



Investigation of lightning incidence on ships

E. P. Nicolopoulou, A. C. Alexandrou, M. F. Georgopoulos, D. E. Vatistas,
I. F. Gonos, I. A. Stathopoulos

High Voltage Laboratory, School of Electrical and Computer Engineering
National Technical University of Athens
Athens, Greece
hveleni@mail.ntua.gr

Abstract—In this paper calculations of lightning incidence on a bulk carrier ship model are presented with comparative application of various lightning attachment models and stroke current distributions. Depending on the ship structure, a lightning strike on coastal areas is expected approximately every two years. Regions exposed to lightning strikes were highlighted with application of the Rolling Sphere Method on the initial structure and after additional measures for the improvement of the external lightning protection system. Furthermore, impulse voltage experiments on a scaled down model of the above ship were conducted to assess the accuracy of lightning interception models. Lightning interception probability and proximity effects arise as factors that should be incorporated in shielding design.

Keywords—lightning incidence; shielding analysis; interception probability; ship electric grids

I. INTRODUCTION

A case of autonomous electric network with special required features such as uninterrupted power supply and continuity of vital navigation and communication services is that of a ship electric grid. Being the highest structures on the sea surface and often passing through regions with severe thunderstorms, ships are likely to be struck by a lightning [1]. Within the increased use of sensitive electronic systems due to their ongoing electrification and the enhanced coupling of lightning surges due to the small extent of their network, the possible impacts of a lightning strike on a ship can be severe, such as explosion of flammable loads or loss of operation of the telecommunication and control systems [2], [3]. External lightning protection is nevertheless required by most marine regulations only for cases of non-metallic ship masts [4]-[9].

In the present work a thorough investigation of lightning incidence phenomena on a full scale cargo ship has been conducted. The total number of expected lightning strikes on the ship has been calculated with the aid of a software package that incorporates the parameter of isoceraunic level and various lightning attachment formulas and stroke current distributions and the influence of these parameters is discussed.

Lightning strikes are not only presented as a total on the entire ship structure but they are also divided according to the type of structure they end on in an attempt to quantify the contribution of some major ship components to lightning interception and to detect which structures are mostly endangered. Furthermore, with application of the Rolling

Sphere Method, the regions exposed to specific lightning current values are highlighted before and after the addition of some extra protection measures. The actual interception procedure affected by additional parameters such as impulse polarity and statistical interception probability is then investigated through experiments on a scaled down metallic model of the above ship and the experimental results are compared to theoretical methods for the calculation of the interception radius and the striking distance.

II. LIGHTNING INCIDENCE CALCULATIONS

A. Electrogeometric Model Formulas

Calculation of the expected number of lightning strikes on a ship surface is indicative of the overall annual probability for a ship to undergo a lightning strike. The expected number of strikes intercepted by an air terminal is given by the following equation [10]:

$$N_d = 10^{-5} A_{eq} N_g T \quad (1)$$

Where T = the observation period, usually one year

N_g = the expected number of ground flashes/(km²·yr)

A_{eq} = the equivalent exposure area (m²)

The average ground flash density measured in strikes/km² per year is derived from the isoceraunic level (else called annual thunderdays T_d) according to (2) [11]:

$$N_g = 0.1 T_d \quad (2)$$

The equivalent exposure area is calculated from the equivalent attractive radius R_{eq} as shown in (3) [10]:

$$A_{eq} = \pi R_{eq}^2 \quad (3)$$

From (4) it is obvious that R_{eq} depends on the lightning current distribution $f(I)$ and on the lightning attachment model which describes the attractive radius (R) as a function of the lightning peak current (I) and the height (h) of the rod [10]:

$$R_{eq} = \sqrt{\int_0^{\infty} R^2(I, h) f(I) dI} \quad (4)$$

The lightning attachment models can belong either to the category of electrogeometric models or to the so called

generalized models. The electrogeometric (EGM) models are based on the concept that interception occurs when the downward leader is closer to the examined structure in comparison to the ground. They connect the striking distance to the object (S) to the lightning peak current and to the striking distance to the ground (D), with formulas in the general form of (5), producing an attractive radius (R) as in (6):

$$S = AI^B = cD \quad (5)$$

$$R = \begin{cases} \sqrt{S^2 - (D - h)^2}, & h < D \\ S, & h \geq D \end{cases} \quad (6)$$

The generalized models on the other hand, using various leader initiation criteria, establish the attractive radius (R) as the maximum distance from the air terminal, within which lightning interception is possible, expressed overall as:

$$R = \xi h^E I^F + \zeta h^G \quad (7)$$

Some of the most common lightning interception models are embedded in the WinIGS libraries [11]:

a) *Brown and Whitehead* [12]:

$$S = 7.1 \cdot I^{0.74} \quad (8)$$

b) *IEEE Working Group (1985)* [13]:

$$S = 8 \cdot I^{0.65} \quad (9)$$

c) *Eriksson* [14]:

$$R = 0.67h^{0.6}I^{0.74} \quad (10)$$

d) *Darveniza* [15]:

$$S_{50\%} = 9.4I^{2/3}, \sigma = 10\% \quad (11)$$

e) *Love* [16]:

$$S = 10 \cdot I^{0.65} \quad (12)$$

f) *Suzuki* [17]:

$$S = 3.3 \cdot I^{0.78} \quad (13)$$

g) *Rizk* [18]:

$$R = 1.5h^{0.45}I^{0.69} \quad (14)$$

Where : S = striking distance (to the object) (m)

I = the lightning peak current (kA)

h = the height of the examined structure (m)

A, B, E, F, G, c, ξ , ζ = constants

The following lightning current distributions are available in the WinIGS environment:

a) *Historical data from the EPRI (Electric Power Research Institute) Red Book* [19]

b) *Anderson's distribution* [20] (adopted by IEEE Std. 1243-1997): the cumulative probability distribution given in (8):

$$P(> I) = \frac{1}{1 + \left(\frac{I}{31}\right)^{2.6}} \quad (9)$$

which is approximately equivalent to a log-normal current distribution with mean value $\bar{I} = 30.1kA$ and standard deviation

$$\sigma_{ln} = 0.76kA.$$

c) *Mousa's distribution* [21] (adopted by IEEE Std.998, 1996): log-normal current distribution with mean value $\bar{I} = 24.0kA$ and standard deviation $\sigma_{ln} = 0.72kA$

B. Simulations with the WinIGS software

A full scale bulk carrier with length 190m and deadweight 50400t, with four cargo cranes, two accommodation and navigation compartments and two antenna masts included was designed in the WinIGS software environment and lightning shielding analysis was performed in order to acquire an overview of possible onboard regions in danger. The lightning shielding analysis algorithm enumerates the lightning strikes that begin from an area of the sky over the analysis system and terminate on the structures of interest. A region of the sky over the analysis system is discretized into a rectangular grid of points and each of these points is considered as a lightning origin. One of the lightning attachment models of (8)-(14) is used to determine the lightning striking points. The range of the lightning current was set to 3kA – 200kA as defined in IEC 62305-1 [22] for the strictest Lightning Protection Level I. For the isoceraunic level two typical values were chosen: 20 and 30. These chosen levels (N_g is 2 and 3 strikes/km² per year respectively according to (2)) are moderate values corresponding to open sea conditions and ground flash density e.g. as in the Mediterranean.

The evaluation of the total number of expected strikes was carried out with all possible combinations of the options provided by WinIGS for the striking distance formula and the probability distribution of the lightning crest in order to investigate the influence of these parameters. Parts of the structures lying on the deck surface with the same degree of importance or the same function are categorized to form a "Layer". Layer No.1 represents the deck surface, Layer No.2 contains the major superstructures lying above the deck surface, namely the accommodation and control/bridge compartments, Layer No.3 contains the cargo cranes and the bow navigation antenna, i.e. lower masts that can function as air terminals and Layer No.4 stands for the highest antenna mast on the bridge roof, which is critical equipment. The overall number of lightning strikes per year (N_d) expected on the whole ship surface is presented in Tables I and III, while the distribution of these strikes on each layer is shown in Tables II and IV (calculated for Anderson's distribution).

TABLE I. N_d ON ALL STRUCTURES (ISOCERAUNIC LEVEL 20)

Lightning attachment model	Lightning current distribution		
	EPRI Red Book	Anderson (IEEE)	Mousa (IEEE)
Brown & Whitehead	0.12133	0.12018	0.10451
IEEE (1985)	0.10037	0.09956	0.08848
Eriksson	0.08695	0.08658	0.07627
Darveniza	0.12128	0.11988	0.10443
Love	0.11801	0.11719	0.10373
Suzuki	0.07632	0.07541	0.06672
Rizk	0.08723	0.08672	0.07679

TABLE II. N_d ON LAYERS (ISOCERAUNIC LEVEL 20)

Layer No.	Lightning attachment model			
	Brown & Whitehead	Love	Eriksson	Rizk
	$N_d=0.12018$	$N_d=0.11719$	$N_d=0.08658$	$N_d=0.08672$
1	0.00139	0.00102	0.00008	0.00033
2	0.01047	0.01084	0.00022	0.00061
3	0.07325	0.07219	0.03648	0.04378
4	0.03508	0.03314	0.04980	0.04201

TABLE III. N_d ON ALL STRUCTURES (ISOCERAUNIC LEVEL 30)

Lightning attachment model	Lightning current distribution		
	EPRI Red Book	Anderson (IEEE)	Mousa (IEEE)
Brown & Whitehead	0.18199	0.18027	0.15677
IEEE (1985)	0.15055	0.14933	0.13272
Eriksson	0.13043	0.12987	0.11440
Darveniza	0.18193	0.17982	0.15665
Love	0.17702	0.17578	0.15560
Suzuki	0.11448	0.11312	0.10007
Rizk	0.13085	0.13009	0.11518

TABLE IV. N_d ON LAYERS (ISOCERAUNIC LEVEL 30)

Layer No.	Lightning attachment model			
	Brown & Whitehead	Love	Eriksson	Rizk
	$N_d=0.18027$	$N_d=0.17578$	$N_d=0.12987$	$N_d=0.13009$
1	0.00208	0.00152	0.00012	0.00050
2	0.01570	0.01626	0.00033	0.00091
3	0.10987	0.10829	0.05471	0.06567
4	0.05262	0.04971	0.07470	0.06301

From the above Tables I-IV it is concluded that the influence of the striking distance formula is much stronger than that of the lightning crest distribution. Brown & Whitehead, Darveniza and Love yield similar results. This is also observed between lightning strikes according to Rizk and Eriksson who consider for the calculation of the striking distance not only the lightning current but also the height of the protected structure. Suzuki's formula leads to the highest underestimation of the lightning strikes. Regarding the statistical distribution of the lightning waveform, the Historical Method (EPRI Red Book) and Anderson's distribution present great proximity, while selection of Mousa's distribution produces fewer strikes. In most cases the ratio of the maximum estimation of lightning strikes (usually selecting EPRI and Brown or Darveniza) over the minimum estimation (usually selecting Mousa and Suzuki or Rizk) reaches 1.8.

As expected, for a larger value of the isoceraunic level the total number of strikes increases linearly. Much higher N_g values between 8 and 10 (isoceraunic level 80 and 100, respectively), recorded near coastlines, will yield multiple N_d values (e.g. Love's EGM formula and Anderson's distribution

will lead to approximately 1.2 strikes on the ship every 2 years).

According to Eriksson's and Rizk's models N_d is almost entirely equally distributed between Layer No.3 and No.4. The EGM models attribute roughly a 10% of the total N_d to the superstructures of Layer No.2, while Layer No.3 attracts the highest percentage of strikes, around 60% of N_d . For all methods, the deck surface of Layer No.1 attracts the minimum N_d , which is in the order of 0.1% of the total N_d according to Eriksson's and Rizk's models but in the order of 1% according to the Love and Brown&Whitehead EGM models.

The next step was the application of the Rolling Sphere command which enables highlighting the regions of the ship model exposed to a specific value of lightning current. The points of the model (Figure 1) that come in touch with the sphere during its rolling over the examined region are shown in the following Figures 2-5 with red dots. Love's formula (12) which is adopted by IEC 62305-1 is chosen for the calculation of the sphere radius and the analysis is executed for lightning currents 3kA and 30kA.

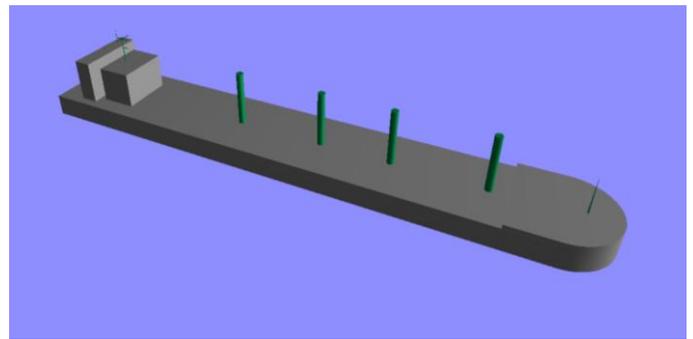


Figure 1. The full scale bulk carrier model

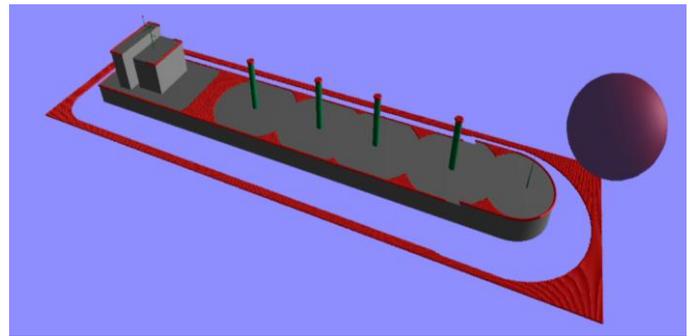


Figure 2. Rolling Sphere Method: initial application (Love's EGM, 3kA)

Taking into consideration that the sphere radius depends on the lightning current, the exposed area to a 3kA strike is greater. Both for 3kA and 30kA the highest antenna mast and the edge of the nearby and underlying accommodation compartments and navigation rooms where the electronic telecommunication equipment are located, are exposed to lightning strikes. Regions of the deck surface are directly exposed to the 3kA strike with possible danger posed on cargo holds or flammable content. These regions are almost eliminated in case of a 30kA strike. The mast of the navigation

antenna at the bow and the tops of the cargo cranes along the deck surface are also endangered.

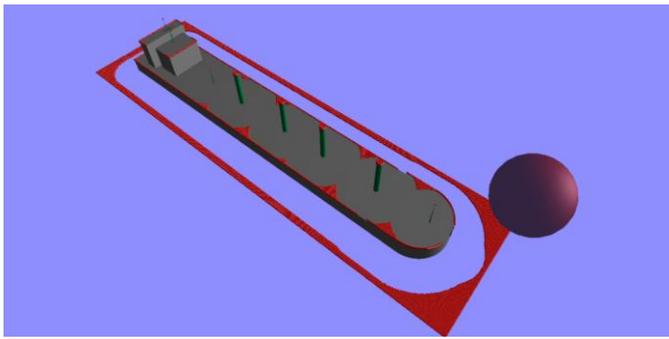


Figure 3. Rolling Sphere Method: after modifications (Love’s EGM, 3kA)

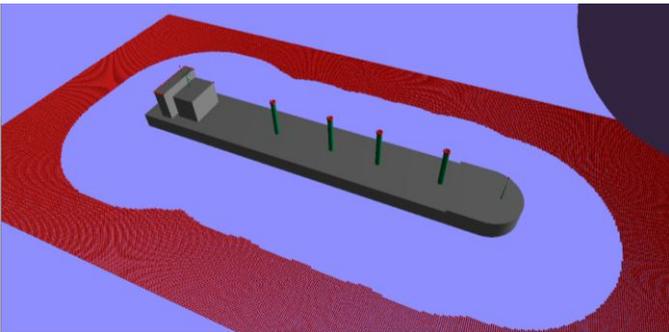


Figure 4. Rolling Sphere Method: initial application (Love’s EGM, 30kA)

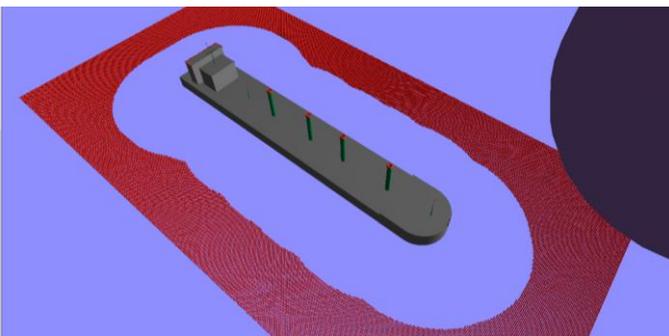


Figure 5. Rolling Sphere Method: after modifications (Love’s EGM, 30kA)

Modifications and proposals for the improvement of the lightning protection are presented not only for the 3kA strike but also for a 30kA strike (according to the EPRI and Anderson distributions there is about 50% probability for a lightning current to exceed this crest value). These modifications in the full scale ship model include addition of rods with the minimum protrusion height 300mm -as required by several regulations only in case of non-metallic masts [4]-[9]- on the already existing bow mast and the antenna mast above the bridge and placement of two new individual rods, one exactly at the bow and one in the middle of the deck surface between the bridge and the first cargo crane. Improvement of lightning protection for the deck surface is achieved but the bridge is still

likely to be hit as shown in Figure 5.

Addition of a rod above the bow navigation antenna can prevent direct damage but not possible induced effects due to lightning current dissipated through the connected protruding rod. Shielding provided by the front cargo crane is a solution thereby. As shown in Figures 3 and 4 strikes intercepted by the top of the crane also reach the bow antenna. The above visualization is conducted with the Rolling Sphere Method which considers the striking distance to earth (D) equal to the striking distance to the object (S) for both impulse polarities although several other models distinguish these two quantities and produce a different protection radius. Moreover, the exposed regions resulting from the above analysis correspond to 50% lightning interception probability although this is an additional parameter that strongly affects lightning protection. For this purpose various methods for the estimation of the protection zone offered by the front cargo crane located behind the bow navigation antenna were experimentally evaluated through measurements on a metallic ship model constructed with a ratio approximately 1:120 as a simplified scaled down replica of the full scale bulk carrier presented in Section II.

III. INTERCEPTION EXPERIMENTS

A. Procedure of measurements

The ship model -with basic dimensions 160cm length and 25cm width on the level of the “deck” surface- was placed on a grounded, 2mm thick, metallic plate which represented the sea surface. A cylindrical rod with a 5mm diameter ending at a hemispherical tip, was suspended over the metallic plate at various distances (rod-plane gap D as mentioned hereafter) in order to simulate the downward lightning leader as shown in the measurement setup of Figure 6. The cylindrical rod was energized with standard lightning impulse voltages (1.2/50 μ s) of both polarities produced by a 9-stage 1.8MV/10kJ Marx generator. The high impulse voltage was monitored by a digital recording system connected to the capacitive divider of the generator [4]. At first the breakdown probability distributions (Table V) of rod plane gaps D=50cm 75cm and 100cm were determined according to the “multiple level” test method [23].

TABLE V. BREAKDOWN VOLTAGES IN ROD-PLANE GAPS [4]

Rod-plane gap D	Positive polarity		Negative polarity	
	$U_{50\%}$ (kV)	σ (kV)	$U_{50\%}$ (kV)	σ (kV)
50cm	265.2	8.2	527	23.5
75cm	396.6	8.9	730.4	29.1
100cm	507	10.4	878.8	36.7

At the next stage the ship model was inserted in the rod-plane gap and “multiple-distance tests” were performed similar to the “multiple level tests” in order to obtain interception probability distributions specifically for position A which represents the front cargo crane next to the navigation antenna mast at the bow. Applying a fixed voltage which leads with 97.5% probability to breakdown for each combination of rod-plane gap and impulse polarity and starting from a position of the examined superstructure at which no discharge interception occurs, the ship model was brought closer to the high voltage

rod until the position at which all discharges are intercepted by the examined superstructure. The ratio of the height of the under protection rod (h_p) to the height of the protective rod (h_m) is $h_p/h_m=0.8$ and the separation distance between them (examined “cargo crane” at position A and “navigation antenna mast” at position B respectively) is $L=22\text{cm}$.

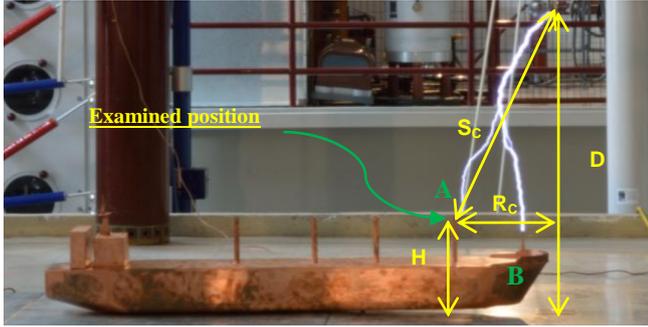


Figure 6. The experimental setup

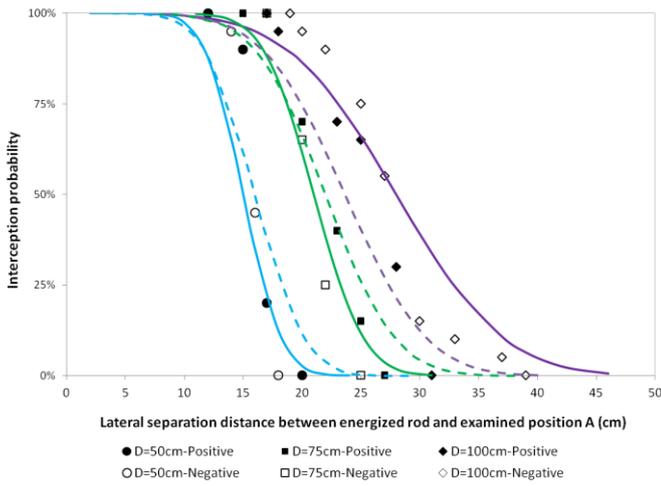


Figure 7. Interception probability distributions of position A

B. Results and Discussion

The experimental values of the mean interception radius R_c and the mean striking distance S_c , both referring to a 50% interception probability derived from distributions of Figure 7 (dashed lines correspond to positive polarity impulses whereas the solid lines to negative polarity), are compared to the theoretical values calculated with the Rolling Sphere Model, an Elliptical Model [24], a Statistical Model based on lightning interception probability and its modified version which takes proximity effects from nearby structures into consideration [4], [10], [25].

The following conclusions arise from the results of Figures 8 and 9. With the exception of $D=100\text{cm}$, the experimental values of R_c and S_c are greater for positive polarity in contrast to those of the negative polarity, although the opposite behaviour is expected. This reverse observation is attributed to the proximity effects from the nearby under protection antenna mast which distorts the interception distribution causing a

reduction in R_c which is more eminent in negative polarity as stated in [26]. For the examined rod arrangement all models, including the Rolling Sphere Model, overestimate the protection zone with that deviation being increased in negative polarity as D increases. Taking into consideration the distance $L=22\text{cm}$ between the two rods it is concluded from Figure 7 that for $D=50\text{cm}$ the antenna is totally unprotected while for $D=75\text{cm}$ and $D=100\text{cm}$ the probability for the antenna to intercept a strike is approximately 15% and 45%, respectively.

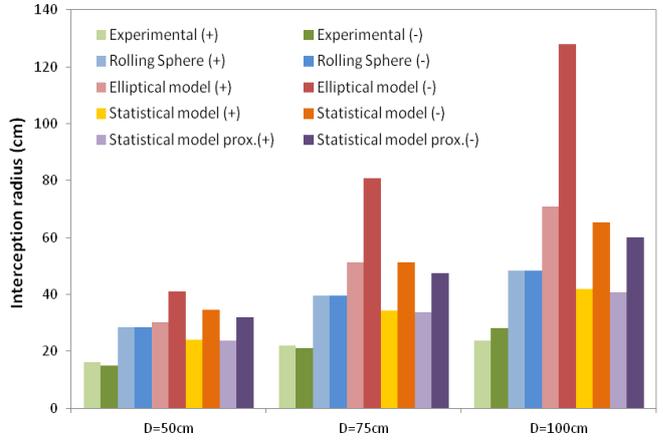


Figure 8. Comparison of the Interception Radius values

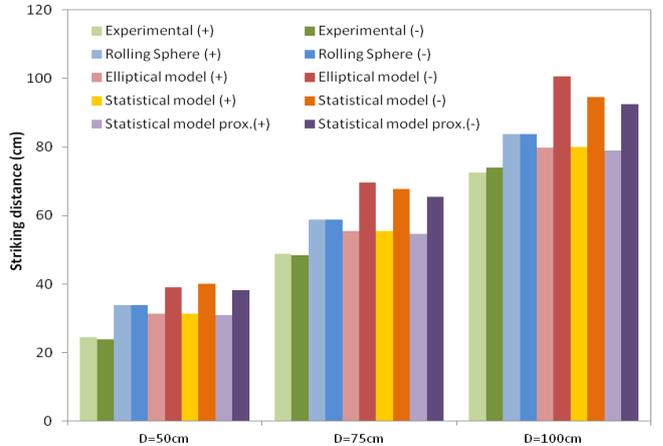


Figure 9. Comparison of the Striking Distance values

For positive polarity impulses R_c and S_c are for all rod-plane gaps D better predicted with both versions of the Statistical Model. For impulses of negative polarity, the Rolling Sphere Model provides the greatest accuracy. Meanwhile, the performance of the Elliptical Model is satisfying in the calculation of the striking distance.

IV. CONCLUSIONS

Lightning incidence calculations on a full scale bulk carrier have demonstrated the probability of a lightning strike on a ship depending on its structure and the lightning activity of the region. The selection of lightning attachment model has a strong influence on the expected number of lightning strikes,

even up to 80%. In general, the estimated number of strikes is expected to be greater for cargo and tanker ships due to the fact that they usually have a greater exposed area, unlike other types of ships which have complex superstructures such as equipment and antennas that function as lightning masts. The alternatives for the improvement of the external lightning protection system include extension of already existing superstructures with the addition of a rod at their top and placement of extra lightning masts. These modifications should always be done with respect to the function/purpose of the vessel and the kind of equipment to be protected.

Visualization of exposed onboard regions with the Rolling Sphere Method has highlighted mainly antenna masts and bridge rooftops as the most threatened points. In an attempt to examine whether the existence of the front cargo crane can provide sufficient shielding to the navigation antenna mast at the bow, impulse voltage experiments on a scaled down model of the ship have pointed out the statistical nature of lightning interception as an important factor that should be incorporated by lightning shielding analysis, especially in the case of the complex topology of a ship. Most theoretical models overestimate the protection radius which was proven to be strongly decreased due to proximity effects in negative polarity and for height ratios exceeding $h_p/h_m=0.6$ [26]. The addition of an actual protrusion height over existing ship masts or the placement of individual lightning rods should be designed on the basis of achieving interception probability on the protective rod greater than 50% and if feasible, 97.5%.

In most vessels antennas and navigation systems are usually placed at the highest points which are always vulnerable to lightning strikes. In the case of tanker ships a protection of the deck surface is also important given the fact that it is used for the placement of containers with flammable substances. The installation of a lightning rod protruding from these masts and of surge protective devices for the protection of the relevant electric circuits is necessary. Internal lightning protection is also required to protect from the lightning current conducted through exposed cabling to the interior electric grid and from the high radiated field through apertures and openings - even when the strike is intercepted by a lightning rod - and the resulting induced overvoltages and overcurrents.

ACKNOWLEDGMENT

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. The authors would like to thank Prof. A. P. Meliopoulos (Georgia Tech) for providing the license of the WinIGS software.

REFERENCES

- [1] Ewen M.Thomson, "A Critical Assessment of the U.S. Code for the Lightning Protection of Ships", IEEE Transactions of Electromagnetic Compatibility, Vol.33, No.2, May 1991.
- [2] C. Gomes and M. Z. A. Ab Kadir, "Protection of naval systems against electromagnetic effects due to lightning", Progress in Electromagnetics Research, Vol. 113, pages 333-349, 2011
- [3] Ronald W.Hotchkiss, Andrea Haa, "Electric ship surge environment", Electric Ship Technologies Symposium, 2007, pp. 301-308
- [4] E. P. Nicolopoulou, V.T. Kontargyri, I. F. Gonos and I. A. Stathopoulos: "Experimental Evaluation Of Lightning Protection Zone Through Impulse Voltage Tests On A Scaled Down Ship Model", Proceedings of the 19th International Symposium on High-Voltage Engineering (ISH 2015), Pilsen, Czech Republic, August 23-28, 2015, paper PB-422
- [5] IEC 60092-507 2008-01: Electrical installations in ships - Part 507: Small vessels.
- [6] Bureau Veritas Rule Note NR 566 DT R00 E: Hull Arrangement, Stability and Systems for Ships less than 500 GT, July 2011
- [7] Ministry of Defense, Defense Standard 02-516, (DEF STAN 02-51) July 2003
- [8] Offshore standard, DNVGL-OS-D201 – Edition July 2015, Electrical installations.
- [9] Rules for classification: Ships, DNVGL-RU-SHIP-Pt4Ch8. Edition October 2015: Electrical installations.
- [10] Pantelis N. Mikropoulos and Thomas E. Tsovilis, "Interception Probability and Shielding against Lightning", IEEE Transactions on Power Delivery, Vol.24, No.2, April 2009, p.863-87.
- [11] Win IGS User Manual, Software Version WinIGS-6.1, October 2015.
- [12] W. Brown and E. R. Whitehead, "Field and analytical studies of transmission line shielding-II", IEEE Trans. Power App. Syst., vol. 88, pp. 617-626, May 1969.
- [13] IEEE Working Group, "A Simplified method for estimating lightning performance of transmission lines", IEEE Trans. Power App. Syst., vol. PAS-104, no. 4, pp. 919-932, Apr. 1985.
- [14] A. J. Eriksson, "An improved electrogeometric model for transmission line shielding analysis", IEEE Trans. Power Del., vol. PWRD-2, no. 3, pp. 871-886, Jul. 1987.
- [15] L. D. Darveniza, F. Popolansky, and E. R. Whitehead, "Lightning protection of UHV lines", Electra, no. 41, pp. 39-69, 1975.
- [16] E. R. Love, "Improvements in lightning stroke modeling and applications to design of EHV and UHV transmission lines", M.Sc. dissertation, Univ. Colorado, Denver, CO, 1973.
- [17] T. Suzuki, K. Miyake, and T. Shindo, "Discharge path model in model test of lightning strokes to tall mast", IEEE Trans. Power App. Syst., vol. PAS-100, no. 7, pp. 3553-3562, Jul. 1981.
- [18] F. A. M. Rizk, "Modeling of transmission line exposure to direct lightning strokes", IEEE Trans. Power Del., vol. 5, no. 4, pp. 1983-1997, Oct. 1990.
- [19] EPRI AC Transmission Line Reference Book—200 kV and Above, Third Edition., EPRI, PaloAlto, CA: 2005. 1011974
- [20] J. G. Anderson, Transmission Line Reference Book—345 kV and above, 2nd Ed. Palo Alto, CA: Elect. Power Res. Inst., 1982, ch. 12.
- [21] A. M. Mousa and K. D. Srivastava, "The Implications of the electrogeometric model regarding the effect of height of structure on the median amplitude of collected lightning strokes", IEEE Trans. Power Del., vol. 4, no. 2, pp. 1450-1460, Apr. 1989.
- [22] IEC 62305-1 2006-01: Protection against lightning - Part 1: General Principles.
- [23] IEC 60060-1: 2010, High-voltage test techniques - Part 1: General definitions and test requirements.
- [24] S. Grzybowski, "Experimental Evaluation of Lightning Protection Zone used on Ship", Electric Ship Technologies Symposium, 2007. ESTS '07. IEEE, pp. 215 – 220.
- [25] Thomas E. Tsovilis, "A statistical lightning attachment model: lightning incidence estimation and shielding design" (in Greek), PhD Thesis, Thessaloniki, 2010.
- [26] Pantelis N. Mikropoulos and Thomas E. Tsovilis, "Interception Probability and Proximity Effects: Implications in Shielding Design against Lightning", IEEE Transactions on Power Delivery, Vol.25, No.3, July 2010, p.1940-1951.