in compliance reporting if one method is used versus the other.

According to MIL-STD-1399_300 for 60 Hz frequency, equipment with power ratings ≥1000 VA any single harmonics line current above the fundamental frequency up to 2000 Hz should be less than 3% of the unit's full rated load fundamental current. Additionally, currents from single harmonics or of any frequency above 2000 Hz through 20 kHz shall be limited to a value of 6000/f percent of the user equipment's full load fundamental current, where f is the nominal operating frequency [17].

TABLE I. HARMONIC LIMITATIONS FOR ONBOARD INSTALLATIONS

Voltage	**Waveform Harmonic Distortion**		
	ABS Guidelines	***IEEE Std45***	***MIL-STD-1399***
Maximum total harmonic distortion	5%	5%	5%
Maximum single line harmonic	3%	3%	3%
Maximum deviation factor	5%	5%	5% (3% for submarines)

Although both commercial and military standards are in accord for the harmonic levels of the AC systems, no regulations have been provided so far for DC distribution. The process of developing standards and specifications for MVDC applications is in early stage and requires more development. The development of specifications for MVDC networks should be done carefully through numerous and detailed simulations and evaluation of the DC grid operation at future ship when they will begin to operate. Where reasonable, the requirements for MVDC applications should be folded into revisions of existing documents, minimizing the creation of new documents and standards. Commercial specifications should be continuously evaluated for naval warship application.

III. GRID ARCHITECTURE

An Integrated Power System (IPS) is a novel power distribution architecture, where a common bus is used to supply both service and propulsion loads and instantly redistribute power as necessary [9]. In contrast to a typical mechanical drive system an IPS would not require different prime movers for the propulsion and the ship's service systems, a fact that offers significant architectural flexibility and allows decentralization of the ships systems and component arrangements [3]. A conceptual IPS with DC Power Distribution is shown in Figure 1. In this chapter, the ship's power system is discussed and a detailed description of each component is given regarding its role on the power quality of the system.

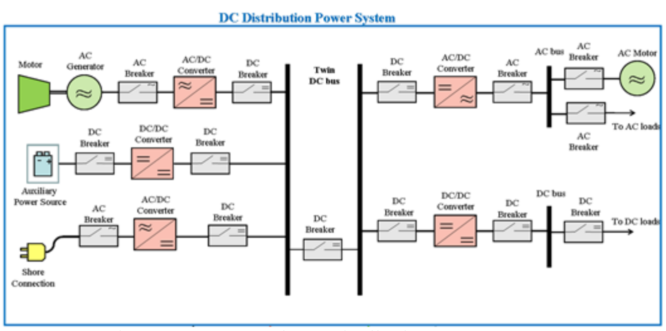

Figure 1: Conceptual DC Distribution Power System

a. Power Generation

The marine generators form the heart of the ship's electrical design. That means that their careful selection is essential for a workable and economical system. When sizing, a marine generator cognisance must be given to the nature of the load. The generator often works on its own and is accordingly susceptible to large system load swings, loads causing distortion, the connection of motors and the connection of large heater elements for air conditioning systems.

1) Diesel Generators

A marine diesel generator consists of the diesel prime mover, the speed governor, the excitation system and the synchronous generator. The block diagram of a marine diesel generator can be found below in figure 2. This system has two closed-loop feedback control systems: a speed feedback control system and an excitation feedback control system. These two feedback loops, ensure that the synchronous generator will operate at a steady speed and generate power at a fixed electrical frequency and voltage. A detailed description of a diesel generator model can be found in [4].

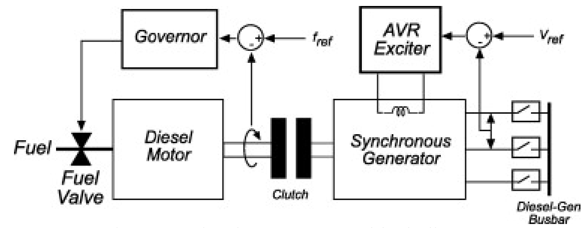

Figure 2: Diesel Generator Set block diagram

2) Fuel Cells

Fuel cell technology has recently been proven successful in naval projects and a lot of work has been performed on the specific topic [4]. Although the specific technology is not new, this success means that it has become relevant to discuss the potential for fuel cell technology in shipboard applications and the present status of the technology [7]. Thanks to the evolution of DC/DC power electronic converters the output voltage of the fuel cell can be regulated and elevated and as a result be connected to the DC Grid in case of operational needs or emergency [6], [7].

The main advantages for developing maritime fuel cells as alternative DC generators, are reduction in fuel consumption and less local and global impacts of emissions to air from ships. Additional benefits include significant reduction of noise and vibration levels which is crucial for warships, and lower maintenance costs compared with traditional power generation methods.

b. DC Grid Implementation

The scheme used to implement the DC distribution network is the connection of two six-pulse SCR bridges in series. Twelve-pulse configuration consist two six-pulse rectifier groups fed either from two sets of three-phase transformers in parallel or from a three-winding transformer and phase shifted by 30 degrees; a common twelve pulse configuration is shown in figure 3 below. Moreover to maintain 12-pulse operation the two 6-pulse groups must operate with the same control angle and, therefore, the fundamental frequency currents on the AC side are in phase with one another [3]. The series current only contains harmonics of order 12n+-1. The harmonic currents of order 6n+-1, where n is odd, circulate between the two converter transformers but do not penetrate the AC network [12].

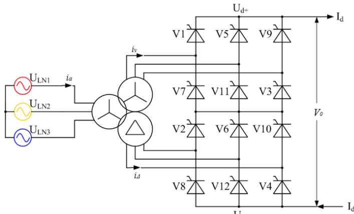

Figure 3: The twelve-pulse rectifier

On the DC side of the 12-pulse converter, 30 degrees of main frequency correspond to a half cycle of the sixth harmonic voltage and therefore, this harmonic will be in phase opposition in the two bridges. The 12th harmonic now, corresponds to one cycle, giving harmonics in phase.

The mean value of the output DC voltage, which is produced from the 12-pulse rectifier, is:

$$\overline{V_0} = \overline{V_{0Y}} + \overline{V_{0\Delta}} = \frac{3}{\pi}\int_{\alpha-\frac{\pi}{6}}^{\alpha+\frac{\pi}{6}} \sqrt{6}\widetilde{V}_1 \cos(\omega t)d(\omega t)$$

$$+\frac{3}{\pi}\int_{\alpha-\frac{\pi}{6}}^{\alpha+\frac{\pi}{6}} \sqrt{6}\widetilde{V}_1 \cos(\omega t)d(\omega t) = \frac{6\sqrt{6}}{\pi}\widetilde{V}_1\cos\alpha \quad (1)$$

The input AC current that is feeding the three-winding transformer is expressed in equation (2) below:

$$i_A = \left(\frac{N_2}{N_1}\right) i_Y + \left(\frac{N_3}{N_1}\right) i_\Delta = \frac{i_Y}{\boldsymbol{\alpha}} + \frac{\sqrt{3}}{\boldsymbol{\alpha}} i_\Delta. \quad (2)$$

According to Fourier Analysis, eq. 2 can be described as an infinite series sum by expanding the currents i_Y, i_Δ.

$$i_A = \frac{4\sqrt{3}}{\boldsymbol{a}\pi}\overline{I_0}\Bigg[\sin(\omega t - a) + \sum_{n=1}^{\infty}\frac{1}{12n-1}\sin[(12n-1)(\omega t - a)] + \sum_{n=1}^{\infty}\frac{1}{12n+1}\sin[(12n+1)(\omega t - a)]\Bigg] \quad (3)$$

As it was stated before, the harmonics of order 5, 7, 17, 19, etc. are cancelled due to the 30^o phase shift of the three-winding transformer. These harmonics flow with opposite phase in the transformer windings, cancelling, thus, each other and not flowing into the network.

The total harmonic distortion coefficient (THD) for the input current can be calculated from the following equation, where $\widetilde{I_a}$ is the total RMS value of the input current and $\widetilde{I_{a1}}$ is the RMS value of the fundamental (1st) harmonic.

$$THD_{i_a} = \frac{\sqrt{\widetilde{I_a}^2 - \widetilde{I_{a1}}^2}}{\widetilde{I_{a,1}}} = 15.7\% \quad (4)$$

With the 12- pulse rectifier there is a major improvement of the THD factor, compared to the 33% that a 6-pulse rectifier would have. However, the harmonic distortion value of 15.7% is not acceptable for modern high-density electrical power systems. At present, as it was stated in the previous chapter, distortion in AC systems is 3% for single harmonics and 5% in total. In order to further reduce the THDi to a tolerable rate of about 5%, an AC filter with quality factor Q=50 was included before the three-winding transformer.

c. Low Pass Filter Design

As it was stated above for most applications Total Harmonic distortion should be less than 5% under normal operating conditions. In order to reduce the harmonic components on the AC and DC sides, a low pass LC filter must be placed in the output of the rectifier. Except from harmonic reduction the filter's role is to smoothen the DC waveform. That leads to a considerable decrease of the DC ripple; i.e. the undesired residual periodic variation of a direct current that in most cases is connected from an AC source with the use of a rectifier. Theoretically, the ripple of the DC voltage produced by a twelve-pulse rectifier can be calculated from equation 10 [6], assuming that the voltage at the two ends of the capacitor is pure DC without any ripple:

$$v_{ripple}(t) = \frac{1}{C_d}\int i_c dt = -\frac{I_d \sin 2\omega t}{2\omega C_d}$$

where C_d is the filter capacitance and i_c is the instantaneous current flowing through it. It is easily deduced the ripple can be additionally reduced via a large capacitance C_d.

d. DC/DC Converters

In order to relegate the MVDC bus voltage to a lower level (LVDC Bus) or elevate the produced voltage from the fuel cells DC/DC power electronic converters can be used. The Low Voltage DC Bus is implemented via a DC/DC step-down converter. This buck converter, relegates the MVDC voltage to a lower level. The equivalent circuit consists of a gate controlled power electronic switch (e.g. IGBT, IGCT), power diodes and LC components. Accordingly, the process to elevate and regulate the voltage produced from the fuel cell a step-up or boost converter is used. The boost converter's equivalent circuit consists of the same elements but the topology is different. Schematic diagrams of the two types of converters are provided in figure 4.

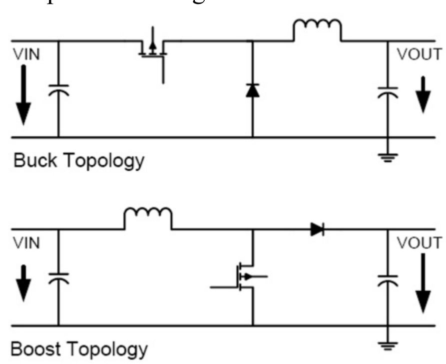

Figure 4 : Buck and Boost Converter Topologies

IV. SIMULATION AND RESULTS

An Integrated Power System, containing the elements presented in the chapter above was modeled and simulated. The system consists of 4 sets of diesel generators, a MVDC 5.5kV bus, a LVDC 1kV bus implemented with the use of a step-down converter and an independent fuel cell module that its output voltage is elevated to 1kV with a boost converter. Both LVDC grid voltage and the fuel cell voltage are regulated with PID tuners. The parameters of the diesel generator set and of the fuel cell stack are provided in table 2 below. The ode23tb discrete solver was used with fixed time step of 1μs. The use of a rather small time step is very important for such simulations because transients and impulses must be depicted clearly.

TABLE II. MARINE DIESEL GENERATOR AND FUEL CELL PARAMETERS

Diesel Generator Parameters	***Value***
Nominal Power, L-L Voltage frequency and poles	2.1 MVA , 450V, 60Hz , 10
Reactances (Xd Xd' Xd'' Xq Xq''Xl)	1.227, 0.157, 0.135, 0.443, 0.213, 0.14
Time Constants(Td0 Td0'' Tq'')	0.40, 0.036, 0.0213
Resistance (Rs) and Inertia	0.102, 0.062
Fuel Cell Parameters	***Value***
Voltage at 0A and 1A	900V, 895V
Nominal Operating Point	80A, 625V
Maximum Operating Point	280A, 430V

The MVDC bus feeds (a) the buck converter (b) the propulsion load which is simulated as a DC Load. The propulsion load is the largest power user in the simulated system. The purpose of the simulation is to evaluate the extent of harmonic distortion at both AC and DC sides.

TABLE III. GRID HARMONIC DISTORTION UNDER VARIOUS OPERATIONAL SCENARIOS

% Total Harmonic Components	**Event Type**		
	Normal Operation	***3-phase AC Fault***	***Sudden Load Change on MVDC Bus***
AC Voltage	4.68%	18.11%	7.72%
AC Current	4.12%	26.09%	8.87%
MVDC Voltage (relative to DC component)	1.36%	10.48%	1.38%
LVDC Voltage (relative to DC component)	1.14%	13.9%	1.79%

Three different scenarios have been employed. The first is the evaluation of harmonics during normal operation, the second is under a three-phase fault on the AC side with Δτ=100ms and the third is during a sudden change at the propulsion load. The results can be found in table 3 above. Also a Fourier analysis of the AC Current and MVDC voltage waveforms is provided in figure 6 below. As it can be deduced from table 4, the major problem with harmonics presents in the case of the AC fault. The percentage of harmonic presence is very high and is a lot higher from the limits that the regulations define. In the case of a sudden load change the harmonic percentage is also higher that the defined limits but at considerably lower value than in the case of the three-phase fault.

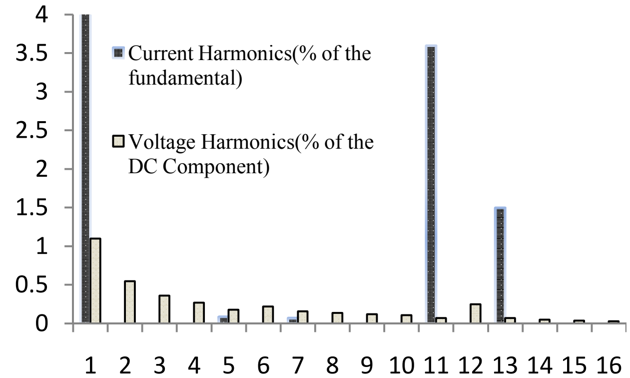

Figure 5 : Fourier Analysis of AC Current and MVDC Voltage

The grid operation waveforms during the three types of events are in figure 6 below.

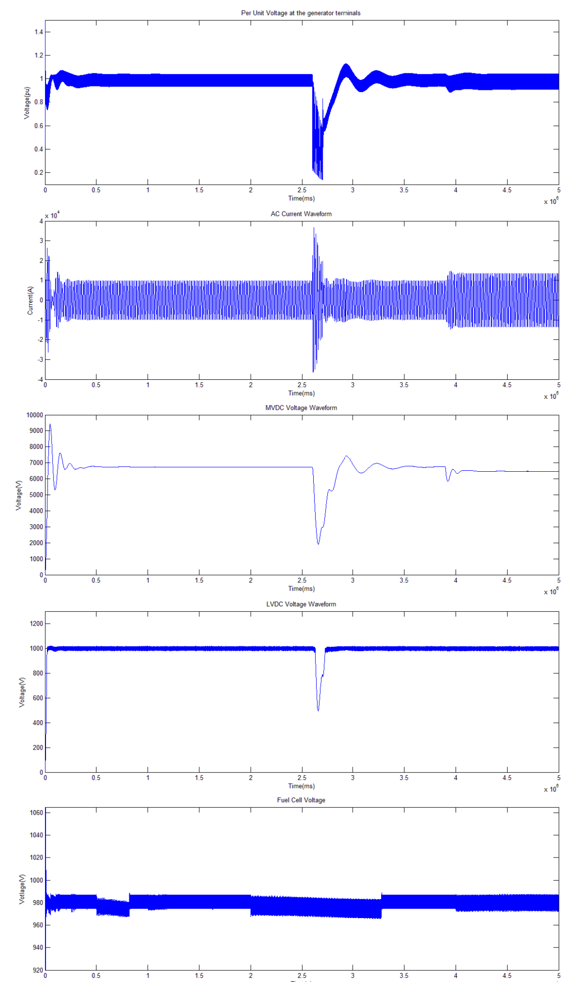

Figure 6 : System Operation Waveforms

V. CONCLUSIONS AND FUTURE WORK

The aim of this paper has been the investigation of power quality phenomena in an Integrated Power System of a ship with DC power distribution. Both commercial and military standards for shipboard power quality are presented and some remarks regarding MVDC distribution are exhibited. Also, a model of an IPS with DC Distribution is presented and each component of the grid is separately discussed. Finally, the model is simulated via Matlab/Simulink software and a power quality assessment is performed regarding three different operational conditions. The simulation results are discussed in detail and the measurements and waveforms of the grid's operation are cited.

Future work includes further deepening on All-Electric Ship power quality and stability issues, investigation of new techniques for MVDC grid optimal operation, investigation of the impact of integrating DC technology upon the ship efficiency, and examination of the operation, maintenance and procurement costs of vessels with DC power distribution.

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