Modeling multi-layered soil by equivalent uniform and two-layer soil models in grounding applications

Marinko Barukčić, Nenad N. Cvetković, Željko Hederić, Toni Varga

The soil models are crucial for calculating the performances of the grounding systems in electrical engineering. Usually, some approximations and simplified calculation procedures are used in engineering practice. These procedures are based on the assumption of the uniform soil model. However, real soil consists of more layers with different resistivities/conductances and thickness. The procedure of obtaining equivalent uniform and two-layer soil models using an optimization approach and numerical simulation is presented here. The grounding system used in the simulations is the single grounding rod as one of the simplest grounding structures. The proposed procedure does not require approximations and neglecting during calculation of the grounding system performances due to using the simulation tool based on numerical method. The equivalent soil model determination through the optimization is performed by using the co-simulation setup between the metaheuristic optimization and numerical simulation tools.

Keywords – co-simulation, grounding system, optimization, soil modeling.

Introduction

In practice, calculation of the grounding system performances such are grounding resistance, touch and step voltages, are usually done according to some standardized procedure. These procedures are given in some standards such as IEEE Std 80 [1]. Two main things have an impact on the grounding system performances the system geometry and soil properties. The standardized procedures assume uniform soil due to simplification of the grounding system calculations in everyday engineering practice. Such approximation makes easier to perform calculations but decreases accuracy in real applications. Decreasing accuracy is due to the fact that the real soil is nonhomogeneous regarding resistivity/conductivity. The real soil can be modeled as multi-layered soil. The calculation procedures based on uniform (one-layer) soil give inaccurate results in this case. In the case of nonhomogeneous soil, some more complex calculation needs to be employed [2]. However, to make a usable standardized calculation procedure applicable for uniform and two-layered soil models in case of multi-layered soil the equivalent homogenous and two-layered soil models are proposed in the literature. The different techniques to obtain parameters of the equivalent uniform and two-layered soil based on measurement data are used in [1], [3].

In this research, the method for obtaining parameters of uniform and two-layer soil models is investigated. The method is based on using a numerical calculation of the grounding system by using the simulation tool and metaheuristic optimization method.

Description of the method

Thanks to the development of the computer techniques the simulation tools based on numerical mathematics methods (Finite Element Method – FEM, Finite Difference Method – FDM, Boundary Element method - BEM …) are available today for application in complex electromagnetic field calculations. These simulation tools have satisfactory accuracy in calculations of the real systems due to fewer approximations and neglecting during the model building process. Based on such features these methods are more and more used in the area of simulation grounding systems also. Thanks to such numerical methods the simulation tools for numerical simulation of the electromagnetic fields are used to analyze the grounding systems in presence of the multi-layered soil. Such an application of the numerical simulation tools can be found in [4]–[6].

Based on the above given it can be concluded that the numerical simulation tools give appropriate results and can be used for modeling multi-layer soil as it is stated in [4].

The parameters of multi-layer soil can be obtained from the measurement as can be seen in [7]. Also, there is the application of the metaheuristic optimization for determining parameters of the equivalent two-layer and multi-layer soil [6], [7].

The proposed procedure is based on the co-simulation approach of using FEM simulation and metaheuristic optimization tools as is presented in Fig.1.The difference from the existing application of the metaheuristic application in literature is using the numerical simulation tool in the optimization process in the co-simulation setup (Fig. 1) in this research.

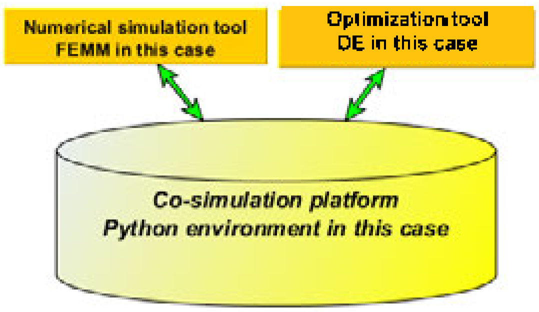

Fig.1. Used co-simulation setup.

The proposed procedure is performed through the next steps:

- Obtain simulation results for single grounding rod in multi-layered soil model using FEM simulation tool (this can be replaced with measured data obtained some of the method (for example Wenner approach))
- Find parameters of equivalent one and two-layer soil models by optimization using co-simulation of the FEM tool and optimization method
- Compare results for more complex grounding system for "real" soil and its uniform and two-layer models.

Definition of the optimization problem and optimization method

The general formulation of the optimization problem is in the form:

(1) $$f(\vec{x}) \to \min \quad subject\ to\ constraints,$$

where f is the problem objective function and $\vec{x}$ is the solution vector (decision variables vector).

Objective function

The single grounding rod is used in the simulations. The objective function is formulated as a square of value differences of simulations for multi-layer and one/two-layer soil models:

(2) $$f(\vec{x}) = \left(R_m - R_e(\vec{x})\right)^2 + \sum_{i=1}^{n} \left(V_{m,i} - V_{e,i}(\vec{x})\right)^2,$$

where R_m and R_e are grounding resistances for multi-layer model and for the equivalent one/two-layer model respectively, $V_{m,i}$ and $V_{e,i}$ are potential value on i-th distance from the rod for multi-layer and one/two-layer models respectively, n is a number of the point where potential is calculated.

The decision variables are conductances of the soil layers and thickness of the upper layer in case of the two-layer model or just conductance in case of the one-layer model:

(3) $$\vec{x} = \begin{cases} \sigma_1 \quad \sigma_2 \quad h_1 & \to two - layer\ soil \\ \quad\ \sigma & \quad\ one - layer\ soil \end{cases},$$

This means that it is a one-dimension and three-dimension optimization problem in case of the one-layer and two-layer models respectively

Constraints

Because the optimization problem has no any required constraints, the bound constraints of decision variables are only used here. The ranges (between lower and upper bounds – *lb* and *ub*) of each decision variable are defined by the bound constraint:

(4) $$x_{i,lb} \le x_i \le x_{i,ub}\ ,$$

Optimization method

Because the objective function is calculated by using the simulation tools, the metaheuristic optimization is used to solve the problem (1)-(3). The Differential Evolution (DE) as one of the very efficient metaheuristics is used here. The details of the used optimization algorithm can be found in [8]. The simulation tool used Finite Element Method (FEM) for calculation of the electromagnetic field is the Finite Element Method Magnetics (FEMM) [9].

Numerical examples

The three different designs of experiments are used to research the proposed procedure. All cases are for four-layer example of the soil. The first example has decreasing conductivity and increasing thickness of the layers depending on the depth. The second example has increasing conductivity and increasing thickness of the layers depending on the depth. The third example has random conductivity and thickness of the layers. The numerical data for these designs of the experiments are given in Table 1. The radius of the rod is 0.05 m, the rod length r_L is 2.2 m and the current value is 10 A. All above given numerical data are arbitrary that is any value can be used in the simulations. The voltage values used in (2) are obtained for the eighth distances from the rod on the ground surface: on the rod, 0.5, 1, 1.5, 2, 3, 4 and 5 meters. The bound constraints (3) used in the simulations are:

$$0 \le \sigma, \sigma_1, \sigma_2 \le 1 \qquad 0 \le h_1 \le 2 \cdot r_L. \tag{5}$$

Table 1

Overview of the design of experiments (DoE) used in the simulations

DoE	Layer	Conductivity [S/m]	Thickness [m]
1	1-2-3-4	0.05-0.04-0.02-0.01	0.2-0.5-0.8-∞
2	1-2-3-4	0.01-0.02-0.04-0.05	0.2-0.5-0.8-∞
3	1-2-3-4	0.01-0.02-0.06-0.02	0.8-1.0-0.5-∞

The obtained optimal values of the one and two-layer soil models, as well as the objective function values (OFv) and the grounding resistances for multi-layer soil and one/two-layer models are given in Table 2.

Table 2

Optimization results

DoE	One layer: σ [S/m] - OFv	Two-layer: σ_1-σ_2 [S/m] – h_1 [m] - OFv	Multi-layer *Rg* [Ω]	One-layer *Rg* [Ω]	Two-layer *Rg* [Ω]
1	0.01866-525.724	0.26181 0.01038-0.125-1.385	14.275	15.377	14.188
2	0.0404-13.145	0.02839-0.05178-1.546-0.067	7.274	7.261	7.268
3	0.02417-14.761	0.03502-0.02178-0.592-0.236	11.655	11.871	11.654

After the parameters of the equivalent one/two-layer soil models are obtained through the optimization these values are used to calculate quantities for the length of the rod different than used in the optimization. Such a simulation can give information about the applicability of the soil models in a more general case. The lengths of the rod of 1.2 and 3.2 m are used for the difference of the rod length of 2.2 m (basic length) used in the optimization. The results of these simulations are presented in Fig.3 and 4 for the rod length lower and higher than basic length respectively. The grounding resistances for these simulations are given in Table 3. As can be seen from these results (Fig.3 and 4 and Table 3) the parameters of the soil models (one and two-layer) cannot be used in general form (for any length of the grounding rod) in case of the one-layer model.

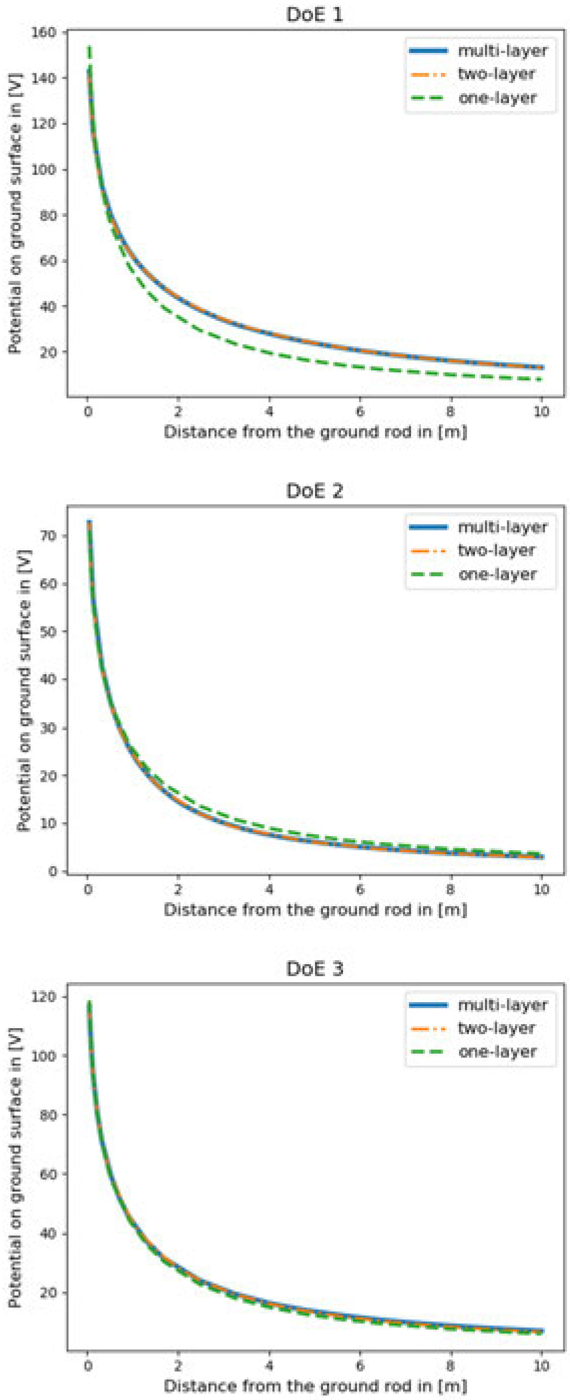

Fig.2. Comparison of the potential distribution on the ground surface for multi-layer soil and equivalent one/two-layer models for all used DoE – basic rod length.

In the case of the two-layer model the obtained model parameters give very good results for the case in which the rod length is higher than one used in the optimization process.

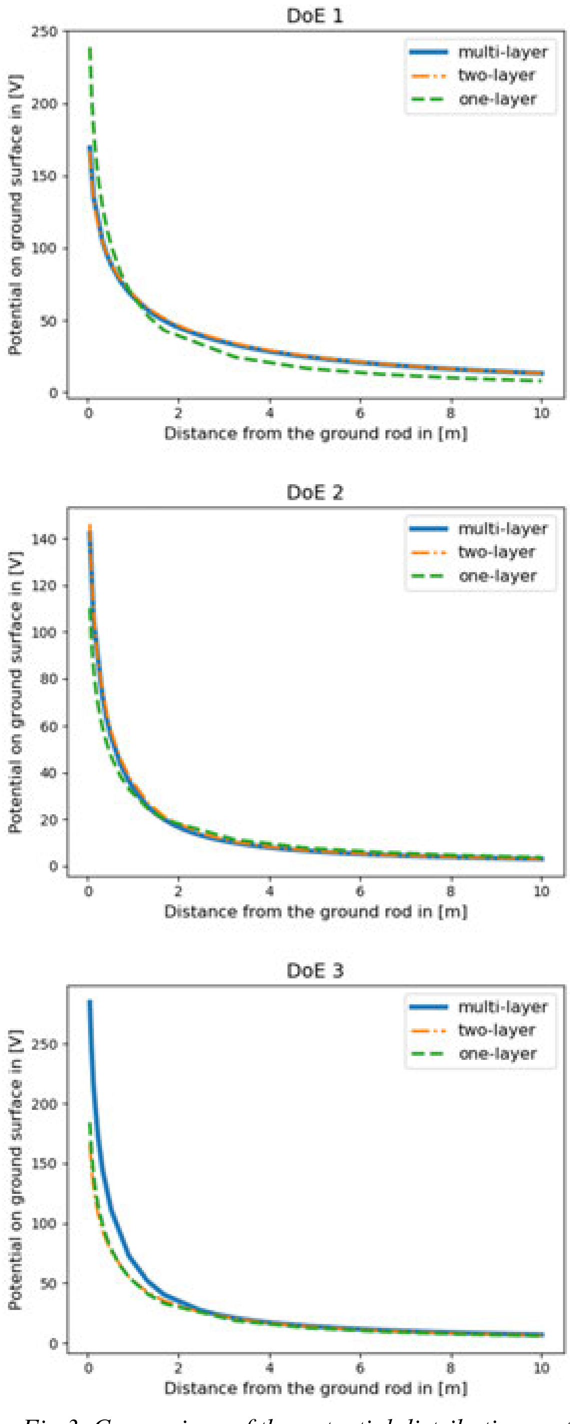

Fig.3. Comparison of the potential distribution on the ground surface for multi-layer soil and equivalent one/two-layer models for all used DoE – the rod length lower than one used in the optimization.

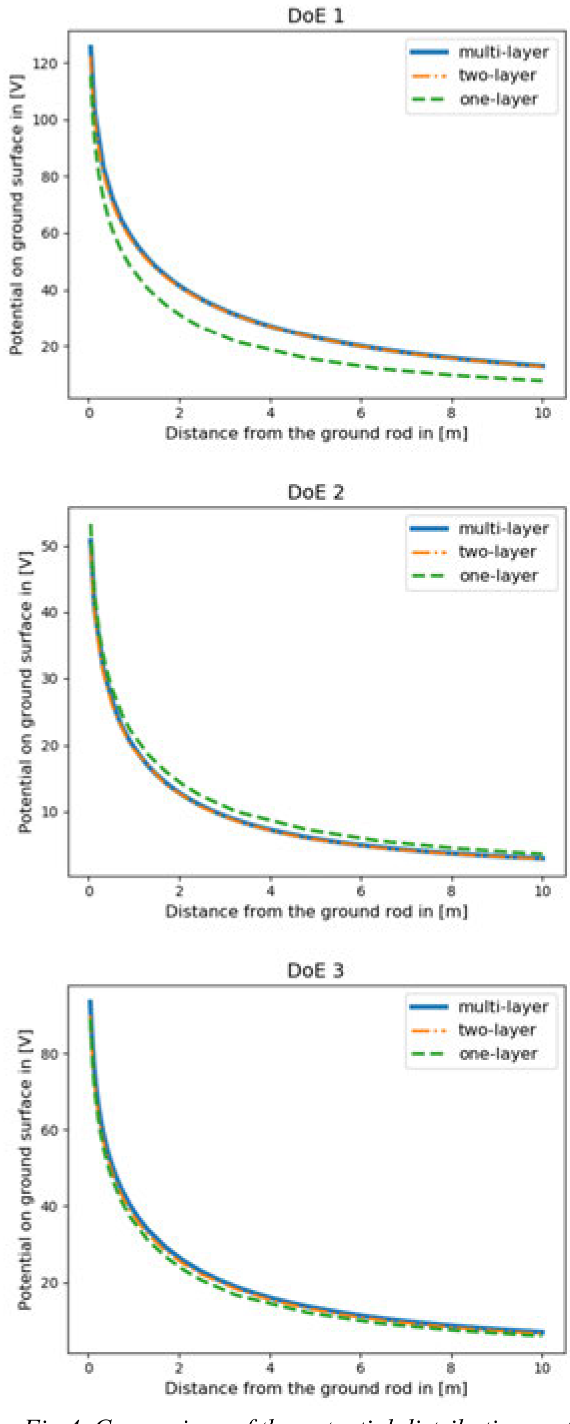

Fig.4. Comparison of the potential distribution on the ground surface for multi-layer soil and equivalent one/two-layer models for all used DoE – the rod length higher than one used in the optimization.

This indicates the need to take care of the rod length in possible practical measurement set to measure the grounding resistance and the voltage profile. This can be explained by the fact that the simulation results highly depend on the rod length.

The results presented in Table 3 indicate that one needs to be careful about the length of the rod in possible practical implementation of the presented procedure. This impact of the rod length on the simulation result is worth further research.

Table 3

The resistance of the grounding rod which length is different than the one used in the optimization

Rod length [m]	DoE	Multi-layer *Rg* [Ω]	One-layer *Rg* [Ω]	Error-one layer [%]	Two-layer *Rg* [Ω]	Error-two layer [%]
1.2	1	16.925	23.862	41.0	16.705	-1.30
	2	14.227	11.021	-22.5	14.624	2.79
	3	28.489	18.422	-35.3	16.682	-41.44
3.2	1	12.541	11.538	-8.00	12.233	-2.46
	2	5.077	5.329	4.96	4.978	-1.95
	3	9.349	8.907	-4.73	9.000	-3.73

Conclusion

The proposed method uses a simulation approach to find the parameters of the equivalent one and two-layer models of non-homogenous soil. The model parameters obtained through the proposed procedure can be used to apply in the method for calculating the grounding systems. Further research will be focused on applying the proposed method on more different non-homogenous soil examples to confirm using the proposed procedure in general, independent of the type of soil non-homogeneities.

Acknowledgments

This work has been supported in part by the Croatian Science Foundation under the project number UIP-05-2017-8572.

This paper is reported in the 14-th International Conference on Applied Electromagnetics – ПЕС 2019, Niš, Serbia.

REFERENCES

[1] 80-2013 IEEE Guide for Safety in AC Substation Grounding.

[2] N. Cvetkovic, M. Barukcic, D. Jovanovic, and Z. Hederic, “Single Wire Grounding Electrode that penetrates Hemi-spherical Non-homogeneity,” 2018 International IEEE Conference and Workshop in Óbuda on Electrical and Power Engineering (CANDO-EPE), 2018, pp. 000207–000210.

[3] A. George and M. Soni, “Estimation of two layer soil parameters using traditional and evolutionary methods,” Int. J. Sci. Eng. Res., vol. 8, no. 7, 2017.

[4] M. Brenna, F. Foiadelli, M. Longo, and D. Zaninelli, “Particular grounding systems analysis using FEM models,” in 2018 18th International Conference on Harmonics and Quality of Power (ICHQP), 2018, pp. 1–6.

[5] A. Martins, S. Mariano, and M. do Rosario Calado, “The IEEE Model for a Ground Rod in a Two Layer Soil – A FEM Approach,” in Finite Element Analysis - New Trends and Developments, InTech, 2012.

[6] I. Gonos and I. Stathopulos, “Estimation of multi-layer soil parameters using genetic algorithms,” in IEEE Power Engineering Society General Meeting, 2004., vol. 2, pp. 1037–1037.

[7] R. T. Senthilkumar, “Optimization of soil parameters in multiple layers of ground structure,” in 2017 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2017, pp. 1–5.

[8] R. Storn and K. Price, “Differential Evolution – A Simple and Efficient Heuristic for Global Optimization over Continuous Spaces,” J. Glob. Optim., vol. 11, pp. 341–359, 1997.

[9] D. C. Meeker, “Finite Element Method Magnetics, Version 4.2 (28Feb2018 Build),” 2019. [Online]. Available: http://www.femm.info/wiki/HomePage. [Accessed: 28-Jul-2019].

Marinko Barukčić *- received his B.Sc., M.Sc. and Ph.D. degrees in electrical engineering from the Faculty of Electrical Engineering, J.J.Strossmayer University of Osijek, in 1998, 2008 and 2012, respectively. He is currently an associate professor at the Faculty of electrical engineering, computer science and information technology Osijek, J.J.Strosmayer University of Osijek. His research interest is application of the computational intelligence in electrical engineering, especially in power engineering.*

tel.:+385 31 224 685 e-mail: marinko.barukcic@ferit.hr

Nenad N. Cvetković *- received the Dipl. Ing, M.Sc. and Ph.D. degrees from the Faculty of Electronic Engineering of University of Niš in 1995, 2002 and 2009, respectively. He is an associate professor at the Department of Theoretical Electrical Engineering, Faculty of Electronic Engineering of Niš. His research interests are numerical methods in electromagnetics, especially in grounding systems theory, transmission lines analyze and biomagnetic. He has published about 130 papers in international journals or conference proceedings, two monographs, one monograph chapter, and two textbooks.*

e-mail: nenad.cvetkovic@elfak.ni.ac.rs

Željko Hederić *- received his B.Sc. and Ph.D. degrees in electrical engineering from the Faculty of Electrical Engineering, J.J.Strossmayer University of Osijek, in 1996 and 2008, respectively. He received his M.Sc. from the Faculty of Electrical Engineering and Computing, Zagreb, in 2002. He is currently full professor at the Faculty of electrical engineering, computer science and information technology Osijek, J.J.Strosmayer University of Osijek. His research interest is in the area of electrical machines, hybrid electrical vehicles, numerical methods, and electromagnetic field theory.*

e-mail: zeljko.hederic@ferit.hr.

Toni Varga *- received his Bachelor's Degree in 2014 and Master Degree in Electrical Engineering in 2017 from the Faculty of Electrical Engineering in Osijek. His past employments include working as a Quality Assurance Engineer for network operators and Embedded Software Engineer for consumer electronics in a startup company. He is also a Vicepresident of the Croatian Speedcubing Association and is currently working at the Faculty of electrical engineering, computer science, and information technology Osijek as a Research Assistant with the interest in the application of computational intelligence in machine control.*

e-mail: toni.varga@ferit.hr.

Received on: 30.08.2019