Achievement of the best design for unequally spaced grounding grids

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Abstract The configuration of grounding grids which are used to earth electrical substations could be equally or unequally spaced. Unequally spaced grids were introduced to improve the requirements of the grids such as grounding grid resistance \(R_g\), ground potential rise (GPR), maximum touch voltage \(E_t\) and maximum step voltage \(E_s\) values.

Also, unequal spacing can reduce the cost of the grids and enhance the level of safety for people and equipments. In this paper two different approaches were used to determine the best possible configuration of grounding grid. These approaches based on sequential multiplicative and sequential power techniques.

1. Introduction

The requirements of any grounding grids could be improved either by modifying the grid configuration or by reducing the earth fault current. Usually reduction of the earth fault current is difficult or impractical to achieve, so the changing of the grid configuration is used, by changing the grid conductor spacing, total conductor length, grid depth and adding driven rods [1]. Many researches study the effect of grounding grid configuration and found that it can make conductor leakage current distribution more uniform, and therefore remarkably decrease earth surface potential gradients and greatly enhance the safety level for people and equipment and also the investment in building a substation grounding grid is 30% less [2], also the analysis in [3,4] shows that the voltage distribution is highly dependent on soil structure type and characteristics and also the spacing between conductors. Changing number of conductors is important to obtain the most possible economic design [5]. The main aim of this paper was to find the best spacing between the conductors of grounding grid.

Touch voltage is one of the main parameters which affected by grid configuration where in [6] a genetic algorithm is used to obtain a grounding grid having minimum value of touch voltage for a pre-arranged number of horizontal and vertical conductors.
Figure 1  Configuration of grounding grid according to different values of (α) and (β).

Table 1  Ground grid resistance (Rg - Ohm).

<table>
<thead>
<tr>
<th>Case study</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE (80-2000) calculations</td>
<td>2.78</td>
<td>2.75</td>
<td>2.62</td>
</tr>
<tr>
<td>EPRI TR-100622 [IEEE (80-2000)]</td>
<td>2.67</td>
<td>2.52</td>
<td>2.28</td>
</tr>
<tr>
<td>ETAP</td>
<td>2.67</td>
<td>2.5</td>
<td>2.25</td>
</tr>
</tbody>
</table>

Table 2  Ground potential rise (GPR - volts).

<table>
<thead>
<tr>
<th>Case study</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE (80-2000) calculations</td>
<td>5304</td>
<td>5247</td>
<td>4998.96</td>
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<tr>
<td>ETAP</td>
<td>5185.2</td>
<td>4847.4</td>
<td>4372.4</td>
</tr>
</tbody>
</table>

Table 3  Maximum touch voltage (Et-volts).

<table>
<thead>
<tr>
<th>Case study</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
</tr>
</thead>
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<tr>
<td>IEEE (80-2000) calculations</td>
<td>1002.1</td>
<td>747.4</td>
<td>595.8</td>
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<tr>
<td>EPRI TR-100622 [IEEE (80-2000)]</td>
<td>984.3</td>
<td>756.2</td>
<td>519.4</td>
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<td>ETAP</td>
<td>1113.6</td>
<td>769</td>
<td>513</td>
</tr>
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</table>

Table 4  Maximum step voltage (Es-volts).

<table>
<thead>
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</thead>
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<td>IEEE (80-2000) calculations</td>
<td>548.9</td>
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<tr>
<td>EPRI TR-100622 [IEEE (80-2000)]</td>
<td>459.1</td>
</tr>
<tr>
<td>ETAP</td>
<td>484.5</td>
</tr>
</tbody>
</table>
Figure 2  Grounding grid with different number of conductors and driven rods as in [1].

Table 5  Summary of cases studied.

<table>
<thead>
<tr>
<th>Case study</th>
<th>Used parameter</th>
<th>Parameter range</th>
<th>Number of conductors</th>
<th>Driven rods</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$\alpha$</td>
<td>0.25:0.25:2.5</td>
<td>5:1:9</td>
<td>X</td>
</tr>
<tr>
<td>2</td>
<td>$\alpha$</td>
<td>0.25:0.25:2.5</td>
<td>6:1:8</td>
<td>✓</td>
</tr>
<tr>
<td>3</td>
<td>$\beta$</td>
<td>0.25:0.25:2.5</td>
<td>5:1:9</td>
<td>X</td>
</tr>
<tr>
<td>4</td>
<td>$\beta$</td>
<td>0.25:0.25:2.5</td>
<td>6:1:8</td>
<td>✓</td>
</tr>
</tbody>
</table>

Figure 3  Illustrating figure as (B.6) in [1].
Different methods were used in the previous researches as in [7–9], to obtain configuration which can give the optimum requirements and reduce the costs. Also the results of researches [10,11] determined the rational number of grounding conductors, which can equalize the leakage current distribution and markedly decrease touch voltage and step voltage on the earth’s surface and also obtain a methodology applicable to equally spaced as well as unequally spaced grounding grids, but in this paper different and effective method used to modify the grids configuration to improve the parameters affect on its performance.

Two mathematical techniques (multiplicative and power rules) were suggested to change the grid's configuration; the number of conductors parallel to \((X\text{-axis})\) is equal to the number of conductors parallel to \((Y\text{-axis})\) that will take the symbol \((n)\). The spacing between any two adjacent conductors according to the sequential multiplication technique is given by:

\[
d(m + 1) = x \times d(m).
\]  

where \((x)\) – the multiplicative rule factor, \((m)\) – conductor’s space order, \(d(m + 1)\) – represents the later distance and \(d(m)\) – represents the previous distance.

The first distance can be calculated by:

\[
X_1 + x \times X_1 + x^2 \times X_1 + \cdots + x^{(n-1)} \times X_1 = L.
\]  

where \((X_1)\) – the first distance and \((L)\) – total length of conductor parallel to \((X\text{-axis})\) or \((Y\text{-axis})\).

The spacing between any two adjacent conductors according to the sequential power technique is given by:

\[
d(m + 1) = (d(m))^\beta.
\]  

where \((\beta)\) – the power rule factor.

The first distance can be calculated by:

\[
X_1 + X_1^\beta + X_1^{2\beta} + \cdots + X_1^{(n-1)\beta} = L.
\]  

The study of grounding grid can be done by Electrical Transient Analyzer Program (ETAP) which is an intelligent software for many applications [12]; using ground rods with unequally spaced horizontal grid conductor is very sound and cost effective solution [13]. The study also includes the effectiveness of the number and positions of the vertical rods.

In the case of equidistance be alpha or beta equal to one right; when the conductors position at the edge of the network grounding be alpha or beta greater than one right and has been selected value (2.5) as an example of this; while concentrated conductors near the center of the network when the values are less than one right and has been selected (0.5) as an example of that. Fig. 1 shows configuration of grounding grid according to different values of \((x)\) and \((\beta)\). We can notice that the convergence between the conductors with factor \((\beta)\) bigger than factor \((x)\).

Grounding grid’s performance can be calculated by different methods like the analytical equations found in IEEE (80-2000), programs like EPRI TR-100622 [IEEE (80-2000)] and ETAP. All these methods give the convergent results as shown.
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Figure 5  Grounding grid resistance ($R_g$), ground potential rise values (GPR), maximum touch voltage ($E_t$) and maximum step voltage ($E_s$) function in (a) and number of conductors. With fixed (16) driven rods.

Figure 6  Grounding grid resistance ($R_g$), ground potential rise values (GPR), maximum touch voltage ($E_t$) and maximum step voltage ($E_s$) function in (b) and number of conductors. Without fixed driven rods.
in Tables 1–4 which are depending on the shapes as shown in Fig. 2 that mentioned in [1]. The parameters to evaluate the performance of grounding grid are ground grid resistance \( R_g \), ground potential rise (GPR), maximum touch voltage \( E_t \) and maximum step voltage \( E_s \).

From Table 1 it can be noticed that the results of ground grid resistance \( R_g \) from models built by ETAP are identical to EPRI and very convergent to IEEE (80-2000) calculations. From Table 2 results of ground potential rise (GPR) are convergent to IEEE (80-2000) calculations. From Table 3 results of maximum touch voltage \( E_t \) are close to IEEE (80-2000) calculations and EPRI. Finally from Table 4 results of maximum step voltage \( E_s \) are close to IEEE (80-2000) calculations and EPRI.

2. Building cases studied

Table 5 gives the details for each case of the following four cases studied.

The inputs of following cases studied depend on data of example (B6) mentioned in [1].

The used software in building cases studied is ETAP.

<table>
<thead>
<tr>
<th>Factor</th>
<th>(Equal space grid) alpha = beta = 1</th>
<th>(Unequal space grid) alpha = 1.5</th>
<th>(Unequal space grid) beta = 1.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground grid resistance</td>
<td>1.57</td>
<td>1.56</td>
<td>1.56</td>
</tr>
<tr>
<td>Ground potential rise</td>
<td>3049.6</td>
<td>3023.5</td>
<td>3023.3</td>
</tr>
<tr>
<td>Maximum touch voltage</td>
<td>694.5</td>
<td>578.9</td>
<td>572.4</td>
</tr>
<tr>
<td>Maximum step voltage</td>
<td>315.4</td>
<td>297.8</td>
<td>295.5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Factor</th>
<th>(Equal space grid) alpha = beta = 1</th>
<th>(Unequal space grid) alpha = 1.5</th>
<th>(Unequal space grid) beta = 1.25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground grid resistance</td>
<td>1.49</td>
<td>1.48</td>
<td>1.48</td>
</tr>
<tr>
<td>Ground potential rise</td>
<td>2900.5</td>
<td>2880.2</td>
<td>2880.9</td>
</tr>
<tr>
<td>Maximum touch voltage</td>
<td>547.7</td>
<td>429.7</td>
<td>486</td>
</tr>
<tr>
<td>Maximum step voltage</td>
<td>298.7</td>
<td>273</td>
<td>266.5</td>
</tr>
</tbody>
</table>
By using ETAP model as (B6) in [1] is constructed as shown in Fig. 3.

3. Results and discussion

3.1. 1st case study

Fig. 4 shows the results of \((R_g, \text{GPR, } E_t \text{ and } E_s)\) for different configuration of the ground grid by using factor \((a)\) without fixing driven rods. The results described in Fig. 4 can be analyzed as follows; from curves shown in Fig. 4a, b and d it is clear that the values of parameters \((R_g, \text{GPR and } E_s)\) are decreased as increasing the number of conductors. Up to certain value of \((a)\) the parameters are decreasing, then they tend to be constant for other range of \((a)\). It is clear from Fig. 4c the parameter \((E_t)\) decreases with increasing the number of conductors as well as increasing the value of \((a)\) up to the certain limit, after that it starts to increase again especially with even number of conductors. The long space between the most inner conductors causes the last mentioned behavior. Seven conductor curve produces better results than eight conductor curve after the intersection point at \((a = 1.75)\) as shown in Fig. 4c that clears also five conductor curve produces same results of six conductor curve with values of \((a = 2.25 \text{ and } 2.5)\).

Figure 8 Absolute voltage profiles along the surface of the earth \((n = 9)\) – with fixed \((16)\) driven rods.
3.2. 2nd case study

Fig. 5 shows the results of \( (R_g, \text{GPR}, E_t, E_s) \) at changing the configuration of the ground grid by using factor \( (\alpha) \) with fixing sixteen driven rods. Analysis of the results described in this Fig. 5 is similar to the analysis of Fig. 4 which were compared in this case on the basis fixing number of driven rods with changing the number of conductors; but here the results of four parameters are improving at a rate ranging from 5% to 25% nearly. Still convergence between five and six conductor and seven, eight and nine conductor curves for the three parameters \( (R_g, \text{GPR} \text{ and } E_t) \) at \( (\alpha = 0.25) \). The intersection point between seven and eight conductor curves moved from \( \alpha = 1.75 \) to \( \alpha = 1.5 \) as shown in Fig. 5c and that achieved the same result illustrated in 1st case study, also still values at \( \alpha = 2.25 \) and 2.5 produce same results of five and six conductor curves.

3.3. 3rd case study

Fig. 6 shows the results of \( (R_g, \text{GPR}, E_t, E_s) \) with changing the configuration of the ground grid by using factor \( (\beta) \) without fixing driven rods. It is clear from curves shown in Fig. 6a, b and d using factor \( (\beta) \) produce different effect on the parameters where after reaching the limit at which the results stop from decreasing, the results increase again; we can note also that seven conductor curve produces equal or better results than curve at eight conductor curve after intersection point \( (\beta = 2) \) for the three parameters. Performance of curves in Fig. 6c which represents \( E_t \) is similar to results arising from using factor \( (\alpha) \) with more sharpness; in addition to previous analysis, most of the results improving by increasing the number of conductors. But:

1. After intersection point at \( \beta = 1.4 \), five conductor curve achieves better results than six conductor curve.
2. After intersection point at \( \beta = 1.6 \), five conductor curve achieves better results than eight conductor curve.
3. After intersection point at \( \beta = 1.25 \), seven conductor curve achieves better results than eight conductor curve.

3.4. 4th case study

Fig. 7 shows the results of \( (R_g, \text{GPR}, E_t, E_s) \) with changing the configuration of the ground grid by using factor \( (\beta) \) with fixing driven rods. As shown, from fixing the driven rods in the ground grid did not affect the performance of results of parameters; but the percentage of improvement which has been reached at this case study is similar to case study number (2). The intersection point between five and eight conductor curves moved from \( \beta = 1.4 \) to \( \beta = 1.5 \) as shown in Fig. 7c and that achieved the same result illustrated in 3rd case study.

Tables 6 and 7 show a comparison of models that have nine conductors without and with sixteen driven rods respectively for the three cases of \( \alpha = \beta = 1 \), \( \alpha = 1.5 \) and \( \beta = 1.25 \). The results show the effect of driven rod’s numbers on the grid parameters for all the cases. Fig. 8 shows the corresponding voltage profile along the grid to the following models with nine conductors and sixteen driven rods where:

\[
\begin{align*}
&\text{a. } (\alpha = \beta = 1) \\
&\text{b. } (\alpha = 1.5) \\
&\text{c. } (\beta = 1.25)
\end{align*}
\]

4. Conclusions

In this paper two different approaches were used to achieve the best design configuration of grounding grid as increasing sequential multiplication factor \( (\alpha) \) or sequential power rule factor \( (\beta) \) leads to better results but that up to certain limit (nearly at \( \alpha = 1.5 \) and \( \beta = 1.25 \)). After this limit, the results tend to be constant at some cases and tend to increase again at other cases. Generally we can consider the models achieved the best results at \( (\alpha = 1.5) \) and \( (\beta = 1.25) \). Selection of \( \alpha \) or \( \beta \) depends on the presence of driven rods which in turn improves the grid’s parameters.

Appendix A

The used data from example (B6) mentioned in [1] data are:

1. Symmetrical ground fault current (kA) = 3.2.
2. Fault duration (s) = 0.5.
3. Depth of grid burial (m) = 0.5.
4. \( X/R \) ratio = 3.33.

\[ X \text{ and } R \] are the components of the system subtransient fault impedance.

5. Current division factor \( (S_d) = 0.6 \).
6. Conductor size (mm\(^2\)) = 78.54.
7. Preliminary layout = 91.44 m \( \times\) 91.44 m.
8. Conductor type is copper-clad steel wire.
9. Rod data; long of each one = 9.2 m.
10. Soil resistivity = 300 \( \Omega \) m.

References


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Mohamed Hasan Abdo was born in Cairo, Egypt, in 1986. He received the B.Sc. degree in electrical engineering from Helwan University, Cairo, in 2008. Now he is studying M.Sc. in the Electrical Power and Machines Engineering, Faculty of Engineering, Helwan University, Cairo, Egypt. His current research interests are in achieving an optimal design for unequally spaced grounding grids.