# Simulation and Analysis of Electromagnetic Fields Resulting From Lightning in the Proximity of Watercraft using Maxwell v.15 Software

Shahrouz Nasiri, Mehdi Tabasi, Alireza Bakhshinejhad
Department of electrical engineering, Sowmesara branch, Islamic Azad University, Sowmesara, Iran.
Email: mehdi.tabasi@gmail.com

Received: November 2017 Revised: November 2017 Accepted: November 2017

**ABSTRACT:**
Strike of lightnings with sea, due to the high conductivity of salty water creates more extreme electromagnetic fields in comparison with lightnings in land. This paper deals with analysis and simulation of electromagnetic fields resulting from lightning in the proximity of a watercraft in sea and its effect on the equipment on the watercraft. The magnitude of electric and magnetic fields is first calculated using Uman integral equations to calculate the electric field resulting from a limited current channel on a perfect conductor. To solve the field integrals, dual precision exponential model was used for the lightning's current. Due to limitations of the solution of field integrals, parametric analysis is difficult. For this reason, the lightning channel and watercraft model was simulated in Maxwell software and the obtained fields were compared with the results of integral solution. Considering the closeness of integral and simulation results, with alteration of the peak lightning current and its distance off the watercraft, the field sensitivity to these variables was measured and the results of parametric analysis have been presented for different parts of the watercraft.

**KEYWORDS:** electromagnetic field, lightning, watercraft, sea, Maxwell.

## 1. INTRODUCTION

Sea is the region where lightning easy to be form. The big ship cruising and watercraft on the open sea could be the target to which lightning attacked mostly because of its high mast and outstanding antennas [1].

The lightning disservice effect to watercraft includes the direct effect and indirect effect. Direct effect is the physical effect produced by the lightning strike, which represent as burning, eroding, explosion, structure distortion, high voltage shock wave, magnetic field produced by big current, and the fatal contact voltage and step voltage formed while the lightning current go down along the lightning conductor to the ground or the sea. The indirect effect is the electromagnetic radiation effect, in which the electromagnetic pulse radiation going with the lightning strike disserves the electrical and electronic equipments and system.

An electric field has vertical and horizontal elements while its magnetic field has a horizontal element. The fields developed by a lightning are similar to the field resulting from a limited length channel current. If the lightning strike plane is a perfect conductor, the current channel is completely mirrored beneath the plane, and its effect is equivalent to the effect of lightning channel with a length twice as long as the initial length. In [2], integral equations have been presented for obtaining such as field. If the lightning strike plane is a limited conductor, the field equations change horizontally. The magnetic field equation resulting from strike of lightnings with a limited conductor plane in [3] is the frequency zone and electric field resulting from it has been calculated in [4] by Cooray-Rubinstein Formula. Calculations of the electromagnetic field indicate that the field domain resulting from lightning can decrease by up to 50% in a plane with conductivity far weaker than a perfect conductor [5].

As solution of the field integrals as unknown is difficult, typically fields are calculated within certain intervals off the lightning strike site. The fields resulting from strike of lightning in sea at specific intervals in [6], [7] have been calculated with different models. However, the obtained responses are far from each other. One of the reasons of this difference is preliminary modeling for the lightning current.

For modeling the lightning current, various models can be used. To prevent complexity of solution of integrals models, many studies have employed a simple triangular signal for simulation of the lightning current [8]. One of the most accurate field modeling is usage of dual exponential model, whose parameters have been calculated in [9] for different lightning pulses with head slope and drop in different waves. However, this model faces problem in solving integral models due to its very high slope at the point zero and the points before it. In this study, using dual exponential model in the field integral, the field equations in perfect conductor plane have been calculated in a way that the times before zero in the exponential model are not considered. Thereafter, the obtained fields have been compared with the simulated fields of strike of lightning in the proximity of the watercraft in Maxwell v.15 software. In case of close correspondence of these fields, one can calculate the magnetic domain sensitivity to them by altering the simulation parameters in Maxwell Software.

Lightnings in sea and their effect on watercrafts have been understudied in a specialized manner in references. In [10] the disserving characteristics of lightning to ship are investigated, as well as the direct lightning and LEMP protection design requirement for ship system are proposed. Survey of Japan, European and Colombia lightning day along coast and land are presented in [11], [12] and [13], respectively. calculations of lightning incidence on a bulk carrier ship model are presented in [14] with comparative application of various lightning attachment models and stroke current distributions. In [15] the effect of an ocean-land mixed propagation path on the lightning electromagnetic fields and their induced voltages is investigated. Calculations of the expected number of lightning strikes on three ship models are presented in [16] with comparative application of various lightning attachment models and stroke current distributions.

In this paper, modeling and analysis of strike of a lightning to water surface in the proximity of a watercraft have been presented. Simulation of electric and magnetic fields on the watercraft has been done by Maxwell software, and investigation of the effect of changes in the distance of the watercraft off the lightning site has also been presented. The rest of this paper is organized as follows: section 2 is dedicated to electromagnetic field and equations resulting from lightning. Lightning current model is presented in section 3. Simulation results are presented in section 4 for different aspects and section 5 is dedicated to paper conclusion.

## 2. ELECTROMAGNETIC FIELD RESULTING FROM THE LIGHTNING

Although moving or stationary watercrafts are seldom a target of direct lightning, incidence of lightning and in turn development of its vertical channel with a height of *H* causes development of electric and magnetic fields around the vertical channel. Since seawater has a high conductivity, it acts as the earth plane and develops a mirror of the lightning height at the height of *–H*. It also causes increased field scattering along horizontal axis. The magnitude of this field at each site depends on the distance off the lightning channel, channel height, and sea conditions. Fig. 1 shows the effect of electromagnetic field resulting from lightning on a body at distance *r*.

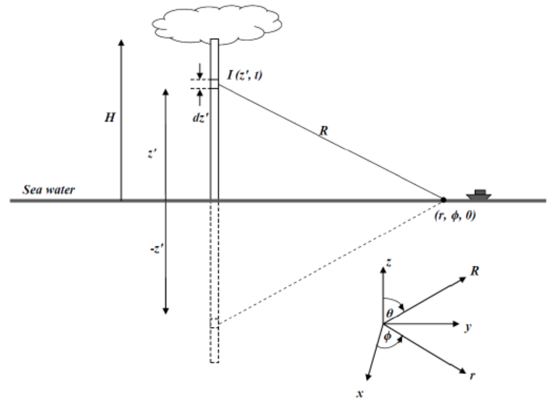



**Fig. 1**. The effect of electromagnetic field resulting from lightning channel in sea on a body at distance *r*

If the surface lies between the lightning and perfect conductor body intersection, the electric and magnetic fields in cylindrical coordinates with a radius of *r* are expressed as (1) and (2), respectively [7]:

$$E(r,\phi,\theta,t)=\frac{1}{2\pi\varepsilon_0}\begin{bmatrix}\int_0^H \frac{2z'^2-r^2}{R^5}\int_0^t i(z',t-R/c)\,d\tau\,dz' \\ +\int_0^H \frac{2z'^2-r^2}{cR^4} i(z',t-R/c)\,dz' \\ -\int_0^H \frac{r^2}{c^2R^3}\frac{\partial i(z',t-R/c)}{\partial t}dz'\end{bmatrix} a_z \quad (1)$$

$$B(r.\phi,\theta,t)=\frac{\mu_0}{2\pi}\begin{bmatrix}\int_0^H \frac{r}{R^3} i(z',t-R/c)\,dz' \\ +\int_0^H \frac{r}{cR^2}\frac{\partial i(z',t-R/c)}{\partial t}dz'\end{bmatrix} a_\phi \quad (2)$$

The first term in (1) is the static part of the electric field, and is dependent on charge variations along the channel, which decreases by moving away from the channel. The second term is the induction part of the electric field and is dependent on current along the channel, which has a relatively low damping rate. The third term is also radiation element, which diminishes with moving away from the channel [17]. The magnetic relationship stated in (2) is almost similar to that of the electric field equation, with the only difference being the fact that the element associated with static charges does not exist in the magnetic field, and its direction is also perpendicular to the magnetic field.

Electric and magnetic field equations can only be applied to perfect conductor planes and in the absence of distortion. If either of these conditions does not hold true, the form of the wave of fields will undergo an extensive distortion and reduction along the propagation path. This drop in the field at high frequencies causes reduced range of time derivatives the electromagnetic field, thereby lowering the voltage induced onto the conductors in the field path.

If the lightning at distance $D$ off the observer collided with a plane with limited $\sigma$ conductivity, the radiation electric field in this distance $D$ will be [18]:

$$E_{\sigma} = \left( 0.24 \left\{ e\left[ \frac{-D/\sigma}{10^{7}} \right] + e\left[ \frac{-D/\sigma}{50\times 10^{7}} \right] \right\} + 0.52 \right) E_{\infty} \quad (3)$$

In the above relation, $E_{\sigma}$ and $E_{\infty}$ are electric fields at distance $D$ on the limited conductor and perfect conductor surfaces, respectively. This relation can be used for distances up to 300 km, where the earth's curve does not develop any changes in that.

## 3. LIGHTNING CURRENT MODEL

A lightning usually consists of several consecutive strikes, with the first brining about the maximum current discharge. The current range of the first strike is around 31kA, and the slope of the wave of the first lightning strike is about 24kA/µs [17]. Although the subsequent strikes have a lower current peak value, they typically have a wave form with a greater current slope, compared to the first strike.

The shape of the wave of lightning is as a high-frequency pulse with a very fast and dramatic wave head, which after reaching the peak value, it diminishes with a lower slope. the electrical discharge current of the first lightning strike is shown in Fig. 2. The most important parameters of this curve are $t_f$, $t_h$, $S_m$, and $I_{max}$, which are the wave's head time, the time of drop until the half-range, the current slope, and maximum current. Typically, the mentioned parameters in standard lightning test for the first strike are considered $I_{\max}$=31kA, $S_{\mathrm{m}}$=24kA/µs, $t_{\mathrm{f}}$=1.2µs, and $t_{\mathrm{h}}$=50µs [19].

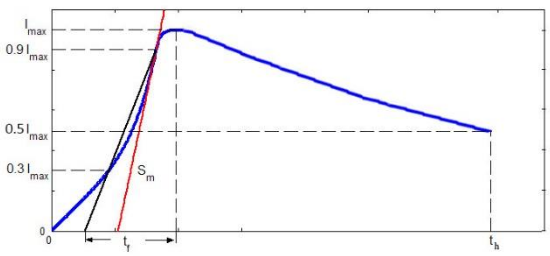



**Fig. 2**. The current wave resulting from the first lightning strike

For the lightning wave, considering the very rapid rise and fall time, two exponential curves with inverse slopes to each other can be used.

$$I_{lightning}(t) = A \times I_{\max}(e^{-at} - e^{-bt}) \quad (4)$$

Where, $A$, $a$, and $b$ are constant numbers. Given the standard values and the calculations performed in [9], the lightning wave is modeled as (5):

$$I_{lightning}(t) = 1.037 \times I_{\max}(e^{-1.47\times 10^{4}t} - e^{-2.47\times 10^{6}t})$$
(5)

This model provides a suitable approximation for the lightning current from 0-300µs. However, the slope of this curve is highly negative at times before zero. Fig. 3 shows the lightning current model before time zero. During these times, the lightning current is equal to zero, but as $i(t-R/c)$ current is calculated in the field integral, at very small times and for large $R$, the final response obtained from this model finds a large distance with the real value.

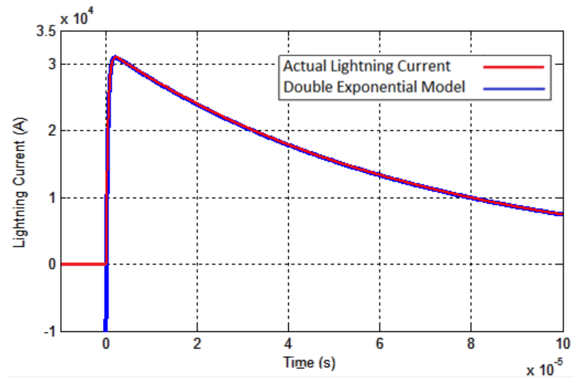


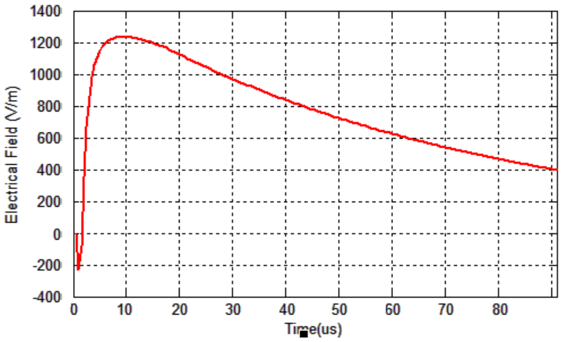

**Fig. 3**. Comparison of the real lightning current with dual exponential model

To solve the difference developed in the form of lightning waves, the integrals of the electromagnetic field have been calculated by up to height $z$, per which $t-R/c$ value would always remain larger than zero. Thus, the electric and magnetic fields are as follows:

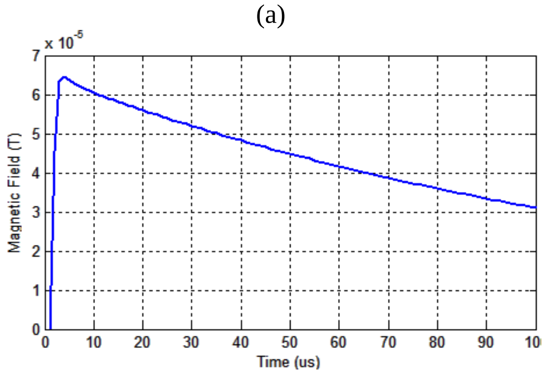
$$E(r,\phi,\theta,t) = \frac{1}{2\pi\varepsilon_0} \left[ \begin{array}{l} \int_0^{\sqrt{t^2c^2-r^2}} \frac{2z'^2 - r^2}{R^5} \int_0^{t} I_l(z', t-R/c)\, d\tau\, dz' \\ + \int_0^{\sqrt{t^2c^2-r^2}} \frac{2z'^2 - r^2}{cR^4} I_l(z', t-R/c)\, dz' \\ - \int_0^{\sqrt{t^2c^2-r^2}} \frac{r^2}{c^2R^3} \frac{\partial I_l(z', t-R/c)}{\partial t}\, dz' \end{array} \right] a_z$$
(6)

$$B(r.\phi,\theta,t) = \frac{\mu_0}{2\pi} \left[ \begin{array}{l} \int_0^{\sqrt{t^2c^2-r^2}} \frac{r}{R^3} I_l(z', t-R/c)\, dz' \\ + \int_0^{\sqrt{t^2c^2-r^2}} \frac{r}{cR^2} \frac{\partial I_l(z', t-R/c)}{\partial t}\, dz' \end{array} \right] a_{\phi}$$
(7)

Where, $I_l$ is the lightning current in terms of the dual exponential model. To have a greater speed in calculation of field integrals, each integral has been calculated for 200 separate times within zero and 100µs. Further, MATLAB code uses *vpa* function for approximation of integrals up to 5 decimal places for having a faster integration. The curves obtained from solving the electromagnetic field integrals have been shown in Fig. 4 for 100μs.




(a)

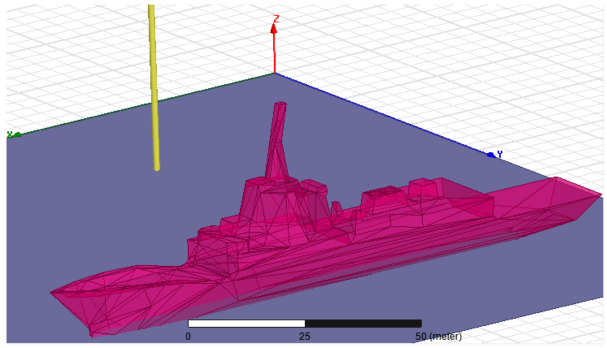



(b)

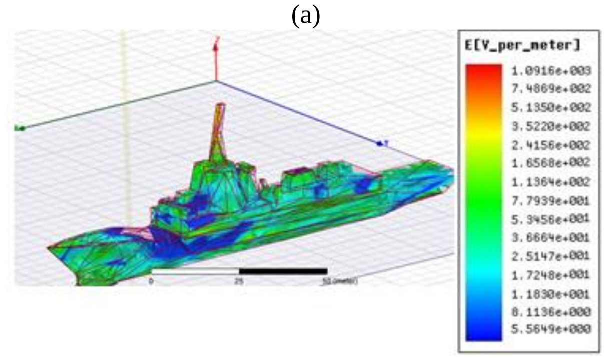
**Fig. 4**. The fields calculated by field integrals; a) electric field, b) magnetic field

## 4. RESULTS AND DISCUSSION

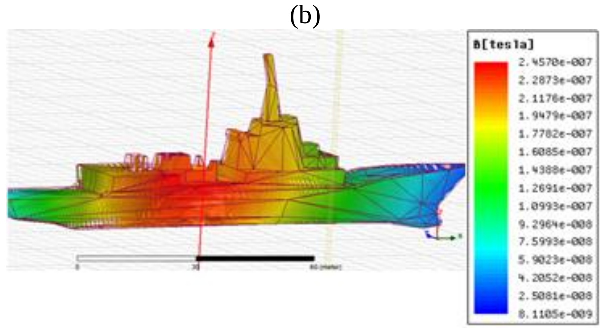
For simulation of the developed fields, Maxwell v.15 has been used. Electric transient solution method has been employed for calculation of the electric field, while magnetic transient method has been used for calculation of the magnetic field. In these two methods, the fields resulting from time variable stimulations. Here, the lightning has been simulated as a cylinder with a height of 5000m and with full conductivity, which eventually strikes the sea water with a conductivity of 5S/m. The water column height has been considered 100m and the distance between the lightning strike point and watercraft has also been taken as 100m. The watercraft has been modeled as a typical ship (a simplified three-dimensional model of a Spanish ship) with a body made of stainless steel. Fig. 5(a)a shows the three-dimensional environment in 200×200m dimensions. A cubic boundary has been considered for the modeling speed in the simulation environment, which models the fields up to infinity. Figs. 5(b) and 5(c) reveal distribution of electric and magnetic fields in the watercraft, respectively.



(a)




(b)




(c)

**Fig. 5**. Simulation of the distribution of the fields developed in the watercraft in response to lightning strike with sea at a distance of 100 m; a) simulation environment and watercraft modeling, b) distribution of electric field, and c) distribution of magnetic field

According to the results of Fig. 5, the electric field has the maximum value at acute angles of the watercraft, reaching a maximum of 1091.6V/m. The maximum electric field has been developed in the watercraft mast, which is the closest point of the watercraft to the channel's starting point. According to field integral relation, this point has the minimum distance off the height *H* and maximum affectability by sum of the field elements. At farthest points between the watercraft and lightning, the electric field value resulting from the lightning has decreased to 54V/m. This small range of field is due to both the far distance off the lightning channel and lower propagation of field in the steel material of the watercraft. However, considering the magnetic field, the only influential factor in the magnetic domain is the closeness or farness of the object in relation to the field origin. The top view of distribution of electric field in the environment surrounding the watercraft is shown in Fig. 6.

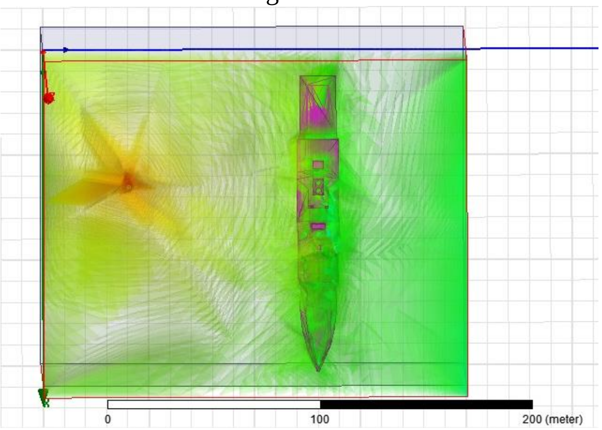



**Fig. 6**. Distribution of electric field resulting from lightning in the environment surrounding the watercraft

The maximum value obtained in the simulation does not fully correspond to the maximum electric field calculated through field integrals. In addition to the approximations used in the integral calculation as well as in electric field simulation, only induction factor of the field is calculated in Maxwell software. Although this element is the largest field element, not considering other elements in the simulation has caused this discrepancy.

For a more thorough investigation, the effect of changes in the problem parameters can be observed in field simulation by Maxwell software. the maximum field induced in the watercraft with changing its distance off the lightning strike point from 100 to 20m is shown in Fig. 7. The relationship between the electric field and inverse square of distance off the field origin is in line with these results. Fig. 8 shows the relationship of the maximum electric field with the peak lightning current, suggesting an almost linear relationship.

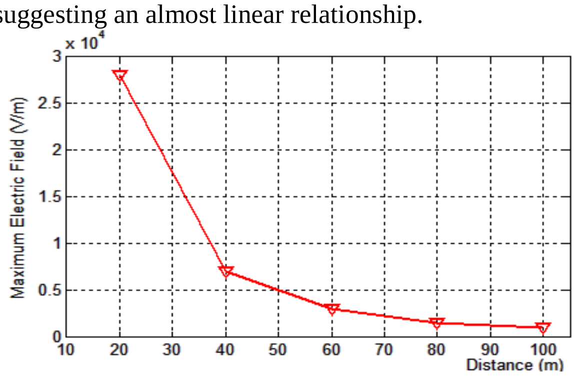



**Fig. 6**. Changes in the maximum electric field resulting from lightning strike in relation to the watercraft distance

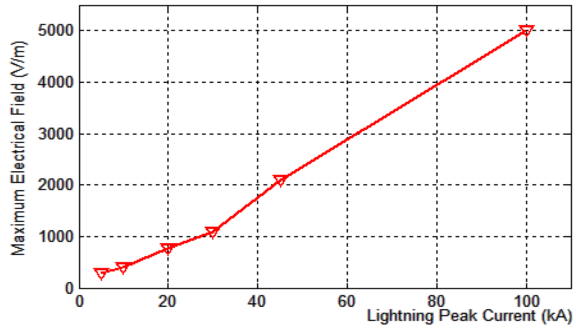



**Fig. 6**. Changes in the maximum electric field resulting from lightning strike in the watercraft in relation to the peak lightning current

An electric field of 1000V/m suggests that at a distance of 5mm, a voltage of 5V can be induced for a short time. In modern electronic equipment, only some extra volts can result in damage to the equipment. In addition to electronic equipment, any conductor lying perpendicular to the magnetic field develops voltage at its two ends considering the fact that it moves in the magnetic field due to the ship's speed.

## 5. CONCLUSION

Lightning strike to the ground surface causes development of electromagnetic fields, where if the ground surface is conductive, the domain of these fields can grow by up to two times. Electromagnetic fields can be calculated using field integral equations and dual exponential model of the lightning current. This way of calculation offers more accurate results in comparison with triangular modeling of the lightning current. Simulation of the lightning channel strike close to a watercraft on a surface with the limited conductivity of seawater in Maxwell software causes development of fields, whose value is relatively in line with the values obtained from the field integrals. Distribution of electric fields resulting from lightning in the watercraft indicates that the field intensity is larger in sharp points and closer to the lightning channel. Reduction of sharp angles and avoiding placement of electronic equipment in these points can be effective in mitigating the destructive effects of this field. Distribution of magnetic field is only dependent on the closeness and farness of the watercraft parts in relation to the lightning channel. The intensity of electric field has an almost inverse relationship with the lightning-to-watercraft distance, while it has a direct relationship with the lightning current. Adding the watercraft transverse protection against lightning can assist in mitigation of the damaging effects resulting from lightning strike close to the watercraft.

## REFERENCES

[1] S. Zheng, D. Hou. Q. Liu and F. Deng, **"Electromagnetic Pulse Threats to Electronic**

**Information system and Corresponding Protection Measures,"** *Proceedings 2011 4th IEEE International Symposium on Microwave, Antenna, Propagation and EMC Technologies for Wireless Communications,* Nov. 2011.

[2] M.J. Master and M.A. Uman, **"Lightning induced voltages on power lines: theory,"** *IEEE Trans. Power App. Syst.*, vol. PAS-103, pp. 2502-2518, 1984.

[3] M. Rubinstein, **"An approximate formula for the calculation of the horizontal electric field from lightning at close, intermediate and long ranges,"** *IEEE Trans. Electromag. Compat.*, vol. 38, pp. 531-535, 1996.

[4] V. Cooray, "**Some considerations on the" Cooray-Rubinstein" formulation used in deriving the horizontal electric field of lightning return strokes over finitely conducting ground**," *IEEE Trans. Electromag. Compat.*, vol. 44, pp. 560-566, 2002.

[5] P. D. Kannu and M. J. Thomas, "**Influence of lightning electric field components on the induced voltages on a power distribution line**," *Electric Power Systems Research.*, vol. 64, pp. 247-255, 2003.

[6] A. Shoory, R. Moini, S.H.H. Sadeghi and V.A. Rakov, "**Analysis of lightning-radiated electromagnetic fields in the vicinity of lossy ground**," *IEEE Trans. Electromag. Compat.*, vol. 47, pp. 131-145, 2005.

[7] Ming, Y. and V. Cooray, "**Propagation effects caused by a rough ocean surface on the electromagnetic fields generated by lightning return strokes**," *Radio Sci.*, vol. 29, pp. 73-85, 1994.

[8] M. Uman, D. K. McLain, and E. P. Krider, "**The electromagnetic radiation from a finite antenna**," *Am. J. Phys*, vol. 43, pp. 33-38, 1975.

[9] J. Wang and Z. Xiaoqing, "**Double-exponential expression of lightning cuRent waveforms, Envir. Electromag**.," *The 2006 4th Asia-Pacific Conference on. IEEE*, (320-323), 2006.

[10] Z. Sheng-quan, H. Dong-yun, D. Feng and W. Dong-dong, "**Lightning Menace to Ship and Corresponding Protection Design Requirements**," *2014 3rd Asia-Pacific Conference on Antennas and Propagation,* Nov. 2014.

[11] D. R. Poelman, W. Schulz, G. Diendorfer and M. Bernardi, "**European cloud-to-ground lightning characteristics**," *2014 International Conference on Lightning Protection (ICLP), Shanghai, China*, 2014.

[12] K. Yamamoto, T. Nakashima, S. Sumi and A. Ametani, "**About 100 Years Survey of the Surface Temperatures of Japan Sea and Lightning Days along the Coast**," *33rd International Conference on Lightning Protection (ICLP),* September 2016.

[13] Jorge A. Cristancho C., John J. Pantoja, C. Rivera and F. Roman, "**Analysis of two nonfatal lightning accidents in Colombia**," *Electric Power Systems Research*, vol. 153, pp. 159-169, 2016.

[14] E. P. Nicolopoulou, A. C. Alexandrou, M. F. Georgopoulos, D. E. Vatistas, I. F. Gonos and I. A. Stathopulos, "**Investigation of lightning incidence on ships**," *33rd International Conference on Lightning Protection (ICLP),* September 2016.

[15] K. Sheshyekani and J. Paknahad, "**The Effect of an Ocean-Land Mixed Propagation Path on the Lightning Electromagnetic Fields and Their Induced Voltages on Overhead Lines**," *IEEE Trans. Power Delivery.*, vol. 30, pp. 229-236, 2015.

[16] E. P. Nicolopoulou, I. F. Gonos and I. A. Stathopulos, "**Lightning shielding analysis on ships**," *IEEE Transactions on Transportation Electrification.*, vol. 3, pp. 779-791, 2017.

[17] J. R. Dwyera and M. A. Umanb, "**The physics of lightning**," *Physics Reports,* vol. 534, pp. 147-241, 2014.

[18] V. Cooray, M. Fernando, T. Sörensen and T. Götschl, "**A. Pedersen, Propagation of lightning generated transient electromagnetic fields over finitely conducting ground**," *Journal of Atm. & Solar-TeRestr. Physics,* vol. 62, pp. 583-600, 2000.

[19] Παπούτσογλου, Θεόδωρος Γ., and Theodoros G. Papoutsoglou. "**A Cold Ironing Study on Modern Ports, Implementation and Benefits Thriving for Worldwide Ports**," *School of Naval Archit. & Marine Eng., National Tech. Univ. of Athens*, 2012.