Cost Effective Grounding Grid Design for Substation

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Abstract: Well-designed grounding system is very much essential as far as the safety of the crew and the substation equipments are concerned. Optimal design of grounding system for a substation is complex due to the involvement of numerous parameters. In this paper grounding system is cost optimized by MATLAB simulation and the results are analyzed. Variation in touch and step voltages for different values of fault currents with variations in conductors spacing, depth of burial and number of ground rods are plotted. The grid design parameters such as ground resistance, ground potential rise, step and mesh voltages, total length of grid and ground rods are calculated based on IEEE Std. 80-2000.

Key words: Grounding grid, ground potential rise, step voltage, mesh voltage, conductor spacing, and depth of burial.

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I. Introduction

Main objectives of a grounding system are to safeguard the life of the sub-station personnel and to protect the sub-station equipments by providing a low resistance discharge path for fault currents to ground. A low grounding resistance ensures touch, step and mesh voltages within tolerable limits, hence ensuring safety under fault conditions. Performance of a grounding grid depends on soil structure and grid configuration. Ground grid can have equally or unequally spaced conductors with or without ground rods. Soil may be uniform, two layer or multilayer.

Research is going on in this field for decades and researchers have come out with many novelties. Cost effectiveness is given equal importance as safety in grounding grid designs. A few among the recent innovations are as follows.

Kaustubh A. Vyas and J. G. Jamnani [3] developed a software as per methods described in IEEE standard 80–2000 which is capable of calculating various performance parameters of grounding system for given input data related to grid geometry, soil and system conditions for all the basic shapes of grounding grid in uniform and two layered soils.

Also this software suggests optimal and safe design of the grounding system under safety constraints.

Navid Khorasani Nezhad et.al.[4] Proposed a method considering the number and diameter of conductors and rods which carry the fault current, space between conductors, depth of burial of the grounding system and investment cost. The

simulation was carried out using Particle Swarm Optimization algorithm. Ferrante Neri [5] Proposed a Hierarchical Evolutionary-Deterministic Algorithm (HEDA) for designing square grounding grids in which design of the grounding grid is here formalized as a min-max problem. The maximization part is the search of the most dangerous point for a given topological structure and the minimization part is the optimization of the topological parameter, compression ratio of the grounding grid.

Lots more literature is available on optimal design of grounding system and research is still being carried out for innovations.

II Optimal ground system design

Table 1 : Grounding grid design data

Soil resistance of upper layer	1500 Ω-m
Soil resistance of lower layer	34.15Ω-m
Thickness of upper layer soil	0.2 m
Duration of fault current	0.5 sec
Fault current	9 kA
Length of Grid	80 m
Breadth of Grid	41 m
Depth of Burial	0.6 m
Length of the Ground Rods	2.4 m
Ambient Temperature	40^{o}C
Duration of Shock Current through body	0.5 s

Table 2: Simulated results (least cost design meeting all the constraints)

Tolerable Step Voltage (Person Weight 70 Kg)	1861.63 V
Tolerable Touch Voltage (Person Weight 70 Kg)	631.933 V
Total length of grid conductor without ground rods	691.43 m
Number of Ground Rods	21
Total length of grid conductor with ground rods	731.19 m
Geometric factor or total number of parallel conductors	6
Conductor Spacing (d m)	11.5 m
Grid resistance	0.3276 Ω
Ground Potential rise	2948.42 V
Calculated step voltage	263 V
Calculated touch voltage	627.43 V
Cost of Grid Conductor	Rs. 26230
Cost of Ground Rods	Rs. 18386
Total Cost	Rs. 44616

Grid design computations are done for the grid design data given in Table 1 [3]. Numerous trial computations are done for varieties of configurations. Conductor spacing, depth of burial and length of ground rods are varied in discrete, small steps within the allowed range. One parameter is varied at a time keeping all other parameters constant for different conductor materials. This has resulted in a large number of feasible solutions. The cost optimal solution is identified form the set of feasible solutions obtained.

In the above example conductor spacing is varied from 2-12m, depth of burial from 0.2-1m and length of ground rods from 2-13m. The trials are repeated for 9 different conductor materials. Out of the 1412 trials made, 903rd trials resulted in feasible solutions. Each feasible solution gives information such as total length of grid conductors, number of ground rods, total length conductors including ground rods, geometric factor, grid resistance, ground potential rise, step voltage, touch voltage and total cost. The cost optimal solution is picked up from the set of feasible solutions obtained and given in Table 2.

III Factors affecting the cost of grounding grid

The primary objective of ground grid design is to ensure safety to the sub-station personnel and the connected equipments with cost optimized. To ensure safety, the step and touch voltages should be within tolerable limits and the fault current should pass safely to earth. A low grounding resistance is essential for the safe passage of fault current to ground and to limit the ground potential rise. Grounding resistance depends on soil resistivity, various grid parameters and depth of burial of the grid. Hence these parameters are to be chosen carefully to optimize the cost and ensuring safety. So to achieve lightning protection and electromagnetic compatibility requirements, an effective grounding system is essential.

a. Soil Resistivity

IEEE Std. 80-2000 says a typical soil has several layers, each having a different resistivity. Resistivity varies vertically and sometimes laterally also, but lateral changes are often more gradual. A site with uniform soil resistivity is seldom found. A soil model is only an approximation of actual soil conditions and a perfect match is often not possible. If the extreme values of apparent resistivity measurements in the four-pin method at different depths are closer, the soil model can be approximated as uniform. In such a case, the uniform resistivity is computed as the average of the measured values. However it has been recognized that the two-layer representation of soil is closer to the actual conditions than its uniform equivalent. Soil receptivity plays very important role in design of grounding system. If ($\rho_1 > \rho_2$), place the grid in the bottom layer and increase the depth of the burial of the grid until mesh and step voltages are within safe limits. When ($\rho_2 > \rho_1$), place the grid in the top layer and adjust the depth of the burial to satisfy the safety criterion. In this case ground rods are not essential and the grid is gradually moved down in the top layer. Example is illustrated in Table 3 and Table 4.

Case 1: (ρ1 > ρ2)
ρ_1 = 1500 Ω-m
ρ_2 = 34.15 Ω-m
h_s (Depth of upper layer) = 0.2m
Length of ground rod = 2.4m
Conductor spacing, d = 11m
Note: Design is not safe above 11m conductor spacing
Number of ground rods= 22
Tolerable Step Voltage = 1861.63 V
Tolerable Touch Voltage = 631.93 V

Table 3: Optimal results, with variation in depth of burial for (ρ1 > ρ2)

Depth of	Ground Potenti	Maximum	Maximum Step	Grid Resistan	Remarks

Burial	al Rise	Touch Voltage	Voltage	ce	
0.2	2971.24	685.50	693.98	0.3301	unsafe design
0.3	2948.20	654.02	477.54	0.3276	unsafe design
0.4	2931.70	633.15	369.27	0.3257	unsafe design
0.5	2918.8	617.95	304.21	0.3243	safe design
0.6	2908.2	606.26	260.77	0.3231	safe design
0.7	2899.2	596.94	229.69	0.3221	safe design
0.8	2891.37	589.32	206.34	0.3213	safe design
0.9	2884.43	582.99	188.14	0.3205	safe design
1	2878.21	577.65	173.54	0.3198	safe design
1.1	2872.56	573.10	161.57	0.3192	safe design

It is clear from the above result that, when the depth of burial is less than 0.5 m, the design is unsafe. Therefore, depth of burial is increased above 0.5m to meet the safety criterion. It can also be observed that as the depth of burial increases, GPR and grid resistance decrease. When the depth of burial is increased, variation in touch voltage is marginal but variation in step voltage is drastic.

Case 2: (ρ1< ρ2).
ρ1 = 25 Ω-m
ρ2 = 800 Ω-m
hs (Depth of upper layer) = 1m
Length of the rod = 2.4m
Conductor spacing d = 5m
Note: Design is not safe above 5m conductor spacing
Number of ground rods= 48
Tolerable Step Voltage = 299.79 V
Tolerable Touch Voltage = 241.47 V

Table 4: Optimal results, with variation in depth of burial for (ρ1 < ρ2)

Depth of Burial	Ground Potential Rise	Maximum Touch Voltage	Maximum Step Voltage	Grid Resistance	Remarks
0.2	1744.89	274.25	431.95	0.1939	unsafe design
0.3	1736.8	258.92	306.95	0.1930	unsafe design
0.4	1731.00	249.70	244.19	0.1923	unsafe design
0.5	1726.44	234.64	206.35	0.1918	safe design
0.6	1722.7	239.56	180.97	0.1914	safe design
0.7	1719.51	236.81	162.73	0.1911	safe design
0.8	1716.74	235.03	148.94	0.1907	safe design
0.9	1714.29	233.97	138.13	0.1905	safe design
1.0	1712.08	233.48	129.41	0.1939	safe design
1.1	54722.68	7470	3911	6.0803	unsafe design
1.2	54664	7480	3717	6.0738	unsafe design

Results indicate that when depth of burial is less than 0.5m and more than 1.1m, the design is unsafe. Therefore depth of burial should be between 0.5m to 1m to meet the safety criterion. It can also be observed that as the depth of the burial increases GPR and grid resistance decrease in the upper layer and there is a sudden increase in GPR and grid resistance at the boundary of the two layers.

b. Conductor spacing

Reduction in conductor spacing results in increase in the number of conductors. Mesh voltage decrease up to certain conductor spacing, then it starts increasing with further reduction in conductor spacing, but the fall in mesh voltage is greater than the rise in step voltage as shown in Fig. (1). Reduced conductor spacing augments the cost as shown in Fig. (2). Total length of the grid is drastically decreasing with increase in conductor spacing. Total cost is equal to cost of grid conductor and cost of ground rods.

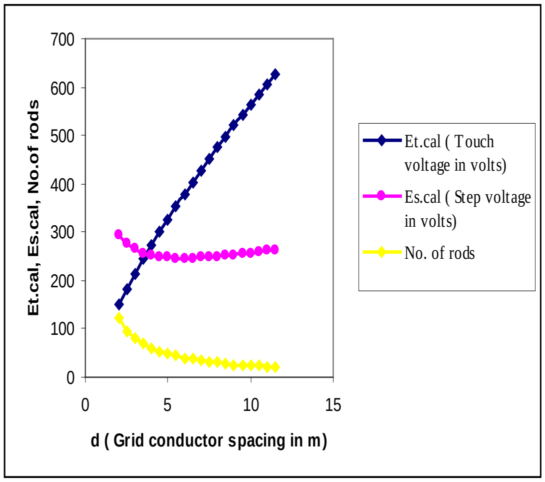

Fig.1: Variation of Mesh and step voltages, Number of ground rods with conductor spacing

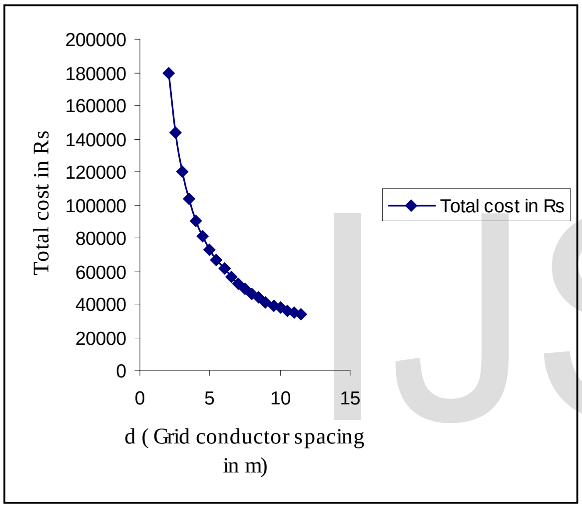

Fig 2. Variation of total cost of the grid with conductor spacing

c. Depth of burial

Mesh voltage is not influenced much with increase in depth of burial, but it has drastic effect on step voltage. Step voltage decreases sharply with increase in depth of burial as shown in Fig (3a).Increased depth of burial augments the labour cost. Labour cost is excluded in the software. In proposed program, when depth of burial is varied from 0.2 m to 1m in step of 0.1m, Mesh voltage is varied from 615.6 V to 617.64 V only and there is sharp decrease in Step voltage from 667.6 V to 175.64 V. It is also observed in Fig (3b) that with the increase in the depth of burial conductor spacing can be increased for optimizing the cost. Fig(3c) shows that total cost is decrease with increase in depth of burial.

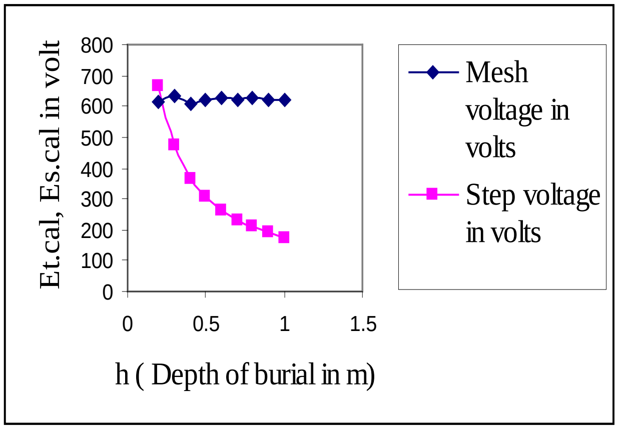

Fig. 3a: Variation of Mesh and step voltages with depth of burial.

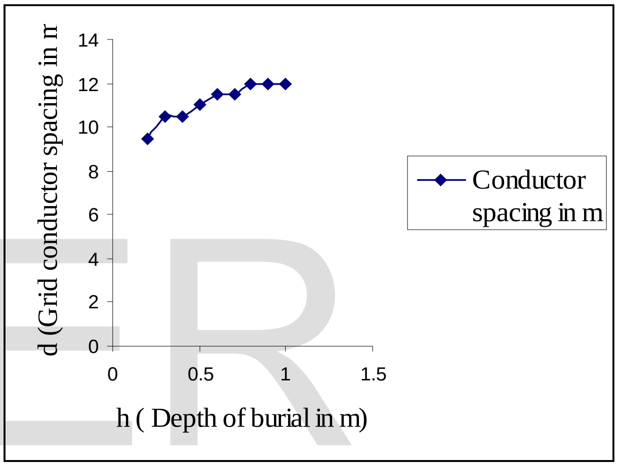

Fig 3bVariation of grid spacing with depth of burial

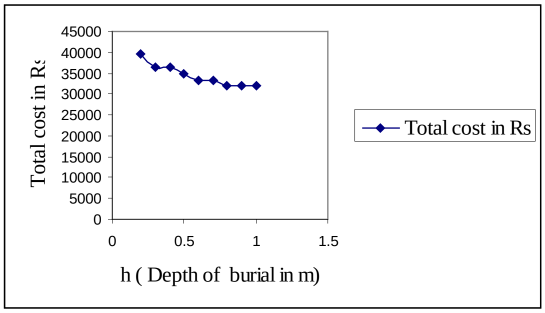

Fig 3c. Variation of total cost with depth of burial

d. Vertical ground rods

As vertical rods penetrate the lower layer of soil, they enhance the performance of grounding system. Soil resistivity tends to vary with depth and the lower layer of soil generally has a low resistivity. This helps in easy discharge of fault current thus significantly reducing GPR, touch and step voltages compared to grid alone. Also they are cost effective. Vertical ground rods are usually placed at the corners or periphery of the grid. Augmentation in cost is marginal. It can be observed from Fig.(4a) that there is a small reduction in mesh and step voltages with increase in number of ground rods. As an illustration; for d = 10 m , h = 0.4 m and length of the rod = 2.4m , with increase in number of rods from 9 to 20, there is variation of mesh voltage from 630 V to 597V and step voltage from 381 to 366 V. It is also observed that below 9 number of ground rods design is not safe. But increase in depth of burial to 0.6 m makes the design safe even with 2 ground rods. At d =10 m and h = 0.6m , with number of ground rods increased from 2 to 11, mesh voltage is varied from 624 to 397 V and step voltage is varied from 276.57 V to 268.18 V . Since the number of ground rods are reduced at h= 0.6 m compared with h= 0.4 m total cost of the grid is optimized. Variation of total cost of the grid with number of ground rods are shown in Fig .4b.

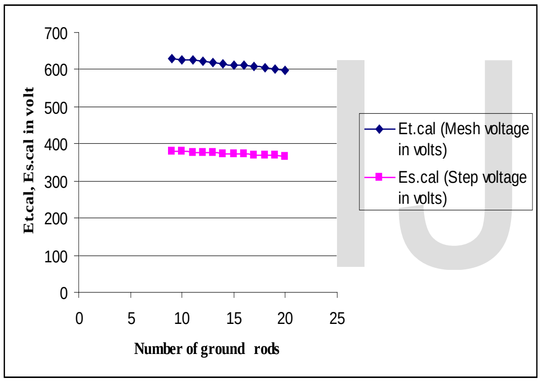

Fig. 4a. Variation of Mesh and Step voltage with number of ground rods

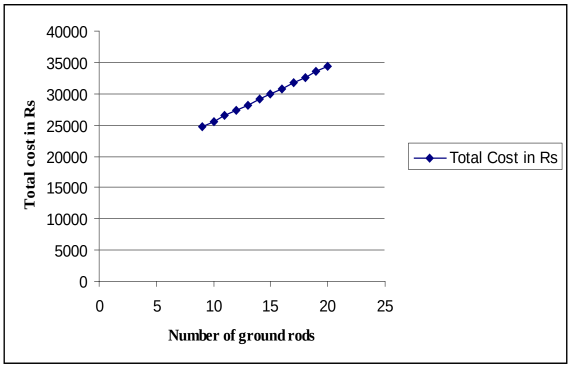

Fig. 4b. Variation of total cost with increase in no. of rods

e. Fault Current

The program is executed with the same data and fault current varied from 5kA to 60kA. The results are tabulated in Table 5 and the corresponding graph in shown in Fig.(5a) and Fig. (5b).

Table 5: Optimal results with variation in fault current

Fault Current (KA)	Conductor spacing (m)	Touch voltage (Volts)	Step voltage (Volts)	No. of ground rods	Total length of grid conductors Lt(m)	Optimal grid cost in Rs
5	12	376	147	20	716.66	31582
10	10	621	285	24	834.6	53764
15	6	597	410	40	1310	111800
20	4.5	604	553	53	1706	179498
25	3.5	580	713	69	2160	270671
30	3	579	881	80	2499	361856
35	2.5	539	1075	96	2975	489020
40	2.5	596	1228	96	2975	546873
45	2	494	1477	121	3691	751044
50	2	530	1641	121	3691	822723
55	2	565	1806	121	3691	894401
56	2	572	1838	121	3691	908737
57	**No Safe Design**					

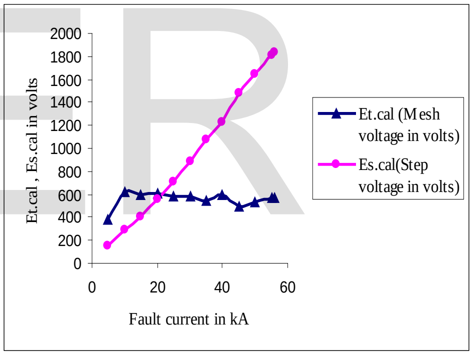

Fig. 5a. Variation of Mesh and Step voltage with increase in fault current

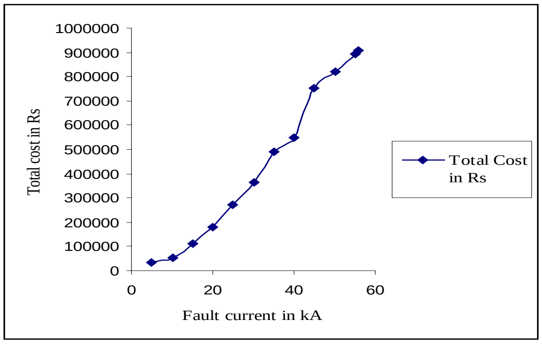

Fig. 5b. Variation of total cost with increase in Fault current

As perceived from the above results, the design is safe up to 56 kA and unsafe above it. Hence above fault current values of 56 kA, solutions are not feasible and unacceptable. Also the following observations are made from the above results with variation in fault current.

1. Grid conductor spacing is reduced which augments the total cost of the grid with ground rods.
2. Variation of mesh voltage and step voltage depend on fault current and grid conductor spacing.
3. Mesh voltage is not influenced much with increase in fault current but step voltage drastically increases with fault current.
4. Number of ground rods increases resulting in increased total cost.

IV. Causes of unsafe design and its remedies

- Maximum mesh voltage is more than tolerable touch voltage, dissatisfying the touch voltage criterion. This can be overcome by increasing the conductor spacing to the optimal value which reduces GPR slightly but mesh voltage drastically.

- Maximum step voltage is more than the tolerable step voltage dissatisfying the step voltage criterion. This is due to non-uniform current distribution in grid conductors which can be overcome by having more number of conductors at the boundary than at the center of the grid,

- Both maximum mesh and step voltage criteria being dissatisfied. In this case above remedial measures are to be adopted.

CONCLUSION

The objective of the work is to design a cost effective ground grid for a given set of parameters. Factors affecting cost such as conductor spacing, depth of burial, number of ground rods, length of ground rods and type of grid material are considered for cost minimization purpose. Keeping rest f the parameter constant, one parameter is varied at a time to obtain a set of solutions. The procedure is repeated for the rest of the parameters and the execution results in a large number of solutions. Out of the solutions obtained, only feasible solutions are retained and the rest are discarded. From the set of feasible solutions optimal solution or least cost solution is identified. A large number of feasible solutions are generated in each execution. If cost is not a limiting factor, user has large number of solutions available to choose from. In one of the simulations, a total of 6660 executions were carried out, of which 4034 solutions were feasible. The optimal solution is identified from the set of feasible solutions.

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