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Comparing IEEE Std 80-2000 with Substation Earth Fault Safety Maximization Criterion in the Optimal Design of Substation Earthing System using Firefly Algorithm

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***Abstract* – Earth fault in substations is one of the most serious safety concerns in the power industry. In order to forestall this menace an earthing grid is always installed in all substations. The installed earthing grid must be efficient and reliable. In this paper an earthing grid was design with efficiency, reliability and safety in mind. To achieve this, the firefly algorithm was used in the mesh voltage minimization which leads to the optimal design of substation earthing grid. The earthing grid square configuration parameters such as number of parallel conductors, conductor spacing, and length of grid conductor, the number of earth rod and length of earth rod were taken as output variables. The output values of the firefly optimization process were validated with the results obtained using genetic algorithm and ETAP's earthing module written in IEEE std 80-2000 format.**

***Keywords* – Earthing/Earth Rod, Firefly Algorithm, Genetic Algorithm, Safety Criteria and Touch/Mesh/Step Voltage.**

Nomenclature

A = grid area; K_m = mesh factor; ρ_{soil} = soil resistivity; h = depth of burial; L_G = length of grid; I_f = grid fault current; t_f = fault duration; K_i = corrective factor ; L_r = length of earth rod ; L_m = total length of grid conductors ; S_f = current division factor ; d = diameter of earth rods; I_g = symmetrical grid current ; I_G = maximum grid current ; T_a = dc offset time constant; D = grid spacing; N = grid configuration, N_r = Number of earth rods, $E_{touch,x}$ = touch voltage limit (V), $E_{step,x}$ = step voltage limit (V), C_s = surface layer derating factor, ρ_s = resistivity of the surface material (Ω.m), t_s = maximum fault clearing time (s).

I. INTRODUCTION

With the deregulation of power supply in Nigeria, the activities of power providers in providing power to the populace will increase thus there will be need to build more substations and construct transmission and distribution lines to meet the growing demand on power even by less densely populated areas. The building of more substations in these areas brings about the inherent danger and hazard associated with it - the destruction of equipment, properties and personnel electrocution due to an earth fault. This safety concern can be prevented with the installation of efficient protection schemes and effective earthing grid system within the network. The design of efficient and effective substation earthing grid system that ensures effective connection of the protection devices and power equipment to the general earth mass is our interest in this study and is now becoming a science of its own. The proper understanding of the science behind the design of an efficient and effective substation earthing grid system will lead to a safer substation environment even in land limited areas. So many mathematical expressions or models are being put forward by several authors with regard to provision of substation earthing that would lead to the protection of personnel and substation equipment [1-5]. The evolving mathematical formulation for substation earthing grid design ranges from the use of analytical equations to the use of intelligent algorithms [3, 6-12]. The analytical equations make use of simpler mathematical expressions derived from basic principles that lead to acceptable approximated results while the intelligent algorithms are formulated with safety or cost in mind subject to certain equality and inequality constraints that lead to accuracy of results.

With the advent of supper- high speed computers, the intelligent algorithm formulations are now being highly preferred due to its accuracy but this does not mean the analytical expression has lost its value. Intelligent algorithms such as particle swarm optimization (PSO) [6], genetic algorithm (GA) [8-9] have all been used in optimization of substation earthing grid designs.

The choice of using an intelligent algorithm as an optimization tool on a complex system such as substation earthing is to reduce the cost of material and labour, and at the same time produce an efficient and effective earthing system that will provide safety to personnel and equipment. In this paper the earth fault safety maximization criterion – mesh voltage criterion - will be used as an objective function subject to a number of grid configuration constraints. The conductor spacing, length of grid conductor, number of earth rods, length of earth rod and the number of parallel conductors will be taken as design output variables.

The use of the mesh voltage – a safety criterion, as an objective function for this work arises from the fact that for an earthing grid design to be certified for implementation, the measured mesh voltage must be compared with the calculated tolerable touch voltage criterion. A lower mesh voltage means that the substation earthing grid designed can provide maximum safety to personnel and equipment during an earth fault.

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The firefly algorithm (FA) [13] and the genetic algorithm (GA) [14] will be used in the minimization of the mesh voltage and their output results are tabulated and validated with the analytical results taken from ETAP's earthing module written in IEEE std 80-2000 format [15] that leads to safety maximization of substation mesh voltage.

II. IEEE2000 SUBSTATION GRID EARTHING EXPRESSIONS [4]

In IEEE2000, the substation earthing grid design has two safety criterions that guide the designer, these are the step and touch voltage criterion. The maximum tolerable voltages for step and touch can be calculated empirically for body weights of 50kg and 70kg using these expressions

$$E_{touch,50} = (1000 + 1.5C_S\rho_s)\frac{0.116}{\sqrt{t_s}} \tag{1}$$

$$E_{touch,70} = (1000 + 1.5C_S\rho_s)\frac{0.157}{\sqrt{t_s}} \tag{2}$$

$$E_{step,50} = (1000 + 6C_S\rho_s)\frac{0.116}{\sqrt{t_s}} \tag{3}$$

$$E_{step,70} = (1000 + 6C_S\rho_s)\frac{0.157}{\sqrt{t_s}} \tag{4}$$

$$C_S = 1 - \frac{0.09\left(1-\frac{\rho_{soil}}{\rho_S}\right)}{2h_S+0.09} \tag{5}$$

The choice of body weight (50kg or 70kg) depends on the expected weight of the personnel at the site. Typically, where women are expected to be on site, the conservative option is to choose 50kg.

Equations (1) - (4) are computed when all other parameters such as the soil resistivity, the surface material resistivity are known.

In the field, the step and mesh voltages are measured using the following expressions,

$$E_m = \frac{\rho_{soil}K_mK_iI_G}{L_M} \tag{6}$$

$$E_S = \frac{\rho_{soil}K_sK_iI_G}{L_S} \tag{7}$$

where,

$$K_m = \frac{1}{2\pi}\left[\ln\frac{D^2}{16hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d}\right] + \ln\left[\frac{8}{\pi(2n-1)}\right] \tag{8}$$

$$K_i = 0.644 + 0.148n \tag{9}$$

$$L_M = L_s = L_c + 1.15L_r \tag{10}$$

$$K_s = \frac{1}{\pi}\left[\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D}(1 - 0.5^{n-2})\right] \tag{11}$$

$$I_G = I_gD_f \tag{12}$$

$$I_g = I_fS_f \tag{13}$$

$$D_f = \sqrt{1 + \frac{T_a}{t_f}\left(1 - e^{\frac{-2t_f}{Ta}}\right)} \tag{14}$$

$$T_a = \frac{X}{R}\cdot\frac{1}{2\pi f} \tag{15}$$

The grid resistance is computed using,

$$R_g = \rho\left[\frac{1}{L_c+L_r} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1+h\sqrt{20/A}}\right)\right] \tag{16}$$

In this work the grid conductor R_c resistance will be computed separately as,

$$R_c = \rho\left[\frac{1}{L_c} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1+h\sqrt{20/A}}\right)\right] \tag{17}$$

While the earth electrode resistance R_{1r} of the grid earth rod is computed from,

$$R_{1r} = \frac{\rho_{soil}}{2\pi L_r}\left(\ln\left(\frac{8L_r}{d_r}\right) - 1\right) \tag{18}$$

For n-number of earth rods R_{nr}, the resultant electrode resistance of n earth rods is given as,

$$R_{nr} = \frac{R_{1r}}{N_r}\left(2 - e^{-0.17(N_r-1)}\right) \tag{19}$$

Using (16) and (17) the total grid resistance would be computed from [10],

$$R_g = \left(\frac{1}{R_c} + \frac{1}{R_{nr}}\right)^{-1} \tag{20}$$

The earth potential rise EPR is given as

$$EPR = I_GR_g \tag{21}$$

III. SAFETY MAXIMIZATION CRITERION FORMULATION

The basis of a safe earthing design is for, $E_m < E_{touch}$, and $E_s < E_{step}$. A look at (6) and (7) reveals that all the parameters required for the installation of the earthing grid, such as the number of parallel conductors, the length of grid conductors, the spacing of conductors and (20) has the number and the length of earth rods. In this paper, the criterion formulation will be based on a square grid configuration.

A. Objective Function

An optimization process that minimizes (6) and (7) can give us the optimal length of grid conductors and the values of other parameters. Thus Equation (6) and (7) will be used as the objective functions as such we have,

$$E_m = \frac{\rho_{soil}}{2\pi(L_c+1.15N_rL_r)}\left(\left(\ln\frac{D^2}{16hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d}\right) + \frac{1}{(2N)^{2/N}\sqrt{1+h/h_0}}\ln\left(\frac{8}{\pi(2n-1)}\right)\right)(0.644 + .148n)\left(I_gS_fD_f\right) \tag{22}$$

$$E_s = \frac{\rho_{soil}}{\pi(L_c+1.15N_rL_r)}\left(\frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D}(1 - 0.5^{N-2})\right)(0.644 + 0.148N)\left(I_gS_fD_f\right) \tag{23}$$

The output variables are that that gives the proposed grid earth design the required grid resistance and also minimizes the mesh and step potential so that their values would be lesser than the calculated touch and step voltages.

B. Constraints

The objective functions are subject to the following constraints:

1) Grid conductor length/earth rod constraint: The minimum length requirement for attaining the minimum allowable resistance is given by [4].

$$\frac{\rho_{soil}\sqrt{t_s}}{2\pi(1000+1.5C_S\rho_S)(0.157)}\left(\left(\ln\frac{D^2}{16hd} + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d}\right) + \frac{1}{(2N)^{2/N}\sqrt{1+h/h_0}}\ln\left(\frac{8}{\pi(2n-1)}\right)\right)(0.644 + 0.148n)\left(I_gS_fD_f\right) \le L_G + 1.15N_rL_r \tag{24}$$

2) Grid length constraint: The grid number of parallel conductors and the spacing distance (D) of the grid conductors are related to the grid length as

$$D(N-1)=\sqrt{A} \tag{25}$$

3) Grid conductor length constraint: The grid configuration is related to the length of the grid conductor by

$$(2N)\sqrt{A}=L_G \tag{26}$$

4) Grid earth resistance constraint: the grid resistance of many substation according to specifications is less than or equal to 1 ohms. Thus the grid resistance constraint is given as,

$$\left(\frac{1}{\rho_{soil}\left[\frac{1}{L_C}+\frac{1}{\sqrt{20A}}\left(1+\frac{1}{1+h\sqrt{\frac{20}{A}}}\right)\right]}+\frac{1}{\frac{\rho_{soil}}{2\pi N_r L_r}\left(\ln\left(\frac{8L_r}{d_r}\right)-1\right)\left(2-e^{-0.17(N_r-1)}\right)}\right)^{-1}\leq 1 \tag{27}$$

Table 1 shows the proposed output design variable and their lower and upper bound limit.

Table1: Design Variable and their Limits

Design Variable	Description	Lower limit	Upper limit
x_1	Separation between parallel conductors (D)	2.5	$\sqrt{A}$
x_2	Mesh configuration (N)	2	25
x_3	Length of grid conductor (L_C)	$4\sqrt{A}$	5000
x_4	Number of earth rods (N_r)	4	200
x_5	Length of earth rod (L_r)	1.2	5

IV. PERFORMANCE EVALUATION AND DISCUSSION

The data used in this work is taken from a 7.5MVA, 33/11 kV, substation earthing design with ETAP. The aim is to compare the results from FA, and GA simulations with that computed by ETAP's earthing module written in IEEE std 80-2000 format. The scheme has the following data:

Fault duration t_f = 0.5 s
Fault current I_f = 2000.00
Weight = 50 kg
Current division factor S_f = 1.00
Line-to-line voltage at worst-fault location = $11k\ V$
Soil resistivity ρ = $140\ \Omega-m$
Crusher run granite resistivity ρ_s = $1318.7\ \Omega-m$
Thickness of crushed rock surfacing h_s = $0.1\ m$
Depth of grid burial h =$0.5\ m$
Available grounding area = $30\times 30\ m^2$
Diameter of earth rod d_r = $0.02\ m$
Cross section of conductor A_c = $70mm^2$
Conductor type = copper, annealed soft drawn
Rod type = copper-clad steel rod.

The computed touch and step voltages using (2) and (4) are given as,

$$E_{touch,70}=466.47\ V$$

$$E_{step,70}=1373.77\ V$$

In the mesh voltage minimization, the minimized mesh voltage must be less than the computed touch voltage. Table 2 show the output results obtained from the optimization process using FA and comparing them with GA and ETAP. Fig.1 shows the Matlab's GA GUI of the mesh potential and the output variable results.

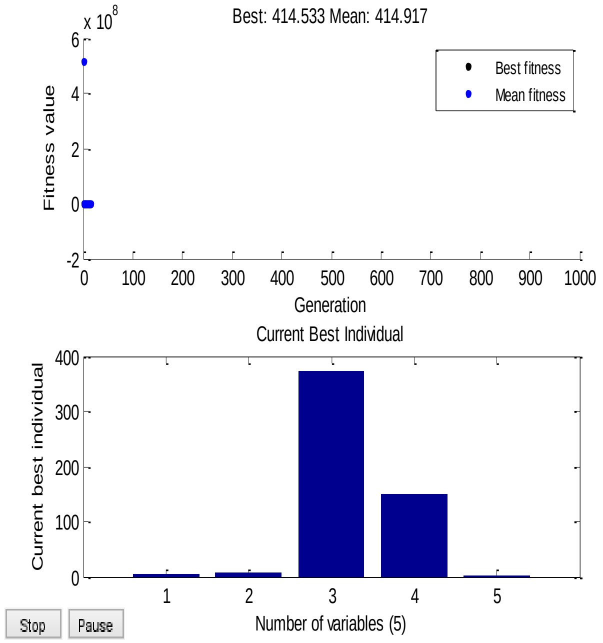

Fig.1. GUI display of optimization result in Matlab's GA

Table 2. Comparison of Optimization results

	FA	GA	ETAP
Mesh Voltage (V)	454.63	414.86	358.3
Step Voltage (V)	371.71	360.82	452.9
EPR (Ω)	1768.79	1879.45	4376.4
Grid resistance (Ω)	0.77	0.84	2.181
Length of mesh conductor(m)	353.08	372..67	600.00
Number of mesh	6.00	6.00	10
Number of earth rods	169	148	200
Length of earth rods (m)	1.2	1.2	1.2
Spacing distance (m)	6.00	5.75	3.3
Total length of conductors(m)	537.88	550.27	840

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The results from FA, and GA gives closely related values which differs from that obtained from ETAP. The total length of conductor and the grid resistance are lower than what was obtained with ETAP. In the optimization processes however a high mesh voltage as compare with ETAP was outputted while the outputted values for the earth potential rise and step voltages were lower. But the values of the mesh and step voltages are lower than the tolerable touch and step voltages values. These two voltages are the safety criterions and thus minimizing the mesh and step potential maximizes the safety of the substation in term of earth faults.

V. CONCLUSION

In this work firefly algorithm (FA) and genetic algorithm (GA) were used in the optimization of substation earthing grid design. The idea was to minimize the mesh and step potentials so that their values will be lower than the touch and step voltages. These two voltages are the safety criterion parameters. Minimization of the mesh and step potential increase the safety of the substation against earth faults. The grid configuration results obtained gives rise to an effective, efficient and a safer substation grid earthing. The cost effect of these techniques shall be presented in future study.

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