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Design of Grounding System for High Voltage Substations

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Abstract— The design of grounding system for high voltage substation is a challenging task. In any substation, a well designed grounding system plays an extremely vital role. Grounding system must be safe as it is directly concerned with safety of persons working within the substation. The ground resistance, grid resistance, ground potential rise, step and touch voltage criteria for safety, maximum grid current, minimum conductor size, electrode size, maximum fault current level and soil resistivity are the basic design quantities of the grounding grid system. In this paper the design of grounding system for 220 KV high voltage substations and simulation for calculation of required parameters has been presented. A careful analysis was carried out in order to obtain the magnitude of total fault current that may occur in the substation. Soil resistivity is a major factor influencing substation grid design. Therefore, a resistivity investigation and analysis was carried out in order to obtain accurate design results. All necessary parameters were computed and assumptions were made using the relevant formulas. It has also been tried to reduce the grid resistance as well as ground potential rise by selecting the proper horizontal conductor size and addition of ground rods. A step by step procedure for the essential design considerations has been considered. Finally, simulations were carried out using software known as ETAP Software for verification of the design. The method proposed for substation grounding is in accordance with IEEE Std 80-2000.

Index Terms— Etap Software, Grounding Grid, Substation Design, Step and Touch Voltage.

I. INTRODUCTION

Grounding system for high voltage substations is very important for the electric power system stability. Any malfunction can cause blackout. The blackout results in loss, which will be crucial for electricity generating companies, boards and for ultimate consumer also. The main functions of grounding system of substation include: the first one is the ability carrying the electric currents into earth under normal and fault conditions without exceeding operating and equipment limits or adversely affecting continuity of service. The second is how this grounding system ensures that the person in the vicinity of grounded facilities is not exposed to the danger of electric shock. Designing grounding systems, building them and putting them in operation is a difficult task. The soil where the grounding system will be installed will generally be non-uniform.

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There are usually measuring errors associated with the soil resistivity, and furthermore, irregular grounding grid area, several data and factors that have impact on the performance of the grounding systems are frequently difficult to be considered in simulation models. With the increase of power system capacity and voltage grade, the fault current is also increased. Meanwhile, the complexity of the multi-layer soil, non-rectangle grounding grid should be considered. How to obtain the optimization design of substation grounding grid; how better uniform the surface potential distribution of grounding grid; how to ensure the safety of equipment and individual has become a most important problem. Optimum design of substation grounding in a two layer earth structure has been explained [1]-[3]. There are seasonal influences on frozen soil layer and external charges effects on grounding grid design [4]-[5]. The grounding system of the substation should ensure the safe and reliable operation of power systems and guarantee a human being's safety in the situation of grounding fault in the power system [6]. Study of unequally spaced grounding grids and optimum grounding grid design by using an evolutionary algorithm is considered [7]-[8]. Due to the different in soil characteristics at each substation, ground grid design must carefully be done to gain acceptable safety as well as optimal investment. From the past, ground grid design without rods and with rods was carried out. A vertical rod is more effective electrode than a horizontal rod [9]. Optimization design of substation grounding grid based on genetic algorithm is discussed [10]-[11].

Vertical ground rods discharge the grid current in the soil at sufficient depth. Thus they effectively reduce grounding system resistance and GPR. Also with more number of ground rods, total length of conductors buried in the earth increases thereby decreasing step and mesh voltages. In actual practice ground rods are considered to be an effective means of reducing resistance of combined grounding system and also actual mesh and step voltages whenever design modifications are necessary. For same total length of conductor to be installed vertical rods are more cost effective than horizontal grid conductors because they penetrate into lower layers of soil in the deep earth which generally have lower resistivity [12]. Multiple driven electrodes are, everything being equal, more effective than equivalent ground grids made of horizontal conductors. This is true even when soil is uniform. However, when lower layer resistivity is high, the horizontal conductors are more effective because they reduce significantly the touch voltages [13]. Area occupied by the grounding grid has major effect on GPR, step voltage as well as on mesh voltage. With increased area step, touch and mesh potentials reduce significantly. Area contributes to reduction in grid resistance and GPR [14].

II. DESIGN OBJECTIVES

According to IEEE Std 80-2000 there are two main design goals to be achieved by any substation grounding system under normal as well as fault conditions. These goals are:

1. To provide means to dissipate electric currents into the earth without exceeding any operating and equipment limits.
2. To assure that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock.

III. DESIGN METHODOLOGY

The design procedure block diagram for high voltage substations is shown in Fig.1.

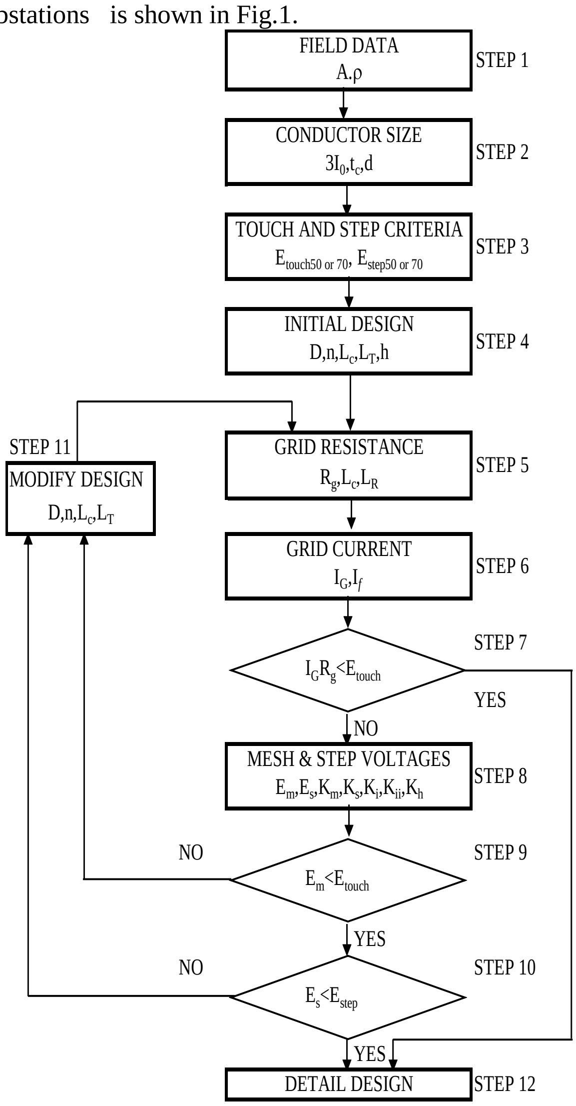

Fig.1 Design procedure block diagram [6]

Step1- The area of the land where substation is required to be constructed and electrical resistance of soil profiles are calculated.

Step 2 - The fault current ($3I_0$) should be the maximum expected future fault current that will be conducted by any conductor in the grounding system, and the time t_c, should reflect the maximum possible clearing time. For practical reasons it is appropriate to investigate single line to ground faults. Therefore, zero sequence current for single line-to-ground fault is given as in (1).

$$3I_0 = V / 3R_f + (R_1+R_2+R_0) + j\,(X_1+X_2+X_0) \qquad (1)$$

It is assumed that fault clearing time for the worst-case fault scenario is 0.5 seconds. The diameter of conductor is determined as in (2).

$$Amm^2 = I_{(KA)} \sqrt{\frac{t_c.\alpha_r.\rho_r.\frac{10^4}{TCAP}}{\ln\left[1+\frac{T_m-T_a}{K_0+T_a}\right]}} \qquad (2)$$

Step 3 - Tolerable Step and touch voltage are based on (3) - (6).

$$E_{step}^{50} = \frac{0.116}{\sqrt{t}}\,(1000 + 6C_s\,\rho_s) \qquad (3)$$

$$E_{step}^{70} = \frac{0.157}{\sqrt{t}}\,(1000 + 6C_s\,\rho_s) \qquad (4)$$

$$E_{touch}^{50} = \frac{0.116}{\sqrt{t}}\,(1000 + 1.5C_s\,\rho_s) \qquad (5)$$

$$E_{touch}^{70} = \frac{0.157}{\sqrt{t}}\,(1000 + 1.5C_s\,\rho_s) \qquad (6)$$

Step 4 - Preliminary design parameters like distance between equally spaced conductors, grid burial depth, total length of horizontal conductors, and number of parallel conductors in one direction are determined.

Step 5 –The grid resistance is determined by (7).

$$R_g = \rho\left[\frac{1}{L} + \frac{1}{\sqrt{\frac{20}{A}}} + \left(1 + \frac{1}{1+h\sqrt{\frac{20}{A}}}\right)\right] \qquad (7)$$

Step 6- The decrement factor and current division factor are selected by keeping in view fault duration. The maximum grid current is determined by combing decrement factor and symmetrical grid current is given by (9).

$$I_g = 3I_0.\,S_f \qquad (8)$$

$$I_G = D_f\,.\,I_g = D_f.\,3I_0.S_f \qquad (9)$$

Step 7 – If the product of maximum grid current and grid resistance is lesser than the touch voltage, then proceed for the detailed design.

$$I_G\,R_g < E_{touch} \qquad (10)$$

Step 8 -The mesh voltages and step voltage is determined as in (11) - (12) respectively.

$$E_m = \rho\,K_m\,K_i\,I_G / L_m \qquad (11)$$

$$E_s = \rho\,K_s\,K_i\,I_G / L_m \qquad (12)$$

Step 9 - If the calculated mesh voltage is lesser than the touch voltage then proceed for step10, otherwise modify the design.

Step 10 - If the calculated step voltage is lesser than the step voltage then proceed for detailed design otherwise modify the design.

Step 11- After calculating and determining all required grid parameters detailed design is prepared.

IV. SIMULATION AND TESTING RESULTS

In this section simulations are carried out in order to verify the results obtained through manual calculations. A software known as ETAP PowerStation is used for the simulations. The objectives of the program are:

1. To provide a low cost computer program running on a personal computer.
2. To provide an easy to use, but technically acceptable solution to the complex problem of grounding grid design.
3. To design a safe, technically acceptable and economically viable grounding grid.

The design of a substation grounding system is very complex due to the number of involved phenomena. One of them comes from the fact that lightning influences the local resistivity of the soil given, when lightning occurs, non-linear phenomena appear in the soil. Nevertheless, this is not the only difference regarding the low frequency case. Indeed, the high frequency response of both grounding grids and human body are not the same for fast transients and power frequency. This very complex phenomenon has not been considered in this paper. The grid parameters for the substation design are shown in Table I. The values of step voltages, mesh voltages and GPR were found larger than tolerable limits and did not satisfy the safety criteria limits, thus, design required modifications. To find the optimal results grid parameters have been modified as shown in Table II. The simulated results are shown in Table III and Table IV. The image of the ground grid without rods is shown in Fig.2. The screenshot of ETAP software is shown in Fig.3.

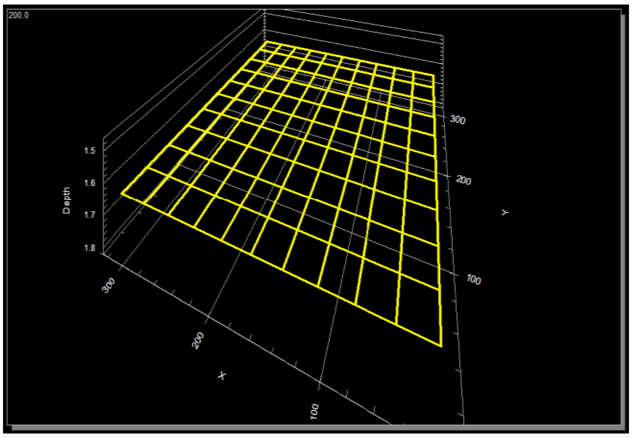

Fig.2 Image of ground grid without rods

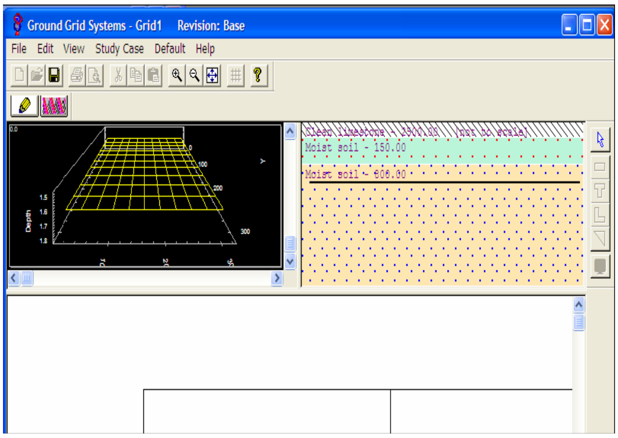

Fig.3 Screenshot of ETAP Software

TABLE I
GRID PARAMETERS

Grid Area (A)	8100 m^2
Grid Dimensions	90 m x 90 m
Soil Resistivity (ρ_a)	170.82 Ω.m
Upper Layer Resistivity (ρ_1)	150 Ω.m
Lower Layer Resistivity (ρ_2)	800 Ω.m
Upper layer thickness (H)	9 m
Grid burial depth (h)	0.5 m
Rod length (L_R)	10 m
Distance Between Equally Spaced Conductors (D)	9 m
Thermal Capacity Per Unit Volume (TCAP)	3.85 J/(cm3·°C)
Grid Conductor Length (L_m)	1940 m
Grid Resistance (R_g)	0.925 Ω
Symmetrical Grid Current(I_g)	4558.2V
Fault Duration (t_f)	0.5 s
Current Division Factor (S_f)	0.6
Crushed Rock Resistivity (Wet) (ρ_s)	2500 Ω.m
Thickness of crushed rock surfacing (h_s)	0.075 m
Total Fault Current ($3I_0$)	11806 A
Fault Clearing Time (t_c)	0.5 s
Diameter of Conductor (d)	0.01 m
Conductors in ‘X’ and ‘Y’ Direction	11
Maximum Grid Current (I_G)	7354 A
Reflection Factor (*K*)	-0.872
Surface Layer De rating Factor (C_s)	0.65
Decrement Factor (D_f)	1.0
Geometry Correction Factor (K_i)	2.272
Geometry Correction Factor (K_{ii})	0.57
Effect of Burial Depth Correction Factor (K_h)	1.225
Geometrical Spacing Factor (K_m)	0.967
Number of Parallel Conductors in One Direction (n)	11
Mesh Voltage (E_m)	1011.65 V
Step Voltage(E_s)	653.7 V

TABLE II
GRID PARAMETERS (AFTER MODIFICATION)

Conductors in ‘X’ and ‘Y’ Direction	21
Grid Conductor Length (L_m)	3780 m
Distance Between Equally Spaced Conductors (D)	4.5 m
Number of Parallel Conductors in One Direction (n)	10.5 m
Geometry Correction Factor (K_{ii})	0.32
Geometry Correction Factor (K_i)	2.198
Effect of Burial Depth Correction Factor (K_h)	1.225
Geometrical Spacing Factor (K_m)	0.923
Mesh Voltage (E_m)	417.97 V
Step Voltage(E_s)	658.9 V

TABLE III
RESULTS FOR GROUND GRID WITHOUT RODS

Ground Resistance (R_g)	0.855	
Ground Potential Rise (GPR)	6285.6	
Touch Potential	Tolerable Volts	761.1
	Calculated volts	1235.6
	Calculated%	162.3
Step Potential	Tolerable Volts	2378.3
	Calculated volts	653.7
	Calculated%	27.5

TABLE IV
RESULTS FOR GROUND GRID WITH RODS

Ground Resistance (R_g)	0.615	
Ground Potential Rise (GPR)	4523.5	
Touch Potential	Tolerable Volts	761.1
	Calculated volts	741.8
	Calculated%	97.5
Step Potential	Tolerable Volts	2378.3
	Calculated volts	658.9
	Calculated%	27.7

V. SYMBOLS DEFINITION

The symbols definitions are shown in Table V.

TABLE V
SYMBOLS DEFINITION

A	Grid Area in square meters
ρ_a	Soil Resistivity in ohm meters
ρ_r	Resistivity of Ground Conductor at Reference Temperature
ρ_1	Upper Layer Resistivity in ohm meters
ρ_2	Lower Layer Resistivity in ohm meters
H	Upper Layer Thickness in meters
h	Grid Burial Depth in meters
L_R	Rod Length in meters
D	Distance Between Equally Spaced Conductors in meters
TCAP	Thermal Capacity Per Unit Volume in joules per cubic centimeter degree centigrade
L_m	Grid Conductor Length in meters
R_g	Grid Resistance in ohms
I_g	Symmetrical Grid Current in amperes
t_f	Fault Duration in seconds
S_f	Current Division Factor
ρ_s	Crushed Rock Resistivity (Wet) in ohm meters
α_r	Thermal Coefficient of Resistivity at Reference Temperature
α_0	Thermal Coefficient of Resistivity at 0°C
h_s	Thickness of Crushed Rock Surface in meters
$3I_0$	Total Fault Current in kilo amperes
t_c	Fault Clearing Time in seconds
D	Diameter of Conductor in meters
I_G	Maximum Grid Current in kilo amperes
K	Reflection Factor
T_m	Maximum Allowable Temperature in °C
T_a	Ambient Temperature in °C
K_0	Material Constant at ℃
C_s	Surface Layer De-rating Factor OR Reduction Factor
D_f	Decrement Factor
K_i	Grid Geometry Correction Factor
K_{ii}	Grid Geometry Correction Factor
K_h	Effect of Burial Depth Correction Factor
K_m	Geometrical Spacing Factor to Determine Mesh Voltage in volts
K_s	Geometrical Spacing Factor to Determine Step Voltage in volts
N	Number of Parallel Conductors in One Direction
E_m	Mesh Voltage in volts
E_s	Step Voltage in volts
E_{step}^{50}	Step Voltage Criteria for a 50kg weight person
E_{step}^{70}	Step Voltage Criteria for a 70kg weight person
E_{touch}^{50}	Touch Voltage Criteria for a 50kg weight person
E_{touch}^{70}	Touch Voltage Criteria for a 70kg weight person

VI. CONCLUSION

The maximum grid current was determined using the maximum fault current and the current division factor. Ground potential rise was determined with the help of maximum grid current and grid resistance. The values of step voltages, mesh voltages and GPR were found larger than tolerable limits and did not satisfy the safety criteria limits, thus, design required modifications. As a result, the new grid resistance and GPR were then taken through the same steps until the grid design safety criterion was achieved. This modification involved reducing the mesh sizes which was very effective in reducing the grid resistance and therefore, the calculated step and touch voltages were much lower than the tolerable limits and this in turn satisfies the safety criteria. It is evident from the results that addition of rods is beneficial as it ensures a higher level of safety by reducing the grid resistance from 0.855Ω to 0.615Ω .Therefore, leading to a reduced ground potential rise from 5893.4V to 4523.5V.

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