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OPTIMIZATION OF GROUNDING SYSTEM USING EVOLUTIONARY ALGORITHM

Abstract: *The electrical resistance of the grounding system has a highly nonlinear character concerning the geometrical parameters, especially in the case of nonhomogeneous soil. Hence, the optimization procedures for such grounding systems are very complex. In this paper, a co-simulation frame is used for the realization of the mentioned optimization. The frame includes two available computer simulation tools, one designed for numerical simulation of the electromagnetic field and the other one specialized for evolutionary optimization. It is applied on the vertical ground rod electrode and the grounding system consisted of two ring electrodes.*

Keywords: conductivity profile, evolutionary computation, grounding, non–homogeneous media, optimization, soil properties.

INTRODUCTION

Generally, the purpose of all grounding systems, regardless of their shape and design, is to conduct fault current into the surrounding soil safely and without consequences for the working environment. In order to provide this feature, a requirement is that the grounding system resistance value is as low as possible. Improperly installed grounding system must lead the fault current and lightning-induced currents into the surrounding soil, ensuring maximum safety and without consequences for the working environment and electrical equipment. Very often, the grounding system is designed with a grid electrode as the main ground electrode [1-13]. It contains several rod electrodes connected to each other, usually in a square or rectangular shape. The number of rod electrodes in the grid depends on the required value of the grid electrode resistance. Because of that, internal meshes are performed in order to reduce grounding resistance. The procedures for calculation of grounding system characteristics placed in the nonhomogeneous ground, such as grounding resistance or surface potential distribution, are usually very complex, even in the case of the simple grounding systems. Therefore, the nonhomogeneous soil is usually modelled as a two or three-layered model. There are variously proposed and published optimization approaches used for grounding systems optimization. Some of them use different mathematical programming techniques, while others are based on heuristic methods. Research results published in the existing literature usually deal with the optimization of the grounding mesh for different objects in the power network. In [1], different population-based and near to global optimization methods are applied for optimization of the grounding grid of the planned power plant. The objective function is calculated using the analytical expression and Particle Swarm Optimization (PSO). Genetic Algorithm (GA) and its hybrids are used for achieving the optimal design of the grounding system. The GA as an optimization method is used in [2] while

Evolutionary Strategy (ES) is used in [3] to optimize ground grid design. The authors have used dynamic programming as an optimization technique in [4] to find the optimal design of the ground mesh. In [5], the authors have applied linear programming to optimize the grounding system. Optimization software tools including linear programming are used in [6] to find the optimal configuration of the grounding grid. In [7], the proposed optimization process includes a variety of values, driven by the user instead of using an optimization technique for grounding mesh optimization. A similar approach is also presented in [8], where the user changes a grounding system design based on the fulfillment of conditions in the proposed optimization process. A closed-form analytical expression or a solution to systems of equations is usually used to obtain objective function value in grounding system optimization as in [1–3, 5-6, 8]. Thanks to the development of different numerical methods and computer techniques, the simulation tools for the calculation of grounding system characteristics have been widely used in recent times. Such simulation tools based on the numerical method are used in [4, 7]. In [4], the authors have implemented the Finite Element Method (FEM) into the MATLAB environment and used dynamic programming for optimization. In [7], ETAP and FEMM software (both based on FEM) have been used to calculate the objective function but, as emphasized earlier, any specific optimization algorithm has not been used. In [9], the procedures based on Green's functions and the Method of Moments (MoM) [10] are used for grounding system calculation.

Unlike methods presented in the existing literature, the co-simulation approach for finding the optimal design of the grounding system has been proposed in this paper. There are software tools specialized for electromagnetic field simulation based on numerical methods, such as the FEM method. In addition, software tools specialized for optimization are also available. There are several reasons why the co-

simulation approach has been proposed. In the case of nonhomogeneous soil, in the literature presented above, two-layered and in some cases three-layered ground models have been usually used. However, some researches indicate that the real soil can have more than 2 or 3 layers [11–12]. Besides, in [13] the 3–D layered ground model of non-straight layer boundaries is presented. In these cases, the characterization of the grounding system based on analytical methods can be very complex. On the other hand, software tools based on numerical mathematical methods can handle such a complex problem. The procedure based on the idea of co-simulation which includes using these tools and tools specialized for evolutionary optimization for solving the complex problem of grounding system optimization in multi-layered soil is presented in this paper. This is different from the approaches used in the above-mentioned literature that use analytical calculation and optimization algorithms within some programming environment. The approach proposed here differs from those in [7] because they used FEM software for grounding calculations, but without an optimization method. Also, the proposed approach differs from the procedure presented in [4] because it used the FEM method and optimization algorithm implemented inside the same programming environment.

The details of the proposed co-simulation procedure are described in the paper. The procedure is applied to several examples.

CO-SIMULATION FRAMEWORK

The proposed co-simulation framework for the optimal design of the grounding system is based on the existing and available numerical simulation, as well as on the evolutionary optimization tools. The main idea is illustrated in Figure 1. The software for simulation of electromagnetic field based on numerical methods gives only the numerical value as the output for given input data. There is no information about the objective function, only its numerical value. For this reason, using such tools in the optimization problem requires the black-box optimization approach. That approach includes using heuristic global optimization techniques which can deal with this type of objective function. Because of this, the Evolutionary Algorithm (EA) is used in the proposed procedure. The EAs belong to the class of the global optimizers, population-based and near to global optimum methods. The main feature of the EAs is the search of the solution space in a parallel process, by which it is possible to avoid getting stuck on the local optimum. There are a lot of different EAs methods, very well covered in the literature, dealing with soft computing techniques. Among different evolutionary optimization tools, the MIDACO (Mixed Integer Distributed Ant Colony Optimization) solver [14] is chosen to be used here. It is based on the ACO technique and can be applied for solving general single/multi-objective optimization problems [15]. It is a powerful and easy EA optimization tool, very suitable

for co-simulation since it is available for different programming languages. For electromagnetic field simulation FEM based FEMM [16] software tool is used in the paper because it can communicate through its COM/ActiveX interface. FEMM can be easily driven from MATLAB/Octave, Scilab and Mathematica software because it has built-in functions for it. Also, thanks to the FEMM COM interface, it can be driven from any programming language. The Python programming environment is used as a co-simulation platform for simultaneously using MIDACO and FEMM tools, as is shown in Figure 1. The communication with FEMM is performed using the FEMM call2femm function. MIDACO distribution intended for Python programming language is implemented in the co-simulation. Its use is realized through the standard Python command (function definition) and built-in interface for the MIDACO dll library. In the proposed framework, the FEMM tool is used to calculate required data for determining the objective function value, which can be obtained from FEMM directly or calculated in a co-simulation platform (Python in this case) using results ensured by FEMM. Afterwards, the MIDACO solver realizes the optimization process performing evolutionary operators (generating new solutions, selecting the next population, evaluate solution goodness), giving the solution at the end of the process. FEMM solver calculates objective functions and sends their values to MIDACO. Then, the MIDACO solver generates improved solutions and sends them back to FEMM in the closed-loop.
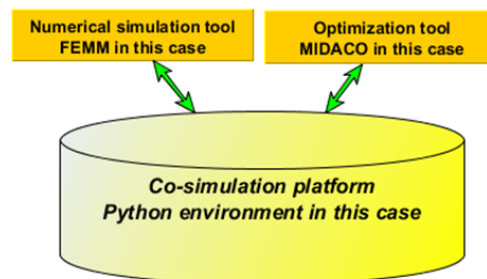

Figure 1. *The proposed co-simulation framework for electromagnetic numerical simulation and evolutionary optimization tools*

The general form of the single and multi-objective optimization problems are defined as in (1) and (2) respectively,

$$f_{SO}(dv) \to \min, g_e(dv) = 0, g_{in}(dv) > 0,$$
$$dv_l \le dv_i \le dv_u, \forall i \in \{1, 2, ..., n\} \quad (1)$$

and

$$f_{MO}(dv) = [f_1, f_2, ..., f_m] \to \min, g_e(dv) = 0,$$
$$g_{in}(dv) > 0, dv_l \le dv_i \le dv_u, \forall i \in \{1, 2, ..., n\}. \quad (2)$$

where f_i is the i-th objective function, g_e is a set of equality constraints, g_{in} is set of inequality constraints, dv_i is i–th problem decision variable and dv_l and dv_u are

lower and upper limits of the decision variable values, respectively.

In the case of the multi-objective optimization (2), the Pareto definition of the non-dominated solution is used in order to obtain the Pareto front approximation.

The different preparation level of the geometry parameters and material properties in the FEMM file used in the co-simulation can be applied. The FEMM file can be generated inside the co-simulation environment i.e. no FEMM file is needed to be predefined. Another possibility is to make the FEMM file, consisting of the defined problem type and geometry and material parameters, which do not change during the optimization process. Then, in such a predefined file, the changeable entries of the grounding system are added during the optimization. This approach is used here in the paper.

The next section describes the application of the proposed co-simulation framework on several examples applying single and multi-objective optimization procedures.

SIMULATION RESULTS

The simulations presented in this section are realized under the assumption that a multi-layered soil profile is given since this is not the subject of the research. They are done for two artificially generated examples of the soil profiles (named as A and B) having parameters given in Table 1. Profile A corresponds to the ground vertical rod, Figure 2, while the grounding system formed from two rings placed in the same plane corresponds to profile B, Figure 2. In both cases, single and multi-objective simulations are performed.
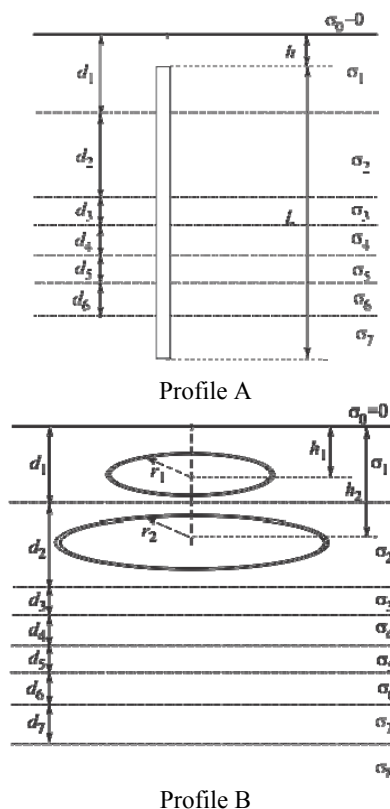

Profile A

Profile B

Figure 2. *Profiles A and B and geometry of the simulated grounding systems*

Table 1. *Examples of multi-layered soil profiles used in simulations*

Layer number i	Profile A		Profile B	
	Layer conductivity σ_i [S/m]	Layer thickness d_i [m]	Layer conductivity σ_i [S/m]	Layer thickness d_i [m]
1	0.020	0.3	0.0017	0.5
2	0.150	0.3	0.0025	2.0
3	0.400	0.4	0.0500	2.0
4	0.006	1.0	0.0025	1.5
5	0.100	1.5	0.0020	1.0
6	0.005	1.5	0.0015	1.0
7	0.001	∞	0.00125	2.5
8	–	–	0.0010	∞

Decision variables in the case of optimization of the vertical rod are buried depth (h) (depth of the upper end of the rod) and the rod length (L). The single objective optimizations for grounding vertical rod are performed for two cases: the first one, when the objective function consists of the grounding resistance (R_g), and the second one when the objective function is aggregated from the grounding resistance and length of the rod. This function has a weighting coefficient w that has a role to bring numerical values of two parts of the objective function to a similar level. Besides this, the weighting coefficient equalizes measurement units of two function parts (w is in [Ω/m]). The inequality constraint defining the maximal step voltage is used in this case. The multi-objective optimization for the rod is performed for the following cases: the first one is two objectives (grounding resistance and length of the rod) optimization and the second one is three objectives (the resistance, the rod length and the step voltage (U_s) placed above the rod) optimization.

The multi-objective optimization has inequality constraints that refer to the maximal step voltage. Decision variables in the case of optimization of the grounding rings are depths (h_1, h_2) and radii (r_1, r_2) of each ring. The objective function in the case of the single-objective optimization is aggregated from touch (U_t) and step (U_s) voltages considering the maximum of these voltages as inequality constraints. In the case of multi-objective optimization, grounding touch and step voltage are the objective functions. Constraints in this case are the maximum step and touch voltages. The described simulation overview is given in Table 2. It is important to emphasize that in the following tables, prefix SO labels single-objective optimization, while MO corresponds to the multi-objective optimization. Simultaneously, added numbers correspond to the number of objective functions.

In simulations of the grounding rod, the radius of the rod is set to 0.035 m. The decision variable ranges are for h, 0–5 m, and L, 0.1–10 m.

Table 2: *Properties of the performed simulations*

Simulation notation	Optimization type	Objective function	Constraints	Decision variables
SO1–rod	single	R_g	$U_s \leq U_{smax}$	h, L
SO2–rod	single	$R_g + wL$	$U_s \leq U_{smax}$	h, L
MO2–rod	multi	$[R_g, L]$	$U_s \leq U_{smax}$	h, L
MO3–rod	multi	$[R_g, L, U_s]$	$U_s \leq U_{smax}$	h, L
SO–ring	single	$U_t + U_s$	$U_s \leq U_{smax}$ $U_t \leq U_{tmax}$	h_1, h_2, r_1, r_2
MO2–ring	multi	$[U_t, U_s]$	$U_s \leq U_{smax}$ $U_t \leq U_{tmax}$	h_1, h_2, r_1, r_2

Table 3: *Optimal results for SO1–rod and SO2–rod problems*

Problem	Objective function value	R_g [Ohm]	h [m]	L [m]	U_s [V]
SO1–rod	4.372	4.372	0.9787	10.00	48.65
SO2–rod	4.879	4.598	0.9820	2.811	49.70

Table 4: *The Pareto front edges for MO2–rod and MO3–rod problems*

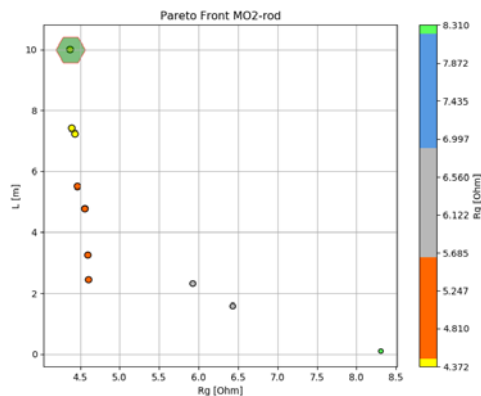| Problem	Objective function 1 R_g [Ohm]	Objective function 2 L [m]	Objective function 3 U_s [V]	h [m]
MO2–rod	4.37100	10.000	–	0.9787
MO2–rod	8.3010	0.1000	–	0.4996
MO3–rod	4.3140	9.8967	49.269	0.9767
MO3–rod	199.59	0.1000	1.4955	4.4202
MO3–rod	51.402	9.6138	0.4374	5.0000

Figure 3. *Pareto front for MO2–rod optimization problem*

Weighting coefficient w in SO2-rod objective function is set to 0.1. It is the experimentally determined value based on numerous problem-solving. In the case of grounding rings, it is assumed that the iron strip with a cross-section 25×4 mm is used for their realization. The decision variable ranges in this case are given as: for h_1 0.5–2.5, for h_2 0.5–2.5, for r_1 0.5–5, and for r_2 0.5–5. The touch and step voltage constraints are set at 50 V.

In Table 3 the simulation results for optimal grounding system designs considering single objective optimizations (with objective function given in Table 2) are shown.

The simulation results for multi-objective optimizations in the case of vertical grounding rod are given in Table 4. Figures 3 and 4 show the Pareto fronts as the optimization results in these cases.

Simulation results for the grounding rings are presented in Tables 5 and 6. In Figure 5, an estimation of the Pareto front for the MO3–ring problem is given. In Figure 6 the ground potential distribution is given for this optimal solution.
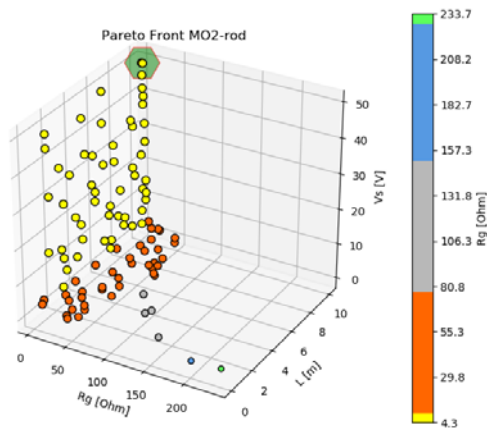
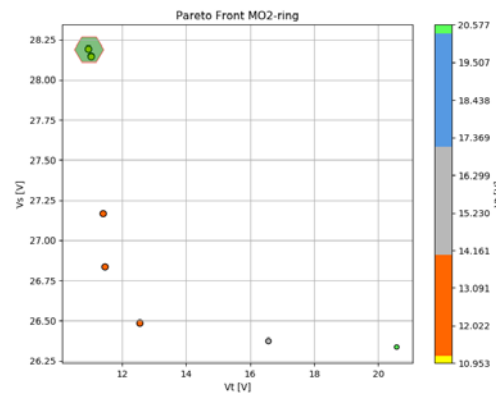**Figure 4.** *Pareto front for MO3–rod optimization problem*

Figure 5. *Estimation of the Pareto front for MO2–ring optimization problem*

Table 5. *Optimal results for SO–ring problem*

Objective function value	R_g [Ohm]	r_1 [m]	h_1 [m]	r_2 [m]	h_2 [m]	U_t [V]	U_s [V]
43.26	3.352	2.434	0.7191	5.00	2.50	15.50	27.76

Table 6. *Pareto front edges for MO2–ring problem*

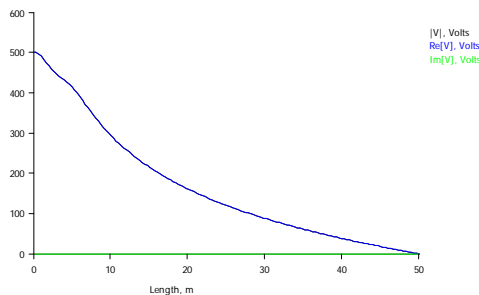| Objective function value 1 U_t [V]	Objective function value 2 U_s [V]	R_g [Ohm]	r_1 [m]	h_1 [m]	r_2 [m]	h_2 [m]
10.95	28.19	3.360	2.124	0.5236	5.00	2.50
20.57	26.34	3.357	1.381	0.7466	5.00	2.50

Figure 6 *Ground voltage distribution for the solution with minimum touch voltage for MO2–ring problem*

The discussion about simulation results is given below. In cases of single objective optimizations, it is interesting to notice that there is a big difference in vertical rod length. In case when grounding resistance is the only objective, the optimization algorithm sets the rod length to the upper bound. This is reasonable and expected since the grounding resistance decreases with the increase of the rod length. If the rod length is added together with the resistance in the aggregated objective function, the result of the optimization is the design that gives the resistance close to the one obtained for the SO1-rod problem but with rod length cca 3.5 times shorter (Table 3). The multi-objective optimizations give more choices of the grounding rod design because the result is not a single solution but the solution set in form of the Pareto fronts (Figure 2 and 3). In this case, the decision-maker can choose the best solution. The Pareto fronts give an overview of the sensitivity of the grounding resistance on the rod length change. Based on such an overview, one can estimate

which increasing limit value of the rod length is useful and after which value the increase of the length has a low impact on the resistance decrease. In the case of the grounding rings system optimization, one can conclude that there are solutions with a large difference in the touch voltage, but a very small difference between step voltage values (Table 6). Also, it can be noticed that the optimization algorithm tries to move the position of the outer ring to the upper values for a given multilayered soil profile.

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CONCLUSION

The proposed approach decreases programming effort for solving the grounding optimization problem in the engineering practice in case of the complex multi-layered ground model. It provides a simple way to optimize some grounding systems in the case of the multi-layered soil. Simulation results indicate that the proposed approach has the capability of solving such a demanding optimization. Further research will be focused on applying the proposed method for practical problems which include more different non-homogeneous soil examples, to confirm the possibility of using the proposed procedure in general, independently on the type of soil non-homogeneities. There are no limits on the complexity of the soil conductance depth profile, and that is the main advantage of the proposed framework. The main

drawback of the proposed method can be computational time because many simulations are required by the EA, and in this case, simulations are performed by using the FEM software. On the contrary, such optimization is not required to be solved in real-time. Using the computer with better performance and parallelization of the EA process the problem can be solved within an acceptable time.

REFERENCES

[1] B. Alik, M. Teguar, A. Mekhaldi: "Minimization of grounding system cost using PSO, GAO, and HPSGAO Techniques", IEEE Transactions on Power Delivery, Vol. 30, 2015, pp. 2561–2569.

[2] Q. Zhang, X. Wu: "Software development of optimal substation ground grid design based on genetic algorithm and pattern search" North American Power Symposium (NAPS), Pullman, WA, USA, 2014, pp.1-6.

[3] S. Ghoneim, H. Hirsch, A. Elmorshedy, R. Amer: "Optimum grounding grid design by using an evolutionary algorithm", Power Engineering Society General Meeting, Tampa, FL, USA, 2007.

[4] E. A. Cano-Plata, O. J. Soto-Marín, G. Jiménez-Lozano, J. H. Estrada-Estrada: "Power grounding optimization", American Journal of Computational Mathematics, Vol. 5, 2015, pp. 243–252.

[5] H. M. Khodr, A. Machado e Moura, V. Miranda: "Optimal design of grounding system in transmission line", International Conference on Intelligent Systems Applications to Power Systems (ISAP), Toki Messe, Niigata, Japan, 2007, pp, 1–9.

[6] H. Khodr, G. Salloum, V. Miranda: "Grounding system design in electrical substation: an optimization approach", IEEE/PES Transmission & Distribution Conference and Exposition: Latin America, Caracas, Venezuela, 2006, pp.1–5.

[7] U. Uma, L. Uzoechi, B. Rober: "Optimization design of ground grid mesh of 132/33 kV substation using ETAP", Nigerian Journal of Technology, Vol. 35, 2016, pp. 926-934.

[8] S. Patted, S. Goudappanavar: "Optimization of the earthing system in industrial plant", Proceedings of IRF International Conference, 2015, Mumbai, India, 2015, pp. 7–11.

[9] D. D. Vuckovic, N. N. Cvetkovic, M. S. Stojanovic, I. Iatcheva: "Approximate model for ground inhomogeneity with rectangular cross section: application to analysis of grounding systems", Electrical Engineering, Vol. 100, 2018, pp. 75-82.

[10] R. F. Harrington: "*Field computation by moment methods*", IEEE Press, 1993.

[11] B. Borchers, T. Uram, J. M. H. Hendrickx: "Tikhonov regularization of electrical conductivity depth profiles in field soils", Soil Science Society of American Journal, Vol. 61, 1997, pp. 1004-1009.

[12] T. Islam, Z. Chik, M. M. Mustafa, H. Sanusi: "Estimation of soil electrical properties in a multilayer earth model with boundary element formulation", Mathematical Problems in Engineering, Volume 2012, 2012, pp. 1-13.

[13] W. P. Calixto, A. P. Coimbra, B. Alvarenga, J. P. Molin, A. Cardoso, L. M. Neto: "3-D soil stratification methodology for geoelectrical prospection", IEEE Transactions on Power Delivery, Vol. 27, 2012, pp. 1636–1643.

[14] M. Schlüter, M. Gerdts, J-J Rückmann: "A numerical study of MIDACO on 100 MINLP benchmarks". A Journal of Mathematical Programming and Operations Research, Vol. 61, 2012, pp. 873–900.

[15] M. Schlüter, J. A. Egea, J. R. Banga: "Extended ant colony optimization for non-convex mixed integer nonlinear programming", Computers & Operations Research, Vol. 36, 2009, 2217–2229.

[16] D. C. Meeker, "Finite Element Method Magnetics", Version 4.2, http://www.femm.info.

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OPTIMIZACIJA UZEMLJIVAČKOG SISTEMA PRIMENOM EVOLUCIONARNOG ALGORITMA

Nenad N. Cvetković, Marinko Barukčić, Dejan B. Jovanović

Rezime: Zavisnost otpornosti uzemljivačkog sistema od geometrijskih parametara ima nelinearni karakter, naročito izražen u slučaju nehomogenog tla, što usložnjava proces optimizacije uzemljenja. U radu je za ovu svrhu predložena jedna kosimulaciona procedura koja ekvivalentira nehomogenu zemlju domenom jednostavnije strukture. Procedura uključuje dva programska alata, jedan za proračun elektromagnetnog polja i drugi za evolucionarnu optimizaciju. Njena primena ilustrovana je na primeru vertikalne štapne uzemljivačke elektrode i uzemljivačkog sistema formiranog od dve prstenaste elektrode.

Ključne reči: raspodela provodnosti, evolucionarni proračun, uzemljenje, nehomogena sredina, karakteristike tla.