Journal of the Nigerian Association of Mathematical Physics
***Volume* 23 (March, 2013), pp 395 – 398**
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Minimization of Substation Earthing Grid Safety Criterion Using Simulated Annealing and Particle Swarm Optimization

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Abstract

This paper presents the use of simulated annealing, particle swarm, and genetic algorithm in the mesh voltage minimization which leads to the optimal design of substation earthing grid. These optimization processes where used as a check on one another in order to know if we are on the right course of getting the best result. The design variable values obtained from the three optimization processes are closely related with the particle swarm optimization (PSO) having a lower mesh voltage, grid resistance and use lesser length of grid materials. In all, the optimization process was faster than the analytical process as used in ANSI/IEEE std 80-1986.

Keywords: simulated annealing, particle swarm optimisation, safety criteria, earthing, touch voltage, mesh voltage, step voltage, earth rod

Nomenclature
A = grid area$a$; K_m = mesh factor; ρ_{soil} = soil resistivity; h = depth of burial; L_G = length of grid; K_s = thickness of primary winding; I_f = grid fault current ; K_i = corrective factor ; L_R =length of earth rod ; L_m = total length of grid, earth rod inclusive ; S_f = current division factor ; d = diameter of grid conductor; I_g =symmetrical grid current ; I_G = maximum grid current ; T_a = dc offset time constant; D = grid spacing; N = grid configuration

1.0 Introduction

The design and proper installation of substation earthing grid system is now becoming a science of its own. The proper understanding of the science behind the design of earthing system leads to a safer substation environment. So many mathematical expressions have being put forward by several authors with regard to earthing and how it could be used in the design of substation earthing that would provide protection to personnel and substation equipments[1]. The evolving mathematical formulation ranges from the analytical [2-4] to numerical [8-9]. The analytical expressions are simpler mathematical expressions that lead to the approximation of results while the numerical are very complex mathematical expressions that lead to accuracy of results.

With the advent of high speed computers, the numerical formulations are now being preferred. Numerical algorithms such as particle swarm optimization (PSO) [6], boundary element method (BEM)[7] and finite element method (FEM)[8] have all been used in optimization of substation earthing grid designs.

Optimization of a complex system such as substation earthing leads to the reduction of cost of material, labour and safety to personnel. In this paper the measured safety criteria – mesh voltage will be used as an objective function with the number of grid configuration, conductor spacing, length of grid conductor, number of earth rods, length of earth rod and depth of burial taken as variables.

The choice of the mesh voltage as an objective function for this work arises from the fact that, measured mesh voltage must be compared with the calculated tolerable touch voltage criterion before an earthing system is regarded as being properly design. A lower mesh voltage means that the earthing design can provide safety to personnel and equipment during earth faults.

The simulated annealing, particle swarm optimization and the genetic algorithm were all used in the minimization of the mesh voltage and their results are tabulated and validated with the analytical result taken from IEEE 86-2000[4]

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2.0 Earthing grid safety criterion

In substation earthing grid design there are 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 as [4],

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

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

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

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

$$C_S = 1 - \frac{0.09\left(1-\frac{\rho_{soil}}{\rho_s}\right)}{2h_s+0.09} \quad (5)$$

where $E_{touch,x}$ is the touch voltage limit (V), $E_{step,x}$ is the step voltage limit (V), C_s is the surface layer derating factor, ρ_s is the resistivity of the surface material (Ω.m), t_s is the maximum fault clearing time (s).

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.

Equation (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 touch voltages are measured using the following expressions,

$$E_m = \frac{\rho_{soil}K_mK_iI_G}{L_M} \quad (6)$$

$$E_S = \frac{\rho_{soil}K_sK_iI_G}{L_S} \quad (7)$$

where,

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

$$K_i = 0.644 + 0.148n \quad (9)$$

$$L_M = L_G + L_R \quad (10)$$

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

$$I_G = I_gD_f \quad (12)$$

$$I_g = I_{k,e}S_f \quad (13)$$

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

$$T_a = \frac{X}{R}\cdot\frac{1}{2\pi f} \quad (15)$$

The basis of a safe earthing design is for, $E_m < E_{touch}$, and $E_s < E_{step}$. A look at (6) reveals that all the parameters required for the installation of the earthing grid, such as the number of mesh, the length of grid conductors, the spacing of conductors and the depth of burial are contained in them. An optimization process that minimizes (6) and (7) can give us the optimal length of grid conductors and the values of other parameters

3.1.Optimization problem

1) Objective Function: The objective is to minimize the touch voltage and hence optimally design a safe substation earthing grid system. The objective function is
$E_m = \frac{\rho_{soil} K_m K_i I_G}{L_M}$
2) Grid conductor length/earth rod constraint: The minimum length requirement for attaining the minimum allowable resistance is given by [4].

$$\frac{\rho_{soil} K_m K_i I_G \sqrt{t_s}}{(1000+1.5C_S\rho_s)(0.157)} \leq L_G + 1.15N_r L_r \quad (16)$$

3) Grid area constraint: The grid configuration (N) and the spacing distance (D) of the grid conductors is given by

$$DN = \sqrt{A} \quad (17)$$

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

$$(2N+2)\sqrt{A} = L_G \quad (18)$$

3.2. Optimization Algorithm Format

Five variables are chosen for this minimization problem. These are D, N, L_G, N_r, L_r and h. The objective of this work is to minimize the touch voltage criteria which will result in a safe substation earthing grid design. The mesh voltage objective function $f_{(x)}$ is

$$f_{(x)} = \frac{\frac{1}{2\pi}\left[\ln\frac{D^2}{16hd}+\frac{(D+2h)^2}{8Dd}-\frac{h}{4d}\right]+\frac{K_{ii}}{K(h)}\ln\left[\frac{8}{\pi(2N-1)}\right](0.644+0.148N)\, I_g D_f \rho_{soil}}{L_G+1.15N_r L_r} \quad (19)$$

In this case we assumed the followings: $x_1 = D$, $x_2 = N$, $x_3 = L_G$, $x_4 = N_r$, $x_5 = h$, and $x_6 = L_r$,
Table 1 shows the design parameter limits. To obtain an acceptable earthing design, the design variables need to be bound between upper and lower limit values.

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)	1	25
x_3	Length of grid conductor (L_G)	$4\sqrt{A}$	5000
x_4	Number of earth rods (N_r)	4	200
x_5	Depth of burial (□)	0.25	0.5
□$_6$	Length of earth rod (□$_□$)	1.2	5

4.0 Performance evaluation and Discussion

The example used in this work is taken from ANSI/IEEE std 80-1986 (pp.181). The aim is to compare the results from SA, PSO and GA simulations with that computed by ANSI/IEEE std 80-1986. The example has the following data:

Fault duration t_f = 0.5 s

Fault impedance Z_1 = $4.0 + j10.0\Omega$

Fault impedance Z_0 = $4.0 + j10.0\Omega$

Current division factor S_f = 0.6

Line-to-line voltage at worst-fault location = $115000\ V$

Soil resistivity ρ = $400\ \Omega - m$

Crushed rock resistivity (wet) ρ_s = $2500\ \Omega - m$

Thickness of crushed rock surfacing h_s = $0.1\ m$

Depth of grid burial h =0.5 m

Available grounding area = $70 \times 70\ m^2$

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

$E_{touch,70} = 746\ V$

$E_{step,70} = 2320\ V$

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 and the corresponding result taken from ANSI/IEEE std 80-1986.

Table 2:Design Variable values obtained after optimization

	SA	PSO	GA	IEEE86-1986
Mesh Voltage (V)	628.70	557.04	564.8	693
Step Voltage (V)	863.47	736.79	797.63	
GPR (Ω)	2557.8	1829.10	2199.52	5170.10
Grid resistance (Ω)	1.341	0.95	1.15	2.71
Length of mesh conductor (m)	3396.6	3491.00	3332.01	1540
Number of mesh	24	24	23	10
Number of earth rods	146	159	92	36
Length of earth rods (m)	1.9	3.3	4.34	15
Spacing distance (m)	2.8	3.2	3.0	7
Total length of conductors(m)	3674.0	3556.71	3731.29	2080

The results from SA, PSO and GA gives closely related values which differs from that obtained from ANSI/IEEE std 80-1986. The total length of conductors and rod required in the optimization is higher than what was obtained in ANSI/IEEE std 80-1986. But a check on the grid resistance shows that the optimization produces lower values than in ANSI/IEEE std 80-1986 and this account for the higher length of grid conductors. The optimization process gives all the variables required in the design of an earthing system in one go and at a faster time frame, while in ANSI/IEEE std 80-1986 the process was a trial by error method which is time consuming. The aim of having an earthing system with a lower mesh voltage is achieved.

5.0 Conclusion

This paper has used simulated annealing (SA), particle swarm optimization (PSO) and genetic algorithm (GA) in the optimization of substation earthing grid design. The design variable values obtained from the three optimization processes are closely related with the PSO having a lower mesh voltage, grid resistance and use lesser length of grid materials. In all the optimization process was faster than the analytical process as used in ANSI/IEEE std 80-1986.

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