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A Review Paper on Parameter for Substation Grounding Design and Various Softwares Used.

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Abstract: The grounding grid design has a vital role for the operation of substation. The grounding system is responsible for safety of the operators and apparatus inside the substation and thus maintaining reliability in the whole power network. This review paper explains the need of grounding system and the parameters related to the designing of grounding system as explained in IEEE Standard 80-2013. Faults concerning ground inside the substation can result into increase of the potential values (GPR)and during the occurrence of fault, high current flowing in the ground area through metal object, can result into severe hazardous situations for the person working in the substation. This paper explains the method of grounding grid calculations, various parameters used in the design by flow chart. The grid modifications are also discussed, if the measured parameters like touch voltage, step voltage in the design are not satisfying the tolerable values. As manual calculations are time consuming and more complex, softwares are used. An extensive study of softwares like ESGSD, SES Auto Grid Pro, CDEGS etc. is done in this review paper which not only gives grid design but also considers the cost optimization parameter. Thus, judiciously designed grounding systems are cost effective and increase the level of safety of person-equipments to acceptable levels.

Keywords: Grounding, Touch voltage, Step voltage, Grid resistance, Ground Potential Rise (GPR), Grounding grid, Grounding rod, Design Software

I. INTRODUCTION TO SUBSTATION GROUNDING

The electrical power reaching at the end consumers from its origin i.e. generating stations is a widespread network. Substations are the most important element in this electrical network. Careful and safe design of substations indirectly ensures the electrical supply continuity and thereby maintaining harmony, synchronization of the generating, transmission, and distribution end in the whole power network [1]– [3]. The substations contain two most important aspects, one is equipments and the other is personnel working in and around the substation. Grounding systems ensure the safety of the personnel and equipment in normal and fault conditions. Faults are prone to occur in any system, but designing a system which can minimize the damage due to faults and maintain the system continuity is in the hands of designer. Inside the substation, ground faults can result in increase of the potential and during the occurrence of fault, current flowing in the ground area through metal object, can result into severe hazardous situation for the person[4].Hence, it is most important to design and install grounding system such that safety is ensured keeping balance the cost of installation using optimization[5].

From the last 6 decades, researchers have shown keen interest in the methods of design for grounding arrangement as the point of substation grid design safety and cost is to be optimized. “IEEE guide of safety in ac substation grounding Standard” IEEE Standard 80-2013, May 2015 is universally accepted standard in the field of design of substation grounding [6]. The grid design can be addressed without construction over dimensioned (which results in over costing) than necessary, ensuring the safety at its priority [4]. A safe grounding design aims following:

a) Without exceeding operating or equipment limits and maintaining continuity of service. It is essential that the grounding system offers required paths to conduct current into the earth in either normal condition or abnormal condition.

b) The risk of persons working in and around the substation should be minimized in case of danger of electric shock. If proper precautions are not taken in design of grounding system, then the maximum potential gradients along the surface of earth will have sufficient magnitude to endanger the person in that area [7]. Hazardous potentials develop between grounded structure, equipments body frames and earth. The human body is responsive to the electric current and in certain cases, the sensitivity is lethal too. The comparison of current and their effect on human body is explained in Table-1[6].

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Table 1-Effect of current on human body

Range of current (mA)	Effect on human body
<1	Slightly tingling sensation in hands (fingertips)
1-6	Unpleasant to sustain, person can release the energized object
9-25	Painful and difficulty in releasing the energized object
60-100	Ventricular fibrillation, stoppage of heart resulting in injury or death.

Thus, a careful designed grounding system, ensures keeping shock current into acceptable limits such that any injury or death can be prevented. It also maintains equipment safety and if optimization is used and cost-effective design can also be implemented [6], [8], [9].

II. SAFETY PARAMETERS WHILE DESIGNING SUBSTATION GROUNDING SYSTEM.

The basic line while designing for substation grounding is that duration and the value of current which would pass through the human body (considering the basic frequency used i.e. 60Hz and 50Hz) should be much lower than that which cause adverse effect like fibrillation of heart muscles possibly leading to cardiac arrest [6].

1. Current conducted through human body.

The magnitude of current when passed through human body and can withstand without ventricular fibrillation is evaluated by the following equation.

$$I_B = \frac{k}{\sqrt{t_s}} \quad (1)$$

where, t_s is the duration of exposure to current in s and $k = \sqrt{S_B}$, where S_B is empirical constant related to the electric shock energy tolerated by a certain percentage of given population [6].

The comparison of standard weights, duration of exposure and magnitude of body current as per weights is shown by the Table-2.

Table 2-Comparsion of Body current and duration of exposure to current

t_s in s	I_B (mA)_50 kg	I_B (mA)_70 kg
0.1	366	496
0.2	259	351
0.5	164	222
0.7	138	187
1	116	157
2	82	111
3	67	92

2. Resistance of human body.

For calculation purpose the approximate value of resistance for the human body for dc and ac (50Hz or 60 Hz) supply, is assumed as R_B=1000 Ω, where R_B is the resistance magnitude of a human body between hand to feet and connecting hand to hand between both foot[6].

3. Types of tolerable voltages.

Under normal, no-fault condition the electrical equipment, which is grounded, operates at near zero earth potential. In case of ground fault, part of fault current that is conducted by the ground grid of the substation into earth results in the increase of grid potentials. The voltages developed during any normal or abnormal conditions in the substation are classified as below [1], [2], [6], [10]– [13].

- Ground potential rise (GPR) is the maximum value of potential that a substation grounding grid may attain relative to distant grounding point, with reference to potential at remote earth.

Mathematically, GPR=Maximum Grid current *Resistance of the grid (2)

- Mesh voltage is the highest touch voltage developed in a mesh of the designed ground grid.
- Touch voltage, specifically Metal-to-Metal is the difference in potential developed connecting the metallic structures inside the substation that is connected by human hand to human feet or human hand to hand connection.
- When the human body experiences the change in potential between the substation metallic structure that may be bridged by connecting hand to hand or hand to feet, then the potential developed is defined as step voltage.
- Touch voltage is the magnitude difference between the potential at place where human body is positioned and GPR assuming one hand in close contact with object which is grounded.
- Transferred voltage is a typical case of touch voltage where potential is transferred in/out the substation from/to a distant remote point external to the site of substation.

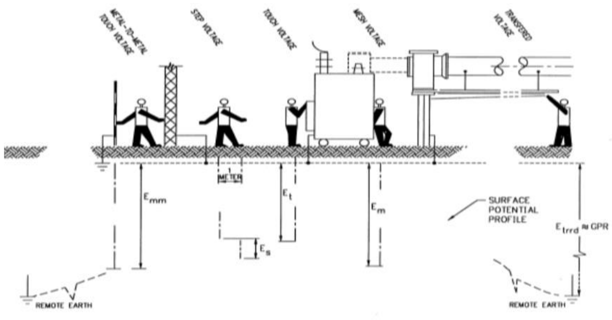

Figure 1-Basic shock situations

Mathematically represented as per following equation in Table-3.

Table 3-Equations for potentials developed as per human body weight.

Potential developed (volts)	Weight of human being as 70Kg	Weight of human being as 50Kg
$E_{\_touch}$	$E_{\_touch\_}70=\frac{0.157}{\sqrt{ts}}(1000+1.5\rho Cs)$	$E_{\_touch\_}50=\frac{0.116}{\sqrt{ts}}(1000+1.5\rho Cs)$
$E_{\_step}$	$E_{\_step\_}70=\frac{0.157}{\sqrt{ts}}(1000+6\rho Cs)$	$E_{\_step\_}50=\frac{0.116}{\sqrt{ts}}(1000+6\rho Cs)$

$E_{\_touch}$ is the touch voltage in V and $E_{\_step}$ is the step voltage in V. C_s is surface layer derating factor given by following empirical equation.

$$C_S = 1 - \frac{0.09(1-\frac{\rho}{\rho s})}{2hs+0.09} \quad (3)$$

Where ρ_s is the magnitude for the resistivity of the surface in Ω-m, ρ is the magnitude for resistivity of the ground under the top surface material in Ω-m and h_s is the magnitude of the thickness of the top layer material in m and t_s is the time duration of the fault current in *s*[14].For calculating the apparent resistivity of the soil the best suitable method is Wenner four pin method[15].The material of contact i.e. surface material may be of crushed rock, concrete or asphalt, noteworthy point is that the resistivity value is also dependent on the moisture content in the soil [16].

III. DESIGN PROCEDURE FOR GROUNDING GRID DESIGN.

The flow chart for grounding design procedure is given in Figure 2[6]

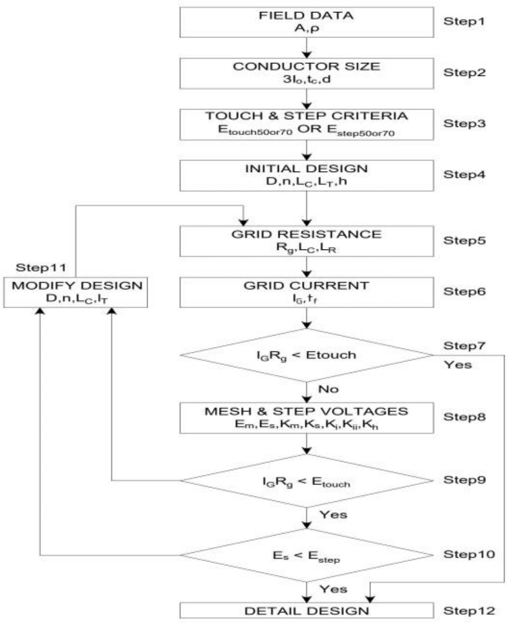

Figure 2-Flow chart

The steps for grounding grid design are explained by simple steps as shown in Figure-2. The procedure starts with acquiring substation map, its dimensions, soil resistivity profile and soil model (two layer or uniform soil model). The conductor size is calculated with maximum expected future worst fault current and maximum possible fault clearing time t_c. In the next step the allowable step and touch voltages are to be determined. In step 4, preliminary design is calculated with the area being grounded. The grid resistance and grid current are calculated. Based on this GPR is calculated, if allowable touch voltage is lesser than the obtained than no modification is necessary but like in major cases, we need to have detailed analysis by calculating the mesh and step voltages in detail. At step 9 and 10 checks are verified, if the obtained values of step and touch potentials are lesser than the set tolerable limits than the design in justified and detailed design can be generated, otherwise the design from Step11 must be modified and the process must be redone.

Sample calculations in IEEE std 80-2013 Guide[6]

The design data selected for sample calculations provided in IEEE standard 80-2013 guide areas shown in Table-10. The system equivalent factor for current division and fault impedances are calculated for the worst fault (location and type both).

Table 4- Grid parameters selected for design.

Parameter	Value
Duration of fault t_s=t_f=t_c	0.5s
S_f is Current division factor	0.6
Soil resistivity ρ	400Ωm
ρ_s is wet crushed rock resistivity	2500 Ωm
h_s is the thickness for surfacing of crushed rock	0.102m
h is the depth of grid burial	0.5m
Area for grounding grid	63mX84m
Maximum allowable temperature T_m	700°C
Ambient temperature T_a in	40°C
Weight of person	70 kg
Grid reference depth h_0	1m

STEP1:Acquiring Field data

Georgraphical area assumed for design calculation is 70x70 m^2. Square grid is selected as primary design without ground rods.

STEP2: Calculating conductor sizing.

After applying equations, the following is the outcome for conductor sizing.

Table 5-Outcome for grid conductor diameter

Parameter	Value	Outcome
$3I_0$	3180kV(115kV side) 6814kV(13kV side)	0.01m diameter Copper clad steel wire
$\frac{X}{R}$	3.3(115kV side) 16.2(13kV side)	

STEP3: Finding Step and Touch voltage range.

After applying equations in Table-3 by using equation-3 the allowable range for 70Kg reference weight is as E_step_70=2686.5V and E_touch_70=832.2V.

STEP4: Generating initial design

As the design selected is square, so 11rods in X and Y directions are set with distance between two adjacent rod is 7m each making total distance in X and Y directions 70m each respectively.

The total length is given by equation,

$$L_T = (No. of\ conductors\ in\ X\ direction * Total\ distance\ in\ Y\ direction) + (No. of\ conductors\ in\ Y\ direction * Total\ distance\ in\ X\ direction) \quad (4)$$

L_T=11*70 +11*70=1540m

STEP5: Finding grid resistance.

The grid resistance offered by the selected conductors is given by formula,

$$R_g = \rho[\frac{1}{L_T} + \frac{1}{\sqrt{20A}}(1 + \frac{1}{1+h\sqrt{\frac{20}{A}}})] \quad (5)$$

The Grid resistance calculated as R_g=2.78Ω

STEP6: Calculation maximum grid current

The maximum grid current as per current grid design is given by equation,

$$I_G = D_f * S_f * 3I_0 \quad (6)$$

Considering GPR values to be concentrated we assume $3I_0$ value as 3180A and thus I_G value comes out to be 1908A.

STEP7: Calculation GPR

$$GPR = I_G * R_G \quad (7)$$

The obtained value of GPR is 5304V which is much greater than E_touch_70=838.2V therefore grid modification is necessary.

STEP8: Calculation of Mesh and Step voltage obtained for the selected design.

Table 6-Obtained value for touch potential.

E_touch_70_allowed	E_touch_70_obtained	Remarks
838.2V	1002.11V	Design modification is necessary as the grid is not safe.

GRID Modifications:

If the available values are not in the tolerable range, grid modification, i.e., change in the geometry of grid is necessary. In the previous design no ground rods were used. Here in the modifications suggested ground rods are used and the whole process is repeated. The outcome is as shown in Table-13.

Table 7-Grid parameters after modifications

Modifications	Parameters	Remarks
20 Ground rods each of 7.5m length are installed at the perimeter of the square grid.	L_T=1690m(considering the ground rods) R_g=2.75m GPR=5247V E_mesh_70_obtained (747.42V) <E_touch_70_allowed (838.2V) E_step_70_obtained (548.92V) <E_Sstep_70_allowed (2686.5V)	The Grid design is justified and safe.
38 Ground rods each of 10 m length are installed in the rectangular grid with dimension 63mX84m	L_T=2039m (considering the ground rods) R_g=2.62m GPR=4998.96V	The Grid design is justified and safe.

	E_mesh_70_obtained (594.8V) <E_touch_70_allowed (838.2V) E_step_70_obtained (449.19V) <E_Sstep_70_allowed (2686.5V)	

IV. SOFTWARES USED FOR ANALYSIS OF GROUNDING GRID DESIGN.

As manual method for grid design is complicated and takes time for the output, various softwares can be used which not only save time but also increase the reliability of the whole grid design process. Software like ESGSD, CDEGS, MATLAB etc have been designed for implementing concepts given in the IEEE 80-2013 guide into analytical domains.

1. Design optimization using ESGSD software [1]

ESGSD (Economical Substation Grounding System Designer) is designed by the use of MATLAB platform. With less knowledge of software engineering this compiler add-on facilitates standalone application mode easily. ESGSD facilitates options for any application of grounding with the following aspects.

- Analysis for simple performance, where all the basic data for grounding like grid geometry, soil parameters etc. are taken into consideration.
- Grounding system optimization design which consists of 5 basic shape option of the grounding grid (rectangular, L shape, square, triangular and T shape). For this option, uniform and 2 layered soil mode can be considered.

The dominating factors which may be varied for achieving the necessary parameters as in comparison with the tolerable values are spacing between adjacent conductors in the ground grid, burial depth, covered area of the grounding grid and the total number of grounding rods which are buried vertically. Both safe and cost-effective design is obtained by selecting options for optimization facility in ESGSD. The intentional overdesigning considering future growth and unexpected case is done in many cases, but such softwares can help for judicial designing of the grid more confidently. To get more reliable results two-layer soil model can be used in comparison with uniform soil model assumption. Different software can get the two or multilayer soil model in a simple and effective way implementation [17].

2. SES Auto Grid Pro Software [5]

This is easy to use software which can model grounding grids of any shape, account for the presence of nearby energized buried structures can be done and interpretation soil resistivity measurements can be applied for complex soil types with full 3D drawing capabilities. Here Pooja Et al. has used this software two different cases equally and unequally spaced grid. The results show that 28% saving in length of grid conductors is there in unequally spaced grid conductors maintaining all the safety parameters in the admissible range.

3. Substation ground grid design using MATLAB [11]

Surya Et al. has implemented grounding grid design for substation using software application MATLAB in which grid using grounding rod and without ground rod options are available. Different grid shapes are considered, namely square, rectangular and L shape. Validation of the obtained result is compared by IEEE80-2013.Manual and application calculation differ by 0.073% which is mere due to rounding calculations. The substation grid design plan using MATLAB is designed under the title name "Design of Grounding Grid". & display sections are there and by the use of genetic algorithm, 2-layer soil analysis can be performed.

4. Grounding resistance reduction by CDEGS

Sigeng Chen Et al. has used CDEGS simulation software to calculate important grounding grid parameters such as grounding resistance, touch and step potential [18]. The effect on grounding grid reduction by unequal spacing of grounding grids and increasing the number of grounding electrodes is studied using Current Distribution, Electromagnetic fields, Grounding and Soil structure analysis software. Considering the safe limits, the step voltage increase in the threshold area making the unequal spacing grids reducing the potential difference between the center mesh and the edge mesh. Thus, the use of unequal spacing grounding grids combining with vertical grounding electrodes can reduce the grounding resistance stabilizing the ground surface potential and protect the electrical equipment and personal safety. The standards and tests used for finding the material resistivity are to be done at the actual site such as the surface material covering the substation soil is selected to have high resistivity resulting in increase of the foot contact resistance.Grid resistance in certain cases can be decreased by increasing the grid installation layout area but is having limitation of the layout area made availability. Deep wells or driven rods can be used as an option to this. There is experimental result indication that this technique can use the ground water for reducing the grounding resistance [19].

5. Design optimization with multilayer soil model using XGSLab software [3]

275kV Nagan Raya substation design is carried out using multilayer soil model using XGSLab software. During the optimization process different mesh voltage and actual touch voltage comes in the range of permissible touch voltage. Various grid mesh size like9x5m, 9x6m, 9x9m 10x10m, 11x11m,12x12m, 13x13m and 14x14 are simulated using software. The most optimal design is of grid mesh 12x12m on 4-layer soil model and can reduce the use of Bare Copper Conductors (BCC) by 2.956,10m.

6. Grounding grid design by CDEGS platform

A 400kV Neiuwehoop AC substation in Northern Cape Province with 400/132/22kV transformer with 250MVA, four feeder's bays two future transformer 400/50kVand a busbar reactor rated at 100 MVAr is taken for designing of earthing grid by CDEGS software. The soil at the application site is highly resistive nature. From the software calculated results, it is concluded that boot resistance of 20kΩ for every person entering the substation site is a mandatory requirement. The results calculated and simulated correlate [13].Different modules for analysis of different grounding, electromagnetic and transient problems are available in CDEGS[20].

7. SGD application using Lab-VIEW software [12]

For 2x500 MVA Galang substation, software Lab-VIEW is used for carrying design and analysis in the SGD (substation grounding designer module) application. By analysis, it is concluded that if option of conductor material replacement is implemented with aluminum 5005, then cost-effective options are created by the reduction in use of grounding rods and conductors of the grid. All these changes can be implemented by maintaining safety criteria in accordance to standard IEEE-80 2000. The outcomes are efficiency is 75.4%, resistance is increased by 0.28Ω and minimum diameter limit of conductors is also increases by 3.45mm.

8. Analysis of grounding grid by ETAP software [10]

Using Electrical Power System Analysis (ETAP) the existing design parameters are calculated and techniques for increasing grounding system safety are studied by Chetan Et al. In ground grid design module of ETAP single line diagram of substation is drawn by short circuit analysis tools, the fault current values are found. Ground design is formed from grid design module. The software shows alarm and warnings if the design is unsafe. These potentials can be brought in limits by increasing the ground rods, decreasing grounding grid spacing and reducing grid resistance values.

V. CONCLUSION

The review paper explains the importance of an efficient grounding grid design for the safety of equipments and personnel working in the substation. The safety criteria values are explained with relevant equations used for calculations of different parameters of the grounding design. Various design case studies are taken into consideration of how the design is actually done and modifications taken into consideration for making the step and touch potential values in the tolerable range. The design procedure is explained with a simple flow chart and then step by step implementation. Manual design procedure takes time while the same if implemented by various softwares is an efficient, less time consuming and simple tool. Various softwares are used in implementing the theoretical concept into a simple programming way and study for these softwares is done in this paper. Various examples provide insight of the change in grid parameters by changing the position and number of grounding rod, changing the grounding grid spacing and grid resistance value. Soil resistivity is also a vital part in the of the substation installation, thus its detailed analysis is to be done without implementing the concepts discussed in this paper. Overdesigning of the grounding system should be avoided, and thus perfect calculations should be implemented. Thus, judiciously designed grounding systems are cost effective and increase the level of safety of person-equipments to efficient level.

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