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Impact of electric propulsion on the electric power quality of vessels

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ABSTRACT

Large-sized watercrafts, for commercial or military purposes, use electrical power systems, which are isolated and autonomous. Maritime technology has begun to replace mechanical propulsion by electric propulsion. As the consequence of using electric propulsion, there is a significant increase of non-linear loads in the system, due to use variable frequency drives to feed the motor, so the study of power quality has become necessary. The non-linear loads generate harmonics that may be inconvenient for energy supply and devices of the ship. This study aims to evaluate the power quality in standard watercrafts and to analyze the feasibility of the recommended changes. It is used a simulation based on real watercraft data to apply regulating norms to the electrical network of the system.

1. Introduction

The use of power electronic devices on ships and offshore installations has increased significantly in the last few decades [1] and discussions about problems of power quality are highlighted in recent publications as Mindykowski and Tarasiuk [2] and Tarasiuk [3]. Electric propulsion has been gaining more space in naval applications, due to its simple and efficient speed control through frequency converters (drives), as well as a reduction in the fuel consumption, number of crew members, pollutants emissions, and maintenance costs. Drives or frequency converters are used commonly in vessels as pointed in Schoyen and Sow [4]. Because the control and the engine can be in different places, it offers greater design flexibility, which, along with the absence of reducing gears, increases the ship's lifetime [5]. The introduction of electric motors in the vessel's main propulsion system changes the characteristics of its electrical grid. This philosophy introduces the so-called "Electric Ships" [6].

A ship's electrical system consists of generation, transmission, and distribution energy, as well as its consumers [6]. On a ship, the main switchboard is the central node of the electrical system, and it is the location of the main protections, bus bars, measurements, and controls. In certain sections of the ship, consumers can be fed directly from the main switchboard or from auxiliary buses.

In "Electric Ships," the electric propulsion system clearly is the greatest load connected to the power grid; thus, its behavior will impact the distribution system. Harmonic currents, generated by frequency converters, will influence the grid, causing voltage distortion. When the voltage distortion interacts with other equipment that is connected on the grid, an unwanted disturbance may occur [7]. Thus, when considering electricity as the propulsion system for ships, it becomes necessary to evaluate the power quality (PQ). This need is greatest for vessels that have their own characteristics and that behave as isolated systems.

According to Moya et al. [8], the voltage or current distortion phenomenon related to harmonic components inconveniences energy suppliers and consumers. This is recent phenomenon since the sources are electronic equipment, such as compact fluorescent lamps, motor speed controllers, rectifiers, and uninterrupted power sources. This atypical load is known as a nonlinear load, and it can deform the sine waveform, adding harmonic frequencies over the electrical distribution network and impacting directly the energy efficiency on the ship due the distortion power. The energy efficiency is one of the main themes discussed in vessels projects but more focused in fuel, engine efficiency and environmental aspects [9–11]. A common parameter used to quantify this is the Total Harmonic Distortion (THD), whose monitoring is an important measure for the preservation of PQ and the operation of the electrical system.

A definition of PQ is described in IEEE 1159-2009 [12]: the term power quality refers to a wide range of electromagnetic phenomena that characterize the voltage and current in a time and location determined in the electric system. According to this definition, the PQ is not just a group of technical parameters, but the result of the interaction of different elements. In this context, the PQ on a ship can be described by the set of parameters involving the processes of

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generation, distribution, and use of the electrical energy in each of the ship's operating states (i.e., anchored, maneuvering, or cruise), as well as its impact on the operation and safety of the ship as a whole. Other studies relating to vessel energy systems, electric motor starting systems, applied engine types, or the direct/indirect analysis of the effects of disturbances in these systems are described in Refs. [13–21].

The primary standards should be those regarding the assessment of the electric power quality in land industrial networks, as they are state of the art in matters here discussed. These standards are the basis of the standards addressing energy quality in shipboard power systems. Some similarities and commonalities between the rules pertaining to land and maritime systems are quite clear, as noted in Refs. [12,22–25], when one assumes that the power quality standard focuses on two main aspects: (i) defining technical benchmarks and their permissible limits and (ii) determining methods for taking their measurements. In addition, some rules from vessel classification societies, as in Refs. [26–29], are a result of the rules previously mentioned.

In this paper, we will discuss a study by simulation, based on the actual data from a large vessel that represents a power system. The main contributions of the paper are related to this non-conventional application and the tutorial characteristic of the proposed study. Section 2 of the paper presents the methodology, a discussion of ways to approach the proposed problem, and an explanation of how these methods were applied in the study. With ATPDraw software support, a simulation of the ship's power grid was carried out, in order to verify PQ disturbances, particularly THD, and determine implications for the components of the electrical grid of a ship. Section 3 discusses the results, evaluates the data collected, compares it with the simulations, and suggests improvements to be adopted in the design and board procedures. Finally, Section 4 presents the conclusion of this study.

2. Methodology

Starting with the ship's electrical equipment data, the on-board electrical grid simulation was executed using ATPDraw as a graphical interface for inputting the equipment models. To validate the study, the simulations will be performed considering only the initial fundamental operation frequency, in order to determine if the simulated values are in accordance with the nominal values. The second step will be to insert the nonlinear loads and the model of the induction electric motor drive of the ship's propulsion system, in order to evaluate the PQ indices and to determine the viability of using electric propulsion, based on the adopted assumptions.

The study of harmonics requires knowledge of the harmonic currents that are generated by nonlinear loads. There are three ways to determine these currents:

- Measure the harmonics generated by each source;
- Calculate the harmonics generated by using a mathematical analysis whenever possible, as in converters or static compensators; or
- Use typical values based on similar applications or published data [30].

The first method was not possible, because the electric propulsion had not been implemented in the vessel, this is a simulation to evaluate the possibility this implementation.

The second method it is not always possible, besides, in some cases the modeling is very difficult and it is not the purpose of this work. For these reasons added to the diverse literature available on variable frequency drive, the third method was chosen for this simulation.

The typical values gathered in the literature [30,31] were used to represent the harmonic currents generated by the different nonlinear loads present in the system. These nonlinear loads were modeled by injecting current at the respective frequency at the point where the load is connected, as described in Dungan et al. [32].

2.1. Modeling the ship's electrical components in ATPDraw

The following models, contained in the ATPDraw files and described in Prikler and Høidalen [33], were used for the simulated components. The complete ATPDraw diagram of the modeled system is presented in three parts due to large size in Appendix A figures (Figs. A1–A3).

For the generators, a model of a "sub-transitory voltage source" was used in series with the respective "sub-transitory reactance." For the source, an "AC source" model was configured to provide a voltage of 13.8 kV to the high-voltage bus and 440 V to the low-voltage bus. For a representation of the sub-transitory reactance, the "RLC-3ph" model was used. The generator model can be seen in Fig. A1.

The cables that connect the generation to the loads were modeled by the equivalent resistance and reactance of the model "RLC-3ph", which can be seen in Fig. A1. The data was obtained in Prysmian [34]. It is worth mentioning that, in this example, the values of the cable impedance are much smaller than those of the transformer's impedance.

Linear loads that do not generate harmonics were introduced using the "RLC-3ph" model in Figs. A2 and A3, as were the linear parts of the nonlinear loads, modeled by their equivalent resistance and reactance. The higher order harmonic components were introduced through several "AC source" models, which were configured to provide current in each of the harmonic frequencies generated in the rectifier, as seen in Figs. A2 and A3.

In order to verify the behavior of the voltage and current at certain points of the system, the "Probe Volt" and "Probe Current" in Figs. A1–A3 were inserted, respectively.

The frequency converters, powered by transformer dephasers of 13.8/3.3 kV, which are responsible for feeding the propulsion engines with 11 MW in each axis line, were modeled so that their influence on the electric grid's voltages and currents could be verified. To this end, we considered the values found in Ref. [35] and the effects of the harmonic currents, which were injected at the connection point as seen in Figs. A2 and A3. The harmonic currents were generated by the topology rectifiers in models used by drive manufacturers applied in the electric propulsion of ships [36].

The ATPDraw is employed in this study, due to its wide use in transitional studies and in the behavior of electric power systems, as shown in the research presented in Refs. [37–41].

2.2. Simulation of PQ

The first simulation held in ATPDraw (Setup 1) represents a commonly applied system on ships with combustion engines, which means that the nonlinear loads are composed only of small groups of rectifiers responsible for feeding a specific set of equipment. Fig. 1 illustrates the configuration of the electrical plant of the ship in such a condition. Note that in this conventional configuration the entire system is at low voltage (440 V in the simulation).

Observing the behavior of the ship's electrical grid with regard to PQ, the electric propulsion system, consisting of two induction electric motors, was inserted into the simulation. Each motor provides power to its axis line, as shown in Fig. 2.

It should be noted that the operation profile evaluated in the simulation is the vessel at its maximum speed; in other words, the electric motors are in full throttle. This represents virtually the