Optimum Grounding Grid Design by using Genetic Algorithms

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Abstract

Grounding systems are necessary for safety of people to be exposed to dangerous voltages during any fault and for equipment by keeping their proper operation. In design of grounding grids, it is important to minimize the cost of grounding grid by considering tolerable touch voltage and step voltage values defined in regulations. For this purpose it is necessary use an optimization tool in order to have an effective design. In this paper, a method for designing grounding grids by using a genetic algorithm is presented. The aim is to minimize the cost function of the grounding grid, while the design parameters are kept according to limits defined by IEEE-Std-80. For the design of the grounding system, which comprises of 100 m × 100 m square grounding grid and ensures tolerable touch and step voltages at reasonable costs, Genetic Algorithm (GA) has been utilized. This design has been made with uniform soil model, and grid parameters which are effective at touch and step voltages have been determined via GA method. Furthermore, burying depths and rod lengths have been compared in order to keep the costs at minimum level. During the studies Matlab has been used for the genetic algorithm application. Different parameters have been studied in order to see the effectiveness of the proposed method and designed grid has been compared with real grounding grids, validating the proposed solution.

1. Introduction

For the power system design one of the most important issues is to design an affective grounding grid meeting the requirements of the regulations such as IEEE-Std-80 as well as providing a low cost solution. The purpose of grounding circuit is to provide a way for the fault currents enabling protection circuit to take necessary action. These currents may result in unsafe situation for people or equipment in case required grounding system is not available. Therefore, step and touch voltage at any point of the installation should not exceed the maximum allowable values.

In general, grids are comprised of buried conductors as grounding circuit. When the amount of grid resistivity is above the limits additional rods can be connected to the circuit in order to reduce the overall resistivity. The cost of the grid depends on the type and size of the conductors, total length of the conductors and installation cost. Fault current defines the minimum size and material type of the conductors by considering magnitude and duration of the fault current.

In the literature, there are studies dealing with finding the optimum solution for grounding grid design by considering cost concerns as well as performance of the grid. In the study [1], an optimization methodology based on the use of response surfaces and genetic algorithms is used for the design of a grounding grid. Similarly fast and efficient adaptive sampling algorithm to obtain the response surface of multivariable objective function is presented in [2]. A mathematical model was described to compute parameters of grounding grids by considering the influences of reflective coefficient of two layer soil and the thickness of upper-layer soil, the irregular grounding grid area in [3]. Effects of high fault currents on ground grid design and detailed design criteria are discussed in study [4]. GA based method for grounding grids design has been presented in [5]. Reference [6] presents software development of optimal substation ground grid design based on genetic algorithm and pattern search. A genetic algorithm method is proposed for the design of grounding grid on the structures of two-layer soil model and grid designs with and without grounding rods [7]. The same authors designed an optimum grounding grid for high voltage stations with GATAT software written in Matlab, based on Genetic Algorithms [8]. In thesis [9], which is the backbone of this paper, design of optimum grounding grid by using genetic algorithms has been realized.

In this paper, a new scheme for designing a grounding grid based on genetic algorithm has been proposed. Although, here, only square grids are considered, the method is applicable to grounding systems design with other shapes.

2. Grounding Grid Design

When designing a grounding grid for a power system, it is crucial to define grounding conductor cross sectional area, maximum touch and step voltages of that grid, maximum values of step and touch voltages defined by regulations and grounding resistance of the whole system.

The objective of grounding grid design is to form a conductor grid comprises of buried conductors that ensures safety of people and equipment revealing safe operation of the system with minimum conductors. Therefore the problem becomes an optimization issue in order to obey safety regulations but to keep the cost as low as possible.

As a starting point, it was thought that genetic algorithms would ease the selection of design parameters. Grounding resistance shall be less than 1 Ω for a common assumption. For the design of grounding grid with genetic algorithm it is required to define fitness functions where the related parameters be optimized. In this study, as the control parameters depth of ground grid, length of grounding rods, touch voltage, step voltage and grounding conductor cross sectional have been selected. Here, maximum touch and step voltages are defined by the regulations given in IEEE-Std-80.

In this study, square shaped grounding grid has been studied. As the output of the analysis, step voltage, touch voltage, grounding resistance, conductor cross sectional area, and cost have been optimized. When forming genetic algorithm based analysis tool Schwarz grounding method has been considered. The grounding grid that will be designed is selected as 100 m × 100 m. Step and touch maximum voltage levels are taken as boundary conditions. The number of populations and generations has been selected as 100 and 30, respectively. The soil resistivity is 50 Ω.m. By using these parameters genetic algorithm routine has been run and obtained results have been verified with real data from the transformer stations located in Turkey.

First thing to find is the total resistance of the system. Equation (1) gives the mesh resistance [10, 11].

$$R_{11} = \frac{\rho}{\pi \cdot L_c}\left[ln\left(\frac{2 \cdot L_c}{l_r\sqrt{(d_0 \cdot h)}}\right) + k_1 \cdot \frac{L_c}{\sqrt{A}} - k_2\right] \quad (1)$$

where;

ρ	Soil resistivity (Ω.m),
L_c	Total buried strip conductor length (m),
l_r	Rod length (m),
d_0	Strip conductor diameter (m),
h	Grid burial depth (m),
k_1, k_2	Schwarz parameters,
A	Grid area (m^2).

When dealing with square grounding meshes Schwarz parameters can be accepted as k_1 = 1.4 ve k_2 = 5.6 by not considering burial depth. On the other hand, resistance component related to conductors are given in (2) and mutual resistivity in (3). Overall resistivity is found by using (4) [11].

$$R_{22} = \frac{\rho}{\pi \cdot n \cdot lr}\left[ln\left(\frac{8 \cdot lr}{d}\right) + \frac{2 \cdot k_1 \cdot lr}{\sqrt{A}} \cdot (n-1) - 1\right] \quad (2)$$

$$R_{12} = \frac{\rho}{\pi \cdot L_c}\left[ln\left(\frac{2 \cdot L_c}{l_r}\right) + k_1 \cdot \frac{L_c}{\sqrt{A}} - k_2 + 1\right] \quad (3)$$

$$R = \frac{R_{11} \cdot R_{22} - R_{12}^2}{R_{11} + R_{22} - 2 \cdot R_{12}} \quad (4)$$

where;

ρ	Soil resistivity (Ω.m),
n	Rod number,
l_r	Rod length (m),
L_c	Total buried strip length (m),
d	Rod diameter (m),
k_1, k_2	Schwarz parameters,
A	Grid area (m^2).

Mesh voltage E_m is calculated by using (5). This value shall be always less than the maximum allowable touch voltage [12].

$$E_m = \frac{\rho I_G K_m K}{L_c + [1.55 + 1.22(\frac{L_r}{\sqrt{(l_x^2 + l_y^2)}})] \cdot L_r} \quad (5)$$

Spacing factor (K_m) for mesh voltage is given in below.

$$K_m = \frac{1}{2\pi}\left[ln\left(\frac{D^2}{16hd} + \frac{(D+2h)^2}{8Dh} - \frac{h}{4d}\right) + \frac{K_{ii}}{K_h} ln\left(\frac{8}{\pi(2n-1)}\right)\right] \quad (6)$$

$$n_a = 2L_c/L_p \quad (7)$$

$$n = n_a \cdot n_b \cdot n_c \cdot n_d \quad (8)$$

For the square grid;

$$n_a = n_b = n_c = n_d = 1 \quad (9)$$

$$K_h = \sqrt{1 + (h/h_0)} \quad (10)$$

$$K_{ii} = 1/(2n)^{2/n} \quad (11)$$

$$K = 0.644 + 0.148 \cdot n \quad (12)$$

where;

D	Spacing between parallel conductors (m),
h	Depth of ground grid conductors (m)
d	Diameter of grid conductor (m),
n	Geometric factor composed of factors n_a, n_b, n_c, and n_d
h_0	Grid reference depth
K	Correction factor for grid geometry,
K_m	Spacing factor for mesh voltage,
K_h	Corrective weighting factor that emphasizes the effects of grid depth,
K_{ii}	Corrective weighting factor that adjusts for the effects of inner conductors on the corner mesh,
L_c	Total length of grid conductor (m)
L_p	Circumference of the grid (m)
L_r	Total length of ground rods (m)
I_G	Maximum grid current that flows between ground grid and surrounding earth (A),
l_x	Maximum length of grid conductor in x direction (m)
l_y	Maximum length of grid conductors in y direction (m)
ρ	Soil resistivity (Ω.m)

On the other hand, step voltage (between a point above the outer corner of the grid and a point 1 m diagonally outside the grid), which is another important parameter for mesh design is given in (13) [10].

$$E_s = \frac{\rho I_G K_s K_{ii}}{0.75L_c + 0.85L_r} \quad (13)$$

$$K_s = \frac{1}{\pi}\left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D}(1 - 0.5^{(n-2)})\right] \quad (14)$$

$$K_{ii} = 1 \quad (15)$$

where;

ρ	Soil resistivity (Ω.m)
I_G	Maximum grid current that flows between ground grid and surrounding earth (A),
K_s	Spacing factor for step voltage,
K_{ii}	Corrective weighting factor,
L_c	Total length of grid conductor (m)
L_r	Total length of ground rods (m)
D	Spacing between parallel conductors (m),
h	Depth of ground grid conductors (m)
n	Geometric factor composed of factors n_a, n_b, n_c, and n_d

Maximum step voltage for 70 kg person;

$$E_{step70} = (1000 + 6C_s\rho_s) \cdot 0.157/\sqrt{t_s} \quad (16)$$

Where touch voltage for 70 kg person,

$$E_{touch70} = (1000 + 1.5C_s\rho_s) \cdot 0.157/\sqrt{t_s} \quad (17)$$

where;

C_s	Surface layer derating factor,
ρ_s	Surface layer resistivity (Ω.m),
t_s	Fault duration (s).

When there is no surface layer $C_s = 1$. For the conductors, selection is made according to IEEE-Std-81-2012 [13]. For the fitness function below given expression is used,

$$F = C + L_s + [P \cdot (E_m - E_{touch})] \tag{18}$$

where;

GPR Ground Potential Rise = $I_G.\rho$ (19)

C Cost

P Penalty factor for contribution correction, in order to balance the parameters weights.

E_m Mesh voltage (V),

E_{touch} Touch voltage (V).

3. Genetic Algorithms

GA is a class of stochastic algorithm based on the biological evolution in the natural world. John Henry Holland is the first researcher who proposed Genetic Algorithm (GA) in 1975 [14]. It has three operators: a) selection and reproduction, b) crossover and c) mutation [9].

Fig. 1 presented a flowchart of genetic algorithm. In this study, the algorithm given in Fig. 1 is followed in order to define design outputs of optimum grounding grid for case studies.

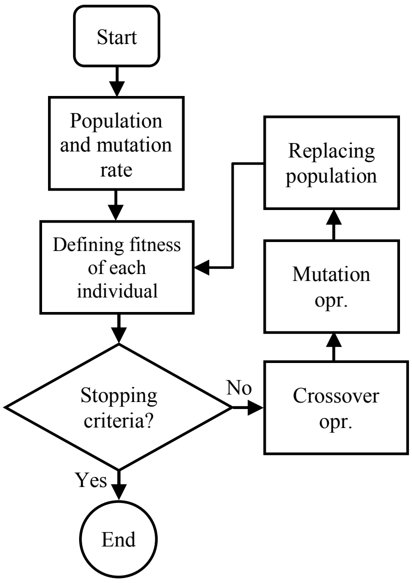

Fig. 1. Flowchart of genetic algorithm.

The steps of genetic algorithms are given below [9];

1) Generate the population size of individuals.
2) Calculate each of the fitness value of those individuals.
3) If stopping criterion is met, the procedure would go to the end; otherwise, proceed to step (4).
4) Reproduce individuals by using the method of roulette wheel selection.
5) If the random number is smaller than Pc, individuals will proceed crossover operator; otherwise, proceed step (6).
6) If the random number is smaller than Pm, individuals will implement mutation operator otherwise, proceed to next.
7) Replace current population, then implement back to step (2).

4. Results

Necessary proposal that should be followed to define grounding grid design parameters were explained in Section 2. Obtained results by using the proposed scheme are given in the following tables. Table 1 indicates the sample inputs and GA design outputs.

Table 1. GA design results.

Inputs		GA Results	
Population	100	Grid depth (m)	0.685
Maximum generations	30	Conductor space (m)	4.18
Soil resistivity (Ω.m)	50	Total conductor length (m)	5860
Surface layer resistivity (Ω.m)	2500	Rod number	10
Surface layer thickness (m)	0.15	Total rod length (m)	25
Rod length (m)	2.5	Mesh voltage (V)	773.02
Rod diameter (m)	0.020	Cost	6350.25
Length of grounding surface (m)	100	Maximum touch voltage (V)	866.34
Width of grounding surface (m)	100	Step voltage (V)	424.86
Short circuit current (A)	20000	Maximum step voltage (V)	2789.3
Fault duration (s)	0.5	Grounding res. (Ω)	0.3458

Table 2 shows the 154 kV transformer station inputs with two different set of parameters as Set-1 and Set-2. The design outputs of genetic algorithm are also given in that table. During the studies optimization problem has been exercised with changing different parameters. Real values from this substation are used to validate our findings.

Table 2. 154 kV transformer station results.

Inputs			GA Results		
	Set-1	Set-2		Set-1	Set-2
Population	50	100	Grid depth (m)	0.685	0.6643
Maximum generations	50	30	Conductor space (m)	4.1882	4.2307
Soil resistivity (Ω.m)	67.9	50	Total conductor length (m)	3975.5	4230.72
Surface layer resistivity (Ω.m)	2500	2500	Rod number	10	35
Surface layer thickness (m)	0.15	0.15	Total rod length (m)	25	87.5
Rod length (m)	2.5	2.5	Mesh voltage (V)	610.51	499.28
Rod diameter (m)	0.022	0.025	Cost	84220	138940
Length of grounding surface (m)	112.5	100	Maximum touch voltage (V)	613.57	866.34
Width of grounding surface (m)	74	100	Step voltage (V)	683.86	384.82
Short circuit current (A)	25000	20000	Maximum step voltage (V)	1983.3	2799.30
Fault duration (s)	1	0.5	Grounding resist. (Ω)	0.349	0.304

As it is seem from Table, change in soil resistivity does not introduce a remarkable change in fitness function but step and touch voltage do affect on fitness function. When Table 2 and Table 3, which is given below, are compared, decrease in grounding resistance is seen.

Surface layer thickness and surface layer resistivity is another important parameter since it is preferred in real applications. Table 3 compares the effect of surface layer thickness.

Table 3. Results of 154 kV transformer station design with changed parameters.

Inputs			GA Results		
	Set-1	Set-2		Set-1	Set-2
Population	100	100	Grid depth (m)	0.62	0.60
Maximum generations	35	30	Conductor space (m)	9.0526	13.464
Soil resistivity (Ω.m)	40	40	Total conductor length (m)	1487.3	1100.7
Surface layer resistivity (Ω.m)	2500	3500	Rod number	4	4
Surface layer thickness (m)	0.15	0.3	Total rod length (m)	10	10
Rod length (m)	2.5	2.5	Mesh voltage (V)	840.81	1191.9
Rod diameter (m)	0.025	0.025	Cost	33281	24705
Length of grounding surface (m)	102	100	Maximum touch voltage (V)	865.96	865.42
Width of grounding surface (m)	66	100	Step voltage (V)	473.37	516.99
Short circuit current (A)	20000	20000	Maximum step voltage (V)	2796.2	2853.5
Fault duration (s)	0.5	0.5	Grounding resist. (Ω)	0.219	0.267

Table 3 indicates that increase in surface layer thickness results in reduced total length of conductor. Step and touch voltage levels are higher. By considering these, cost is reduced.

Effect of burial depth is studied and obtained results for the same station are given Table 4 for the two different burial depth.

Table 5 compares the rod length effect. When the tables are reviewed it is seen that the same amount of resistivity obtained, but with changed cost. As it can be seen from Table 5, there is no remarkable effect of rod length on step and touch voltages, but cost has been affected.

Different design parameters are used in our study in order to see the effectiveness of the proposed solution for optimum grounding design and designed grid parameters have been compared with real grounding grids.

As seen from the given tables, genetic algorithm based optimum grounding grid design enables user to define design derivers such as rod number, conductor space, grid depth and cost by using the defined inputs. In addition, mesh, step, maximum touch voltage levels and overall grounding resistance values are calculated.

Table 4. Design parameter inputs and outputs for different burial depth.

Inputs			GA Results		
	0.5 m Rod depth	1 m Rod depth		0.5 m Rod depth	1 m Rod depth
Population	100	100	Grid depth (m)	0.60	0.60
Maximum generations	30	30	Conductor space (m)	13.464	13.464
Soil resistivity (Ω.m)	50	50	Total conductor length (m)	989.28	1100.7
Surface layer resistivity (Ω.m)	3500	3500	Rod number	3	4
Surface layer thickness (m)	0.1	0.1	Total rod length (m)	7.5	10
Rod length (m)	2.5	2.5	Mesh voltage (V)	1015.9	1015.9
Rod diameter (m)	0.025	0.025	Cost	22705	24705
Length of grounding surface (m)	100	100	Maximum touch voltage (V)	1020.25	1020.25
Width of grounding surface (m)	0.5	1	Step voltage (V)	516.99	516.996
Short circuit current (A)	20000	20000	Maximum step voltage (V)	2853.5	2853.5
Fault duration (s)	0.5	0.5	Grounding resist. (Ω)	0.247	0.267

Table 5. Simulation results for 3 m and 2.5 m rod lengths.

Inputs			GA Results		
	3 m Rod	2.5 m Rod		3 m Rod	2.5 m Rod
Population	100	100	Grid depth (m)	0.67	0.76
Maximum generations	30	30	Conductor space (m)	3.93	3.93
Soil resistivity (Ω.m)	83.32	83.32	Total conductor length (m)	3242	3242
Surface layer resistivity (Ω.m)	2500	2500	Rod number	6	6
Surface layer thickness (m)	0.15	0.15	Total rod length (m)	18	15
Rod length (m)	3	2.5	Mesh voltage (V)	828	800
Rod diameter (m)	0.020	0.020	Cost	6890	6995
Length of grounding surface (m)	98	98	Maximum touch voltage (V)	869	850
Width of grounding surface (m)	67	67	Step voltage (V)	1024	1024
Short circuit current (A)	25000	25000	Maximum step voltage (V)	2810	2750
Fault duration (s)	0.5	0.5	Grounding resist. (Ω)	0.48	0.48

5. Conclusions

In this study genetic algorithm based optimum grounding grid design is proposed. The objective of the study is to find optimum design parameters such as required length of conductors, conductor distance, required number of rods, mesh voltage, step voltage, grounding resistance and minimum cost value by meeting the technical requirements defined by regulations such as IEEE-Std-80 for safety.

Designed grounding system comprises of 100 m × 100 m grounding grid ensuring tolerable touch and step voltages. As the output of the analysis, step voltage, touch voltage, grounding resistance, conductor cross sectional area and cost have been optimized according to defined optimization scheme for grounding grid design defined in this study. Beside finding optimum solution for the grounding grid, effect of different design parameters have studied such as burial depth, rod length, soil resistivity, surface layer thickness and resistivity. Although, here, only square grids are considered, the method is applicable to grounding systems design with other shapes by following the same optimization solution.

6. References

[1] C. C. Mauricio, et al., "Optimization of grounding grids by response surfaces and genetic algorithms", *IEEE Trans. Magn.*, vol. 39, no. 3, pp. 1301 -1304, 2003.

[2] J. Zou, J. Guo, B. Zhang, J. L. He, J. Lee, "Creating Multivariable Response Surfaces by the Two-Stage Adaptive Sampling Techniques and Its Application in the Optimization of Grounding Grid", *IEEE Transaction on magnetic*, vol. 42, no. 4, April 2006.

[3] Y. Yang, M. Peng, H. Hong, and Y. Yuan, "Optimal Design of Grounding Grids Based on Genetic Algorithm", *3rd International Conference on Genetic and Evolutionary Computing* (*WGEC*), Guilin, 14-17 October 2009.

[4] M. Mitolo , P. E. Sutherland and R. Natarajan, "Effects of high fault currents on ground grid design", *IEEE Trans. Ind. Appl.*, vol. 46, no. 3, pp. 1118 -1124, 2010.

[5] A. F. Otero, J. Cidras, C. Garrido., "Genetic Algorithm Based Method for Grounding Grids Design" *IEEE International Conference on Evolutionary Computation*, *World Congress of Computational Intelligence*, pp. 120-123, 1998.

[6] Q. Zhang, X. Wu, "Software Development of Optimal Substation Ground Grid Design Based on Genetic Algorithm and Pattern Search", *North American Power Symposium* (*NAPS*), 07-09 September 2014.

[7] B. Gursu, M. C. Ince, "Design of Grounding Grid With and Without Grounding Rod in Two-Layer Soil Model via Genetic Algorithms", *Journal of Engineering and Natural Sciences*, Sigma 26, pp. 247-266, 2008.

[8] B. Gursu, M. C. Ince, "Designing of the Optimum Grounding Grid for High Voltage Stations via Genetic Algorithms", *Science and Engineering Journal of Fırat University*, vol. 19, no. 4, pp. 511-524, 2007.

[9] S. Kara, "Design of Optimum Grounding Grid by Using Genetic Algorithms", B.S. thesis, Electrical Engineering Dept., Istanbul Technical University, Istanbul, 2013.

[10] *IEEE Guide for Safety in AC Substation Grounding*, IEEE Standard 80-2000.

[11] M. Bayram, "Grounding in Electrical Installations", Birsen Press, Istanbul, Turkey, 2000.

[12] *Effects of Current on Human Beings and Livestock—Part 1: General Aspects*, IEC 60479-1, 3rd ed., Sept. 1994.

[13] *IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Grounding System*, IEEE Standard 81-2012.

[14] J. H. Holland, "Adaptation in Natural Artifical System: An Introductory Analysis with Applications to Biology, Control, and Artificial Intelligence", Ann Arbor, the University of Michigan Press, 1975.