International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 6 (2018) pp. 4124-4132

Evaluation of Grounding System Design for Wind Farm Using COMSOL

Nehmdoh A. Sabiha[1,3] and Nagy I. Elkalashy[2,3]

[1]*Stream Science, Preparatory Year Deanship, Taif University, Taif, KSA.*

[2]*Department of Electrical Engineering, Faculty of Engineering, Taif University, Taif, KSA.*

[3]*Department of Electrical Engineering, Faculty of Engineering, Menofia University, 32511, Menofia, Egypt.*

Abstract:

This paper evaluates the grounding system design for the wind farm that can be installed in Taif region, Saudi Arabia. Taif Region is considered as it has good enough wind speed rating appropriate for installing electric power conversion systems driven by the wind. However, the Taif region is a mountain area that has high soil resistivity. In order to perform such a study, the apparent resistivity of the Taif region soil is measured at several places considering the Wenner method and then one of the measurements is selected to evaluate the soil construction. In order to estimate the optimum number of layers and corresponding resistivity and depth, the optimization problem is designed based on the Sunde mathematical model of the multi-layer earth soil and solved using the Genetic Algorithm. The optimized multi-layer soil parameters are simulated using the COMSOL Multiphysics that is a finite element program in order to electrically evaluate the wind turbine grounding system and therefore to present the best grounding system design. The parameters of the grounding system are exploited to interpret the design by accomplishing a comparative study concerning the contour, isosurface, and slice of the electric potentials of the grounding systems. The results attain a suitable designed grounding system can be installed for wind farms in Taif region, Saudi Arabia.

INTRODUCTION

As the wind turbine is subjected to lightning strokes, an efficient grounding system is essential for absorbing the dangerous energy and limiting the corresponding overvoltages on the neighbor wind turbines. However, the wind farms are usually installed in mountainous area that is characterized as a high soil resistivity as in Kingdom of Saudi Arabia (KSA). Establishment of wind farms at Taif, Western Province, Kingdom of Saudi Arabia (KSA) has been recommended due to the achievement of the required wind speed [1]. However, the lightning strokes are frequently occurred in Taif region due to closing clouds to the earth.

The grounding system is the main path to withdraw the lightning-based over-energy induced in the wind farms due to specially and extremely height of the wind turbine blades. Furthermore, the wind turbine blades have dynamic movement pushed by the air for converting the horizontal air movement into rotational drive to the electrical generation unit. This movement affected on the attraction mechanism of the lightning strokes to the blades. Accordingly, the grounding system design is finally to attain the low grounding resistance that help to dissipate the lightning energy stroke the wind turbine blade. The other point behind studying the grounding design is to attain low touch voltage and low step voltage. However, the high soil resistivity in the mountain area such as in Taif region makes the design process difficult and hard in which several efforts are to be taken in order to achieve low grounding system resistance.

Based on IEC 61400-24, the type B has been agreed [3]. However, further studies such as in [4]-[8] have modified the grounding system design. One of the important finding was the effect of using the vertical grounding electrodes in the design system on the net grounding resistance. Other study reported in [8] was to evaluate different earthing system configurations such as the effect of involving diagonals in the rectangular grounding system, involving across in the middle of the rectangular grounding system, and involving radial conductors. However, estimating the appropriate grounding design system for certain earth soil region needs further studies to ascertain an optimum design dimension for this specified application.

In order to practically design and install the grounding system in a specific earth region, the multi-layer soil structure must be accurately known in detail such as the number of layers, layers thickness, and layers resistivity. Fetching the layer structure by digging is a hard and cost task as the depths are expectedly very long. However, the optimization techniques have been recently applied to find the optimum soil structure producing apparent resistivity matched with the measured resistivity. This optimization problem is designed to produce minimum error objective function between the calculated apparent resistivity of the modeled soil equations and measured soil resistivity. Such studies were as reported in [9]-[26]. Such a concept of soil parameter estimation suitable for grounding system design is considered in this paper to define the soil structure.

In this paper, field measurements of the apparent resistivity have been attained in the Taif region soil. The measuring procedure has been based on the Wenner method. These measurements of the apparent resistivity have been substituted in the optimization problem of the grounding system apparent resistivity designed based on the Sunde equations where the problem implementation and solving was done in the Matlab field. The optimization problem is implemented in Matlab script file and then solved with the aid of the optimization toolbox and optimization problem solver where the genetic algorithm was selected as an optimization solver technique. The extracted multi-layer soil structure by the Matlab-based optimization solver was considered in the simulation of the grounding system involved in this soil using the COMSOL Multiphysics software to evaluate the electric potential of different parameters of the grounding system. The electric potential was considered as the vital factor for modifying the grounding system design until attaining the suitable grounding system for the wind turbine installed in Taif region, Saudi Arabia.

MEASUREMENTS OF SOIL APPARENT RESISTIVITY

The principles of the soil apparent resistivity were considered based on the Wenner method. As shown in Figure 1 for multi-layer soil, the arrangement of Wenner method was based on four electrodes fixed at constant interspace *a*. The apparent resistance is calculating using the injected current between the external two electrodes and the corresponding induced potential between the internal two electrodes. Then the apparent resistivity is computed as proportional to this resistance and the adjusted distance *a* between the electrodes.

The apparent soil resistivity was measured at different places in Taif region. Figure 2(a) shows a place example of measuring in Taif region, Saudi Arabia. The KYORITSU KEW4106 earth resistance/earth resistivity tester was used as a megger tester to measure the soil apparent resistivity. Figure 2(b) shows the measured soil resistivity as a function of the adjusted interspace *a* between the electrodes. As depicted in this figure, there are three oscillations that ensure the soil is multi-layer type.

Using the measured field resistivities shown in Figure 2(b), the genetic algorithm is applied to determine the unknown soil parameters with the aid of Matlab optimization toolbox [27], representing the apparent resistivity of each layer in the soil using Sunde mathematical model, and using the data collected from the field measurements. The Sunde model and optimization problem are discussed in the following sections.

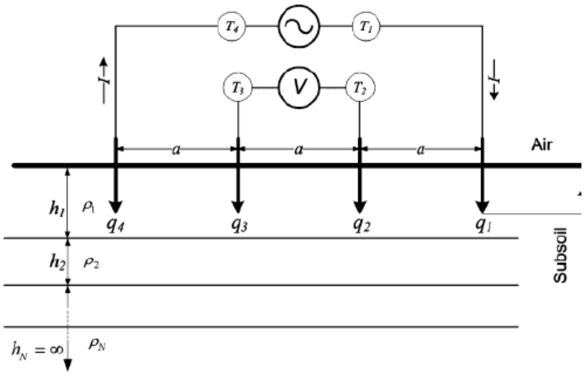
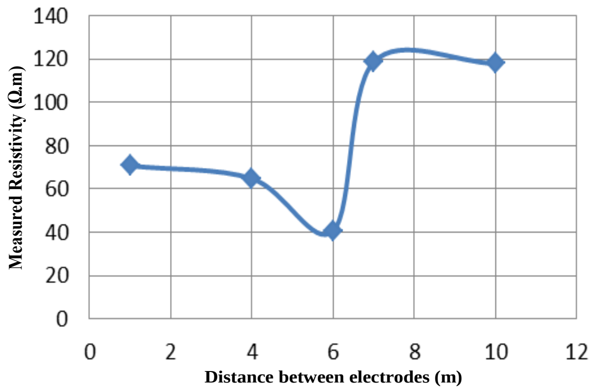


Figure 1. Arrangement of Wenner method [9].

a) Taken photograph of the earth field measurement.



b) Apparent soil resistivity.

Figure 2. Field measurements considering Wenner method.

SOIL PARAMETERS ESTIMATION

In this section the optimization problem is designed using the Sunde equations and then the soil parameters are estimated using the optimization solver – genetic algorithm. The Sunde model equations are presented in this section for two-layer soil structure, where they can be modified for three, four, ... etc. layers until obtaining the optimum number of layers. For the two-layer soil example, there are three unknown parameters that are resistivities of the two layers (ρ_1 and ρ_2,) and a depth of the upper layer (h_1) where the lower layer has infinity depth. Toward estimating these three unknown parameters, the Sunde equations of the multi-layer soil representation is used for problem design of the apparent soil resistivity where the rules of Sunde equations were analytically reported in [28]. The corresponding minimizing optimization objective function is applied on the error between the measured and computed apparent resistivity as in the following form;

$$minimize\ F_{error} = minimize\ \sum_{n=1}^{N}\left(\frac{\rho_m-\rho_c}{\rho_c}\right) \qquad (1)$$

where N is the total measured number of the apparent resistivity samples while ρ_m and ρ_c are respectively the measured and calculated apparent resistivity. With the principles of the apparent soil resistivity reported by the Sunde in [28], the mutual resistance numerically integrated in a systematic way as follows. For the two layers soil case, the

International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 6 (2018) pp. 4124-4132

mutual (apparent) resistivity $\rho_c(a)$ for the distance a between the electrodes is attained at points on the surfaces by [28];

$$\rho_c(a) = \rho_1 \int_0^{\infty} k_{12} J_0(\lambda a) d\lambda \qquad (2)$$

where J_0 is the Bessel function, λ is the integration variable, and k_{12} is the kernel of the two layers soil. For the case of the two layers kernel implementation, the Sunde-based processing is;

$$\mu_{12} = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2}, \qquad k_{12} = \frac{1 - \mu_{12} e^{-2\lambda h_1}}{1 + \mu_{12} e^{-2\lambda h_1}} \qquad (3)$$

For three-layer, four-layer, or other number of layers, equations (2) is modified and the kernel implementation (3) is extended to further equations based on the layer number as carefully discussed and modeled in [28]. Using the Sunde model in implementing the soil resistivity ρ_c, the objective function (1) is represented for the optimization problem and then the problem is solved by the genetic algorithm.

As it is known in the literature, the genetic algorithm is one of the efficient and intelligent optimization processes. The genetic algorithm implementations are initiated by the generation evolutionary concept and parallel researches. The fitness of each individuals was first measured and then the best individuals were selected. There are four stages for the algorithm implementation. The first one is to randomly initialize the chromosome population initialization, the second one is to exclusively evaluate the chromosomes fitness in the population, the third one is to select the best chromosomes toward reproductions, and the final one is to use the genetic rules in order to manipulate the chromosome. Further condition of repeating the generation process until achieving the stop criteria of the genetic algorithm loop is used. Further discussions and declarations are in [29].

As aforementioned, the genetic algorithm was used as an optimization solver in the Matlab field where the mathematical description of the optimization problem was implemented using the Matlab script file and the genetic algorithm was processed using the optimization toolbox. It was obvious that such implementation and solving of the optimization problem was facilitated with the aid of the Matlab capabilities as follows. In the Matlab command window, writing the function “optimtool” and then entering opened the “Optimization Tool” window such as the shown window in Figure 3. In this window, there were several solver techniques where the “ga — Genetic Algorithm” solver could be selected to solve the designed optimization problem represented by the objective function in (1) for this study. Also, in this window shown in Figure 3, there were constraints and boundaries to be defined based on the problem description. Also, at the right-hand side, there were important options with the quick reference declaration.

Reference to Figure 3, it was an optimization example of four layers soil description problem. The optimization solver technique adjusted “ga — Genetic Algorithm” and processed on the fitness function defined using the matlab script err_fun. As the shown example was to find optimum soil parameters of the four-layer soil, the number of variables was defined 7. The boundaries of soil layer resistivities and layer thicknesses were defined in between 1 to 20000 Ω.m and 1 to 100 m, respectively. At the right-hand side in Figure 3, the options were defined as follows. The default settings were the selection done for the population size, population initialization, hybrid function, reproduction, and stopping criteria. The fitness scaling was “Rank”, the selection function was “Stochastic Uniform”, the mutation was “Gaussian” with default parameters, the crossover was “Scattered”, and the migration was adjusted “Forward”.

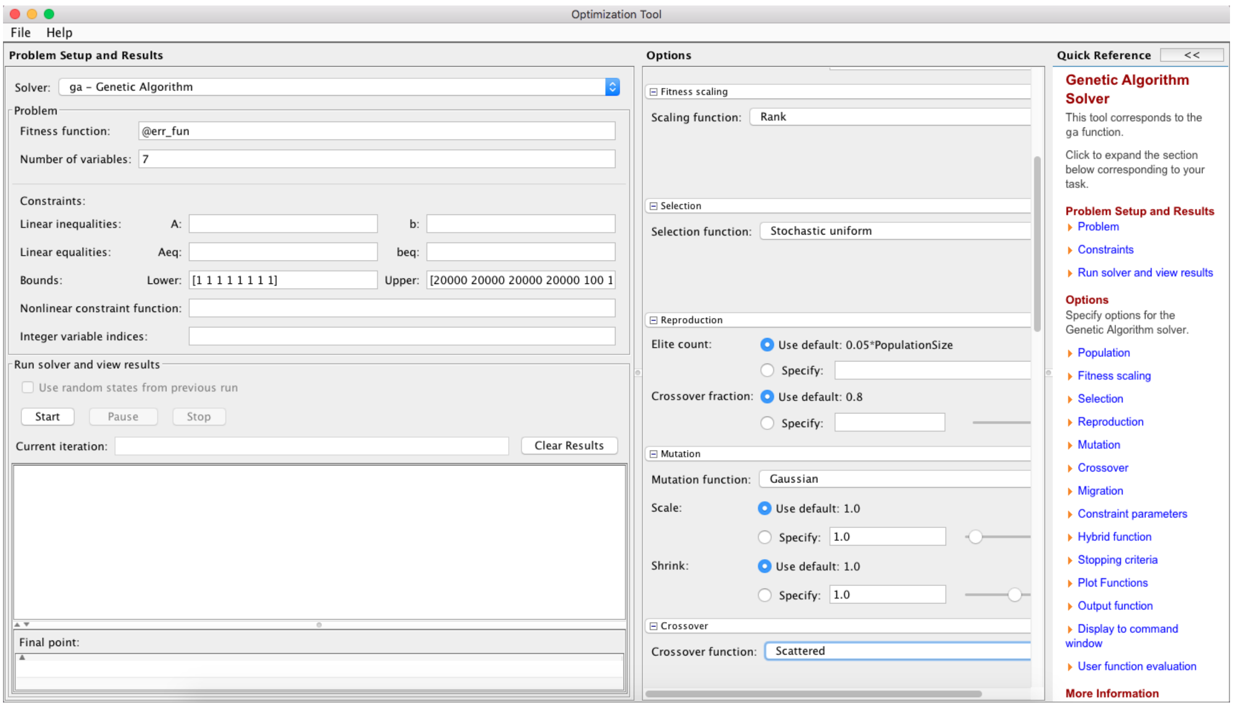


Figure 3. “Optimization Tool” problem solver [27].

This solver setup shown in Figure 3 provided the possibility of finding the optimum values of the soil resistivities and corresponding depths for individual considerations of the different numbers of the layers. For example, the optimization problem was solved concerning two layers, three layers, four layers, five layers, six layers, and other number of layers. The selected optimum number of layers as a solution was that had the most minimized error of the objective function (1). For the soil example having apparent resistivity shown in Figure 2(b), the soil structure of four layers was found the optimum solution that had the most minimized error between the modeled apparent resistivity and the measured one. Table 1 declared the corresponding solved construction of the soil using the optimization problem, soil resistivity with corresponding thickness. In this soil, the upper layer had 60.36 Ω.m resistivity with 13.08 m thickness, the second layer had 2903.38 Ω.m resistivity with 1.21 m thickness, the third layer had 1.246 Ω.m resistivity with 88.98 m thickness, and the last layer had 187.75 Ω.m resistivity for infinity height. From these results, the third layer has extremely low resistivity started at depth equal to 14.29 m (13.08 + 1.21) where this depth can be reachable using the suitable dig method. Accordingly, if the vertical rods arrived at this layer, the grounding resistance dramatically reduced.

Table 1. The soil resistivity extracted from solving the optimization problem.

Layer Number	Layer Thickness (m)	Layer Resistivity (Ω.m)
1	13.08	60.36
2	1.21	2903.38
3	88.98	1.246
4	Inf.	187.75

GROUNDING SYSTEM EVALUATION USING FEM

The partial differential equations are the best mathematical modeling in time and space domains that is suitable for the grounding design evaluation. The numerical solutions of the systems described by partial differential equations are generally done using the finite element methods (FEM). Accordingly, a lot of programs are presented to implement the solution method based on the FEM. One of these programs is the COMSOL Multiphysics [30], which is a high reputed FEM program. Accordingly, it is used for evaluating the performance of the grounding system design by investigating the electric potentials for different modified grounding parameters of the designed systems as discussed as follows.

Considered Grounding System Design

In the rocky area such as most places in Saudi Arabia, IEC std. [3] recommended to use two concentric ring electrodes. All the manufacturers have average wind turbine grounding system diameter of 11 m [5]. However, this grounding design is not sufficient to achieve the standard requirements of the grounding system especially in the rocky area. Accordingly, a modification should be done to improve the grounding design for the estimated soil resistivity in the previous section. This modification is done on varying the vertical electrode lengths.

Among different designs of wind turbine grounding system, a proposed model of grounding system was introduced in [4] where the grounding system geometry is shown in Figure 4. In this grounding system, there are six vertical electrodes that their length can be adjusted to attain the grounding system design. Calculating the electric potential distribution due to high dc current applied on the wind turbine grounding system using FEM is the most suitable evaluation in order to attain the objective grounding system. Therefore, the grounding system evaluation is numerically done using COMSOL multiphysics [30]. The geometry used in COMSOL multiphysics for the abovementioned cases is shown in Figure 4. However, the first step in the simulation using the COMSOL-based FEM program is to represent a semi-sphere earth containing soil of the four layers with considering the soil resistivity and thickness of these layers as summarized in Table 1. Then, the grounding system shown in Figure 4 and considering modifications in the vertical rods lengths is involved in the simulated earth. Changing the vertical rod lengths can easily enhance the grounding system performance as ensured by the simulation results.

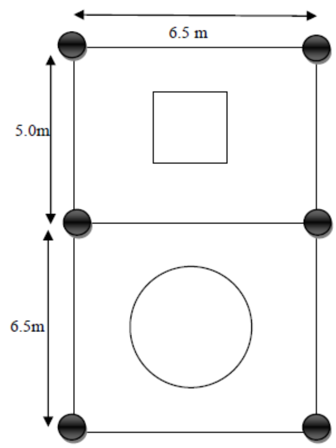


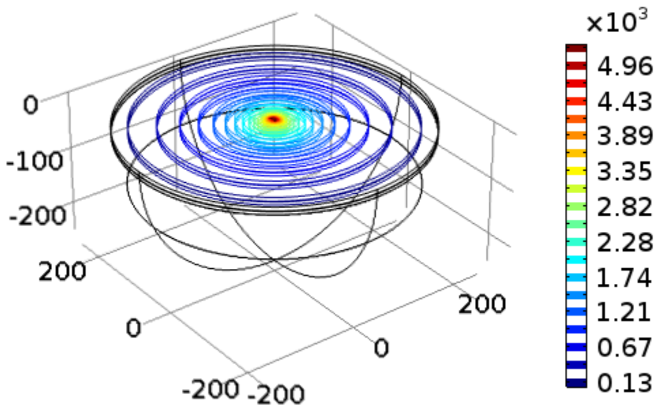
Figure 4. Geometry of the used grounding system [4].

Electric Potential Evaluation

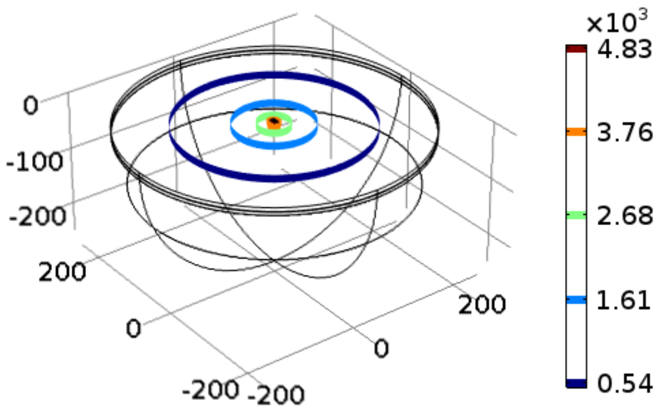
In order to give explanations of the results of the simulation using the COMSOL Multiphysics, the postprocessing and visualization tools are used considering the orientation, coloring, and arrangement of the object under study. For example, the contour plots are used to visualize scalar quantities on a series of lines with different colors that are suitable for 2D and 3D simulations. The isosurface plots are used for 3D analyses in order to display result quantity of color surfaces for quantities having the same values. These values can be for example the electric potential as in the current study. The third type is the slice plots where these plots are the cross-sectional surface plotting to monitor the changing of variables over sliced distances. These several postprocessing and visualization tools are utilized in this current study in order to declare the effect of the grounding system design modification on the electric potential field. The contour, isosurface, and slice plots of the electric potential are investigated over the semi-sphere geometry representing the earth and containing the grounding system design.

By injecting 1000 A dc current into the grounding system shown in Figure 4, the corresponding contour, isosurface, and slice plots are shown in Figure 5 when the vertical rods are 1.5 m. In Figure 5(a), the contour plots are shown where the highest potential is at the center that is the place of grounding system and then gradually reduced as depicted by the color distribution. In Figure 5(b), the isosurface plots are shown where the same information is attained. However, the contour and isosurface plots only show the surface gradients of the electric potential. Accordingly, the slice plots are used to show the electric distribution due to the grounding system inside the soil through slices at different distances in the x direction.

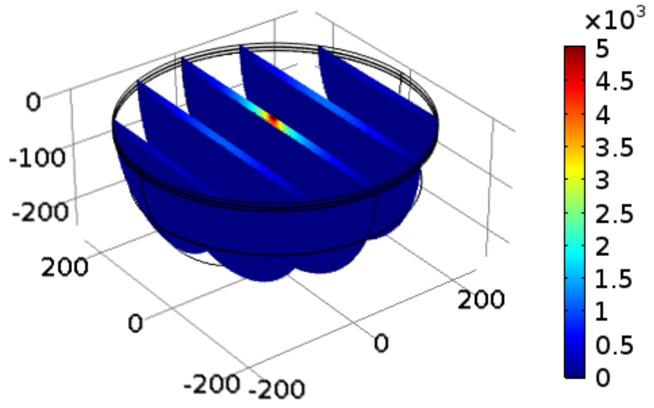
The same evaluation is repeated for other vertical electrode lengths such as 12.68 and 21 m as depicted in Figures 6 and 7, respectively. Off course, there is an effect for increasing the vertical rod lengths, however, it cannot be exactly decided using the visualization plots in Figures 5, 6, and 7. Accordingly, Figure 8 is presented in order to show the values of the maximum potential on the grounding system modified using different vertical electrode lengths. Accordingly, this Figure precisely summarizes the impact of electrode length on electric potential values. From this figure, it shows that the maximum voltage collapse from 4500 V to approximately 340 V when the electrode penetrates into the third layer which has minimum resistivity of 1.246 Ω.m. This potential is close to the standard safe value of 300 V of the zone of influence. Accordingly, the grounding system is successfully designed however with considering vertical electrode of approximately 14 m length.



(a) Contour of the electric potential (V).

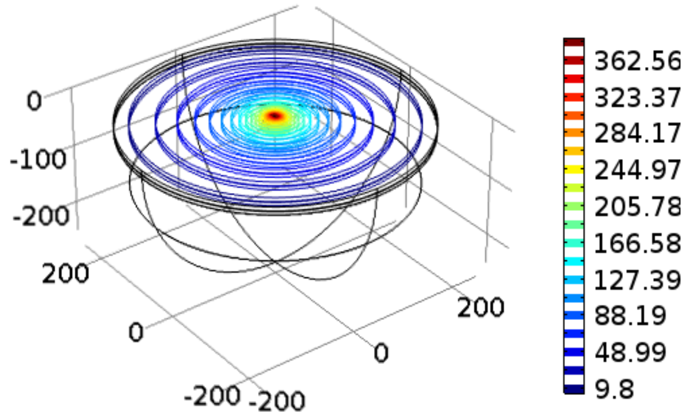


(b) Isosurface of the electric potential (V).

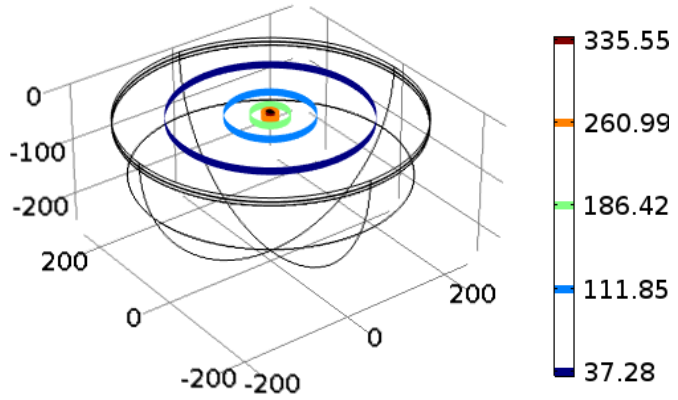


(c) Slice of the electric potential (V)

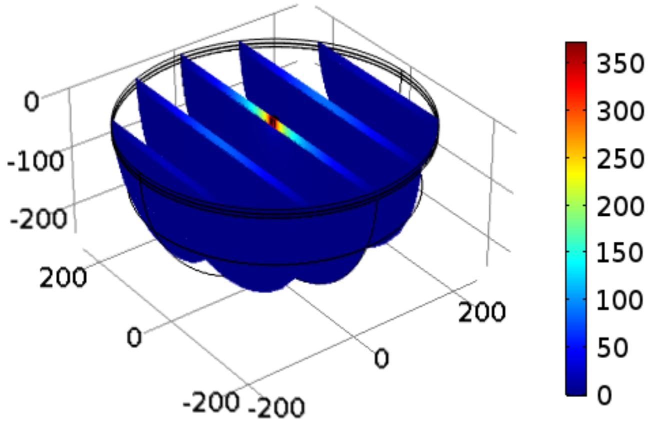
Figure 5. Electric Potential Evaluation for 1.5 m depth of the electrode



(a) Contour of the electric potential (V).

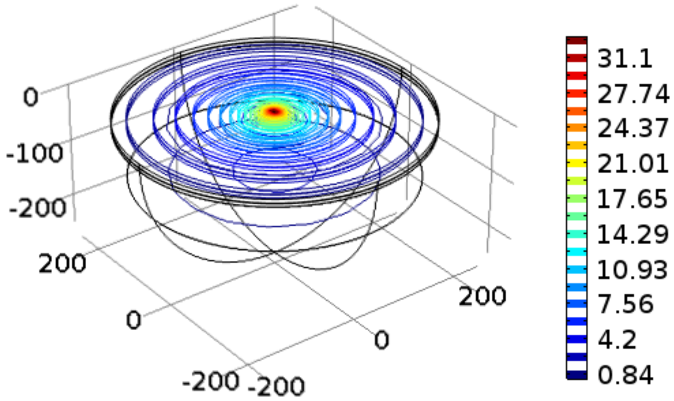


(b) Isosurface of the electric potential (V).

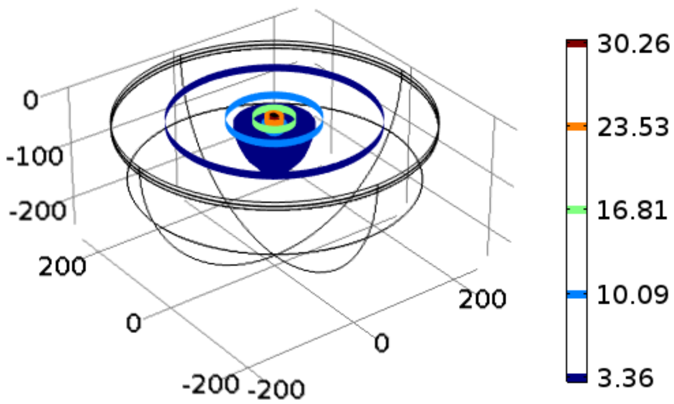


(c) Slice of the electric potential (V).

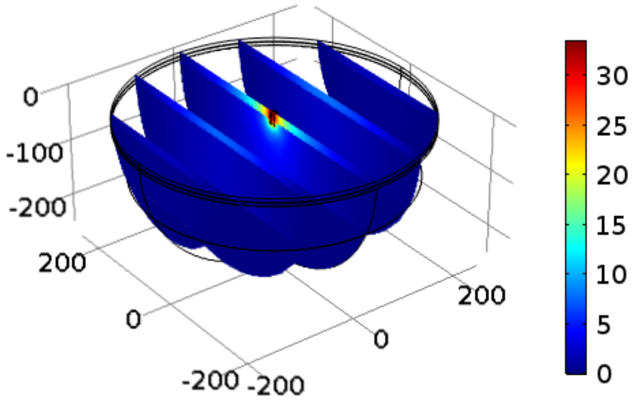
Figure 6. Electric Potential Evaluation for the electrode length 12.68 m.



(a) Contour of the electric potential (V).



(b) Isosurface of the electric potential (V).



(c) Slice of the electric potential (V).

Figure 7. Electric Potential Evaluation for the electrode length 21 m.

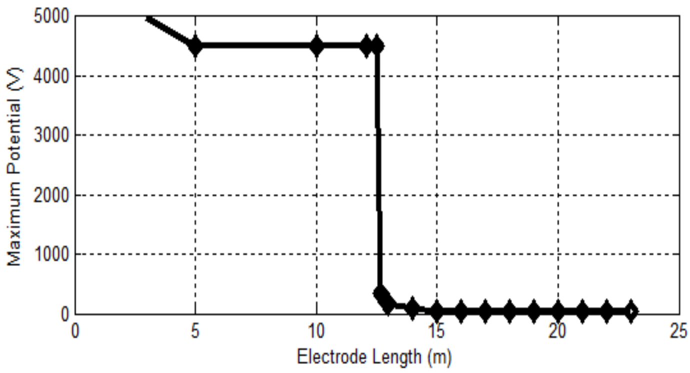


Figure 8. Maximum Potential Evaluation against the electrode length.

CONCLUSIONS

This paper presented the study of grounding system design for wind farms in Taif region, Saudi Arabia. By measuring the apparent resistivity, an optimization problem of minimizing the objective error function was designed using Sunde mathematical model of the apparent resistivity and then solved by the genetic algorithm with the aid of Matlab optimization toolbox. Based on the selected place of the field measurements, the optimized multi-layer soil parameters were estimated, and it was found that there was a very low soil layer resistivity, however at depth 14 m. Accordingly, the vertical rods of the grounding system that had length around 14 m were found the best modified design for attaining the best grounding system.

ACKNOWLEDGMENT

This work was supported by the research project grant number 5556-438-1, Scientific Research Deanship, Taif University. The authors acknowledge the faithful discussions with Dr. Sherif Ghoneim.

REFERENCES

[1] S. M. Shaahid, L. M. Al-Hadhrami, and M. K. Rahman, “Potential of Establishment of Wind Farms in Western Province of Saudi Arabia”, Energy Procedia 52, 2014, pp. 497 – 505.

[2] IEEE STD-142, “IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems”, 2007.

[3] IEC 61400-24, Wind Turbines – Part 24: Lightning Protection, 2010.

[4] P. Manikandan, M. Rajamani, P. Subburaj, and D. Venkatkumar, “Design and Analysis of Grounding Systems for Wind Turbines Using Finite Element Method”, International Conference on Emerging Trends in Electrical and Computer Technology, ICETECT 2011, 23-24 March 2011, Nagercoil, India.

[5] O. Ukar and I. Zamora, “Wind Farm Grounding System Design for Transient Currents”, Renewable Energy, vol. 36, No. 7, 2011, pp. 2004-2010.

[6] D. Cavka, D. Poljak, V. Doric, and R. Goic, “Transient Analysis of Grounding Systems for Wind Turbines”, Renewable Energy 43, 2012, pp. 284-291.

[7] A. M. Abd-Elhady, N. A. Sabiha, and M. A. Izzularab, "High-Frequency Modeling of Zafarana Wind Farm and Reduction of Backflow Current-Overvoltages", Int. Trans. Electr. Energ. Syst. 2014, 24, PP.457–476.

[8] V. T. Kontargyri, I. F. Gonos, and I. A. Stathopulos, "Study on Wind Farm Grounding System", IEEE Transactions on Industry Applications, vol. 51, NO. 6, Nov./Dec. 2015.

[9] W. P. Calixto, A. P. Coimbra, B. Alvarenga, and J. P. Molin, A. Cardoso, and L. M. Neto, "3-D Soil Stratification Methodology for Geoelectrical Prospection", IEEE Transactions on Power Delivery, vOL. 27, No. 3, July 2012

[10] D. Oliveira, W. P. Calixto, A. Alves, C. L. Borges, and I. Mota, "Multilayer Soil Parameters Estimation Optimization Using Genetic Algorithms", International Conference on Grounding and Earthing, 6th International Conference on Lightning Physics and Effects, Manaus, Brazil, May 2014.

[11] https://hurricane193.wordpress.com/tag/wenner-soil-resistivity-test-method/, available online Sep. 2017.

[12] F. Dawalibi, J. Ma, and R. Southey, "Behaviour of Grounding Systems in Multilayer Soils: A Parametric Analysis", IEEE Transactions on Power Delivery, vol. 9, No. 1, pp 334 – 342, 1994.

[13] L. Choun, C. Gomes, M. Kadir, and W. Ahmad, "Analysis of Earth Resistance of Electrodes and Soil Resistivity at Different Environments", International Conference on Lightning Protection (ICLP), 2-7 Sep. 2012, Vienna, Austria.

[14] I. Colominas, J. Parýs, D. Fernández, F. Navarrina, and M. Casteleiro, "A nNumerical Simulation Tool for Multilayer Grounding Analysis Integrated in an Open-Source CAD Interface", International Journal in Electrical Power and Energy Systems, vol. 45, No. 1, pp 353–361, 2013.

[15] T. Takahashi and T. Kawase, "Calculation of Earth Resistance for a Deep-Driven Rod in a Multi-layer Earth Structure", IEEE Transactions on Power De1ivery, vol. 6, No. 2, pp 608-614, 1991.

[16] J. Ma and F. Dawalibi, "Computerized Analysis of Grounding Plates in Multilayer Soils", IEEE Transactions on Power Delivery, vol. 24, No. 2, pp 650-655, 2009.

[17] S. Dessouky, S. Ghoneim, and S. Awad, "Grounding Resistance, Step and Touch Voltages for a Driven Vertical Rod into Two Layer Model Soil", International Conference on Power System Technology (POWERCON), 24-28 Oct. 2010, Hangzhou, China.

[18] M. Abd-Elrahman, "An Advanced Technique for Grounding System Analysis", IEEE Transactions on Power Delivery, vol. 28, no. 1, pp 268 – 275, 2013.

[19] G. Kamas, G. Maslowski, R. Ziembaand, and S. Wyderka, "Influence of Different Multilayer Soil Models on Grounding System Resistance", International Conference on Lightning Protection (ICLP), 2-7 Sep. 2012, Vienna, Austria.

[20] N. Nor, M. Trlep, S. Abdullah, and R. Rajab, "Investigations of Grounding Systems under Steady-State and Transients with FEM and Experimental Work", International Journal on Electrical Power and Energy Systems, vol. 44, No. 1, pp 758–763, 2013.

[21] K. Nixon, "The Lightning Transient Behavior of a Driven Rod Earth Electrode in Multi-Layer Soil, PhD thesis, University of the Witwatersrand, Johannesburg, 2006.

[22] B. Zhang, X. Cui, L. Li, and J. He, "Parameter Estimation of Horizontal Multilayer Earth by Complex Image Method", IEEE Transactions on Power Delivery, vol. 20, No. 2, pp 1394 – 1401, 2005.

[23] F. Ioannis and A. Ioannis, "Estimation of Multilayer Soil Parameters Using Genetic Algorithms", IEEE Transactions on Power Delivery, vol. 20, No. 1, pp 100-106, 2005.

[24] W. Calixto, L. Neto, M. Wu, K. Yamanaka, and E. Moreira, "Parameters Estimation of a Horizontal Multilayer Soil Using Genetic Algorithm", IEEE Transactions on Power Delivery, vol. 25, No. 3, pp. 1250 -257, 2010.

[25] H. Zhiqiang and Z. Bin, "Soil Model's Inversion Calculation Based on Genetic Algorithm", 7th Asia Pacific International Conference on Lightning, 1-4 Nov. 2011, Chengdu, China.

[26] W. P. Calixto, L. M. Neto, M. Wu, H. J. Kliemann, S. S.de Castro, K. Yamanaka, "Review Calculation of Soil Electrical Conductivity Using a Genetic Algorithm", Computers and Electronics in Agriculture 71, pp. 1-6, 2010.

[27] Mathworks, Optimization Toolbox™, Toolbox Solvers, https://www.mathworks.com/help/optim/index.html.

[28] E. D. Sunde "Earth Conduction Effects in Transmission Systems", MacMilan, New Yourk, 1968.

[29] H. A. Abdel-Ghany, A. M. Azmy, N. I. Elkalashy, E. M. Rashad "Optimizing DG Penetration in Distribution Networks Concerning Protection Schemes and Technical Impact" Electric Power System Research, Vol. 128, pp. 113-122, Nov. 2015.

[30] AC/DC Module user's guide, 1998-2015 COMSOL.