Electromechanical Energy Conversion Systems (EECS),
Niroo Research Institute.
Vol. 1, Issue. 4 . Autumn 20219

Investigating the effect of ground resistivity on off-shore wind turbines losses reduction during lightning strike via FEKO software

Monire Taghvaei[1*], MohammadJavad Nasiri[2]

1-Faculty of Electrical Engineering, Shahid Beheshti University, Evin, Tehran, Iran
2- Faculty of Electrical Engineering ,Iran University of Science and Technology

** Email: m.taghvaei@sbu.ac.ir*

Abstract

With the growth of wind power energy's importance throughout the world, losses caused by lightning strike to off-shore wind turbines are taken into consideration more than ever due to massive costs of installation and maintenance of the wind turbines. In this study, a new method for analyzing overcurrent created by a lightning strike to the turbines body and the distribution of magnetic and electrical fields around the wind turbine's tower is presented for two different cases of the tower with one leg, and the other case tower with three legs, using FEKO and MATLAB software. In the major part of the simulation, which is done by the comprehensive electromagnetic simulator software for analyzing magnetic and electrical fields of 3D structures called FEKO, various environmental conditions are applied and the outputs are compared on different diagrams including current, electrical fields, and magnetic fields in various environmental conditions. The results of simulations indicate that with the decrease of ground's resistivity, the peak of magnetic and electrical fields will decrease too which can be achieved by different methods and as a result of that, the losses caused by lightning strike to the turbine decreases.

Keywords: Off-shore wind turbine, lightning protection, losses reduction, electrical field, Ground resistivity.

1. Introduction

Lightning strike effects on wind turbine generators have recently become a major concern as the number and the height of wind turbines continue to increase. The impact on wind turbines ranges from disturbances on control electronics, damages to single components, such as blades or electronic components, to fires resulting in a complete loss of the installation. Most of these effects result in undesirable downtimes with its financial implications for the wind turbine operator. Further costs are added if components need to be replaced [1].there are different studies on simulating and analyzing methods in this concept [2-4]. Furthermore Mathematical functions for describing the ground resistance were proposed in some other works that prove the importance of modeling methods in electromagnetic field effects[5-7].

Therefore, in this paper a new method for analyzing and optimizing the effects of magnetic and electric fields around an off-shore wind turbine's tower in FEKO software, regarding to height of the tower and peak value of the fields in both frequency domain and time domain as well is presented. Ground's resistivity and depth of ocean are also considered and designed using 3D models in order to minimize the effects of magnetic and electric fields caused by lightning strike and the outputs are presented as waveforms using FEKO software. Electromagnetic fields near the path of strike's current in wind turbine's body are analyzed where the method of moment (MoM) is used to describe electromagnetic field's analysis in transient state and also for distributed current caused by lightning strike. Furthermore, in order to obtain more accurate results and comparison between different values of ground's resistivity and magnetic and electric fields, MATLAB software is used as well.

The rest of this paper is organized as follow. Section 2 represents an introduction to the deployed software for the study. Equations related to the lightning pulse are stated Then, the modeling of the lightning strike in the FEKO environment is discussed in section 4. Afterwards, the obtained results and discussion are presented in section 5 and finally, conclusions are given in Section 6.

2. An Introduction to the FEKO

FEKO is used in order to describe and use MOM in details. This software presents new methods to solve Maxwell equations which enable users to solve a wide range of electromagnetic problems which exist in various industries. It is also capable of analyzing multiple dielectric layers in big structures. One of the particular features of this software is simulating the wind turbine's leg model in ocean atmosphere and lightning model in both frequency and time domain, which will give outputs including current, electric field, and magnetic field around wind turbine's tower [8].

3. Formulation

The relative permittivity of a material is its (absolute) permittivity expressed as a ratio relative to the permittivity of vacuum. Permittivity is a material property that affects the Coulomb force between two point charges in the material. Relative permittivity is the factor by which the electric field between the charges is decreased relative to vacuum. Relative permittivity is typically denoted as ε_r and is defined as follows:

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0} \tag{1}$$

Where ε is the complex frequency-dependent absolute permittivity of the material, and ε_0 is the vacuum permittivity which its value in software is equal to 8.8541×10^{-12} by default. Relative permittivity is a dimensionless number that is in general a complex-valued. The imaginary part corresponds to a phase shift of the polarization relative to electric field and leads to the attenuation of electromagnetic waves passing through the medium. In this paper, relative permittivity of ocean's water and ground below ocean (where the turbine's leg is buried) are considered 10 and 30 respectively. Electrical conductivity or specific conductance is the reciprocal of electrical resistivity, and measures a material's ability to conduct an electric current. It is commonly represented by the Greek letter and Its SI unit is siemens per meter (S/m). Electrical conductivity is defined as:

$$\sigma = \frac{1}{R}\frac{l}{A} \tag{1}$$

Where R is electrical resistance, l is the length of the piece of material and A is the cross-sectional area of the specimen. In this paper, electrical conductivity of ocean's water value is 1 and ground below ocean is considered differently as 10 Ωm and 200 Ωm in two different simulations in order to determine the effect of electrical conductivity of ground below ocean on magnetic and electrical fields created by lightning strike around turbine's body. In time domain analysis, double exponential piecewise pulse is used for making and simulating lightning strike's condition. Fig. 1 depicts the applied lightning pulse in time domain.

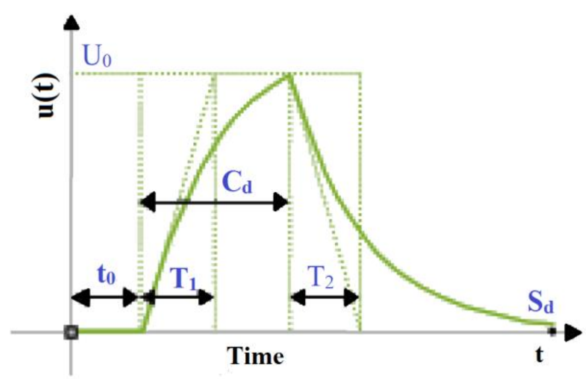

Fig. 1. NORMAL WAVEFORM OF LIGHTNING PULSE IN TIME DOMAIN.

In Fig. 1, S_d is The total length of the signal in the specified units, u_0 is the amplitude of the time signal which is assumed 103 in this paper, t_0 is pulse delay, or in other words, the duration of the rest period before the pulse begins to charge up which is considered as 5 ns here, C_d is the time from the end of pulse delay until the signal begins to discharge (or in other words, the peak position of the pulse) which value is considered 5 ns as well, τ_1 is the time that would be required to charge the signal up to 63.2% of its full potential, and τ_2 is the time that would be required to discharge the signal down to 36.8% of its full potential which are considered 2 and 1 ns respectively. (3), (4), and (5) equations represent the equations of lightning pulse related to Fig. 1 [9, 10]. The applied time signal of lightning is shown in Fig. 2.

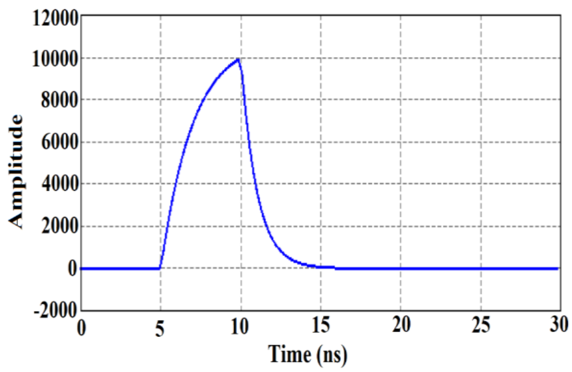

Fig. 2. APPLIED LIGHTNING PULSE IN TIME DOMAIN.

$$u(t)=\begin{cases} 0 & for \quad t\le t_0 \\ u_1\left(1-e^{-\frac{t-t_0}{\tau_1}}\right) & for \quad t\le t_0\le C_d+t_0 \\ u_2 e^{-\frac{t-t_0}{\tau_2}} & for \quad t\ge C_d+t_0 \end{cases} \qquad (3)$$

$$u_1=\frac{u_0}{1-e^{-\frac{C_d}{\tau_1}}} \qquad (4)$$

$$u_2=\frac{u_0}{1-e^{-\frac{C_d}{\tau_2}}} \qquad (5)$$

4. Modeling of the lightning strike

For simulating lightning strike according to the modeled pulse, a space with three layers is designed which its first layer is air with infinite thickness, second layer is water with thickness of 1m, and the third and last layer is ground again with infinite thickness. For simulating the turbine's tower, the height of turbine is assumed 15m in a way that 1m of it is buried in the ground beneath the water, 1m is in the water and the remaining 13m starts from surface of water to the air. 3D modeling of turbine's tower with one leg and turbine with three legs is shown in Figs. 3 and 4 respectively.

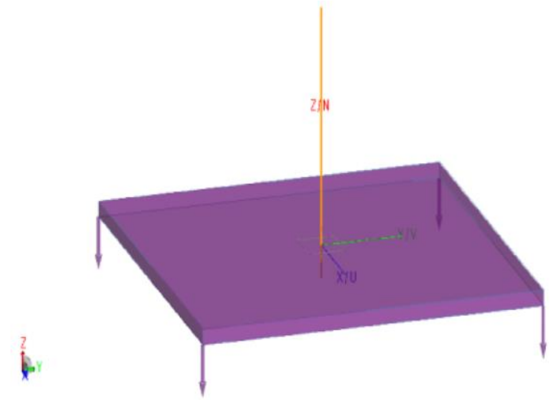

Fig. 3. 3D SCHEME OF AN OFF-SHORE WIND TURBINE'S TOWER WITH ONE LEG.

In order to conduct the analysis in frequency domain, the minimum value of frequency is set on 10kHz and the maximum value of it is set on 10MHz; frequency increase steps is also set on 10. In order to apply lightning and simulating the over-current created by it, a downward lightning wave with maximum peak current of 10kA is applied to a specific coordinate where begins from 1m upper than the ending point of turbine in the air downward to its end. After adding these models, outputs including magnetic and electric fields around wind turbine's tower are obtained and analyzed

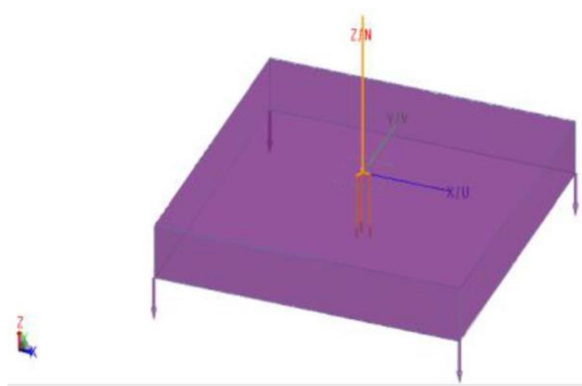

Fig. 4. 3D SCHEME OF AN OFF-SHORE WIND TURBINE'S TOWER WITH THREE LEG.

5. Results and discussion

5.1 Off-shore wind turbine's tower with one leg

Passing lightning's current through wind turbine's body creates intense electric field around it which its intensity is varied from turbine's bottom to the top. By checking this variation of field it can be determined that which part of turbine is more affected by lightning strike and at which part this affection would be reduced [11, 12]. In this paper, for reducing the effects and losses caused by lightning's over-current, the resistivity of the ground where turbine is buried is changed in two different values of 200 and 10 Ωm and the results are compared for each case. The output of these changes are shown in Figs. 5 and 6. In Fig. 5, the diagram of changing of the electric field with the changing of tower's height with the ground's resistivity equal to 200 Ωm is shown, while in Fig. 6 the diagram of changing of electric field with the changing of turbine's height when the ground's resistivity equal to 10 Ωm is visible.

It can be seen from Figs. 7 and 8 that in a given frequency range from 2MHz to 6MHz, when the resistivity of the ground is 10 Ωm, in some specific frequencies, the magnitude of electric field is less compared to Fig. 7 where the resistivity of the ground is 200 Ωm. It can be concluded that generally as the frequency increase, the electric field decreases and has a downward trend. More important result that is obtained from these diagrams is that as the resistivity of the ground decreases, the magnitude of field in each specific frequency decreases. Also it can be seen that in both cases of ground with different resistivity, as the height of turbine (z axis) decrease, the peak value of field will decrease too in frequency range which indicates that as the lightning wave reaches to the ocean level, its current would be dissipated.

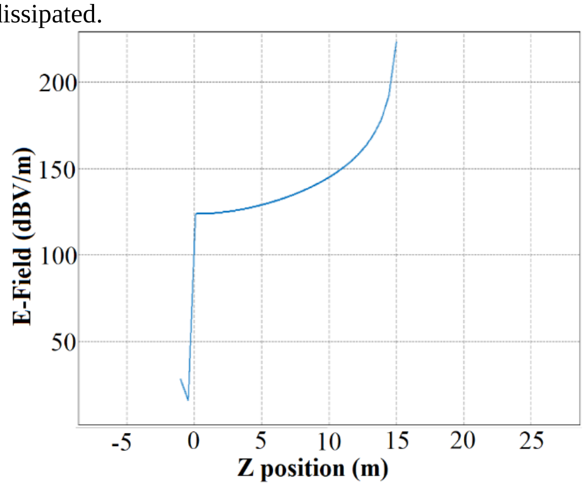

Fig. 5. DIAGRAM OF ELECTRIC FIELD VARIATION (IN dBV/m) WITH THE CHANGES OF TOWER'S HEIGHT (IN m) WHEN THE RESISTIVITY OF THE GROUND IS EQUAL TO 200 Ωm.

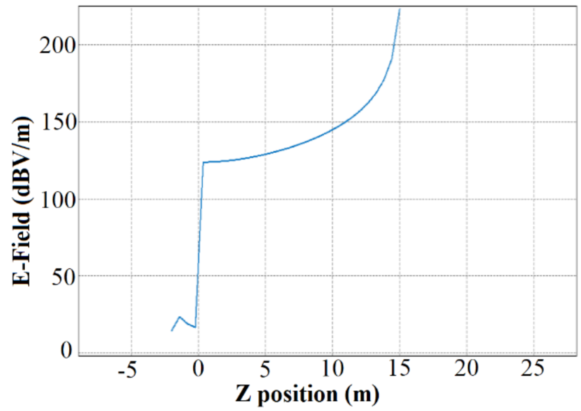

Fig. 6. DIAGRAM OF ELECTRIC FIELD VARIATION (IN dBV/m) WITH THE CHANGES OF TOWER'S HEIGHT (IN m) WHEN THE RESISTIVITY OF THE GROUND IS EQUAL TO 10 Ωm.

Figs. 9 and 10 depict the diagram of changing of magnetic field (in A/m) with the changes of frequency (in MHz) with two different resistivity for ground below the sea where the tower is buried in the height of 10m in tower (z=10m). It can be derived from these figures that magnetic field has the most magnitudes between 4MHz to 6MHz frequency ranges and same as electric field, as the height of turbine (z axis) decrease, the peak value of magnetic field will decrease too. More importantly, again as the resistivity of the ground decreases, the peak value of the magnetic field would decrease too.

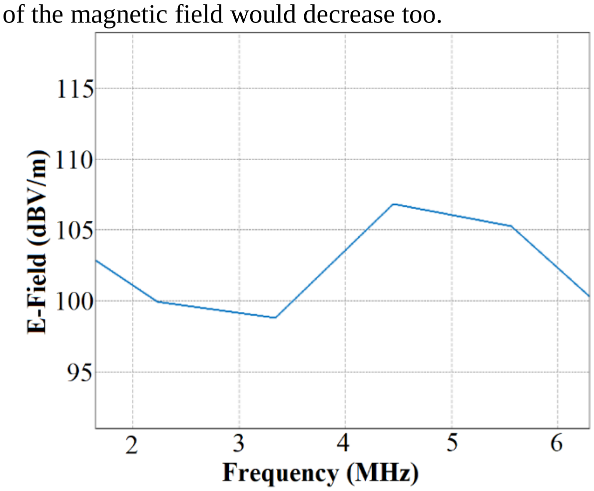

Fig. 7. DIAGRAM OF ELECTRIC FIELD VARIATION (IN dBV/m) WITH THE CHANGES OF FREQUENCY (IN MHz) WHEN THE RESISTIVITY OF THE GROUND IS EQUAL TO 200 Ωm AND THE COORDINATE OF TOWER'S HEIGHT IS z=10m.

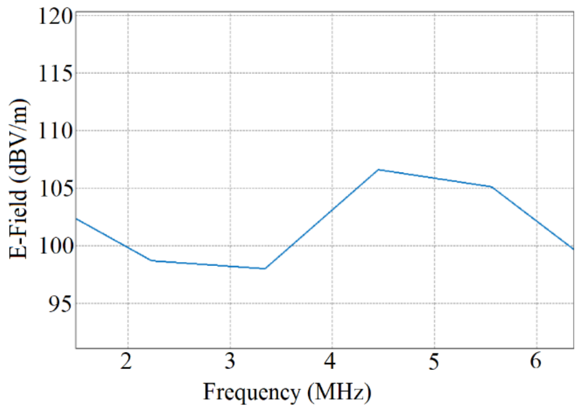

Fig. 8. DIAGRAM OF ELECTRIC FIELD VARIATION (IN dBV/m) WITH THE CHANGES OF FREQUENCY (IN MHz) WHEN THE RESISTIVITY OF THE GROUND IS EQUAL TO 10 Ωm AND THE COORDINATE OF TOWER'S HEIGHT IS z=10m.

By comparing figures 9 and 10 it is found out that when the frequencies are equal, the magnitude of magnetic field is lesser in the case that the resistivity of the ground is 10 Ωm, compared to when it is 200 Ωm.

This software runs the time domain analysis in a very short amount of time (as nanosecond), as a result, it is hard to obtain a very visible changes. However, it can almost be seen from Figs. 11, 12, and 13 that in a little range of time, the field has a downward trend with time and in different heights, as the height of tower decreases from the top in the z axis, the magnitude of field decreases too as expected.

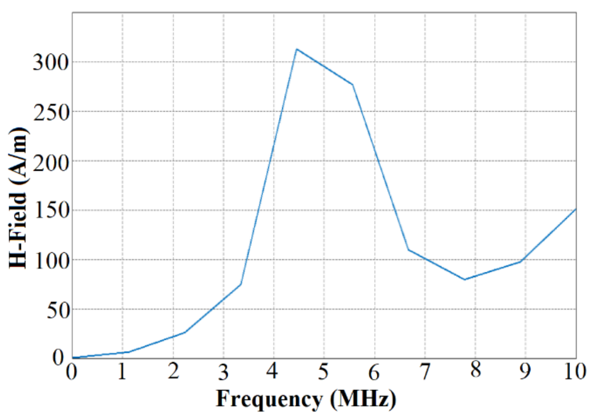

Fig. 9. DIAGRAM OF MAGNETIC FIELD CHANGES (IN A/m) VURSES THE CHANGES OF FREQUENCY (IN MHz) WHEN THE RESISTIVITY OF THE GROUND IS EQUAL TO 200 Ωm AND THE COORDINATE OF TOWER'S HEIGHT IS z=10m.

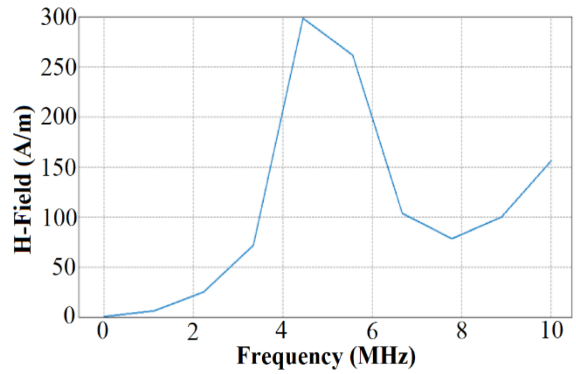

Fig. 10. DIAGRAM OF MAGNETIC FIELD CHANGES (IN A/m) VURSES THE CHANGES OF FREQUENCY (IN MHz) WHEN THE RESISTIVITY OF THE GROUND IS EQUAL TO 10 Ωm AND THE COORDINATE OF TOWER'S HEIGHT IS z=10m.

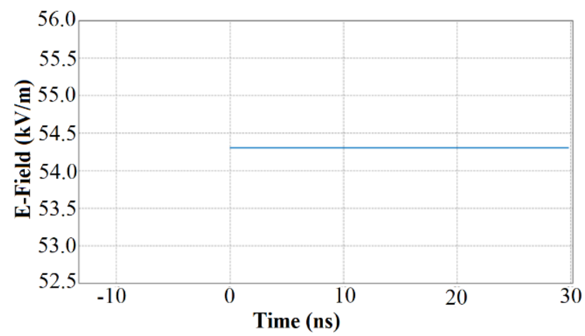

Fig. 11. DIAGRAM OF ELECTRIC FIELD CHANGES (IN kV/m) WITH TIME (IN ns) WHEN THE RESISTIVITY OF THE GROUND IS 10 Ωm AND THE COORDINATE OF TOWER'S HEIGHT IS z=15m.

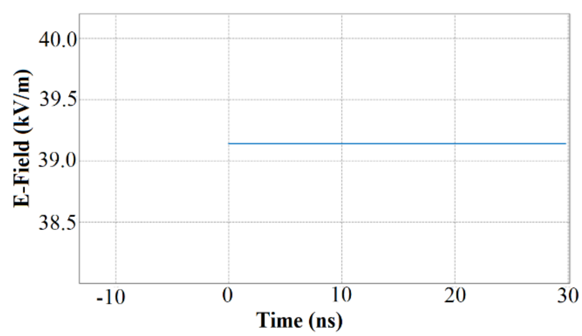

Fig. 12. DIAGRAM OF ELECTRIC FIELD CHANGES (IN kV/m) WITH TIME (IN ns) WHEN THE RESISTIVITY OF THE GROUND IS 10 Ωm AND THE COORDINATE OF TOWER'S HEIGHT IS z=10m.

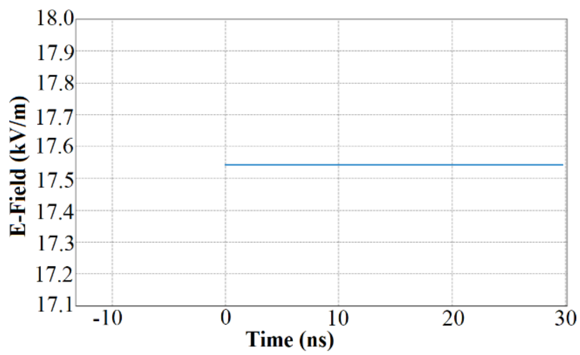

Fig. 13. DIAGRAM OF ELECTRIC FIELD CHANGES (IN kV/m) WITH TIME (IN ns) WHEN THE RESISTIVITY OF THE GROUND IS 10 Ωm AND THE COORDINATE OF TOWER'S HEIGHT IS z=5m.

5.2 Off-shore wind turbine's tower with three legs

Since in real models three legs are usually used to bury the turbine in ground, this model is considered in this study as well. The created fields caused by lightning strike from top of turbine to the end of one of legs are studied and checked. In this simulation, tower's length from the top to surface of water is assumed 15m, length of each leg is considered 6m which 1m of each one is buried in ground. In order to determine output, electric field around one of legs is analyzed in a way that the field is calculated in adjacent and parallel axis with one of legs which starts from 1m upper from water's surface and end in 1m below ground, the scheme of this simulation is shown in Fig. 14. The yellow line in Fig. 14 represent the output field.

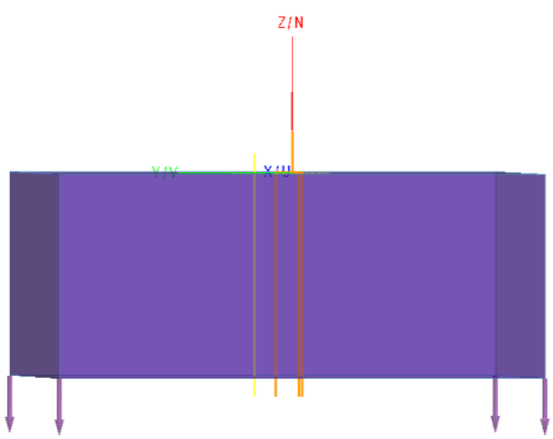

Fig. 14. OFF-SHORE WIND TURBINE'S TOWER WITH THREE LEGS AND VARIATION OF THE ELECTRIC FIELD.

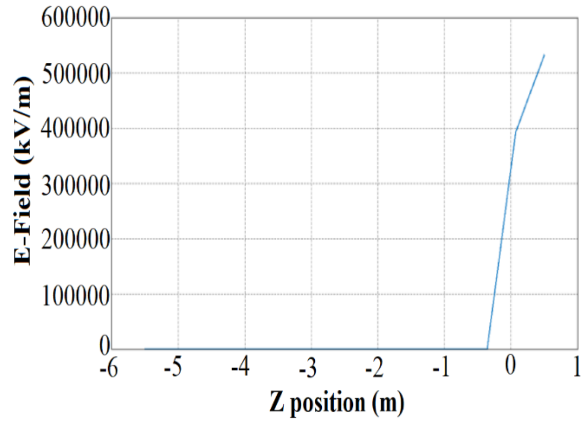

Fig. 15. DIAGRAM OF ELECTRIC FIELD CHANGES (IN kV/m) WITH THE CHANGES OF HEIGHT (IN m) IN OFF-SHORE WIND TURBINES'S TOWER WITH THREE LEGS.

It can be concluded from Fig. 15 the electric field is completely discharged immediately after it reaches the water surface.

5.3 Plotting the outputs in MATLAB

One of the useful features of FEKO software is that it can save the outputs as matrix which can be exported in MATLAB and with plot the diagrams and compare them with each other. The results of magnetic fields for two cases of ground's resistivity equal to 10 Ωm, and ground's resistivity equal to 200 Ωm are imported and by adding outputs data including frequency, turbine's axis length (from 1m to 16m), and magnetic fields with specific frequencies in separate matrixes, the simulation was done in MATLAB. Fig. 16 shows the diagram showing the changes of magnetic field with the change of turbine's height with two modes of ground's resistivity equal to 10 Ωm, and 200 Ωm in MATLAB. It can be seen that in as the height of turbine decreases, magnetic field decrease too in both cases and the magnitude of field in the case where the resistivity of the ground is 10 Ωm, is lesser than the other case where the ground's resistivity is 200 Ωm.

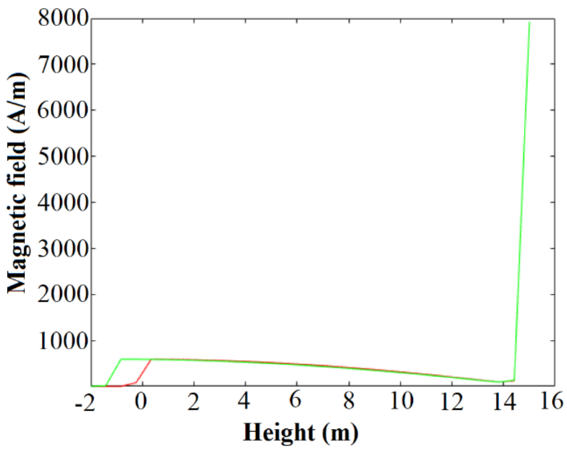

Fig. 16. DIAGRAM OF MAGNETIC FIELD CHANGES (IN A/m) WITH THE CHANGES OF TOWER'S HEIGHT (IN m) IN TWO CASES OF THE GROUND'S RESISTIVITY OF 10 Ωm IN RED LINE, AND THE GROUND'S RESISTIVITY OF 200 Ωm IN GREEN LINE.

6. Conclusion

In this paper, an electromagnetic model of an off-shore wind turbine's tower is presented to analyze the effect of lightning strike in FEKO software. By comparing the outputs obtained from simulations, it is determined that the values of electric and magnetic fields decrease as the lightning current goes downward from top of turbine to the ocean's surface. Also, it is found out that in specific frequencies in a given height of turbine's tower, the magnitude of field in a case that the resistivity of the ground below ocean is equal to 10 Ωm is lesser compared to when it is equal to 200 Ωm. Therefore, it can be concluded that with decreasing the resistivity of the ground where off-shore turbine is buried by different methods, losses caused by lightning would reduce too.

7. References

[1] Krug, Florian, et al. "Lightning Protection Optimization for Large Wind Turbines with Method-of-Moments." WSEAS Transactions on Circuits and Systems 6.3 (2004): 1504-1509.

[2] Zhu, D., Xiang, N., Li, W., Dong, B., Yang, J., & Wan, Y. (2020). Lightning electromagnetic transient characteristics of the space launch site. Energy Reports, 6, 483-490.

[3] de Azevedo, W. L., D'Annibale, J. L., de Araújo, A. R., & Pissolato Filho, J. (2020, November). Transient Voltages on Lightning Protection System with Stratified Soils and Damage Conditions. In 2020 Workshop on Communication Networks and Power Systems (WCNPS) (pp. 1-6). IEEE.

[4] Bachelier, E., Issac, F., Bertuol, S., & Parmantier, J. P. (2010, September). Electromagnetic numerical study for optimizing the lightning protection system of the VEGA launching pad. In 2010 30th International Conference on Lightning Protection (ICLP) (pp. 1-6). IEEE.

[5] Tsegaye, A. B., Gloppestad, J. S., Bendzovski, R., & Giese, S. (2021, April). Towards the modelling of uplift resistance of skirted offshore mudmat foundations. In IOP Conference Series: Earth and Environmental Science (Vol. 727, No. 1, p. 012025). IOP Publishing.

[6] Li, X., Gaudin, C., Tian, Y., & Cassidy, M. J. (2014). Effect of perforations on uplift capacity of skirted foundations on clay. Canadian geotechnical journal, 51(3), 322-331.

[7] Li, X., Gaudin, C., Tian, Y., & Cassidy, M. J. (2015). Effects of preloading and consolidation on the uplift capacity of skirted foundations. Géotechnique, 65(12), 1010-1022..

[8] FEKO, software product of EM Software & Systems, see http://www.feko.info.

[9] Jia, Wang, and Zhang Xiaoqing. "Double-exponential expression of lightning current waveforms." Environmental Electromagnetics, the 2006 4th Asia-Pacific Conference on. IEEE, 2006.

10] Bennett, William Geoffrey. Efficient Characterization of Transient Pulse Shapes from Radiation Induced Upsets. Diss. Vanderbilt University, 2012.

[11] Sorensen, T., et al. "Lightning protection for offshore wind turbines." Electricity Distribution, 2001. Part 1: Contributions. CIRED. 16th International Conference and Exhibition on (IEE Conf. Publ No. 482). Vol. 4. IET, 2001.

[12] Whitelonis, Nick, Shang-Te Yang, and Hao Ling. "Application of near-field to far-field transformation to Doppler features from wind turbine scattering." IEEE Transactions on Antennas and Propagation 60.3 (2012): 1660-1665.