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Research Article

An Optimal Design of Substation Grounding Grid Considering Economic Aspects Using Particle Swarm Optimization

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Abstract: Design of a safety grounding system is an important part of substation design in power systems. An appropriate designed grounding system ensures the adequate safety for people and protects the installation. Also, due to increasing the electrical equipment price and cost of land, the implementation of grounding system is faced with restrictions. Therefore, the design of optimal substation grounding grid considering the practical limits such as economic aspects is one of the important problem in system designing. This study presents to design an optimal grounding grid considering the economic aspects of designing. In this study, the number and diameters of conductors and rods which can carry the fault current, space between conductors for having the safety factors, the depth of burring the grounding system and investment cost are considered as parameters which affected on total cost of grounding system. Also to conducting the simulation to finding the best parameters of grounding grid to be optimum in all aspects, the Particle Swarm Optimization (PSO) algorithm is employed. Finally, the PSO is applied to a typical grounding system in two different scenarios and the results are compared to each other.

Keywords: Equivalent circuit, grounding grid, objective function, particle swarm optimization, step voltage, touch voltage

INTRODUCTION

Design of a safety grounding system is an important part of substation design in power systems. An appropriate designed grounding system ensures the adequate safety for people and protects the installation (Meliopoulos, 1988). With development of power systems in whole of world and following by it, increasing the capability of systems for security of energy consumers; the higher level voltages will be used. Nowadays, in several developmental countries, the ultra-high voltage power system (i.e., 1000 KV and above) (UHV) are operated. Such as in China, India and Russia the 1200 kV transmission lines are used for electric power transmission (Huang *et al*., 2007a, b). Also this is predicted that the other countries will be reached to mentioned high level voltages, too. With these high levels voltage, the fault current and the area of grounding system will increase. Consequently, with increasing the fault current, the design of grounding system will be more sensitive due to fault condition. In the fault condition, the produced voltage in grounding system will be high and dangerous for human safety and operating power equipment. Another aspect of design of grounding systems is the economic aspect. The grounding system in substations consists of many of rods and conductors. These conductors often made of cupper that is expensive. Therefore, the design of an economic substation grounding system which fulfilling the safety factors is as an objective function in system designing. The personnel safety is analyzed by two factors so-called step and touch voltages. These factors are obtained theoretically by solving the Maxwell's equations (Meliopoulos, 1988). It is obvious that the safety factors are affected by geometrical grounding system and electromagnetic soil characteristics.

The optimum design of grounding system is affected by optimum decide of number and diameters of conductors and rods which can carry the fault current, best space between conductors for having the safety factors, the height of burring the grounding system and reduce the resistant of grounding system, surface potential gradient and protect the safety of person and equipment. All of mentioned parameters addition to the investment cost must be considered in objective function.

In this study the numerical calculation of grounding system parameters is done based on the Electromagnetic Field (EMF) and circuit combining theoretical. In this model, not only the conductive effect of currents leaking into the soil is, but also capacitive and inductive effects have been considered.

Providing the safety factors with the lowest cost is the nondeterministic polynomial-time hard (i.e.

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nonlinear problem with relative minimum points). There are some techniques to finding the best solution for a goal function with complex and nonlinear characteristics and heavy equality and inequality constraints. Recently, the heuristics techniques such as Genetic Algorithm, simulated annealing and Particle Swarm Optimization (PSO) are applied (Lee and El-Sharkawi, 2008; Kennedy and Eberhart, 1995). Among these techniques the PSO is recognized as a more powerful scheme than others for solution of problems. Therefore, it is can be suitable for determining the best design of a substation grounding system.

MATERIALS AND METHODS

A substation ground grid is composed of horizontal interconnected cylindrical thin conductors and vertical ground rods buried in the earth. The thin-wire condition means the radius is much smaller than the conductor length (usual in real electrodes). Although in this study, the conductors are considered cylindrical, the result may be applied to conductors of any other shape. The grounding network conductors are assumed to be completely buried in a conductive semi-infinite medium (earth) with conductivity σ and permittivity ε = εr.ε0. The air is assumed to be a non-conductive medium with permittivity ε0 = 10-9/36π F/m. All media have permeability $\mu = \mu_0 = 10^{-7}/4\pi$ *H/m* (Otero *et al*., 1999).

The methodology proposed is based on the study of all the inductive, capacitive and conductive couplings between the different grounding system conductors. First, the electrode is divided in a number of segments that can be studied as an elemental unit. A higher segmented rate of the electrode can enhance the model's accuracy but increase its computational time. Therefore, it is necessary to achieve a compromise solution between the two determinants.

For the numerical calculation of the safety factors (touch and step voltages) of a substation grounding grid, assumption that:

- The leakage current of each conductor concentrate at the central node and inject to the ground
- Branch voltage (infinity as a reference point) equal to the average of endpoint voltage

According to electromagnetic field combined with the circuit idea and using above assumptions, the problem will reduce to a simple circuit with m branch and n node. Each branch has a leakage current I_K that is injected to the surrounding earth.

The grounding grid is energized by injection of single frequency currents at one or more nodes. In general, we consider that a sinusoidal current source of value *F* is connected in each node. In the low frequency case, the ground electrode may be considered equipotential. However, at higher frequencies, because of the electromagnetic couplings and the currents flowing along the conductors, voltages between different points of the grounding system are not zero. Define the voltage V_j of point *j* as the difference potential across *j* and infinite points (reference point).

When the length of conductor of branch is smaller, think that the voltage of each branch is constant. Based on the above assumptions section of the K_{th} branch voltage can be obtained using the following formula (Otero *et al*., 1999):

$$U_k = \frac{V_l + V_m}{2} \tag{1}$$

where, *1* and *m* are the nodes of the segment k. For all branches and nodes we have a matrix:

$$[U] = [K].[V] \tag{2}$$

where,

[*U*] = The voltage column vector of m branches
[*V*] = The column vector of n nodes voltage
[*K*] = A two-dimension coefficient matrix of $m \times n$

$$K_{i,j} \begin{cases} 0.5 & \text{branch i is connected to node j} \\ 0 & \text{branch i is not connected to node j} \end{cases}$$

The equivalent circuit of grounding grid was made up from *m* branch and *n* nodes. For any branch, in addition to branch resistance, the self-inductance and mutual inductance, each branch has parallel impedance. On the other hand, due to the conductivity of the surrounding medium and capacitive effects, each branch *k* drains a leakage current I_k to the earth. Consider all the branches voltage and leakage current; between these currents which are flowing into the surroundings at each branch and the respective potentials, there is a matrix relationship, as we shall see later:

$$[I] = [G].[U] \tag{3}$$

Each leakage current I_k is broken down into two currents ($I_k/2$) that are placed in the segment nodes. In this way, each node j has a source current define by:

$$J_j = \sum_{k=1}^{r} C_{k,j} \frac{I_k}{2} \tag{4}$$

where,

$$K_{k,j} \begin{cases} 1 & \text{if branch k is connected to node j} \\ 0 & \text{if branch k is not connected to node j} \end{cases}$$

Consider all the branches of grounding grid, we have:

$$[J] = [K]^t.[I] \tag{5}$$

where,
[J] = Leakage current vector of equivalent nodes,
$[K]^t$ = The transpose matrix of [K].

Using node voltage method of circuit, for the whole grounding grid, the following formula can be get:

$$[F]-[J]=[Y].[V] \tag{6}$$

$$[Y]=[A].[Y_b].[A]^t \tag{7}$$

where,
[Y] = The nodal admittance matrix of the circuit including resistive and inductive effects
$[Y_b]$ = The branch admittance matrix
[A] = Incidence matrix, which is used to relate to branches and nodes
[J] = The vector of current sources modeling the capacitive and conductive effects
[F] = The vector of external current sources:

From (1) to (6) can write:

$$[F]=[K]^t.[I]+[Y].[V] \tag{8}$$

$$[F]=[K]^t.[G].[U]+[Y].[V] \tag{9}$$

$$[F]=[K]^t.[G].[K].[V]+[Y].[V]\Rightarrow\Rightarrow[F]=[Y'] .[V] \tag{10}$$

where,

$$[Y'] =[K]^t.[G].[K]+[Y] \tag{11}$$

Now, if we have the matrix [F], we can obtain the column vector of node voltage [V] from (6), then the touch and step voltage can be given by as follows:

$$V_T = GPR - V_P \tag{12}$$

where,
V_T = The touch potential; *GPR* is grounding potential rise comparing with the infinite distance
V_p = Any point potential of the surface comparing with the infinite distance

The step voltage is obtained by:

$$V_{step} = \max(V_2 - V_1) \tag{13}$$

where, V_1 and V_2 are the surface potentials at two points 1m far from each other.

The study of the grounding systems performance has been reduced to the computation of the [G] and [Y] matrix.

Resistances and inductances: As before said, in this study the grounding system is modeled by a circuit that is composed by m branch and n nodes. Each branch has a resistance and self-inductance. Mutual inductances between branch branches are also included in the model as following:

$$[Y_b]_{m\times m}=\begin{bmatrix} R_1+j\omega L_1 & +j\omega M_{12} & .... & +j\omega M_{1m} \\ +j\omega M_{21} & R_2+j\omega L_2 & .... & +j\omega M_{2m} \\ . & . & .... & . \\ +j\omega M_{m1} & +j\omega M_{m2} & .... & R_m+j\omega L_m \end{bmatrix} \tag{14}$$

Self-resistance R_K: The self-resistance of each branch is dependent on the material resistivity, the physical dimensions and the feeding current frequency. This last factor produces the known "Skin effect". With ignoring the last factor (skin effect) the self-resistance of K_{th} segment can be obtained by a well-known following formula:

$$R_k = \frac{l_k}{\sigma.A} \tag{15}$$

where,
σ = The conductivity of the material with the ℧/m unit
l_k = The length of the K_{th} branch segment with meters unit and A is the effective cross-sectional area with unit.

Self-Inductance L_K: The self-inductance of the grounding system's conductor is calculated using the following equation (Huang and Kasten, 2001):

$$L_k = 2\times10^{-7}.l_k \,.\, \left[\ln\left(\frac{2.l_k}{\alpha}\right)-1+0.25.\beta\right] \tag{16}$$

where, the factor is taken as 1 for nonmagnetic materials; is the radius of the grounding system conductor in meters.

Mutual inductance M_K: The mutual inductance coefficient between two thin conductors, separated by a distance much bigger than their radius, may be obtained by means of the Neumann formula:

$$M_{j,k} = \frac{\mu}{4\pi} \int_{l_j} \int_{l_k} \frac{1}{r_{jk}} dl_j . dl_k \tag{17}$$

In the case of straight and parallel conductors, the above integral can be analytically solved. However, in the most general case a numerical computation of the integral is necessary (Huang and Kasten, 2001; Li, 1999).

Conductance: In the Equivalent Circuit (EC) of the grounding system, the relation among the leakage currents flowing at earth and the average potentials in each branch can be written in a matrix way:

$$[I] = [G][U]$$

Or

$$[I] = [Z]^{-1}.[U] \tag{18}$$

where,

$$[G] = [Z]^{-1} \tag{19}$$

In fact, the conductive and capacitive effect of the conductors are modeled by matrix [G] or $[Z]^{-1}$.

For infinite homogeneous conductivity medium, it has (Li, 1999).

$$Z_{jk} = \int_{l_j} \int_{l_k} G(r, r') \frac{dl_j}{l_j} \frac{dl_k}{l_k}$$

$$Z_{jk} = \frac{1}{4\pi\sigma . l_j . l_k} \int_{l_j} \int_{l_k} \frac{1}{r_{jk}} dl_j dl_k \tag{20}$$

where, G (r, r') is the Green function of a point source in uniform infinite conductivity medium. The above integral can be analytically solved (Otero *et al*., 1999; Heppe, 1979).

Objective function: In this study the objective function for design of ground system is summarized as:

- The cost of related to ground grid rods and conductors that is proportional with their length and diameters. This cost is different for rods and conductors due to their materials. In really this cost can be divided in two parts: rods cost and conductors cost.
- The required cost for digging of the ground grid in earth that is dependent on the depth of grid burring. It is clear that as the grid is buried in more depth the cost will be increase.

According to above mentioned the Objective Function (OF) of scenario I can be described as follow:

$$OF = C_1 + C_2 + C_3 \tag{21}$$

where,

C_1 = The cost of conductors
C_2 = The cost of rods
C_3 = The cost of digging that related with depth of burring

This objective function analyzed the ground grid from economic view point only in range of standard step and touch voltages without attend to value of them. If it is required to attend to amount of safety factors, these parameters must be added to the objective function too. For this aim the different between touch (step) voltage and tolerable touch (step) voltage with the specific weight factor (ω) that shows the importance of this difference, is added to objective function. In this state addition to decreasing the total cost, the value of touch and step voltages must be decreased simultaneously. The objective function in this scenario (scenario II) can be written as below:

$$OF = C_1 + C_2 + C_3 + \omega_1 \left(V_{touch}^{tolerable} - V_{touch} \right) + \omega_2 \left(V_{step}^{tolerable} - V_{step} \right) \tag{22}$$

where ω_1 and ω_2 are the positive weight coefficient. Therefore, for study of design a substation ground grid two different scenarios can be considered, with and without considering the absolute value of safety factors in objective function.

For finding the best design of ground system six parameters is considered in the goal function:

- Diameter and space between of conductors
- Number, length and diameter of rods
- Depth of grid burring

The safety factors (i.e., touch and step voltages) are considered in problem as inequality constrains. The tolerable values of voltages can be obtained from standard IEEE std. 80-2000 (IEEE, 2000).

Each function has inequality application constraints that are applied in designing such as cross area of conductors that must be able to conduct fault current without melting that can be obtained by following equation:

$$A = \frac{I}{\sqrt{\left(\frac{TCAP.10^{-4}}{t_c \alpha_r \rho_r} \right) \ln \left(\frac{K_0 + T_m}{K_0 + T_a} \right)}} \tag{23}$$

where,

$$TCAP\,[J/(cm^3.^oC)] = 4.18.C.\rho$$

C : Specific heat of conductor (cal/ (gram/°C))
P : Conductor density (gram/cm^3)
α_r : (1/K_0) temperature coefficient of resistance of conductors at reference temperature (1/°C)
T_m : Melting point of conductor (C)
T_a : Ambient temperature (C)
I : Maximum fault current (kA)
A : Effective cross area of conductor (mm^2)
ρ_r : Grid conductors resistivity at reference temperature (μΩ/m)
t_c : Time of continuing fault current in grid conductors (second)

On the other hand, the conductors have to be enough thick to tolerate against to the erosion. So a margin for conductor's diameter must be added to problem. These all limitations and constrains are considered to be results practical and more really.

As can be seen this problem has the nonlinear characteristics and heavy equality and inequality constraints that cannot solve with conventional mathematical techniques and need to the new techniques like heuristic methods to finding the best answer. In this study, the PSO technique is used for this problem that described in next section.

Implementation of particle swarm optimization to finding the optimum parameters of grounding grid: Kennedy and Eberhart (1995) developed a PSO algorithm based on the behavior of individuals (i.e. particles or agents) of a swarm. An individual in a swarm approaches to the optimum by its present velocity, previous experience and the experience of its neighbors.

In a physical n-dimensional search space, parameters of PSO technique are defined as follows:

$X_i = (x_{i1}, \dots, x_{in})$: Position individual i.
$V_i = (v_{i1}, \dots, v_{in})$: Velocity individual i.
$Pbest_i = (X_{i1}^{Pbest}, \dots, X_{in}^{Pbest})$: Best position of individual i.
$Gbest_i = (X_{i1}^{Gbest}, \dots, X_{in}^{Gbest})$: Best position neighbors of individual i.

Using the information, the updated velocity of individual i is modified by the following equation in the PSO algorithm:

$$V_i^{k+1} = wV_i^k + c_1 rand_1 \times (Pbest_i^k - X_i^k) + c_2 rand_2 \times (Gbest_i^k - X_i^k) \quad (24)$$

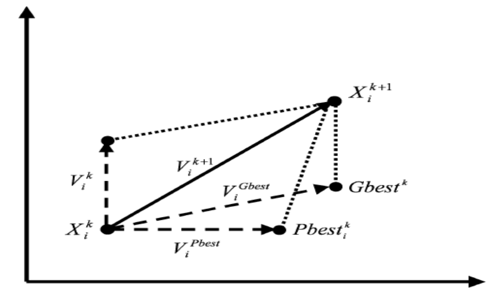

Fig. 1: Mechanism of particle swarm optimization

where,
V_i^k : Velocity of individual *i* at iteration *k*.
c1, c2 : Weight factors
rand1, rand2: Random numbers between 0 and 1.
X_i^k : Position of individual *i* at iteration *k*.
$Pbest_i^k$: Best position of individual *i* until iteration *k*.
$Gbest_i^k$: Best position of the group until iteration *k*.
ω : Weight parameter.

The individual moves from the current position to the next position by Eq. (25):

$$X_i^{k+1} = X_i^k + V_i^{k+1} \quad (25)$$

The search mechanism of the PSO using the modified velocity and position of individual *i* based on Eq. (26) and (24) is illustrated in Fig. 1.

The solution algorithm can be briefly described as follows:

Step 1: Generate particles from a set of uniformly random numbers ranging over the upper and lower limits of the optimization variables. Each particle includes six variables (i.e., parameters which are mentioned in above section).
Step 2: By using the mentioned equations the objective function could be calculated according to (21), (22).
Step 3: Using the global best (*Gbest*) and individual best (*Pbest*), velocity vector of particles is updated. Based on the updated velocity, each particle changes its position based on (24) and (25).
Step 4: Repeat calculations from step 2, until the stopping criterion is satisfied.

RESULTS AND DISCUSSION

To demonstrate the validity of the proposed model to design an optimal grounding system using particle swarm optimization, the authors considered a substation ground system that the ground grid area is 200×150 m^2

Table 1: Characteristics of grid conductors

Type of conductor	Copper annealed soft-drawn
TCAP (J/Cm3/ °C)	3.42
ρ_r at 20 ^{oC} (MΩ/Cm)	1.72
Melting point T_m (°C)	1083
K_0 at 0 °C	234
α_r at 20 °C (1/°C)	0.00393

Table 2: Given costs for both scenarios at fifty trials running program

Compared item	Value of objective functions	
	Scenario I	Scenario II
Best	7349600	7406000
Average	7644500	7757700
Worst	8569100	8924800

Table 3: Voltages and parameters of optimum substation ground grid for each scenario

Parameter	Value of parameter	
	Scenario I	Scenario II
Space between the conductors(m)	1.1528	1.1497
Diameter of conductors (m)	0.0517	0.0523
Length of rods (m)	0.5004	5
Diameter of rods (m)	0.01	0.01
Number of rods	5	100
Height of grid burring (m)	0.3078	0.3121
Touch voltage in best answer (v)	1012	1011.6
Step voltage in best answer (v)	3375.3	3341.6

and conductors are placed in equally space in grid. Also, the maximum short circuit current of system is 21000 A. The substation grounding system has a gravel layer with depth of 0.15m. Substation ground short circuit equivalent time is 0.5 second; soil resistivity of substation is 290 Ωm while the resistivity of gravel layer is assumed 3000 Ωm. The touch and step voltage tolerable for a 70 Kg person according to standard IEEE std. 80-2000 will be 1011.35 V and 3379 V respectively. The characteristics of grid conductors are given in Table 1.

Because of heuristics property of PSO and ensuring of the given results, the PSO is applied to objective function in each scenario for fifty trials and obtained results are shown as best, average and worst result in Table 2 according to Scenario I and Scenario II that mentioned in formulation section.

The value of parameters that satisfied the optimal substation grounding system that are obtained as the optimum parameters for the best result of each scenarios are illustrated in Table 3. Also, the touch voltage and step voltage for best results are shown in Table 3.

By comparing the results in two different scenarios, it is obtained that in scenario II due to considering the safety factors and difference between tolerable voltages and step and touch voltages in objective functions, the final touch voltage and step voltage in best result are decreased dramatically. Consequently, by decreasing the mentioned voltages, the safety in practical operation increases. Also, by comparing the result in Table 2, one can find out that by using the objective function in two scenarios the cost of grounding system design are equal approximately. The reason of this low difference in price in two scenarios is that in objective function with safety factors the PSO increases the number of rods which made of steel and not cause to increase the total cost. But, in scenario I, the final goal of PSO is decreasing the cost and when obtained the process of optimization has been finished. Finally, it could be realized that by using the objective functions mentioned in Eq. (22) the parameters with best safety and suitable cost of design is obtained successfully.

CONCLUSION

This study presents a novel approach to design an optimal grounding system considering economic aspects using particle swarm optimization. The cost of conductors, rods and cost of digging related with depth of grounding grid is investigated in objective function. Also in another scenario, the safety factor is added to objective function due to increasing the safety in the network studied. To conducting the simulation, the step voltage and touch voltage are considered as an index of safety in operation. The diameter and space between of conductors, number, length and diameter of rods and depth of grid burring are considered as influential parameters on objective functions and value of index voltages. Due to high nonlinearity of designing, the PSO has been successfully employed to finding the global optimum parameters. By comparing the results one can find out that objective function incorporating safety factors has powerful performance to design an economical grounding grid by finding the optimum parameters.

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