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Optimal Grounding Grid Design for Substaion and its Analysis

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***Abstract* - Grounding grid design of the substation is essential to reducing grounding potential rise hence touch voltage inside the substation to safe guard the works of the subatation and substation equipment. The grounding grid performance is affected by many factors such as soil resistivity, depth of the burial, conductor spacig, vertical ground rods and fault current. MATLAB programme is developed to analyse the gounding grid with all factors affecting it and results are shown by plotting the graphs , MATLAB progrmme is tested for refelection factor (k) greater than zero and lesser than zero. Using the programme developed one optimal solution is obtained out of many feasible solution.**
***Keywords*: Soil Resisitiviey, Depth of Burial, Condcuotr Spacing, Touch Voltage, Step Voltage, Grounding Grid, Ground Potential Rise**

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 s oftware 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. GROUDING GRID DESIGN INPUT DATA

TABLE I GROUNDING GRID DESIGN DATA

Soil resistance of upper layer	1000Ω-m
Soil resistance of lower layer	100-m
Thickness of upper layer soil	0.2 m
Duration of fault current	0.5 sec
Fault current	8 kA
Length of Grid	80 m
Breadth of Grid	80 m
Depth of Burial	0.5 m
Length of the Ground Rods	3 m
Ambient Temperature	40^{o}C
Duration of Shock Current through body	0.5 s

Grid design computations are done for the grid design data given in Table I [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 d ifferent 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 bural from 0.2-1.1m and lenth of ground rods from 2-13m. The trials are repeated for 9 different conductor materials. Out of the 270 trials made, 43rd 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, geometic 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 II.

TABLE II SIMULATED RESULTS FOR OPTIMAL SOLUTION

Tolerable Step Voltage (Person Weight 70 Kg)	1334.001V
Tolerable Touch Voltage (Person Weight 70 Kg)	500.024V
Total length of grid conductor without ground rods	3069.09m
Total length of grid conductor with ground rods	3285.09
Geometric factor or total number of parallel conductors	19
Conductor Spacing (d m)	4.4 m
Grid resistance	0.5775 Ω
Ground Potential rise	4619.94 V
Calculated step voltage	372.75V
Calculated touch voltage	499.38V
Cost of Grid Conductor	Rs.104768.37
Cost of Ground Rods	Rs.317925.00
Total Cost	Rs.422693.37

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 resistivity 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 III and Table IV.

Case 1: ($\rho1 > \rho2$)
ρ_1 = 1000 Ω-m ,ρ_2 = 100 Ω-m
h_s (Depth of upper layer) = 0.2m ,Length of ground rod = 3m
Conductor spacing, d = 4.4m
Note: Design is not safe above 4.4m conductor spacing
Number of ground rods= 22
Tolerable Step Voltage = 1334.0 V ,
Tolerable Touch Voltage = 500.02 V

TABLE III OPTIMAL RESULTS, WITH VARIATION IN DEPTH OF BURIAL FOR (P1 > P2)

Depth of Burial	Ground Potential Rise	Maximum Touch Voltage	Maximum Step Voltage	Grid Resistance	Remarks
0.2	4690.9	577.03	1050.79	0.5864	unsafe design
0.3	4678.7	543.46	751.77	0.5848	unsafe design
0.4	4666.7	524.13	601.50	0.5833	unsafe design
0.5	4654.8	512.35	510.77	0.5819	unsafe design
0.6	4643.0	505.21	449.84	0.5804	unsafe design
0.7	4631.4	501.18	405.96	0.5789	unsafe design
0.8	4619.9	499.3	372.75	0.5775	safe design
0.9	4608.5	499.2	346.67	0.5761	safe design
1	4597.2	500.0	325.6	0.5743	safe design
1.1	4586.1	502.55	308.16	0.5733	unsafe design

It is clear from the above result that, when the depth of burial is less than 0.7 m, the design is unsafe. Therefore, depth of burial is increased above 0.7m 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 = 75 Ω-m

ρ2 = 200 Ω-m

hs (Depth of upper layer) = 1m

Length of the rod = 3 m

Conductor spacing d = 2.4m

Note: Design is not safe above 2.4 m conductor spacing

Tolerable Step Voltage = 329.11 V

Tolerable Touch Voltage = 248.8 V

TABLE IV OPTIMAL RESULTS, WITH VARIATION IN DEPTH OF BURIAL FOR (P1 < P2)

Depth of Burial	Ground Potential Rise	Maximum Touch Voltage	Maximum Step Voltage	Grid Resistance	Remarks
0.2	3429.1	244.26	819.02	0.4286	unsafe design
0.3	3419.9	209.08	612.51	0.4275	unsafe design
0.4	3410.9	203.88	507.55	0.4264	unsafe design
0.5	3402.0	204.01	443.35	0.4253	unsafe design
0.6	3393.2	207.39	399.65	0.4242	unsafe design
0.7	3384.5	212.87	367.73	0.4231	unsafe design
0.8	3375.8	219.75	343.25	0.4220	safe design
0.9	3369.3	227.56	323.77	0.4206	safe design
1.0	3358.8	235.98	307.8	0.4199	safe design
1.1	3350.5	244.76	294.48	0.4188	safe design

Results indicate that when depth of burial is less than 0.7m and more than 1.1m, the design is unsafe. Therefore depth of burial should be between 0.7m 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.

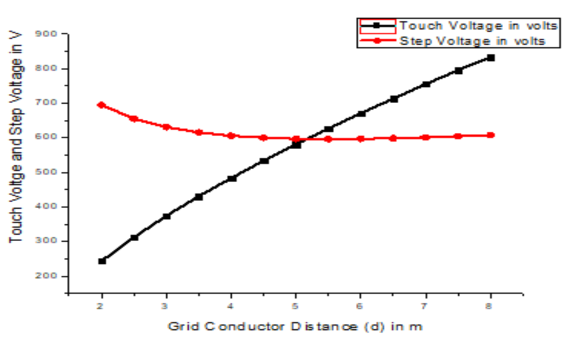

Fig. 1 Variation of, Mesh and step voltages, Number of ground rods with conductor spacing

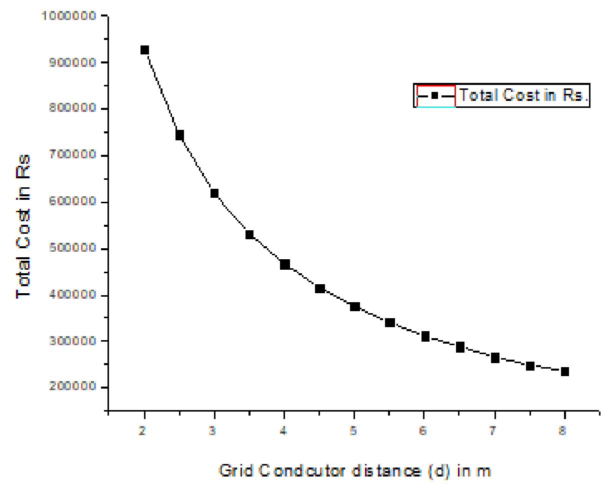

Fig. 2 Variation of total cost of the grid with conductor spacing

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 (3).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 1.1m in step of 0.1m, Mesh voltage is varied from 307.6 V to 342.21 V only and there is sharp decrease in Step voltage from 802.2 V to 378.26 V. It is also observed in Fig (4) that with the increase in the depth of burial conductor spacing can be increased for optimizing the cost. Fig(5) showes that total cost is decrease with increase in depth of burial.

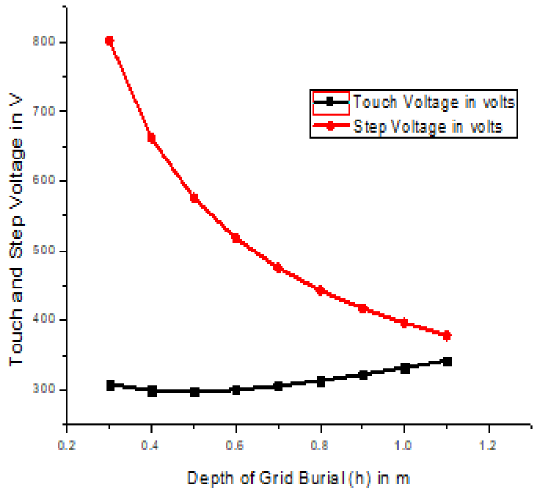

Fig. 3 Variation of Mesh and step voltages with depth of burial.

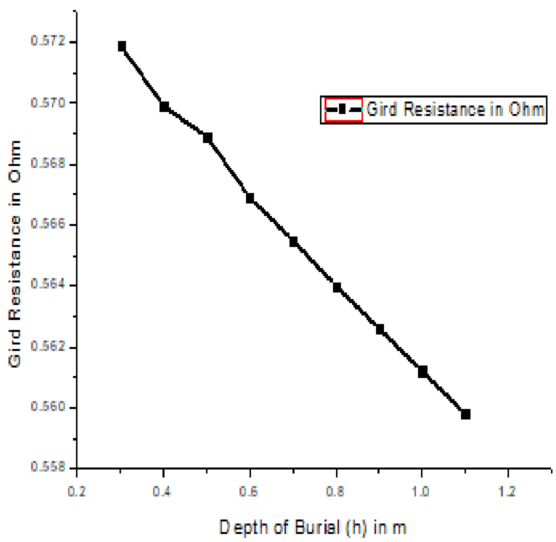

Fig. 4 Variation of Grid Resistace with depth of burial

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.(5) that there is a small reduction in mesh and step voltages with increase in number of ground rods. As an illustration; for d = 2.4 m , h = 0.4 m and length of the rod =3 m, with increase in number of rods from 50 to 130, there is variation of mesh voltage from 319.36 V to 299.51 V and step voltage from 694.66 to 662.3V. It is also observed that below 50 number of ground rods design is not safe. Variation of total cost of the grid with number of ground rods are shown in Fig. 4b.

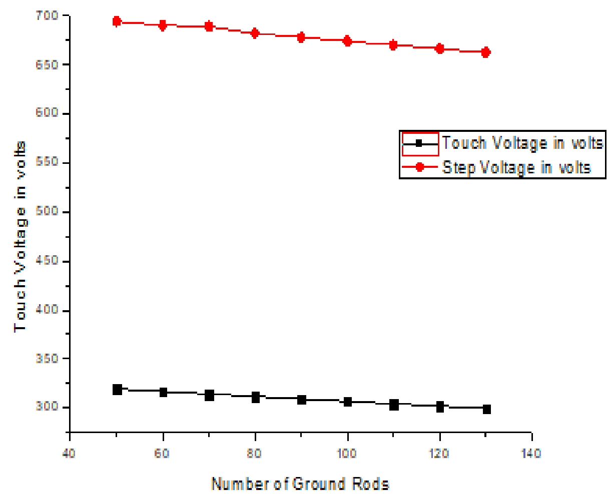

Fig. 5 Variation of Mesh and Step voltage with number of ground rods

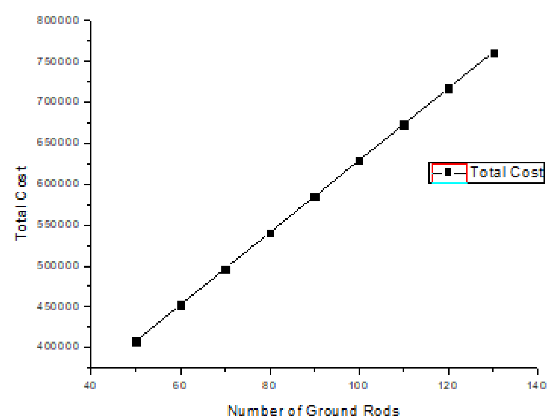

Fig. 6 Variation of total cost with increase in no. of rods

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 V and the corresponding graph in shown in Fig 5 and Fig 6.

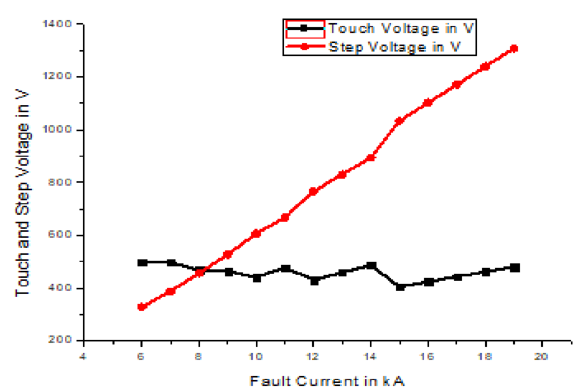

Fig. 7 Variation of Mesh, Step voltage with increase in Fault current

TABLE V OPTIMAL RESULTS WITH VARIATION IN FAULT CURRENT

Fault Current (KA)	Conductor Spacing (m)	Touch Voltage (Volts)	Step Voltage (Volts)	No. of Ground Rods
6	6	497.6	327.8	53
7	5	496.5	387.3	64
8	4	467.2	456.2	80
9	3.5	462.4	526.7	91
10	3	441.2	606.8	106
11	3	477.3	667.52	106
12	2.5	430.5	766.46	128
13	2.5	458.7	830.3	128
14	2.5	486.2	894.2	128
15	2	404.4	1033.3	160
16	2	423.8	1102.	160
17	2	442.8	1171.1	160
18	2	461.4	1239.9	160
19	2	479.5	1308.8	160
20	Not Feasible			

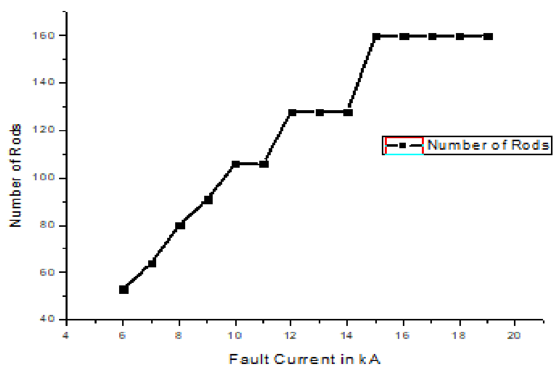

Fig 8. Variation of Number of Rods with increase in Fauclt current

As perceived from the above results, the design is safe up to 19 kA and unsafe above it. Hence above fault current values of 19 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

1. 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.
2. 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,
3. Both maximum mesh and step voltage criteria being dissatisfied. In this case above remedial measures are to be adopted.

V. CONCLUSION

The objective of the work is to design a co st 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 of the parameters 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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