Original Article

Multi-Variable Optimization of AC Substation Grounding Grid

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Abstract - The design of the AC substation grounding grid plays a pivotal role in maintaining safety during fault conditions. This paper presents a comparative study of grounding grid performance for various shapes of grounding grid, such as rectangular, square, triangular, L-shaped, and T-shaped. It mainly focuses on the number of conductors in X and Y directions, the number and length of ground rods, and the depth of installation of the grid. The outcome shows clear differences in grid behavior when the geometry and optimization parameters are changed. For each configuration, the ground resistance, ground potential rise, mesh voltage, and step voltage are assessed with respect to safety limits. The study presents that careful selection and optimization of the number of conductors in the X and Y directions, the number of ground rods, the length of ground rods, and depth can lead to obvious improvement in electrical safety as well as reductions in material usage and installation cost. Uniform soil resistivity is considered for the analysis of the grid using ESGSD software for obtaining an optimal design. This analysis provides useful direction for achieving safe and cost-efficient grounding grid layouts in practical substation applications.

Keywords - Grid, Conductors, Step voltage, Ground potential rise, Ground rods, Cost.

1. Introduction

Electrical power is transmitted from a generating station to an end consumer through a substation. The grounding grid of a substation is a vital part of its protection and safety facility. Its main purpose is to dissipate fault currents safely into the earth without the risk of electric shock to personnel and equipment damage. An efficiently designed grounding grid provides a low resistance path for fault current to dissipate into the ground by keeping potential distribution on the surface of the substation within safe limits [1-4]. The injurious effects of electric current on the human body can be largely categorized as electric shock and electrical injury. The unsafe effects on the regular functions of the heart, lungs, and nervous system when an electric current flows through the human body can be referred to as electric shock. Electrical injuries, also known as electrical burns, refer to localized damage to human tissue due to the thermal, chemical, or mechanical effects of current flowing through the body [5, 6].

So, to avoid the above situation, careful design of the substation is necessary. Substation ground grid design includes several parameters such as soil resistivity, grid geometry, conductor size, number and length of ground rods, and depth of burial [7, 8]. When fault current is dissipated into the ground, depending upon the magnitude of fault current and

grid resistance, Ground Potential Rise (GPR) is developed on the surface of the substation ground. To avoid a shock situation, actual touch potential and actual step potential are less than tolerable touch potential and tolerable step potential safety limits according to IEEE 80- 2013 guidelines [5]. There are several standards related to grounding systems available. These are (1) BS7354-1990 Code of Practice for Design of High Voltage Open Terminal Stations (2) BS 7430 Code of Practice for Protective Earthing of Electrical Installations (3) IEEE Std.80-2013 IEEE Guide for Safety in AC Substation Grounding (4) EATS 41-24-Guidelines for the Design, Installation, Testing and Maintenance of Main Earthing Systems in Substations. Maintaining the Integrity of the Specifications (5) IS 3043 Code of Practice for Earthing [4]. It is also required to avoid overdesign of substation grounding grid. Insufficient grounding can lead to dangerous touch potential and step potential while excessive material use increases cost. So design of it is such that it satisfies safety criteria as well as cost effective [9-11]. Therefore, optimization studies mean to minimize cost without compromising compliance with safety standards, such as those given by IEEE Std. 80-2013, which specifies acceptable limits for touch and step potentials under various soil and system conditions [12, 13].

The grid design is evaluated under multiple optimization constraints to identify the most cost-effective design while maintaining safe operating limits. The key parameters for optimization include the number of horizontal conductors in the X and Y directions (*Nx* and *Ny*), the number and length of vertical ground rods (*Nr* and *Lr*), and the burial depth of the conductors (*h*).

In this study, five constraints of optimization are considered for analysis.

1. Basic Design (Before Optimization) – It is obtained from the given field data.
2. N_X and N_Y Optimization – It is obtained by changing the number of conductors in the X and Y directions.
3. Nr and Lr Optimization – it is obtained by changing the number of ground rods and the length of ground rods.
4. N_X, N_Y, Nr, Lr Combined Optimization – Included optimization of grid and rod parameters.
5. N_X, N_Y, Nr, Lr, h Optimization – Optimization including grid, rod parameters, and also burial depth variation.

The analysis focuses on the impact of these optimizations on grounding resistance, Ground Potential Rise (GPR), mesh potential, step potential, length of conductors, length of ground rods, and overall cost. Results show that calculated adjustment of grid spacing, rod quantity, and burial depth can lead to significant cost savings up to 18.6% while maintaining all touch and step potentials well within IEEE 80 -2013 safety limits. Such results emphasize the importance of multi-parameter optimization in the design of cost-effective and safe substation earthing systems [14-17].

2. Manual Calculation Methodology

The manual calculations are time-consuming and very complex. After calculation, if the safety criteria are not satisfied, then again modification is required until it satisfies the safety criteria limit. The mathematical calculations in this study are carried out in accordance with the IEEE standard 80-2013 safety guidelines. For analysis, rectangular, square, L – shape, triangular, and T- shape grounding grid is taken into consideration [18]. All input parameters used for these calculations are taken from the illustrative example provided in IEEE Std. 80-2013 [5], as in Table 1.

Table 1. Input data for grid design

Parameters	Values
Fault Current (kA)	3.180
Shock Duration (s)	0.5
Fault Duration (s)	0.5
Grid Length X (m) rectangular grid	63
Grid Length Y (m) rectangular grid	84
Depth of Grid (m)	0.5
Number of Ground Rods	38
Length of Each Ground Rod (m)	10

Surface Layer Resistivity (Ωm)	2500
Thickness Surface Layer (m)	0.102
Soil Resistivity (Ωm)	400
Ambient temperature (˚C)	40
Cost of material (₹/m)	1000
Conductor material	Copper, commercial hard-drawn

For safe operation, actual touch and step potentials are less than tolerable touch and step potentials. Tolerable values of touch and step potential are listed in Table 2 with equations for 50 kg and 70 kg working personnel.

Table 2. Equations for step and touch potential as per the weight of the working personnel

Potential	50 kg working personnel
Step	$E_{step\ 50} = \dfrac{0.116}{\sqrt{t}}(1000 + 6C_s\varrho_s)$
Touch	$E_{touch\ 50} = \dfrac{0.116}{\sqrt{t}}(1000 + 1.5C_s\varrho_s)$
Potential	**70 kg working personnel**
Step	$E_{step\ 70} = \dfrac{0.157}{\sqrt{t}}(1000 + 6C_s\varrho_s)$
Touch	$E_{touch\ 70} = \dfrac{0.157}{\sqrt{t}}(1000 + 1.5C_s\varrho_s)$

Where,
ϱs = Surface layer resistivity in Ω.m
t = shock duration in (S)
Cs = Surface layer derating factor

$$Cs = 1 - \frac{0.009(1-\frac{\varrho}{\varrho s})}{2hs+0.09} = 0.74 \qquad (1)$$

Where,
ϱ = resistivity of the earth beneath the surface material in Ω.m
hs = thickness of the surface material in m

From Table 2 Equations E $_{touch\ 70}$ = 838.2V and E $_{step\ 70}$ = 2686.6V

For a rectangular shape grid, the geometric area is 5292 m². Grid wire pattern is 10x13 for a 63x84 m grid. So the grid conductor combined length is 13x63 m + 10x84 m = 1659 m. The number of ground rods is 38, and each is 10 m long, so the total length L_T = 1659 m + 38 x 10 m = 2039 m.

Grid resistance is calculated with Equation 2

$$Rg = \rho\left[\frac{1}{LT} + \frac{1}{\sqrt{20A}}\left(1 + \frac{1}{1+h\sqrt{20/A}}\right)\right] = 2.62\Omega \qquad (2)$$

Where,
LT = total buried length of conductor in m
A = area enclosed by the earth grid in m^2
h = depth of earth grid in m

Grid current is calculated with Equation 3

$$IG = Df * Sf * If = 1908A \qquad (3)$$

Where,
IG = Maximum grid current in A
Df = Determinant factor for determining IG
Sf = Fault current division factor
If = Symmetrical ground fault current in A

Ground Potential Rise (GPR) is calculated with Equation (4).

$$GPR = IG * Rg = 4998.96V \qquad (4)$$

The mesh voltage is calculated using Equation 12 with the help of parameters calculated by Equations 5 to 11.

$$Kh = \sqrt{1 + \frac{h}{h0}} \qquad (5)$$

$$n = na * nb * nc * nd \qquad (6)$$

$$na = \frac{2 * Lc}{Lp} \qquad (7)$$

$$Lp = \{(2 * Lx) + (2 * Ly)\} \qquad (8)$$

$$Lc = \{(Lx * Nx) + (Ly * Ny)\} \qquad (9)$$

$$Km = \frac{1}{2 * \pi} * \left[\ln\left[\frac{D^2}{16 * h * d} + \frac{(D + 2 * h)^2}{8 * D * d} - \frac{h}{4 * d} \right] + \frac{Kii}{Kh} \right. \qquad (10)$$
$$\left. * \ln\left[\frac{8}{\pi(2 * n - 1)} \right] \right]$$

Where,
Kh = A weighting factor for depth of burial
Km = Spacing factor for mesh voltage
Kii = Corrective weighting factor for rods on corner mesh
Kii = 1 for grids with earth electrodes along the grid perimeter or corners
Kii = [1/2n $^{n/2}$] for grids with no earth electrodes along the grid perimeter or corners
n = geometric factor
nb = 1 for square grid or otherwise

$$nb = \sqrt{Lp/4\sqrt{A}}$$

nc = 1 for square and rectangular grid,
otherwise $nc = \left[\frac{LxLy}{A}\right]^{0.7A/LxLy}$
nd = 1 for square, rectangular grid, and L- shape grid,
otherwise nd = $\frac{Dm}{\sqrt{Lx^2 + Ly^2}}$
Lx = Length of Grid conductor in X direction
Ly = Length of Grid conductor in Y direction
Nx = No. of the grid conductor in the X direction
Ny = No. of the grid conductor in the Y direction
D = Spacing between parallel conductors

$$LM = LC + \left[1.55 + 1.22\left(\frac{Lr}{\sqrt{Lx^2 + Ly^2}}\right)\right] LR \qquad (11)$$

$$Em = \frac{\rho * Km * Ki * IG}{LM} = 595.8V \qquad (12)$$

Where,
LR = Total length of ground rods

The step voltage is calculated using Equation 15

$$Ls = 0.75 * LC + 0.85 * LR \qquad (13)$$

$$Ks = \frac{1}{\pi}\left[\frac{1}{2 * h} + \frac{1}{D + h} + \frac{1}{D}(1 - 0.5^{n-2})\right] \qquad (14)$$

$$Es = \frac{\rho * Ks * Ki * IG}{Ls} \qquad (15)$$

The result of mathematically calculated values for touch potential is shown in Table 3.

Table 3. Calculated values for touch potential

Shape of grid	Tolerable value of $E_{touch\ 70}$	Actual value of $E_{touch\ 70}$	Grid safety
Rectangular	838.2V	595.8V	Safe as the actual value of touch voltage is less than the Tolerable Value
Square	838.2V	1002.11V	Not safe, as the actual value of touch voltage is higher than the tolerable value
L -shape	838.2V	896V	Not safe, as the actual value of touch voltage is higher than the tolerable value

The results of Table 3 indicate that square and L-shaped grid designs are not safe and require modification in design. Doing these calculations manually is time-consuming and complicated. If these calculations are done with software, modifications can be made quickly and easily [19, 20]. With the help of software, optimization of the design is also possible. So all possible improvements required can be done before the actual implementation of it. This makes it much easier to identify the safest and most efficient design.

3. Software Details

The Economical Substation Grounding System Designer (ESGSD) was developed and run in the MATLAB environment. The user has to select the grid shape at the beginning, and after that, it asks for conductor and ground rod materials. Then, as shown in Figure 1, the required input data is entered.

Figure 2 provides data for soil resistivity, and system data is entered as shown in Figure 3. After entering the required data, this software gives a detailed analysis and optimized design. It includes all shapes such as rectangular, square, L-shaped, triangular, and T-shaped. It supports both uniform soil and two-layer soil models. By using the optimization features in ESGSD, users can create designs that are not only safe but also cost-efficient.
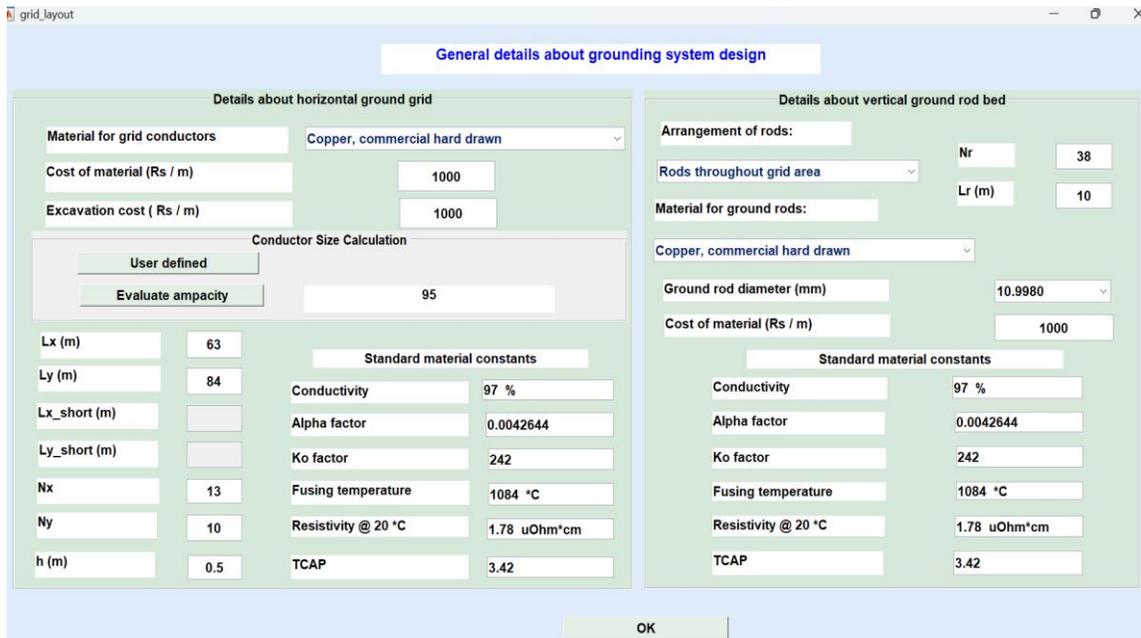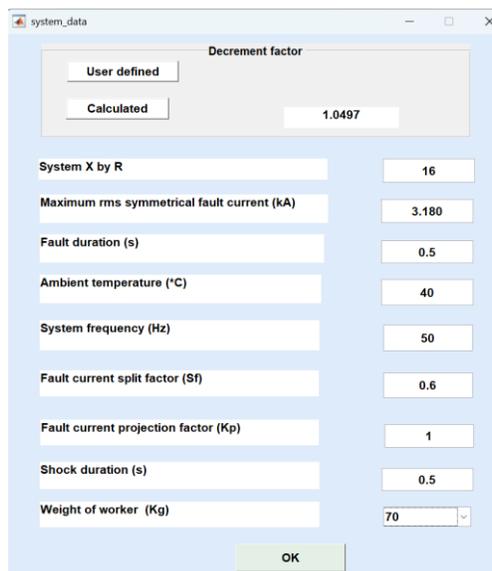

Fig. 1 Input data
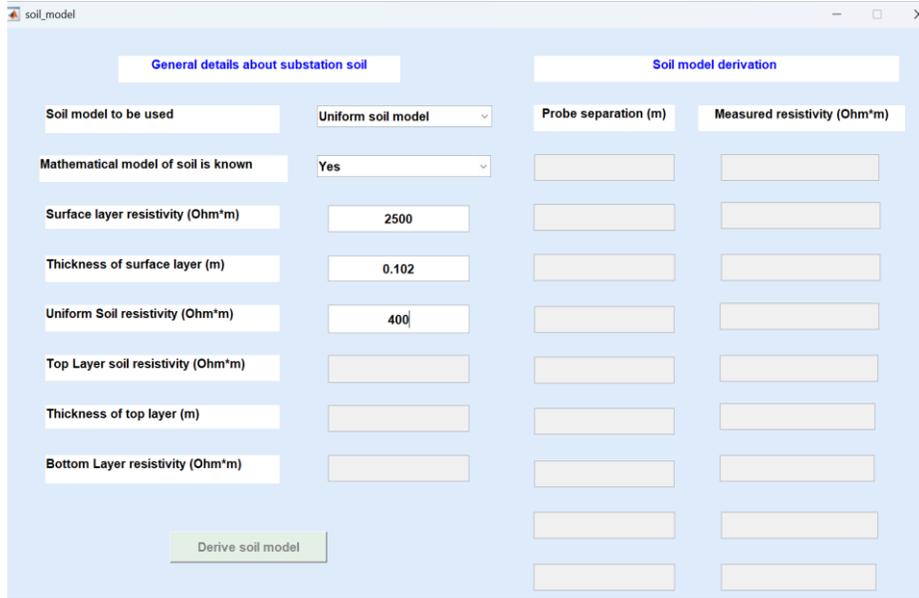

Fig. 2 Soil resistivity data

Fig. 3 System data

4. Results and Discussion

For analysis in this study, a uniform soil model is taken into account. Four constraints (only Nx and Ny, only Nr and Lr, only Nx, Ny, Nr, and Lr, and considering Nx, Ny, Nr, Lr, and burial depth) are considered for optimization. A rectangular grid dimension is 5292 m². It consists of 38 ground rods, each of 10 m. Results for the rectangular grid shape are listed in Table 4.

Table 4. Rectangular shape grid design parameters

Parameters	Values Before Optimization	Values after optimization, considering			
		Nx and Ny	Nr and Lr	Nx, Ny, Nr, Lr	Nx, Ny, Nr, Lr, h
Substation ground area (m²⁾)	5292	5292	5292	5292	5292
Optimal No. of conductors in X direction	13	8	13	10	9
Optimal No. of conductors in Y direction	10	10	10	13	12
No. of ground rods provided	38	38	19	19	20
Total length of horizontal conductors (m)	1722	1302	1722	1659	1512
Total length of ground rods provided (m)	380	380	190	190	200
Total overall conductor length provided (m)	2102	1682	1912	1849	1712
Peripheral length of grid conductors (m)	294	294	294	294	294
Resistance of ground grid (Ω)	2.613	2.660	2.6316	2.639	2.628
Tolerable touch potential (V)	840.548	840.548	840.548	840.548	840.548
Tolerable step potential (V)	2696.097	2696.097	2696.097	2696.097	2696.097
Ground potential rise (V)	5232.720	5327.889	5270.5935	5284.8699	5263.874
Actual mesh potential (V)	616.389	702.644	712.11	708.7042	708.702
Actual Step Potential (V)	476.993	466.406	530.01	537.6754	339.9799
Mesh potential as a % of the tolerable value	73.332	83.594	84.7197	84.3145	84.3143
Step potential as a % of the tolerable value	17.692	17.299	19.6584	19.9427	12.6101
Taking the Cost of the conductor	1000	1000	1000	1000	1000
Taking the Cost of the ground rod	1000	1000	1000	1000	1000
Cost (₹)	2102000	1682500	1912500	849000	1712000
Lr (m)	10	10	10	10	10
h (m)	0.5	0.5	0.5	0.5	0.9

Significant improvement in safety and efficiency can be obtained by careful optimization of design parameters. The ground area remained constant at 5292 m² for all cases. Reduction in material and cost savings obtained by adjustments in the number of conductors in the X and Y directions (Nx and Ny), the number and length of ground rods (Nr and Lr), and burial depth (h). For example, before optimization, the system required 13 conductors in the X direction and 10 in the Y direction, with 38 ground rods, resulting in a total conductor length of 2102 m and an overall cost of ₹ 2,102,000. Optimizing Nx and Ny reduced the conductor length to 1682 m and lowered the cost to ₹ 1,682,500, while optimization including Nx, Ny, Nr, Lr, and a burial depth of 0.9 m achieved a total conductor length of 1712 m and a minimum cost of ₹ 1,712,000, an overall reduction of nearly 18.5%. Electrical performance remained within safe limits throughout. Ground grid resistance remains between 2.613 Ω and 2.628 Ω, mesh potential ranged from 616 V to 708 V, and step potential dropped from 477 V before optimized design to 340 V in the optimized system. These results indicate that multi-parameter optimization not only reduces cost and material usage but also enhances safety.

Grid dimension for the square grid is 4900 m². It consists of 20 ground rods, each of 7.5 m. Results for the square grid shape are listed in Table 5.

Table 5. Square shape grid design parameters

Parameters	Values Before Optimization	Values after optimization, considering			
		N_X and N_Y	N_r and Lr	Nx, Ny, Nr, Lr	Nx, Ny, Nr, Lr, h
Substation ground area (m²)	4900	4900	4900	4900	4900
Optimal No. of conductors in X direction	11	13	11	12	11
Optimal No. of conductors in Y direction	11	13	11	12	11
No. of ground rods provided	20	20	25	22	23
Total length of horizontal conductors (m)	1540	1820	1540	1680	1540
Total length of ground rods provided (m)	150	150	237.500	165	172.500
Total overall conductor length provided (m)	1690	1970	1777.500	1845	1712.500
Peripheral length of grid conductors (m)	280	280	280	280	280.000
Resistance of ground grid (Ω)	2.753	2.719	2.741	2.733	2.720
Tolerable touch potential (V)	840.548	840.548	840.548	840.548	840.548
Tolerable step potential (V)	2696.097	2696.097	2696.097	2696.097	2696.097
Ground potential rise (V)	5513.063	5445.686	5489.728	5473.238	5446.906
Actual mesh potential (V)	770.859	678.188	711.30	712.519	714.464
Actual Step Potential (V)	576.4016	583.227	544.81	574.120	367.097
Mesh potential as a % of tolerable value	91.71	80.684	84.624	84.768	85.000
Step potential as a % of the tolerable value	21.38	21.632	20.207	21.294	13.616
Taking the Cost of the conductor (₹)	1000	1000	1000	1000	1000
Taking the Cost of the ground rod (₹)	1000	1000	1000	1000	1000
Cost (₹)	1690000	1970500	1777500	1845000	1712500
Lr (m)	7.5	7.5	9.5	7.5	7.5
h (m)	0.5	0.5	0.5	0.5	0.9

In this grid geometry, the total area is 4900 m² and remains constant for all cases. The total horizontal conductor length before optimization was 1690 m. After optimization, it increased slightly to 1712.50 m. Because of this increase in conductor length, the overall cost also increased. However, the optimization considerably improved safety. The mesh potential safety margin dropped from 91.71% to 85%, and the step potential decreased from 576.40 V to 367.10 V. Ground potential rise was also reduced from 5513.063 V to 5446.906 V. These results show that grounding design is a tradeoff between cost and safety. So the parameters must be preferred to achieve an appropriate balance between the cost and safety. Grid dimension for the L-shape grid is 4900m². It consists of 24 ground rods, each of 7.5 m. Results for the L-shape grid are listed in Table 6.

Table 6. L – Shape grid design parameters

Parameters	Values Before Optimization	Values after optimization, considering			
		N_X and N_Y	N_r and L_r	Nx, Ny, Nr, Lr	Nx, Ny, Nr, Lr, h
Substation ground area (m²)	4900	4900	4900	4900	4900
Optimal No. of conductors in X direction	13	13	NA	12	11
Optimal No. of conductors in Y direction	10	19	-	17	16
No. of ground rods provided	24	24	-	30	29
Total length of horizontal conductors (m)	1295	1855	-	1691.308	1575
Total length of ground rods provided (m)	180	180	-	225	217.500
Total overall conductor length provided (m)	1475	2035	-	1916.308	1792.500
Peripheral length of grid conductors (m)	350	350	-	350	350
Resistance of ground grid (Ω)	2.787	2.713	-	2.725	2.709Ω
Tolerable touch potential (V)	840.548	840.548	-	840.548	840.548
Tolerable step potential (V)	2696.097	2696.097	-	2696.097	2696.097
Ground potential rise (V)	5582.161	5432.697	-	5457.081	5426.028
Actual mesh potential (V)	895.544	688.899	-	712.715	714.426
Actual Step Potential (V)	588.575	606.580	-	584.310	376.226
Mesh potential as a % of the tolerable value	106.543	81.958	-	84.792	84.995
Step potential as a % of the tolerable value	21.831	22.498	-	21.672	13.954
Taking the Cost of the conductor (₹)	1000	1000	-	1000	1000
Taking the Cost of the ground rod (₹)	1000	1000	-	1000	1000
Cost (₹)	1475000	2035500	-	1916307.692	1792500
Lr (m)	7.5	7.5	-	7.5	7.5
h (m)	0.5	0.5	-	0.5	0.9

In this configuration, the total area of the grid is 4900 m². The actual mesh voltage is 895.54 V, which is higher than the tolerable touch voltage of 840.548 V. This means the present grid design is not safe for working personnel. So a modification is required in the design of the grid. By optimizing the grid design by considering the number of horizontal conductors (Nx and Ny) or changing the number of ground rods(Nr) or their length (Lr) or increasing or decreasing the depth of burial, the actual value of touch potential is reduced below the tolerable touch potential. When this criterion is fulfilled, the design becomes safe. But these improvements increase the overall cost. Grid dimension for the triangular grid is 2646 m². It consists of 38 ground rods, each of 10 m. Results for the Triangular grid shape are listed in Table 7.

Table 7. Triangular shape grid design parameters

Parameters	Values Before optimization	Values after optimization, considering			
		N_X and N_Y	N_r and L_r	Nx, Ny, Nr, Lr	Nx, Ny, Nr, Lr, h
Substation ground area (m²)	2646	2646	2646	2646	2646
Optimal No. of conductors in X direction	13	13	-	17	16
Optimal No. of conductors in Y direction	10	17	-	22	21
No. of ground rods provided	38	38	-	18	20
Total length of horizontal conductors (m)	1004.938	1228.500	-	1554.078	1480.500
Total length of ground rods provided (m)	380	380	-	180.000	200.000
Total overall conductor length provided (m)	1384.938	1608.500	-	1734.078	1680.500
Peripheral length of grid conductors (m)	294.000	294	-	294	294.000
Resistance of ground grid (Ω)	3.694	3.654	-	3.636	3.616
Tolerable touch potential (V)	840.548	840.548	-	840.548	840.548
Tolerable step potential (V)	2696.097	2696.097	-	2696.097	2696.097

Ground potential rise (V)	7398.422	7318.023	-	7281.954	7241.981
Actual mesh potential (V)	829.350	711.676	-	713.714V	711.811
Actual Step Potential (V)	654.825	706.892	-	864.155	671.386
Mesh potential as a % of the tolerable value	98.668	84.668	-	84.911	84.684
Step potential as a % of the tolerable value	24.288	26.219	-	32.052	24.902
Taking the Cost of the conductor (₹)	1000	1000	-	1000	1000
Taking the Cost of the ground rod (₹)	1000	1000	-	1000	1000
Cost (₹)	1384937.500	1609000	-	1734078.13	1680500
Lr (m)	10	10	-	10	10
h (m)	0.5	0.5	-	0.5	0.7

The above results indicate that the original grounding grid was unsafe because the actual mesh potential was 829.35 V, very close to the tolerable limit of 840.55 V. When only the number of horizontal conductors (Nx and Ny) was optimized, the conductor count increased from 13 × 10 to 13 × 17, increasing the horizontal conductor length from 1004.94 m to 1228.50 m. This increased the cost from ₹ 1,384,938 to ₹1,609,000, but significantly reduced the mesh potential to 711.68 V. When Nx, Ny, Nr, and Lr were optimized, rods were reduced from 38 to 18, cutting rod length from 380 m to 180 m, which lowered cost but increased step potential to 864.16V. Increased total conductor length to 1554.08 m,

costing ₹ 1,734,078, reducing mesh potential to 713.71 V. The best balance was achieved when burial depth (h) was also optimized from 0.5 m to 0.7 m along with Nx, Ny, Nr, and Lr. This configuration used 1480.50 m of horizontal conductors and 200 m of rods, costing ₹ 1,680,500 and delivered the safest performance with mesh potential 711.81 V and step potential 671.39 V, both well within tolerable limits. Thus, the final configuration provides the optimal tradeoff between cost and safety. Grid dimension for the T-shape grid is 3920 m^2. It consists of 38 ground rods, each of 10m. A result for the T-shape grid is listed in Table 8.

Table 8. T – Shape grid design parameters

Parameters	Values Before Optimization	Values after optimization, considering			
		Nx and Ny	Nr and Lr	Nx, Ny, Nr, Lr	Nx, Ny, Nr, Lr, h
Substation ground area (m^2)	3920	3920	3920	3920	3920
Optimal No. of conductors in X direction	13	10	-	13	12
Optimal No. of conductors in Y direction	10	13	-	17	15
No. of ground rods provided	38	38	-	16	18
Total length of horizontal conductors (m)	1222.200	1267	-	1640.333	1484.05
Total length of ground rods provided (m)	380	380	-	160	180
Total overall conductor length provided (m)	1602.200	1647	-	1800.333	1664.054
Peripheral length of grid conductors (m)	294	294	-	294	294
Resistance of ground grid (Ω)	3.058	3.051	-	3.030	3.011
Tolerable touch potential (V)	840.548	840.548	-	840.548	840.548
Tolerable step potential (V)	2696.097	2696.097	-	2696.097	2696.097
Ground potential rise (V)	6123.722	6110.121	-	6068.694	6030.975
Actual mesh potential (V)	707.295	692.901	-	705.052	710.940
Actual Step Potential (V)	542.942	546.649	-	657.052	421.647
Mesh potential as a % of the tolerable value	84.147	82.434	-	83.880	84.581
Step potential as a % of the tolerable value	20.138	20.276	-	24.370	15.639
Taking the Cost of the conductor (₹)	1000	1000	-	1000	1000
Taking the Cost of the ground rod (₹)	1000	1000	-	1000	1000
Cost (₹)	1602200	1647500	-	1800333.33	1664054.26
Lr (m)	10	10	-	10	10
h (m)	0.5	0.5	-	0.5	0.9

The result shows that the original grounding grid design, with 13×10 conductors and 38 ground rods, produced a mesh

potential of 707.30 V and a step potential of 542.94 V, both within safe limits, at a cost of ₹1,602,200. Adjusting only the

horizontal conductors (to 10×13) slightly improved mesh potential to 692.90 V, but increased cost to ₹1,647,500. Optimizing with Nx, Ny, Nr, and Lr reduced the number of ground rods from 38 to 16 and the rod length from 380 m to 160 m, but raised the step potential to 657.05 V and increased the cost to ₹1,800,333. In this optimization, the conductor length is 1640.33 m, and the mesh potential is 705.05 V. The best overall performance was achieved when burial depth was also optimized from 0.5 m to 0.9 m, along with conductor and rod adjustments (12×15 conductors and 18 rods). This configuration resulted in a mesh potential of 710.94 V, a significantly lower step potential of 421.65 V, and a moderate cost of ₹1664054. Thus, the final optimized design provides the most balanced solution between safety and cost. Cost comparisons of various shapes of grid design are shown in Figure 4 for different optimization types.
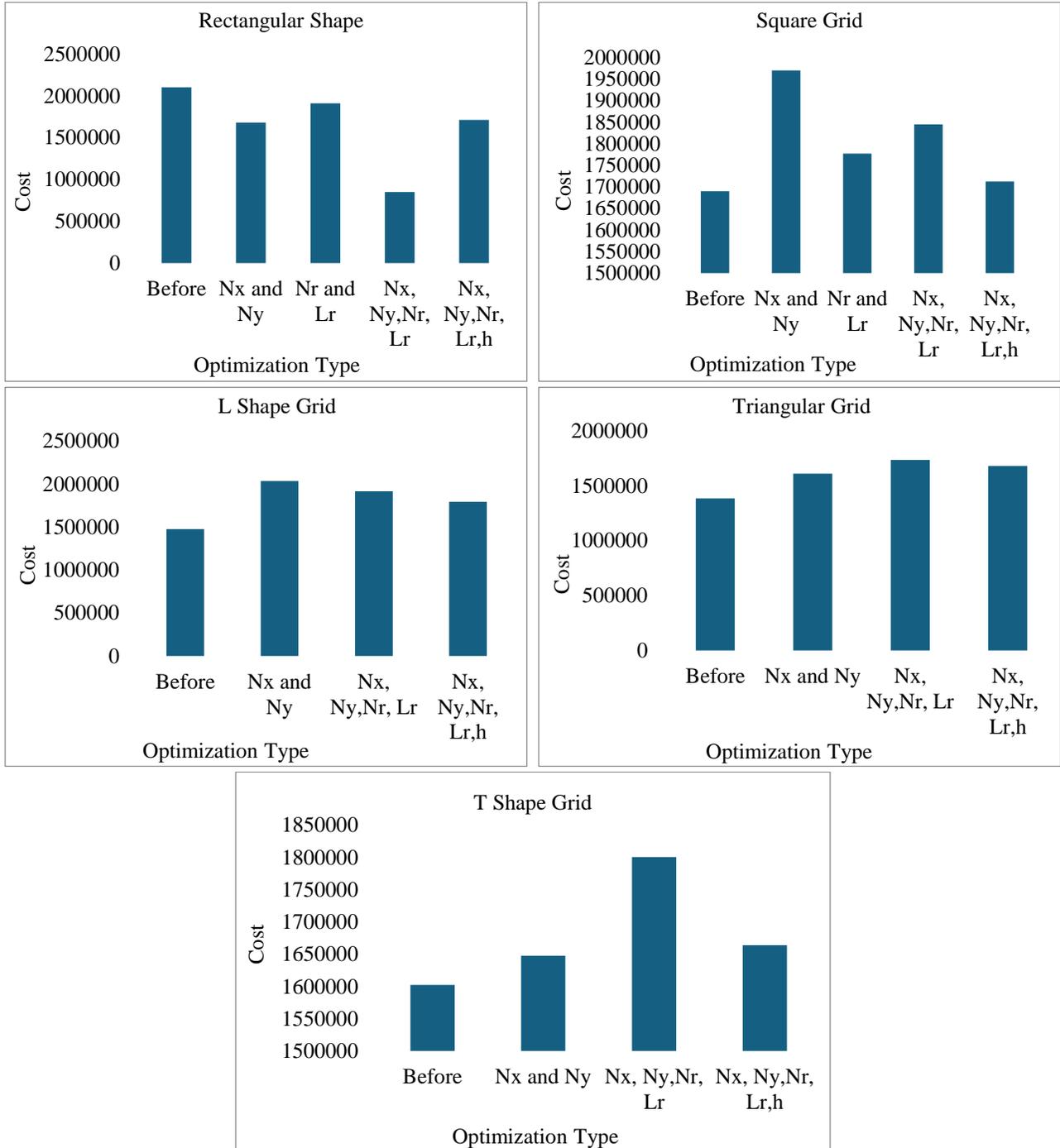

Fig. 4 Cost comparison of Rectangular, Square, L – shape, Triangular, T -shape

For all types of grounding grid designs, whether rectangular, square, L-shaped, triangular, or T-shaped, the most balanced and effective results are achieved when multiple design parameters are optimized simultaneously. Key parameters include the number of horizontal conductors (Nx and Ny), the number and length of ground rods (Nr and Lr), and the burial depth of the conductors and rods (h). Adjusting these factors together ensures that mesh potential, step potential, and ground potential rise remain within safe limits as per IEEE 80-2013 guidelines while avoiding unnecessary increases in cost. Optimizing only one parameter at a time may improve one aspect of safety but can compromise another or lead to overdesign. By considering all applicable parameters together, the grounding system can be designed in a balanced manner, achieving both safety and cost efficiency.

5. Conclusion

In a substation, the safety of personnel and equipment is vital, which requires efficient grounding grid design. With relevant equations, various parameters of grounding grids are calculated and compared with software-calculated parameters. The tolerable limit of touch potential and step potential is higher than the actual value of touch and step potential, so that safe operation of the grid is obtained. This study analyzes how grounding grid designs of various shapes, rectangular, square, L-shaped, triangular, and T-shaped, can be modified to ensure all safety criteria remain within tolerable limits. The table of optimization results confirms that multi-parameter optimization, including the number of horizontal conductors (Nx and Ny), number and length of ground rods (Nr and Lr),

and burial depth (h), provides the most balanced performance for different grid shapes. By adjusting these parameters, mesh potential, step potential, and ground potential rise can be kept safely below tolerable limits while controlling overall cost. Software-based implementation simplifies the design process, making it faster and more accurate compared to manual calculations, which are more complex and time-consuming. Software design allows possible variation in parameters to observe the performance of the design in various constraints, and the best one is selected for actual implementation. Proper consideration of soil resistivity and cautious optimization avoids overdesign, resulting in grounding systems that are both safe and cost-effective.

During this analysis, a uniform soil model is considered in which soil resistivity remains constant throughout the depth of the grounding system. Assuming uniform soil resistivity simplifies the grounding grid analysis and allows for the calculation of grounding resistance, touch voltage, and step voltage. In actual field conditions, soil resistivity typically varies with depth due to changes in moisture content, temperature, and soil composition. These variations have a major impact on the performance and safety of the grounding grid. For a more accurate and practical assessment, a two-layered soil model should be used, where the upper and lower soil layers have different resistivity values. By considering a two-layered soil model, a more accurate calculation of ground resistance, ground potential rise, touch voltage, and step voltage is possible. As a result, a more reliable and safe grounding grid design is possible.

References

[1] Xuan Wu, Qianzhi Zhang, and Jiahong He, "Substation Grounding System Optimization with Utilizing a Novel MATLAB Application," *2016 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC),* Xi'an, China, pp. 628-633, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[2] Benamrane Alik, Madjid Teguar, and Abdelouahab Mekhaldi, "Minimization of Grounding System Cost using PSO, GAO, and HPSGAO Techniques," *IEEE Transactions on Power Delivery*, vol. 30, no. 6, pp. 2561-2569, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[3] Muhammad Usman Cheema et al., "A Comparison of Ground Grid Mesh Design and Optimization for 500KV Substation using IEEE 80-2000 and Finite Element Methods," *Electrical and Electronics Engineering: An International Journal (ELELIJ)*, vol. 4, no. 1, pp. 131-146, 2015. [CrossRef] [Google Scholar] [Publisher Link]

[4] T. Tamanna Sharma, and O.P. Rahi, "Optimizing Substation Earthing Systems: A Finite Difference Approach for Grounding Resistance Minimization and Potential Distribution Analysis," *2024 IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS)*, Bhopal, India, pp. 1-5, 2024. [CrossRef] [Google Scholar] [Publisher Link]

[5] "80-2013 - IEEE Guide for Safety in AC Substation Grounding," *IEEE*, pp. 1-192, 2013. [Publisher Link]

[6] K. Sushma Reddy, G.S. Raju, and Poonam Upadhyay, "Design of Optimal Grounding Mats for High Voltage Substation," *2012 International Conference on Advances in Power Conversion and Energy Technologies (APCET)*, Mylavaram, India, pp. 1-4, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[7] Navinesshani Permal et al., "Optimization of Substation Grounding Grid Design for Horizontal and Vertical Multilayer and Uniform Soil Condition using Simulated Annealing Method," *PLoS One*, vol. 16, no. 9, pp. 1-16, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[8] Hammad Ali Al-Khayari, Venkateswara Sarma Mallela, and Satish Tanavade, "Design of Sub-Station Grounding System-A Case Study at PDO, and MZEC, Sultanate of Oman," *2017 International Conference on Electrical and Computing Technologies and Applications (ICECTA)*, Ras Al Khaimah, United Arab Emirates, pp. 1-5, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[9] Soni Mohammed, and Abraham George, "Cost Effective Grounding Grid Design for Substation," *International Journal of Scientific and Engineering Research*, vol. 6, no. 8, pp. 1558-1563, 2015. [Google Scholar]

[10] Elsayed M. Elrefaie et al., "Evolutionary Strategy Technique to Optimize the Grounding Grids Design," *2012 IEEE Power and Energy Society General Meeting*, San Diego, CA, USA, pp. 1-6, 2012. [CrossRef] [Google Scholar] [Publisher Link]

[11] Sherif S.M. Ghoneim, and Ibrahim B.M. Taha, "Control the Cost, Touch and Step Voltages of the Grounding Grids Design," *IET Science Measurement and Technology*, vol. 10, no. 8, pp. 943-951, 2016. [CrossRef] [Google Scholar] [Publisher Link]

[12] Faouzi Aboura, and Omar Touhami, "Grounding System Cost Reduction using Multiobjective Optimisation Method," *IET Science Measurement and Technology*, vol. 14, no. 10, pp. 893-900, 2020. [CrossRef] [Google Scholar] [Publisher Link]

[13] Amnit Dhindsa, "Optimization of AC Substation Ground Grid Design and Calculations," *2022 IEEE IAS Petroleum and Chemical Industry Technical Conference (PCIC)*, Denver, CO, USA, pp. 503-511, 2022. [CrossRef] [Google Scholar] [Publisher Link]

[14] Ahmed Taher et al., "Optimum Design of Substation Grounding Grid based on Grid Balancing Parameters using Genetic Algorithm," *2018 Twentieth International Middle East Power Systems Conference (MEPCON)*, Cairo, Egypt, pp. 352-360, 2018. [CrossRef] [Google Scholar] [Publisher Link]

[15] Ishak Kasim, Syamsir Abduh, and Nur Fitryah, "Grounding System Design Optimization on 275 KV Betung Substation based on IEEE Standard 80-2000," *2017 15th International Conference on Quality in Research (QiR): International Symposium on Electrical and Computer Engineering*, Nusa Dua, Bali, Indonesia, pp. 400-407, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[16] Surya Hardi et al., "Economic Design of Substation Grounding Grid using ETAP Software: A Case Study of 2 x 500 MVA Galang Substation," *Journal of Physics: Conference Series*, vol. 1811, no. 1, pp. 1-9, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[17] Hanliang Lin et al., "Evaluation and Optimization of Safety Performance State of Grounding Grid," *2021 IEEE 4th International Electrical and Energy Conference (CIEEC)*, Wuhan, China, pp. 1-4, 2021. [CrossRef] [Google Scholar] [Publisher Link]

[18] B. Thapar et al., "Evaluation of Ground Resistance of a Grounding Grid of Any Shape," *IEEE Transactions on Power Delivery*, vol. 6, no. 2, pp. 640-647, 1991. [CrossRef] [Google Scholar] [Publisher Link]

[19] Ankita B. Patel, and Keval Velani, "Digital Application for Grounding Grid Design Calculations of Substation," *2017 Innovations in Power and Advanced Computing Technologies (i-PACT)*, Vellore, India, pp. 1-6, 2017. [CrossRef] [Google Scholar] [Publisher Link]

[20] Surya Hardi, Azwar Nasution, and Fanindia Purnamasari, "Modeling of Substation Grounding Grid Design using Lab View Graphical User Interface," *2019 3rd International Conference on Electrical, Telecommunication and Computer Engineering (ELTICOM)*, Medan, Indonesia, pp. 149-154, 2019. [CrossRef] [Google Scholar] [Publisher Link]