IMPROVING SHIP EFFICIENCY BY TREATING ELECTRIC POWER QUALITY IN SHIP GRIDS: THE "DEFKALION-THALIS" AND "DC-SHIP" PROJECTS

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ABSTRACT

This paper provides an overview of the research efforts in progress to investigate the performance of the ship electric grids at the early design stage as well as during operation. This is of particular interest, nowadays, that the discussions on ship performance in terms of efficiency and emissions are sufficiently mature, while the holistic approach of improving ship efficiency indices has started including the ship electric energy systems. To this end, the way that "MARINELIVE" project is aligned with other projects namely "DEFKALION-THALIS", "DC-Ship" and "Ship Electric Power System Audit" is discussed.

KEYWORDS

Ship electric grids, power quality, ship performance

1. INTRODUCTION

Electric power plant onboard has always been a rather complicated power system, comprising AC and DC subsystems of several operating voltage and frequency levels, especially in sophisticated structures with electric propulsion. The aforementioned complicacy is worsened even further with today's trend to extend electrification of shipboard installations, often towards the All Electric Ship concept. On the other hand, similarly to continental grids, several steady- and transient-state phenomena emerge, especially concerning power quality issues, and their consequences have to be thoroughly studied, analyzed and investigated.

The trend of further electrification of shipboard installation is closely related to the stricter emissions regulations and fuel economy standards that apply today, due to the environmental pollution caused by ships, worldwide concern about air quality, greenhouse gas emissions and oil supplies. Annex VI of the MARPOL Convention, adopted by the International Maritime Organization (IMO) in 1997, sets regulations for the prevention of air pollution by ships [1]. Specifically, MARPOL Annex VI sets limits on sulphur oxide (Sox) and nitrogen oxides (NOx) emissions from ship exhaust gases.

The above conditions create the need for:

- the shipbuilding industry to continue optimizing traditional ship types with the goals of increased safety and environmental protection
- existing vessels to become more energy efficient, in order to be competitive for the remaining of their life cycle.

These trends for more efficient ships have been the incentive for an investigation of turning all energy subsystems aboard (including power generation units) into more efficient ones [2]. This policy involving green power technology in many cases is summarized in “take the best out of each unit but having resolved any technical problems emerged”. In a sense, there are several common points with the evolution of the “smart-grid” concept [3-4] of continental grids, and hence, the related experience can be exploited in ships too.

The “MARINELIVE” project, aiming at establishing NTUA as a Centre of Excellence in the scientific domain of All Electric Ship, has enhanced the research capacity of the School of Naval Architecture and Marine Engineering of the National Technical University of Athens (S-NAME/NTUA) in terms of software/hardware and human resources. This has enabled research dedicated to analyzing the ship electric grid performance from the holistic point of view introduced by the ship efficiency restrictions established by the International Maritime Organization (IMO). Thus, more research projects focusing on ship performance form the electric energy system point of view have been approved and launched recently. This paper presents an overview of this research in progress.

2. SHIP ELECTRIC GRID STUDIES

The electric power grid of a ship can be regarded as a small scale autonomous, industrial type compact power system, although several differences between a continental grid and a shipboard installation can be identified. Some of the special features of ship installations are:

- The power system is completely autonomous.
- The total power installed per volume unit is large, especially in the electric propulsion applications.
- Electric energy is often generated by Diesel generator sets, or by shaft generators which are coupled to the main propulsion engine. Often, the fuel used is the (less costly) Heavy Fuel Oil.
- Referring to prime movers, their relative rotational inertia with respect to electric load demand is fairly small.
- The largest amount of energy is demanded by electric motors (acting either as main propulsion or as drivers of auxiliary engines).
- The electric power grid is composed of cables of small length (50m – 1000m).
- Adopting insulated neutral, i.e. ‘unearthed’ or “IT” system is a common practice.
- The metal ship hull is used as a means to provide “ideal earth” for Protective Earthing (PE).
- A considerable number of electronic devices installed onboard (automation systems, controllers, navigation systems) are sensitive to power quality and EMI problems provoked, in particular, by the extensive use of power electronics. Hence, the power quality problems are of extreme importance, and have to be analyzed thoroughly.
- Power Quality (PQ) problems onboard are of different significance, in comparison to the corresponding problems that occur in a continental power grid. In land, power quality problems may result in problematic production processes, while they may also affect the pricing relations (tariffs applied and penalties) between the utility and its clients. The latter is meaningless onboard, where the most important issue is the uninterruptible operation of the system, and its redundancy. A possible malfunction in a critical load may lead to a total loss of the whole vessel, resulting in possible human casualties and heavy environmental pollution.

2.1 TYPES OF STUDIES - SOFTWARE

Considering the particular characteristics of the configuration and operation of ship electric grids, especially those with electric propulsion, a joint effort between NTUA and PROTASIS SA has been made to identify those studies that need to be performed during the design stage, which are:

- Electric load balance
- Generator selection
- Load flow
- Parametric machine design
- Load sharing

- Stability
- Short circuit and protection coordination
- Contingency analysis
- Power Quality: harmonics, electromagnetic transients

To perform these studies, a number of specialized software tools, which are available either for research (S-NAME/NTUA) or commercial applications (PROTASIS SA) can be exploited:

- PSCAD Pro/Educational (of Manitoba HVDC Center): exploited mainly for Power Quality event studies.
- FLUX2D/3D (of CEDRAT/France): exploited mainly for parametric electric machine design.
- MOTORCAD (of Motor Design Ltd/UK, CEDRAT/France): exploited for thermal analyses of electric machines.
- MATLAB (of Mathworks/USA): generic multi-purpose tool.
- ASPEN (of AspenTech/USA): exploited for load-flow, short circuit and protection coordination studies.
- PSS/E (of Siemens-PTI/Germany): exploited for load flow, short circuit, stability studies.
- EMTP-RV (of CYME/Canada-USA): exploited for electromagnetic transients studies.
- CYME (of CYME/Canada-USA): exploited for harmonic analysis, stability studies.

Within the frame discussed, a schedule for an audit of a ship electric power plant is under development as described next.

2.2 SHIP ELECTRIC POWER SYSTEM AUDIT

As already mentioned, as new stricter emissions regulations and fuel economy standards apply for the maritime industry, there is an increased need for more efficient electric power systems onboard. Besides, the extensive electrification of ship systems, including propulsion, has become a most appealing alternative as -as a rule of thumb- the more electrified a ship, the greener and more efficient it turns.

The concept of an “Electric Power System Audit” is that starting from the single-line diagram of the ship electric grid, we proceed to

- Series of simulation analyses (load flows, load sharing, short-circuit and protection coordination study, contingency analysis, stability analysis, etc.)
- Series of measurements in key-points of the network identifying high energy losses, power quality issues, etc. (in order to conduct measurements, PROTASIS SA has a number of Power Quality Analyzers by DRANETZ).

From the measurements and analysis of the ship electric power system stems an evaluation of the system performance and recommendations for various system aspects such as equipment rating, protection relay settings, controller settings, electric power quality, system operation, cost minimization, etc.

3. STUDY VIA EMULATIONS – LAB EXPERIMENTS

In the framework of the EU project “MARINELIVE”, a ship electric power system emulator has been developed at S-NAME/NTUA. The design of this prototype ship grid emulator has been performed by the NTUA team along with PROTASIS SA which commissioned the complete final system. The system is an AC three-phase one, comprising Generation, Distribution, Consumption, Protection and Supervising Monitoring-Control sub-systems.

3.1 GENERAL ARCHITECTURE

A simplified one-line diagram of the system is shown in Fig. 1, in which dashed lines indicate installations planned for the future. The power generation sub-system comprises three synchronous generators (two of 6.5 kVA/400V/50Hz/pf=0.8 ind. and one of 5 kVA/400V/50Hz/pf=0.8 ind.). The installation of some other power sources via a DC/AC inverter (e.g. a fuel cell) is foreseen to be integrated in the future, especially considering that a fuel cell unit has also been purchased (NEXA K00-792 complete model with incorporated DC load and monitoring system purchased by “Heliocentris EnergieSysteme GmbH” – Germany). Note that as the generators are of low power, they produce Low Voltage (400 V), so no transformers are used in the system.

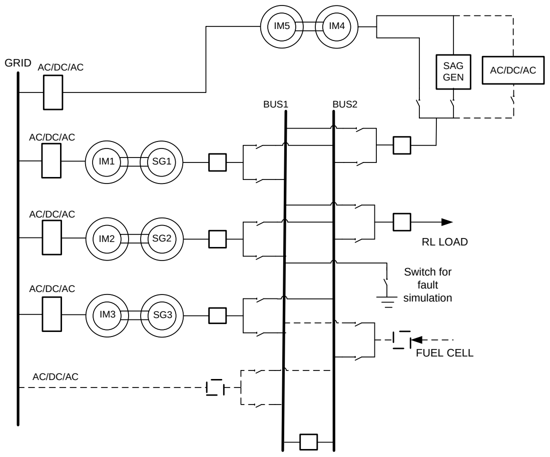

Figure 1. One-line diagram of grid emulator.

An induction motor fed by the local grid via an AC/DC/AC converter plays the role of the prime mover for each generator, while the fuel injection rule is emulated via the power electronic inverter rotating the prime mover - electric motor. On the other hand, the generator output voltage is regulated via installed Automatic Voltage Regulators (AVR's) of BASLER. It is noted that the system is essentially *electrically isolated* with respect to the local grid, with the exception of auxiliary circuits (e.g. the AVR's of the synchronous generators and protection relays).

The system loads are a passive RL load and a three-phase induction motor (see Figure 1). Similarly to the synchronous generators (but with opposite power flow), the mechanical load of the motor is another induction motor connected to an AC/DC/AC converter and acting as a regenerative brake. The ensemble of the motor and AC/DC/AC converter can be used to simulate various mechanical loads, e.g. a propeller.

To create contingencies to the system, a power circuit breaker has been installed to emulate three-phase faults, as well as a Power Quality event generator. The Power Quality event generator has been purchased from Power Standards Laboratory - PSL (USA). It is a complete unit **IPC-480V/200A**, which is connected in series to the grid and can be programmed/controlled via a PC-based software so that well pre-defined power quality events (e.g. voltage sags of prescribed duration and amplitude) are provoked to the network.

The installation of an AC/DC/AC converter, which will be optionally used to feed the induction motor load of the system, is foreseen in the near future. In this way, it will also be possible to emulate motor loadings e.g. the electric propulsion by uploading the propeller dynamics (look-up tables of torque vs time) to the regenerative brake controller.

3.2 ELECTRIC POWER MANAGEMENT AND CONTROL SYSTEM (EPMACS)

For control and monitoring of the system, there is an Electric Power Management And Control System (EPMACS), which is consolidated with the system protection relays. The protection scheme installed comprises sophisticated SEL-relays and other associated equipment. It includes generator, feeder and motor protection relays, as well as a bus differential protection scheme. Apart from their protection functions, the digital protection relays used offer possibilities for telemetering and remote control.

Using the IEC-61580 protocol, all available measurements are collected to a Supervisory Control And Data Acquisition (SCADA) System. The data network, on which the SCADA application is based, includes the digital protection relays, the central Managed Ethernet Switch (ETHSW), a Real Time Automation Controller (RTAC) and the central system computer, which is also the SCADA Server (see Fig. 2).

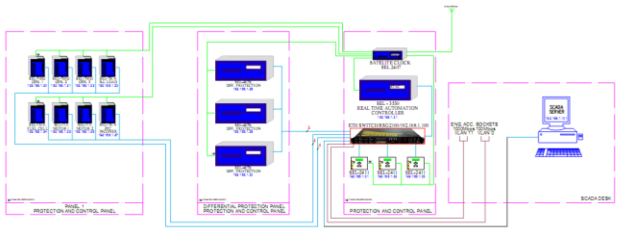

Figure 2. Data network architecture.

As shown in Fig. 2, all the relays and other devices are connected radially to the ETHSW via an Ethernet network (100Mbps - UTP Cat6). The data network functions are:

- Telemetering and remote control data collection, IEC-61850.MMS protocol
- Exchange of data between the relays and between the relays and RTAC, IEC61850.Goose protocol
- Data for relay configuration event recording, TELNET & FTP protocol.

The data network includes a GPS clock which distributes the time signal to all the devices of the data network by means of the IRIG-B00x protocol.

By means of the Human-Machine Interface (HMI) of the SCADA system (realized with specialized commercial software), various capabilities are provided:

- Close/Trip circuit breakers
- Close/Trip disconnectors
- Automated commands

- Increase/Decrease Step on Inverters (e.g. frequency control, active power sharing)

4. EXPLOITATION IN RESEARCH PROJECTS

A major way to exploit the tools and facilities mentioned above is research of S-NAME/NTUA. Two new research projects are briefly presented in this Section.

4.1 THE “DEFKALION” PROJECT

The “DEFKALION” project focuses in the thorough investigation of electric Power Quality (PQ) issues occurring in ship systems, and in working out solutions from the energy saving and environmental friendliness point of view. To this end, an inter-disciplinary research plan is proposed, involving the scientific fields of marine engineering, naval architecture, energy systems optimization, and electric power engineering. This is accomplished via the inter-university and inter-departmental cooperation of researchers in the project.

The main general goals of the “DEFKALION” project are:

- Establish a Centre of Excellence in PQ issues of ship electric energy systems
- In-depth interdisciplinary investigation of complex Power Quality problems that influence ship operation, in the light of intense electrification of all ship systems.
- Propose solutions for PQ problems, in the light of energy saving and environmental issues.
- Design and implementation of a monitoring system for analysis and indentification of PQ problems in naval power systems within the framework of improved energy efficiency and by the integration of this system with the existing on-board power management tools (Power Management Systems – PMS or Electric Power Management and Control System – EPMACS)
- Improve the quality of the education provided by Universities, considering the needs of the modern job market for Naval Architecture and Marine Engineering, especially Marine Electrical Engineering, as well as the recent developments and requirements in energy efficiency.

Specific targets of the project are:

- Study of the optimum shaft generator configuration/exploitation, considering fuel cost, fuel consumption, emission rates, optimum performance, production and operation cost.
- Study of mitigation practices for PQ problems due to thruster starting and operation.
- Study of mitigation practices for PQ problems due to pod operation, especially during maneuvering.
- Study of PQ problems due to ship grounding practices.
- Study of PQ problems due to lighting strikes directly on or nearby ships.
- By combining the above items, study and analysis of PQ phenomena during the different types of ship operation (maneuvering, mooring, disembarkation, etc.), as well as design of an integrated monitoring system for PQ.

4.2 DIRECT CURRENT IN SHIP INITIATIVE (“DC-SHIP” PROJECT)

The widespread electrification of ship systems introduces novel concepts, with a favourable one being the introduction of Direct Current (DC) aboard, especially in the power distribution subsystem. It is noted that research on the introduction of DC has recently been initiated in USA, but with a heavy focus on military vessels. With the exception of a few specific ship types, research dedicated to commercial ships has hardly begun, while commercial shipping is the backbone of surface transportation throughout the Globe and of particular interest for the Hellenic National Economy.

The “DC-Ship” project, comprising 8 work-packages, aims at investigating important design and operation aspects of DC power systems, via theoretical analyses, simulations and experiments. Furthermore, the behaviour of DC systems will be compared to that of AC ones, via tests of actual grid emulators (using the existing AC one presented above, as well as a DC one, which is to be procured in the course of “DC-Ship”). Moreover, the impact of DC on fuel economy and emissions reduction will be assessed. Finally, Life Cycle Cost analysis for a DC-operated ship will be performed. The conclusions drawn will be formulated in a way, that can be integrated into the Ship Energy Efficiency Management Plan (SEEMP) set by IMO.

Key targets of the DC-Ship research project are:

- Investigate the impact of integrating DC energy systems aboard on the total ship efficiency

- Investigate extensively the operational issues associated with DC networks installed in ships.
- Provide qualitative and quantitative analysis of the advantages and disadvantages of different grid configurations, considering the relevant technical and economic aspects.
- Exploit the project results for the benefit of the commercial shipping sector.

5. CONCLUSIONS

This paper provides an overview of the research efforts performed at S-NAME/NTUA focused on investigating the performance of the ship electric grids at the design stage as well as during operation. This is of particular interest, nowadays, that the discussions on ship performance in terms of efficiency and emissions are sufficiently mature, considering the IMO directives. Thus, the way that "MARINELIVE" project is aligned with other projects namely "DEFKALION-THALIS", "DC-Ship" and "Ship Electric Power System Audit" is discussed.

6. ACKNOWLEDGMENTS

The authors wish to thank the European Commission and the Hellenic Government for funding significant part of their research via research projects "MARINELIVE" (EU-FP7 cotract No 264057), as well as "DEFKALION" ("THALIS"-ESPA framework funded by European and National Hellenic Resources) and "DC-Ship" ("ARISTEIA"-ESPA framework funded by European and National Hellenic Resources) .

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