Accelerated Particle Swarm Optimization-based Approach to the Optimal Design of Substation Grounding Grid

Abstract. This article presents an application of the Accelerated Particle Swarm Optimization based approach to minimize the cost of grounding grids in high voltage substations while maintaining the legitimacy of safety necessities. The cost effectiveness and the constraints of ground potential rise, step and touch potentials are adapted to formulate optimized solutions for the grounding grid planning problem. The proposed approach attempts to calculate the optimal values of the grounding conductor lengths, cross sectional area, number of vertical rods, and depth of conductor burial while respecting a set of constraints within pre-set acceptable limits. Several test cases of grounding grid planning, some of them for real projects, are demonstrated to validate the proposed method. The superiority and efficacy of Accelerated Particle Swarm Optimization have been acknowledged in terms of grounding grid cost minimization, stable performance and short CPU computational time.

Streszczenie. W artykule zaprezentowano wykorzystanie algorytmu rojowego do minimalizacji kosztów sieci uziemiającej w podstacji wysokiego napięcia. Zaproponowany algorytm optymalizuje długość przewodu uziemiającego, liczbę prętów i głębokość przy założonych kryteriach. Przedstawiono wyniki symulacji i eksperymentu. (Optymalizacja projektowania sieci uziemiającej w podstacji wysokonapięciowej z wykorzystaniem algorytmów rojowych)

Keywords: Accelerated Particle Swarm Optimization, Cost Minimization, Grounding Grid, Safety Criteria.

1. Introduction
A grounding system is one of the most important items inside power plants and substation systems. Poor design methods and simplified calculations can lead to high erection costs and unsafe conditions. A grounding network dissipates electrical fault currents into the earth without producing harmful potential gradients that could be fatal to humans. To ensure fault currents are dissipated in a safe manner, three parameters must be calculated: GPR, step, and touch potentials [1]. Substation safety criteria are different in different countries, with two main approaches being adopted. American and European methods assess “step” and “touch” potentials, while the UK focus is given to evaluating the GPR [2-3]. The GG is regularly done at the foundation stage of substation design and, firstly, its design purpose is considered suitable for both the human safety and equipment protection [4]. The voltage changes and call the number step conductors earth system to determine efficiency in reducing conductors increased contact and step potentials provided the tolerance values, has been compared to evaluate safety was demonstrated [5]. The concept of optimal design of a GG in a two layer soil structure has been initially introduced [6]. More recently, GAs applied to optimize the design of grounding grids were successfully demonstrated [7-10]. The study on compression ratio and its relationship with the conductors and the voltage step was to contact and appropriate compression ratio achieved with minimal contact voltage compared with the values of tolerance not to evaluate safety was studied [11-13]. The advantage of GA optimization of the network with the purpose of minimizing voltage contact is presented [14]. An application of GA and PSO methods is discussed and presented for the research of optimal design of the GG [15].

In this article, an APSO algorithm is applied to optimize the design of grounding grids of HV substations. The standard recognized shapes by IEEE Std. 80-2000 are incorporated within the proposed method. All the calculations of important factors for the GG design are executed based on latest edition of ANSI/IEEE Std. 80-2000. However, the optimization practice is carried out using APSO-based approach. The algorithm has been tested and validated using several test cases and some of them are for real projects.

2. Overviews of Some Important Terms for the Design of GG
2.1 Tolerable Step and Touch potentials
In the procedure of designing the GG system, safety criteria is first calculated to specify a safety level, then the maximum touch and step potentials are calculated to compare with the safety criteria in order to assess whether it is safe to work on the area of substation. The tolerable step and touch potentials [2] are calculated by Eq. (1);

\[ E_{\text{Tolerable}} = \left[ 1000 + K_1 \times C_S \times \rho_S \right] \frac{K_2}{\sqrt{I_S}} \]

\[ C_S = 1 - 0.09 \left( 1 - \frac{\rho}{\rho_S} \right) \]

\[ \frac{2h_S}{2h_S + \rho} \]

Table I tabulated the values for \( K_1 \) and \( K_2 \) for step and touch potentials with weights of 50 and 70 kg for tolerable step and touch potentials.

Table 1. Values of \( K_1 \) and \( K_2 \)

<table>
<thead>
<tr>
<th>Tolerable potential</th>
<th>Weight=50 kg</th>
<th>Weight=70 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Touch</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

The actual touch potential, mesh potential, or transferred voltage should be less than the maximum allowable touch potential, \( E_{\text{touch}} \), to ensure safety. Generally, touch potentials represent a much more serious hazard than step potential; these are the usual basis for design.

2.2 Sizing of Grounding Conductors
The minimum size of the grounding conductor is expressed and calculated using Eq. (2).

\[ A_{\text{kmil}} = I_p \times K_C \times \sqrt{C} \]

\[ A_{\text{mm}^2} = \frac{A_{\text{kmil}} \times 1000}{197.35^2} \]

The common material constants (\( K_c \)) can be obtained [2].

2.3 Ground Resistance
Ground resistance of the substation primarily depends on soil resistivity, area available and grid configuration [16-18]. Estimation of the total resistance to remote earth is one of the first steps in determining the size and basic layout of a
grounding system. Sverak [16] has developed the formula to take into account the effect of grid depth.

\[
R_g = \frac{1}{\frac{1}{L_r} + \frac{1}{\sqrt{20A}} \left(1 + \frac{1}{1 + h \sqrt{\frac{20A}{A}}}ight)}
\]

However, Schwarz [17] proposed a formula to combine the resistance of the grid, rods, and mutual grounding resistance to calculate the total system resistance as follows;

\[
R_g = \frac{R_{RR} - R_m}{R_c + R_{RR} - 2R_m}
\]

2.4 Ground Potential Rise

The maximum electrical potential that a substation GG may attain relative to a distant grounding point assumed to be at the potential of remote earth is called GPR. The GPR is calculated as follows;

\[
GPR = I_g - R_g
\]

2.5 Maximum Actual Mesh and Step Potentials

As per ANSI/IEEE Std. 80 [2], the formulas to calculate maximum step potential and maximum mesh/touch potential are expressed in Eq. (6) and Eq. (7), respectively.

\[
E_m = \frac{\rho.K_m.K_1.I_G}{l_m}
\]

\[
E_s = \frac{\rho.K_s.K_1.I_G}{l_s}
\]

Step potential depends on grid geometry irregularity factor \(K_s\), spacing factor \(K_1\), grid depth and current per meter length of the conductor [2, 19]. The mesh voltage depends on resistivity of the soil, conductor spacing, number of meshes, current per meter length of the conductor and depth at which the grid is buried, while parameters such as the conductor diameter and the thickness of the surfacing material have less impact [2, 20]. Nevertheless, step potential is one of the important criteria for the safety of the person [1].

3. Problem Formulation and Objective Function

The increase in number of meshes and use of ground rods of varying length with horizontal grid makes the surface potential distribution more favorable for personal safety. It also decreases the grid resistance and ground potential rise which enhances the reliability of controlling devices. However, the cost will be a concern. To have the optimal design of grounding grid with minimum cost of installation and purchasing, the objective function has to be minimized while satisfying a set of safety criteria and other constraints;

\[
\text{Minimise } (L_c \times C_c + N_r \times L_r \times C_r + h \times A \times C_{ex})
\]

Subject to the following constraints;

3.1 Safety Criteria Constraints

These safety criteria include actual mesh and step potentials which must be less than values of the corresponding tolerable potentials;

\[
E_{\text{mesh-Actual}} < E_{\text{touch-tolerable}}
\]

\[
E_{\text{step-Actual}} < E_{\text{step-tolerable}}
\]

3.2 Grounding Resistance

For most transmission and other large substations, the ground resistance is usually about 1 \(\Omega\) or less. In smaller distribution substations, the usually acceptable range is from 1 \(\Omega\) to 5 \(\Omega\), depending on the local conditions.

\[
R_g \leq R_{\text{Target}}
\]

3.3 Maximum Allowed Ground Potential Rise

Recommended practices provided the limits of the GPR, which is typically 5000V for most substations.

\[
GPR \leq GPR_{\text{max}}
\]

3.4 Spacing between Adjacent Conductors

The separation between the conductors in \(x\) and \(y\) directions should be uniform and proportional to the grid dimensions.

\[
D_{x,\text{min}} \leq D_x \leq D_{x,\text{max}}
\]

\[
D_{y,\text{min}} \leq D_y \leq D_{y,\text{max}}
\]

3.5 Depth of Earth Grid Conductor

The grid burial depth influences the step and touch potentials significantly. The touch voltage decreases, due mainly to the reduced grid resistance and corresponding reduction in the GPR. However, for very large increases in depth, the touch potential may actually increase. The typical variations of burial depth found within the industry (i.e. approximately 0.5-1.5 m) and the change in grounding resistance with depth are negligible for uniform soil.

\[
h_{\text{min}} \leq h \leq h_{\text{max}}
\]

Finally, the mathematical model can be formulated as a general constrained optimization problem as follows;

\[
\text{Minimize } \{F(x, u) = GG_{\text{Cost}}\}
\]

\[
\text{S.t. } \{g(x, u) = 0\}
\]

\[
(h(x, u) \leq 0)
\]

Where \(F(x, u)\) is the objective function; \(g(x, u)\) and \(h(x, u)\) are the set of equality and inequality constraints, respectively. \(x\) is the state variables and \(u\) is the vector of continuous and discrete control variables. The control variables are the spacing between adjacent conductors (continuous variable), depth of burial (continuous variable), number of rods (integer number and continuous variable), and grounding conductor cross sectional area (discrete variable).

4. Overview of the PSO Algorithm

The PSO is an optimization technique and was first introduced in the year 1995 by Kennedy and Eberhart [21]. PSO has been recognized as an EC technique and has introduced in the year 1995 by Kennedy and Eberhart [21]. The standard PSO uses both the current global, \(p_{best}\) and the individual best, \(s_{best}\). The modification of the particle’s position can be mathematically modeled according the following;

\[
v_{i}^{k+1} = w \times v_{i}^{k} + a \times r(...) \times (p_{best} - s_{i}^{k}) + b \times r(...) \times (gbest - s_{i}^{k})
\]

The parameters \(a\) and \(b\) are the learning parameters, which can typically be taken as, say, \(a \approx b \approx 2\). The following weighting function is usually utilized;

\[
w = w_{\text{max}} - \frac{w_{\text{max}} - w_{\text{min}}}{\text{iter}_{\text{max}}} \times \text{iter}
\]

Using the above equation, a velocity, which gradually gets close to \(p_{best}\) and \(gbest\) can be calculated. The current position (searching point in the solution space) can be modified as follows;

\[
s_{i}^{k+1} = s_{i}^{k} + v_{i}^{k+1}
\]
Fig. 1 shows a concept of modification of a searching point by PSO algorithm and each agent changes its current position in a solution space using the integration of vectors as shown in Fig. 2.

4.1 Accelerated PSO

A simplified version which could accelerate the convergence of the algorithm is to use the global best only. Thus, in the APSO [24], the velocity vector is generated by a simpler formula as:

\[ v^{k+1}_i = v_i^k + \alpha \cdot r(...) + \beta \cdot (g_{\text{best}} - s_i^k) \] (19)

This is equivalent to introduce an implicit mass to stabilize the motion of the agents, and thus the algorithm is likely to converge more quickly.

In order to increase the convergence even further, the update of the location can be written in a single step, as:

\[ s^{k+1}_i = (1 - \beta) \cdot s_i^k + \beta \cdot g_{\text{best}} + \alpha \cdot r(...) - 0.5 \] (20)

This simpler version will give the same order of convergence [25]. Typically, \( \alpha = 0.1 \sim 0.5 \), while \( \beta = 0.2 \sim 0.7 \) is sufficient for most applications, though \( \alpha \approx 0.2 \) and \( \beta \approx 0.4 \) can be taken as the initial values for most unimodal objective functions.

\[ \alpha = 0.7^k \] (21)

The details of the implementation of APSO to achieve the optimal design of high voltage substation are illustrated in the flow chart shown in Fig. 3.

5. Test Cases, Numerical Results and Discussions

To evaluate the performance of the proposed method, two test cases to be presented and demonstrated. Case 1 is for real case of a project located in United Arab Emirates in the field of Umm Al Nar independent water and power (Abu Dhabi-based). However, the second case is for 33/11 kV package substation (Al Wathba South – Abu Dhabi) with 1.8 kA grounding grid current.

The proposed method developed and implemented in MATLAB platform [26] to run the proposed methodology. In all optimization runs, the parameter settings to execute APSO; the population size is 15, and the maximum cycles is 150. The type of grounding conductor material is assumed to be Copper hard-drawn, bare circular and the ambient temperature is 40°C used in the two test cases reported in this article.
$/m^2$ for soft-medium soil and rocky soil, respectively. Accurate design of a grounding system requires an accurate assessment of the site’s soil conditions. Roughly, the soil with resistivity’s of 500 Ω·m and below is being considered as soft-medium soil type. However, soil with higher resistivity’s is being considered as rocky type. The field and network data for cases 1 and 2 are depicted in Table 3. The minimum grounding conductors cross sectional areas are 300 mm², and 240 mm² for the cases 1, and 2, respectively as recommended by the project specifications.

As depicted in Tables 5-6; which are self-explanatory, all the constraint parameters of the GG design obeys the IEEE Std. 80-2000 requirements. The results of safety characteristics obtained for case 1 is better than those calculated during real project design with being paid better net saving. The proposed approach was able to reduce the cost of GG by 31.21%, and 55.68% for the cases 1 and 2, respectively as indicated in Table 4.

These obtained values are comparable and demonstrate the accuracy of the proposed method with significant reductions in the GG overall cost and at the same, satisfying the tolerable safety criteria. Moreover, it might be noted; the computational time of APSO method is very short, and considerably competitive.

It is worth pointing out that the APSO is much simpler compared with many PSO variants, as the APSO uses only short, and considerably competitive.

### 6. Conclusions

In this manuscript, an APSO-based approach for the optimal design of the grounding grids has been proposed and implemented. The proposed method has been tested and within the recommended grounding parameters, so it is easy to judge the safety of the substation. The obtained results show the importance of the proposed algorithm to explore the grid optimal parameters that satisfy safety requirements and achieve the optimum design for the GG with significant reductions in the cost aspects. The accuracy and reliability of the proposed approach have been validated using several test systems. The numerical results illustrate its effectiveness, applicability, good performance, and the computational CPU is noticeable as well.

### Nomenclatures & Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>The reduction factor</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>The resistivity of crushed rock</td>
</tr>
<tr>
<td>$\rho$</td>
<td>The uniform resistivity of the soil</td>
</tr>
<tr>
<td>$b_c$</td>
<td>The thickness of the crushed layer material</td>
</tr>
<tr>
<td>$t_c$</td>
<td>The fault-clearing time</td>
</tr>
<tr>
<td>$K_{f,2}$</td>
<td>The constant factors for step and touch potentials</td>
</tr>
<tr>
<td>$I_{f}$</td>
<td>The maximum RMS current (include for future growth)</td>
</tr>
<tr>
<td>$K_C$</td>
<td>The conductor material constant</td>
</tr>
<tr>
<td>$T_r$</td>
<td>The duration of fault current (between 0.25 to 3 s)</td>
</tr>
<tr>
<td>$T_s$</td>
<td>The duration for shock exposure</td>
</tr>
<tr>
<td>$A_{crosse}$</td>
<td>The conductor cross section in mm²</td>
</tr>
<tr>
<td>$A_{constr}$</td>
<td>The conductor cross section in kcmil</td>
</tr>
<tr>
<td>$A$</td>
<td>The total area enclosed by the grounding grid</td>
</tr>
<tr>
<td>$l_s$</td>
<td>The total buried length of conductors includes rods</td>
</tr>
<tr>
<td>$h$</td>
<td>The depth of the grid</td>
</tr>
<tr>
<td>$R_g$</td>
<td>The ground resistance of grid conductors</td>
</tr>
<tr>
<td>$R_n$</td>
<td>The ground resistance of all ground rods</td>
</tr>
<tr>
<td>$R_m$</td>
<td>The mutual ground resistance between the group of grid conductors</td>
</tr>
<tr>
<td>$R_{g}$</td>
<td>The grounding resistance</td>
</tr>
<tr>
<td>$S_F$</td>
<td>The fault current division factor</td>
</tr>
<tr>
<td>$D_P$</td>
<td>The corrective projection factor</td>
</tr>
<tr>
<td>$G$</td>
<td>The price of conductor/unit length including installation cost</td>
</tr>
</tbody>
</table>

### Table 5. Case 1: Results for safety characteristics of GG design – Weight is 50 kg

<table>
<thead>
<tr>
<th>Item</th>
<th>Tolerable Value</th>
<th>Project Design</th>
<th>Proposed Approach</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{step}$</td>
<td>1052.17</td>
<td>46.749</td>
<td>118.589</td>
<td>Pass</td>
</tr>
<tr>
<td>$E_{touch}$</td>
<td>313.271</td>
<td>312.749</td>
<td>292.543</td>
<td>Pass</td>
</tr>
<tr>
<td>$R_g$</td>
<td>≤5 Ω</td>
<td>0.032</td>
<td>0.0315</td>
<td>Pass</td>
</tr>
<tr>
<td>GPR</td>
<td>≤5000 V</td>
<td>1280.2</td>
<td>1258.82</td>
<td>Pass</td>
</tr>
</tbody>
</table>

### Table 6. Case 2: Results for safety characteristics of GG design – Weight is 70 kg

<table>
<thead>
<tr>
<th>Item</th>
<th>Tolerable Value</th>
<th>Project Design</th>
<th>Proposed Approach</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{step}$</td>
<td>644.67</td>
<td>11.063</td>
<td>42.550</td>
<td>Pass</td>
</tr>
<tr>
<td>$E_{touch}$</td>
<td>2107.66</td>
<td>24.381</td>
<td>128.091</td>
<td>Pass</td>
</tr>
<tr>
<td>$R_g$</td>
<td>≤5 Ω</td>
<td>0.1069</td>
<td>0.1556</td>
<td>Pass</td>
</tr>
<tr>
<td>GPR</td>
<td>≤5000 V</td>
<td>192,449</td>
<td>280,163</td>
<td>Pass</td>
</tr>
</tbody>
</table>

### Table 4. Optimal values for the design of cases 1 and 2 compared to the real project calculations

<table>
<thead>
<tr>
<th>Item</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_c$</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>$N_v$</td>
<td>13</td>
<td>16</td>
</tr>
</tbody>
</table>

### Table 3. Input Data for the test cases for land, soil characteristics and network data

<table>
<thead>
<tr>
<th>Item</th>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body weight (kg)</td>
<td>50</td>
<td>70</td>
</tr>
<tr>
<td>$\rho_s$ (Ω·m)</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>$k_0$ (m)</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>$\rho$ (Ω·m)</td>
<td>15</td>
<td>5.81</td>
</tr>
<tr>
<td>$l_c$ (s)</td>
<td>3.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$r_c$ (s)</td>
<td>3.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$(L_x \times L_y)$ m</td>
<td>340 × 160</td>
<td>29 × 22</td>
</tr>
<tr>
<td>$L_y$ (m)</td>
<td>3.0</td>
<td>3.6</td>
</tr>
<tr>
<td>$d_0$</td>
<td>0.0172</td>
<td>0.02</td>
</tr>
<tr>
<td>$h$ (m)</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>$l_1$ (kA)</td>
<td>40.0</td>
<td>1.80</td>
</tr>
<tr>
<td>$\rho$</td>
<td>0.33</td>
<td>0</td>
</tr>
<tr>
<td>$S_F$</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$L_{c}$</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
installation cost
$C_{se}$ The cost of soil excavation
$D_x$ The spacing between conductors in x-direction
$D_{x,\text{min}}$ The lower limit for spacing in x-direction
$D_{x,\text{max}}$ The upper limit for spacing in x-direction
$N_x$ The number of conductors in x-direction
$L_y$ The length of grounding grid in y-direction
$D_y$ The spacing between conductors in y-direction
$D_{y,\text{min}}$ The lower limit for spacing in y-direction
$D_{y,\text{max}}$ The upper limit for spacing in y-direction
$N_y$ The number of conductors in y-direction
$L_z$ The length of grounding grid in z-direction
$h_{\text{min}}$ The lower limit for the grounding grid depth
$h_{\text{max}}$ The upper limit for the grounding grid depth
$k$ The pointer of iterations
$v_i^k$ The velocity of agent $i$ at iteration $k$
$s_i^k$ The weighting function
$a, \beta$ The acceleration coefficients
$r(-)$ Random number between 0 and 1
$s_i^k$ Current position of agent $i$ at iteration $k$
$p_{best}$ The personnel best of agent $i$
$g_{best}$ The global best of the group
$w_{\text{min}}$ Initial weight
$w_{\text{max}}$ Final weight
$\text{iter}_{\text{max}}$ Maximum iteration number
$\text{iter}$ Current iteration number
$x^k$ The current searching point
$x^{k+1}$ The modified searching point
$v^k$ The current velocity
$v^{k+1}$ The modified velocity
$v_{\text{best}}$ The velocity based on $p_{best}$
$v_{\text{gbest}}$ The velocity based on $g_{best}$

**Abbreviations**
- PSO: Particle swarm optimization
- APSO: Accelerated particle swarm optimization
- GA: Genetic algorithm
- ES: Evolutionary strategy
- EC: Evolutionary computational
- GPR: Ground potential rise
- GG: Grounding grid
- RMS: Root mean square
- HV: High Voltage

**REFERENCES**


Attila El-Fergany was born in Sharkia, Egypt, on 1971. He graduated from the University of Zagazig (Zagazig – Egypt). He received M.Sc. and Ph.D. degrees from Zagazig University in 1998 and 2001, respectively. He has been on the Faculty of Engineering as a Lecturer of Electrical Power and Machines Department (Zagazig University – Zagazig). His research interests include power system protection, optimization of power system operations and AI applications in power systems. Dr. El-Fergany is a senior member of IACSIT and member of IET, IEEE, and IEEE PES.

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