INVESTIGATING THE PROTECTION OF SHIP ELECTRIC GRIDS AGAINST LIGHTNING STRIKES – THE DEFKALION-THALIS PROJECT

E. P. Nicolopoulou
National Technical University of Athens,
School of Electrical and Computer
Engineering, High Voltage Laboratory
9 Iroon Politechniou St., Zografou Campus,
GR 15780, Athens, Greece
hveleni@mail.ntua.gr

V. T. Kontargyri
National Technical University of Athens,
School of Electrical and Computer
Engineering, High Voltage Laboratory
9 Iroon Politechniou St., Zografou Campus,
GR 15780, Athens, Greece
vkont@power.ece.ntua.gr

I. F. Gonos
National Technical University of Athens,
School of Electrical and Computer
Engineering, High Voltage Laboratory
9 Iroon Politechniou St., Zografou Campus,
GR 15780, Athens, Greece
igonos@ieee.org

G. J. Tsekouras
Hellenic Naval Academy,
Department of Electrical Engineering and
Computer Science
Terma Hatzikiriakou
18539 Piraeus (Hatziakiakio), Greece
tsekouras_george_j@yahoo.gr

E. C. Pyrgioti
University of Patras
Department of Electrical and Computer
Engineering, High Voltage Laboratory
26500, Patras
e.pyrgioti@ece.upatras.gr

I. A. Stathopulos
National Technical University of Athens,
School of Electrical and Computer
Engineering, High Voltage Laboratory
9 Iroon Politechniou St., Zografou Campus,
GR 15780, Athens, Greece
stathop@power.ece.ntua.gr

J. M. Prousalidis
National Technical University of Athens,
School of Naval Architecture and Marine Engineering, Division of Marine Engineering
9 Iroon Politechniou St., Zografou Campus,
GR 15773, Athens, Greece
jprousal@naval.ntua.gr

ABSTRACT

"DEFKALION" aims at performing a thorough investigation and analysis of Power Quality (PQ) phenomena during the different types of ship operation, as well as at designing an integrated monitoring system for PQ. PQ problems appear due to shaft generator operation, thruster operation, electric part of the pod system (electric motor, converter for speed control) and protection system operation in short circuit conditions or lightning strikes. The ultimate goal is a greener, safer, more reliable and more economic electrified ship. The present article focuses on the parts of the "DEFKALION" project that deal with the lightning protection of ships. The future experimental work planned on scaled ship models and the necessary theoretical approach based on the methods of similarity theory and dimensional analysis are outlined.

KEYWORDS

Ship electric grids, All Electric Ship (AES), power quality problems, lightning strike.

1. INTRODUCTION

Electric power plant onboard has always been a rather complicated power system, comprising DC and AC subsystems of several operating voltage and frequency levels, especially in sophisticated structures with electric propulsion. The aforementioned complicacy is worsened even further in the All Electric Ship (AES) systems, referring to full electric propulsion and extended electrification of all shipboard installations. 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 environmental pollution.

2. THE DEFKALION-THALIS PROJECT

Specific targets of the “DEFKALION” 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 lightning strikes directly 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.

2.1 PROTECTION SCHEMES AGAINST LIGHTNING

Formerly, it was conceived that due to the almost entirely metal nature of the ship hull, in case of a lightning strike, no problem could occur (e.g. induced overcurrents or overvoltage spikes). However, several problems (sparks, flashovers, induced currents to sensitive electronic equipment, failures, etc) have been recorded, pointing to the need for a more in-depth analysis.

The aforementioned problems appear due to the following reasons:

- The hull structure is not always made by homogeneous metal (steel). Actually, it appears several discontinuities either due to soldering or due to a complex structure combining steel and composite materials (plastic, fiberglass). Composite materials are used in order to reduce weight, corrosion problems, maintenance requirements, radar visibility. In such complex structures, the lightning strike can cause significant damage to the hull.
- In electrified ships, the main part of the installed equipment consists of electronic devices. A lightning strike in the hull (metallic or semi-metallic) has a direct effect on electronic equipment.

Damages can be caused due to induced overcurrents or overvoltages, even if lightning is not striking the ship directly. During a lightning strike (even if it occurs nearby the ship), various problems appear, such as:

- overvoltages that result in insulation damages.
- overcurrents that result in thermal stresses and damages on hull, cables, pipes, equipment etc.

Apart from the previous problems, induced overvoltages and overcurrents can cause:

- melting of the copper/aluminum wires in metallic ships due to overheating and possible subsequent fire or change in the strength characteristics of the steel.
- fire, melting and puncture in ships made by wood or composite materials.

2.2 WORK PROCESS

In order to study the aforementioned phenomena concerning the damages on ships due to lightning strikes, the researchers will follow the steps below:

✓ *Data collection*

Regulations and standards will be collected and investigated regarding lightning striking on ships and the safety risks for humans and vessels. Historic data on lightning, as well as data on the different types of lightning will be also collected.

✓ *Study of the interaction between lightning and the ship metal hull in the PQ framework*

For the solution of the electromagnetic problem, an equivalent network will be developed. The existing methodology for continental systems [1], [2], which analyzes the voltage distribution along and across the mesh of the "grounding" means will be used for this purpose. The same approach will be adopted for the analysis of a fault occurrence as described in the corresponding work-package of the project. For the case of the ship that will be studied in the course of "DEFKALION", the mesh of a ship's steel hull will be used, exploiting the experience in marine structure design of naval architects. Lightning is considered as an injected current containing a wide spectrum of frequencies. Therefore, the following must be determined:

- The minimum allowed size of the finite elements, which should be lower than the lightning wavelength.
- The validity of the approximations in the wave propagation equation, that are usually considered to reduce the complexity of the mathematical problem.
- It is also important to identify the points of discontinuity in the network (joints, changes in the material, etc), due to their impact on wave propagation.

Software suitable for electromagnetic analysis will be used for the analysis of this complex problem. A time-domain solver that will take into consideration the various material properties is necessary for the analysis under a transient excitation such as a lightning strike.

✓ *Test in a High Voltage Laboratory with a small scale ship model*

The aim of these tests is the experimental investigation of the development and striking of a lightning impulse on the external side of the ship or near it. These tests will be carried out in the accredited (according to EN ISO 17025:2005) High Voltage Laboratory of NTUA, using small scale metal ship models in a water tank.

3. THEORETICAL BACKGROUND FOR THE PREPARATION OF THE SCALE EXPERIMENTS

For over a hundred years engineers have used small-scale models of engineering structures to help provide information that will make their analysis or design more effective. The Similarity Theory is an applied scientific method employed in this experimental analysis. It allows the derivation of scale laws from the equations which describe a physical process without having to solve them [3]. It is based on the principle of physical similarity between model and prototype, which entails the condition that the equations for original and model differ only by a constant and demands geometrical similarity as a prerequisite.

Therefore, in order to derive the similarity between the model and the prototype, the dimensional analysis can be applied. By this method we must seek dimensionless products formed from the representative values of the quantities that appear in the equations that describe the problem. According to the Buckingham Pi Theorem [4], these dimensionless parameters must be identical between physical and scaled model so that results gained from experiments on scaled models can be converted to the original model.

The application of the Similarity Theory as a scientific method has a long tradition in some areas. In naval engineering, dimensional analysis has various applications in the hydrodynamic analysis of the propulsion process [4]. In the field of telecommunications, models of electromagnetic systems have been widely used for studies of wave radiation, scattering and transmission [5]. Model measurement has also proven to be a useful tool in studying the properties of radar targets and specifically for determining their RCS (radar cross section) [6].

Since experiments are being made in the area of lightning protection, the Similarity Theory can also be a valuable aid here in the conversion of test results from models to full scale [3], [7], [8], [9]. Scale laws for transient phenomena during lightning strikes allow, with proper application, the construction of experimental models where phenomena similar to those occurring in the original are reproduced. The results can then be recalculated, using the scale factor for the physical quantity into the original configuration. If the scale laws for some primary quantities such as length, current and time are known, a calculation of the scale factors for the remaining parameters and the measured quantities is possible.

A first attempt to introduce the Similarity Theory in the field of electrical engineering surge analysis was done by Korsuncev in 1958, who applied it to the calculation of surge characteristics of earth electrodes [10]. He described the impulse impedance in terms of two dimensionless arguments and published a collection of relevant data points with an experimentally determined curve.

In 1988 Oettle proposed a new general estimation curve which predicts the impulse impedance of concentrated earth electrodes as a further development of Korsuncev's experimental curve [11]. The characteristic dimension of an electrode was redefined to give a good resolution between two-dimensional and three-dimensional electrode geometries.

Chisholm and Janischewskyj further extended Korsuncev's model for the calculation of the low current footing resistance [12]. This new similarity model, based only on the surface area of the electrode, is matched to a previous model for a hemisphere but applies for a wide range of ground electrode shapes.

Various scaled experiments have been conducted for the simulation of lightning strikes on overhead transmission lines and lightning protection systems of buildings [3], [7], [8], [9].

Scaled model structures that simulate the lightning protection system of a building have been set up in the High Current Laboratory of the University of the Federal Armed Forces in Munich (UAFM) using a geometrical scale factor of 1:6 [7]. An injection rod was used in order to simulate the lightning channel and a quasi coaxial arrangement of return path rods assured the flow of the lightning current back to the impulse generator. The magnetic fields and the loop voltages caused by induction effects in installation loops were calculated and furthermore simulated with a computer model.

Recently, lightning-strike experiments with a scaled down ship model were conducted by Prof. Grzybowski at the High Voltage Laboratory of the Mississippi State University aiming at a comparison between the well established Rolling Sphere Method and a newly proposed Elliptical Model for the determination of the lightning protection zone created by a Franklin rod [13].

For the theoretical preparation of the scaled experiments in the framework of the "DEFKALION" project, the first step is a determination of the physical quantities that describe the problem. The application of the dimensional analysis as the next step will provide us the necessary scale factors for the selection of experimental parameters such as the dimensions of the ship model and of the water tank, the material properties of the ship model and of the water solution as well as the excitation parameters (lightning current or voltage amplitude).

4. EXPERIMENTAL SETUP

The experiment will be conducted on a scaled down metallic ship model placed in a water tank filled with saline water solution. The water tank will be of appropriate dimensions with metallic walls connected to the grounding system of the laboratory. A variation of the water salinity will enable measurements under different water conductivity values. An initial testing scheme consists of the following phases:

- Injection of lightning current on the scale model and recording of the voltage and current waveforms on specific critical points of interest in order to acquire some basic information about the current distribution on the surface of the model and the resulting overvoltages. The excitation will be produced by an impulse current generator (8/20 μs, up to 25 kA).
- The impulse voltage produced by an impulse voltage generator (1.2/50μs, 1800 kV, 18 kWs) will be imposed on a metallic setup that will simulate the generation of the lightning channel. The recording of the strike incidents and the lightning attachment positions followed by a statistical analysis and a probabilistic-quantitative distribution of current strikes on the ship surface will provide conclusions regarding possible onboard regions in danger.
- Investigation of the interaction induced from lightning currents or power fault currents between the steel hull of the ship and other onboard neighboring "electrodes" either made of steel (i.e. another adjacent metal part of the ship, electrically insulated from the part where the injected current flows) or made of copper/aluminum (cable/winding of the ship electrical installation).
- Investigation of the effect of nearby and not direct strikes aiming at a recording of the induced signals on the ship structure.

A general layout of the experimental setup is presented in Figure 1.

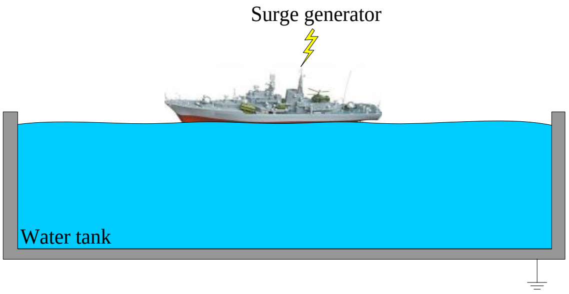

Figure 1. The experimental setup

5. FUTURE WORK

The basic aim of the experiments is to deduce the corresponding full-scale magnitudes from the scale-model measurements by applying the scale factors obtained from the dimensional analysis and draw conclusions about the behaviour of the ship's hull during a lightning strike. The experimental results will be compared to the simulations of the full-scale and the scaled down model carried out with the software, assessing thus the validity of the proposed scaling procedure.

The resulting overview of the vulnerable regions and the developed overvoltages and overcurrents - direct or induced - during a lightning strike will be followed by proposals for protection measures.

6. ACKNOWLEDGMENTS

European Union European Social Fund
OPERATIONAL PROGRAMME EDUCATION AND LIFELONG LEARNING investing in knowledge society
MINISTRY OF EDUCATION, LIFELONG LEARNING AND RELIGIOUS AFFAIRS
MANAGING AUTHORITY
NSRF 2007-2013 EUROPEAN SOCIAL FUND
Co- financed by Greece and the European Union

This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: THALES: Reinforcement of the interdisciplinary and/or inter-institutional research and innovation

7. REFERENCES

1. Meliopoulos A.P., Moharam M.G. 1983, "Transient Analysis of Grounding Systems", *IEEE Transactions on Power Apparatus and Systems, Vol. PAS-102, no 2,* pp. 389-399.
2. Meliopoulos A.P., Webb R.P., Joy E.B. 1981, "Analysis of Grounding Systems", IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, no 3, pp. 1039-1048.
3. Frentzel R. 1997, "Use of Similarity Relations in the Analysis of Lightning-Induced Transient Phenomena", European Transactions on Electric Power Engineering (ETEP), Vol. 7, no 3, pp. 173-177.
4. Politis G.K., Lamprinidis G.N. 1993, "Hydrodynamics of ship propulsion", 1st Edition, Astir Publications.
5. Shi Z., Ding C., Chen J. 1993, "Dimensional Analysis and Physical Similarity of Lossy Electromagnetic Systems", Chinese Physics Letters, Vol. 10, no 6, pp. 347-350.
6. Liu H., Shi Z., Wu Z., Antar Y.M.M. 1998, "A Novel Method of Radar Cross-Section Measurement for a Fully Coated Target Using a Scale Model of Varying Size", Microwave and Optical Technology Letters, Vol.19, no 1, pp. 57-59.
7. Metwally I.A., Heidler F.H., Zischank W.J. 2006, "Magnetic Fields and Loop Voltages Inside Reduced- and Full-Scale Structures Produced by Direct Lightning Strikes", IEEE Transactions on Electromagnetic Compatibility, Vol. 48, no 2, pp. 414-426.
8. Kern A., Heidler F., Seevers M., Zischank W., "Magnetic Fields and Induced Voltages in case of a Direct Strike – Comparison of Results obtained from Measurements at a Scaled Building to those of IEC 62305-4", Proceedings of the 27th International Conf. on Lightning Protection, 13-16 September 2004, Avignon, France, paper 3b1.
9. Zischank W., Heidler F., Kern A., Seevers M., Stimper K., Wiesinger J., "Magnetic Fields and Induced Voltages inside LPZ 1 measured at a 1:6 Scale Model Building", Proceedings of the 27th International Conf. on Lightning Protection, 13-16 September 2004 Avignon, France, paper 3b2.
10. Korsuncev A.V. 1958, "Application of the Theory of Similitude to the Calculation of Concentrated Earth Electrodes", Elektrichestvo, no 5, pp. 31-35.
11. Oettle E.E. 1988, "A New General Estimation Curve for Predicting the Impulse Impedance of Concentrated Earth Electrodes", IEEE Transactions on Power Delivery, Vol. 3, no 4, pp. 2020-2029.
12. Chisholm W.A., Janischewskyj W. 1989, "Lightning Surge Response of Ground Electrodes", IEEE Transactions on Power Delivery, Vol. 4, no 2, pp. 1329-1337.
13. Grzybowski S. 2007, "Experimental Evaluation of Lightning Protection Zone used on Ship", Proceedings of the 2nd IEEE Electric Ship Technologies Symposium (ESTS 2007), pp. 215-220.