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OPTIMAL DESIGN OF ELECTRICAL GROUNDING SYSTEMS USING GENETIC ALGORITHMS

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Abstract - Projects of grounding systems must respect the safety limits and a limit of resistance that is a function of the voltage class. This study aims to find the best combination of parameters that make the most economic project possible without breaching the standardized limits of security, this is possible using Genetic Algorithms (GA) where the design of the grounding system is not only done in an automatic way but optimally. As a form of validation of the presented methodology, it is compared with well-known literature projects and also a project made from real measurement data.

1 - INTRODUCTION

Projects of grounding systems should have a step potential; touch potential and a grounding resistance below a limit in order to provide security to those who are in a substation at the time of a short circuit. The complete methodology for the design of a grounding system is found in the IEEE 80 standard [1], where from the field measurement of electrical resistivity by the Wenner method at the substation area, the level and the duration of the short circuit is possible to determine the constructive characteristics of the project.

Figure 1 – Soil resistivity field test at Federal University of Ceará: removing auxiliary rods with a lever. Source: own elaboration

This paper seeks to improve a project of a grounding grid using the methodology proposed in the IEEE 80 standard together with an optimization meta-heuristic aiming at reducing the cost with electrical material. The design is done in such a way that makes it as economical as possible within the standardized limits of security.

2 - DESIGN OF GROUNDING SYSTEMS ACCORDING TO THE IEEE 80 STANDARD

An initial stage of the project combined with the sizing of conductors is the determination of the safety limits, which are taken based on the equivalent uniform soil resistivity ρ of the local of the substation for a person of 50 or 70kg. These safety limits can be improved with the insertion of a surface layer consisting of a high resistivity material like crushed rock. The value of the correction index for the surface layer C_s is given by equation (1), where h_S is the thickness of the surface layer.

$$C_s = 1 - \frac{0.09\left(1 - \frac{\rho}{\rho_s}\right)}{2\mathrm{h}_s + 0.09} \tag{1}$$

The limit value of step potential E_{step} is calculated by equation (2), where t_s is the maximum operating time of the protection.

$$E_{step} = \left(1000 + 6\mathrm{C}_s\rho_s\right)\frac{0.157}{\sqrt{t_s}} \tag{2}$$

In an analogous way the limit value of the touch potential E_{touch} is calculated by equation (3).

$$E_{touch} = \left(1000 + 1.5\mathrm{C}_s\rho_s\right)\frac{0.157}{\sqrt{t_s}} \tag{3}$$

The value of the grounding resistance of a ground mesh is calculated by equation (4) where L_t is the effective length of the conductor, h is the mesh depth and A is the area of the ground system.

$$R_g = \rho\left[\frac{1}{L_t} + \frac{1}{\sqrt{20\mathrm{A}}}\left(1 + \frac{1}{1 + h\sqrt{20/A}}\right)\right] \tag{4}$$

The value of the maximum mesh potential rise in relation to a remote earth point E_m is given by equation (5), being K_m and K_i adjustment coefficients, I_G the single phase short-circuit current and L_m a function of the length of vertical and horizontal conductors.

$$E_m = \frac{\rho K_m K_i I_G}{L_M} \tag{5}$$

The value of the correction factor K_m is given by equation (6), being D the largest spacing between parallel conductors, d the diameter of the mesh forming conductors, K_{ii}, K_h and n correction factors.

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

For a mesh with ground rods distributed in the periphery the value of K_{ii} is equal to one, if there is no rods or only a few, it is given by equation (7).

$$K_{ii} = \frac{1}{(2\mathrm{n})^{\frac{2}{n}}} \tag{7}$$

The value of K_h is given by equation (8).

$$K_h = \sqrt{1+h} \tag{8}$$

The correction factor n is given by equations (9-11).

$$n = n_a n_b n_c n_d \tag{9}$$

The value of n_a is given by equation (10),

$$n_a = \frac{2\mathrm{L}_c}{L_p} \tag{10}$$

where the value of n_b is equal to one for square meshes and given by equation (11) otherwise,

$$n_b = \sqrt{\frac{L_p}{4\sqrt{A}}} \tag{11}$$

the value of n_c is equal to one for square and rectangular grids, the value of n_d is equal to one for square, rectangular and "L-shape" meshes. The other cases shown in the standard are not discussed in this paper so that the value of K_i is given by equation (12).

$$K_i = 0.644 + 0.148n \tag{12}$$

The value of L_M is given by equation (13) where L_C is the cable length, L_R is the length of the rods, L_x and L_y are the maximum distances in the mesh on x and y directions respectively.

$$L_M = L_C + \left[1.55 + 1.22\left(\frac{L_y}{\sqrt{L_x^2 + L_y^2}}\right)\right]L_R \tag{13}$$

If the mesh has only a few rods that are not located on its periphery or edges, equation (13) becomes the equation (14).

$$L_M = L_C + L_R \tag{14}$$

The value of the step potential E_S at the periphery of the mesh is given by equation (15),

$$E_S = \frac{\rho K_S K_i I_G}{L_S} \tag{15}$$

where L_S is given by equation (16),

$$L_S = 0.75L_C + 0.85L_R \tag{16}$$

and K_S is given by equation (17).

$$K_S = \frac{1}{\pi}\left[\frac{1}{2\mathrm{h}} + \frac{1}{D+h} + \frac{1}{D}\left(1-0.5^{n-2}\right)\right] \tag{17}$$

For a project be considered valid $E_m < E_{touch}$ and $E_S < E_{step}$ with the grounding resistance value less than the limit specified for the substation voltage class.

3 - GENETIC ALGORITHMS

Genetic algorithms (GA) are an area of evolutionary algorithms that can be defined as a search technique based on a metaphor of the biological process of natural evolution [3], these algorithms use global optimization heuristic techniques based on the mechanisms of natural selection and genetics. GA's consists of the creation of populations of individuals who are subjected to genetic operators of selection, crossover and mutation. These operators use a characterization of the quality of each individual as a solution to a specific problem called evaluation or fitness, generating a process of natural evolution of these individuals.

For the proposed GA a population of 20 individuals, within a specified range of values is used. The chromosome is encoded as a vector of real numbers consisting of the number of conductors parallel to the x direction (N_x), number of conductors parallel to the y direction (N_y) and the quantity of ground rods (N_h). The roulette wheel selection algorithm was used, it was adopted a fixed rate of crossover and mutation with a crossover rate of 90% and a mutation rate of 1%. To preserve the best solution in the course of 20.000 generations it was also considered the elitism where the best solution is transferred to the next generation.

The fitness function has been implemented as the cost in reais (the Brazilian currency) of the electrical material taken from the price list of a large supplier of the state of Ceará in Brazil. For projects that do not comply with safety limits a penalty of 10 times the value of the fitness was applied for one potential condition breakdown, 100 times its value if don't respect two maximum potential limits and an additional 10 times the fitness value if it does not respect the ground resistance limit.

Note that when a limit is not satisfied the project cost do not reflects the real one, but the convergence of the solution in an optimization meta-heuristic depends on it so that the optimal solution will be the best solution as possible without despising the less fit solutions at the evolutionary process. The fitness value at the last generation of a suitable project corresponds to the real value of the project at the lowest possible cost.

3 - APPLICATION OF THE PRESENTED METHOD

The methodology presented in this work was tested with design examples of the references [1,6,7] and also a complete design example with real field data measurements of the soil electrical resistivity.

For each project was considered the reserved area for the grounding system, the model of the soil and the short circuit characteristics. Models taken from [1] and [6] were made considering a uniform soil model; the project with real data and the one from the reference [7] were made by stratifying the soil with the optimization algorithm developed by [4]. The apparent resistivity or the homogeneous soil equivalent was calculated with data stratification methodology applying the method proposed by [5] so that the cost of electrical material was optimized respecting the safety limits calculated in equations (2) and (3).

3.1 - CASE STUDY 1

For this case study it was simulated a design for a 72.5kV voltage class substation found in reference [6], it was used ground rods of 2.4m length being the price of the coppered rod equal to R$ 7.30 and the price of copper cable 35 of mm² equal to R$ 10.65. The soil was modeled as homogeneous with the resistivity value equal to 411.8$\Omega \cdot m$ in an area of 40x50m, the level of short-circuit was 1200A with a maximum operating time of the protection of 0.6s, it was also adopted a layer of crushed rock of 20cm thick as a surface layer.

3.2 - CASE STUDY 2

For this case study it was simulated a design of a 72.5kV voltage class substation found in reference [1] using 35mm² cables. The soil was modeled as a homogeneous with resistivity value equal to 400$\Omega \cdot m$ in an area of 70x70m, the level of short-circuit was 1908A with the maximum protection operating time of 0.5s , it was used a 10cm thick crushed rock as a surface layer.

3.3 - CASE STUDY 3

For this case study the data was identical to the case study 2, but ground rods were included in the project.

3.4 - CASE STUDY 4

For this case study was simulated the design of a 15kV voltage class substation with real field data measurement in a terrain located at Federal University of Ceará using ground rods of 2.4m and cables of 35mm² in the project. Figure 2 shows the sketch of the field measurements, where the letters "A" through "F" indicates the position of the six measurement lines made.

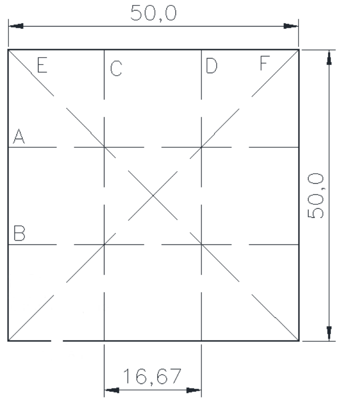

Figure 2 – Lines of measurements. Source: own elaboration

The soil was modeled from field measurements data according to the methodology proposed by [2] on an area of 50x50m, the short-circuit was 1200A with a maximum protection operating time of 0.5s, it was adopted a 10cm thick crushed rock as a surface layer.

3.5 - CASE STUDY 5

For this case study was simulated a design for a 15kV voltage class substation with the soil resistivity measurement data as found in the reference [7]. For this project were used 2.4m ground rods and cables of 35mm², the dimensions of this aerial substation are shown in Figure 3.

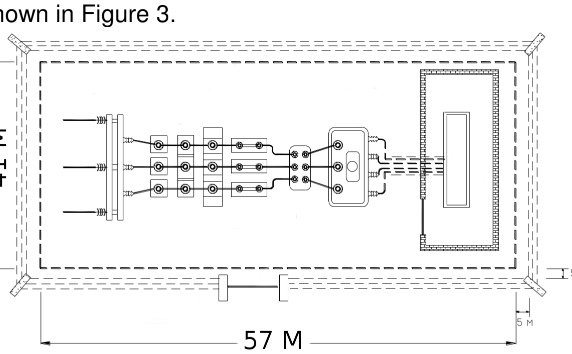

Figure 3 – Details of the top view of the substation. Source: adapted from [7]

The soil was also modeled from the field measurements according to the methodology of [2] on an area of 47x51m, with a 871A short-circuit level, maximum protection operating time of 0.5s and it was used a 15cm layer of crushed rock as a surface layer.

4 - RESULTS

The simulated projects met the safety requirements at the lowest possible cost. The results obtained in simulations and a comparison with the proposed method and the references models are shown as follows:

4.1 - CASE STUDY 1

The calculated grounding resistance was 4.33 Ω which is less than the tolerable limit of 5 Ω, the mesh potential was 682.19V from a limit of 682.47V and step potential was 409.83V which is less than the tolerable of 2280.62V. The grid was composed of 10 conductors on the x direction and 12 on the y direction, the total length of copper cable was 980m and the total number of rods used was 98 units, the cost with electric material was R$ 11.152.40.

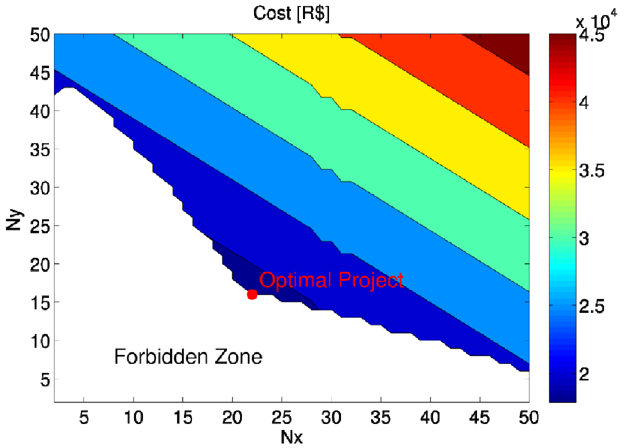

Figure 4 – Possible projects without ground rods. Source: own elaboration

As a way of illustration the figure 4 shows the cost function of all possible designs for this example without the use of ground rods. The forbidden zone is where the divisions in x and y directions pair correspond to a project that does not comply with the safety limits, the optimal design in relation to the economy of material is the point of lowest cost that does not exceed the safety limits.

4.2 - CASE STUDY 2

The grounding resistance was 2.67 Ω from a tolerable limit of 5 Ω, the mesh potential was 814.20V from a tolerable of 838.20V and the step potential was 537.12V from a tolerable of 2686.60V. The mesh was composed of 18 conductors in the x direction and 18 in the y direction, the total length of copper cables were 2520m and no ground rods were used. The cost with electric material was R$ 26.838.00.

4.3 - CASE STUDY 3

The grounding resistance was 2.73 Ω from a tolerable limit of 5 Ω, the mesh potential was 837.56V from a limit of 838.20V and the step potential was 429,61V from a tolerable of 2686.60V. The mesh was composed of 11 conductors in the x direction and 11 conductors in the y direction. The total length of copper cable was 1540m, the number of rods used were 123 units and the cost with material was R$ 17.291.60.

Note that for this particular project, due to the price of the ground rods was lower than the copper cables price, taking into account that the electric current flows better to the soil with the use of ground rods the cost with electrical material has been reduced from R$ 10.000.00 using ground rods for this project.

4.4 - CASE STUDY 4

The field measurement results for the soil electrical resistivity by the Wenner method after the statistical analysis proposed by [2] are shown in Table 1, where a is the spacing between the auxiliary rods. The values for the optimized soil model in two layers were 1542.81 $\Omega \cdot m$ for the first layer resistivity, 10.99 $\Omega \cdot m$ for the second layer resistivity and 7.46m for the thickness of the first layer.

ρ [Ω.m]	1434.33	1432.83	1164.4	304.73
a [m]	2	4	8	16

Table 1 – Average resistivity for each auxiliary rods spacing.

The figure 5 shows the theoretical curve plotted for the resistivity values obtained in the soil stratification, this curve is the minimization of the error function between the apparent resistivity and the field readings [4].

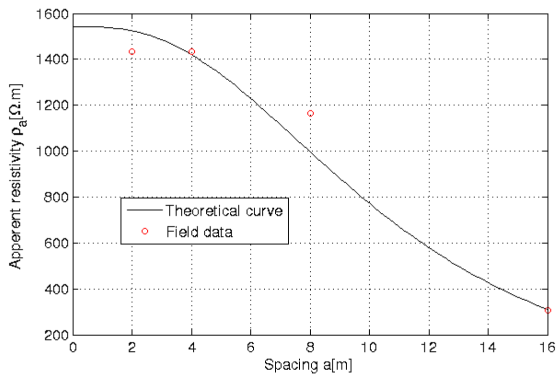

Figure 5 – Performed optimized soil stratification. Source: own elaboration

The equivalent resistivity for a homogeneous soil was obtained by applying the methodology of [5], finding the value of 968. 31 $\Omega \cdot m$. The grounding resistance was 8.78 Ω from a tolerable limit of 10 Ω, the mesh potential was 946.85V from a tolerable of 947.22V and step potential was 1357.58V from a tolerable of 3122.80V. The grid was composed of 29 conductors in the x direction and 29 conductors in the y direction, the total length of the cables was 2950m and there were 79 ground rods, giving a cost with material of R$ 31.994.20.

4.5 - CASE STUDY 5

The field measurement results for the soil electrical resistivity by the Wenner method after the statistical analysis proposed by [2] are shown in Table 2. The values for the optimized soil model in two layers were 474.16 $\Omega \cdot m$ for the resistivity of the first layer, 389.96 $\Omega \cdot m$ for the resistivity of the second layer and 5,76m for the first layer thickness.

ρ [Ω.m]	470	467	450	409	397
a [m]	2	4	8	16	32

Table 2 – Average resistivity for each auxiliary rods spacing.

The figure 6 shows the theoretical apparent resistivity curve compared to the one with the stratification values obtained by [7] that obtained as results the resistivity of the first layer 472 $\Omega \cdot m$, the second layer resistivity equal to 395 $\Omega \cdot m$ and the thickness of the first layer 7.8m.

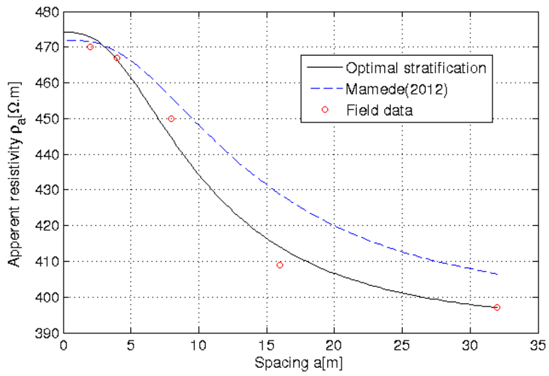

Figure 6 – Optimum soil stratification compared to [7]. Source: own elaboration

The homogeneous soil equivalent resistivity was obtained by applying the methodology of [5], finding the value of 444.37 $\Omega \cdot m$. Even using a graphical method the project designed by [7] obtained as result 445 $\Omega \cdot m$, quite close to the value found in this paper using the algorithm proposed by [5].

The grounding resistance was 4.63 Ω from a tolerable limit of 10 Ω, the mesh potential was 899.06V from a tolerable of 902.20V and the step potential was 339.49V from a tolerable than 3133V. The mesh was composed of 7 conductors in the x direction and 6 conductors in the y direction, the total length of copper cable was 588m and the number of ground rods was 53 units, obtaining as electrical material cost R$ 6.649.10.

5 - ANALYSIS OF RESULTS

The results obtained using this methodology showed values of grounding resistance within the tolerable limit and values of touch potential near the maximum. The summary of the values for step potential, touch potential and grounding resistance are shown in Table 3, where the quantities related to electric potential as E_s, E_{step}, E_m and E_{touch} are in V and those for electrical resistance as R_g and R_{max} are in Ω.

Case study	E_s	E_{step}	E_m	E_{touch}	R_g	R_{max}
1	409.83	2280.62	682.19	682.47	4.33	5
2	537.12	2686.60	814.20	838.20	2.67	5
3	429.61	2686.60	837.56	838.20	2.73	5
4	1357.58	3122.80	946.85	947.22	8.78	10
5	339.49	3133	899.06	902.20	4.63	10

Table 3 – Summary of results

The constructive data as the number of conductors parallel to the x direction, the number parallel to the y direction, the number of ground rods used in the project and the final cost of the project are shown in Table 4, where L_c is in meters and the cost is in reais.

Case study	N_x	N_y	L_c	N_h	Cost
1	10	12	980	98	11 152.40
2	18	18	2520	0	26 838.00
3	11	11	1540	123	17 291.60
4	29	29	2950	79	31 994.20
5	7	6	588	53	6 649.10

Table 4 – Design features and the final cost of projects of the case studies

In order to compare the performance of the implemented algorithm, the cost of the project found in reference [6] using the fee schedule adopted in this work is compared with a cost optimized project as shown in Table 5.

Case study 4	N_x	N_y	N_h	Cost
Kindermann [6]	18	14	73	17 308.30
Proposed	9	11	123	11 840.30

Table 5 – Comparison of cost of the project [6] with the same design developed using the proposed methodology.

Also as a way to compare the performance of the implemented algorithm, the cost of the project found in reference [7] with the fee schedule adopted in this paper was compared with a cost optimized design as shown in Table 6.

Case study 5	N_x	N_y	L_c	N_h	Cost
Proposed without rods	12	7	891	0	9 489.15
MAMEDE [7] without rods	18	13	1479	0	15 751.35
Proposed with rods	7	6	588	57	6 649.10

Table 6 – Comparison of the project proposed by [7] cost with the same design using the proposed methodology.

6 - CONCLUSIONS

For electrical power systems grounding design several variables are taken into account, the methodology presented in this paper seeks to find the combination that makes the project acceptable in relation to safety, maximum level of electrical resistance and the lowest cost with electrical equipment as possible.

The case studies 1 and 2 showed that due to the price of the 2.4m coppered grounding rod is less than the 35mm² copper conductor, the optimized design using ground rods was almost 60% more economical than the optimized design without ground rods. The cost of this project with the same constructive data found in reference [6] (with the materials price table shown in section 3 of this paper) was about 32% higher than using the presented methodology.

The original design for the case study 3, which is shown in [1] presents a total of 1540m of copper cables and twenty 7.5m length deep ground rods. This paper suggested a length of 1540m from horizontal conductors and 123 coppered ground rods of 2.4 m length, note that the results found in this case study is quite similar to that suggested in the IEEE standard.

The case study 4 was done using real measurement data, being held optimum soil stratification after a statistical analysis of the values for the six measurements lines. To estimate the equivalent resistivity of a homogeneous soil, the method of [5] was used obtaining a homogeneous soil equivalent to a specific grounding system. The results show that even in a high resistivity soil, in that area reserved for the installation of the substation, it was possible to design a grounding system that meets the security specifications for a 15kV voltage class. Note that due to the high resistivity soil the cost for this voltage class was far superior to the 72.5 kV class projects presented in this paper.

The case study 5 is an example of design of a grounding system for a 15kV class aerial substation found in reference [7]. The soil model was developed using optimization methods finding values very close to those of [7] for the soil stratification and an almost identical value for the apparent resistivity, being possible to conclude that the values found in the original design are conservative for the safety of the substation operators. By applying the methodology proposed in this paper for this case study was possible to obtain a fairly significant savings with electric material, especially when adopting a high amount of coppered ground rods.

7 - ACKNOWLEDGMENTS

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