A STUDY ON EFFECT OF GROUNDING GRID CONFIGURATION ON GROUND POTENTIAL RISE OF GAS INSULATED SUBSTATION INSTALLATIONS DURING FAULT CONDITIONS

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Abstract: The grounding system of a high voltage gas insulated substation (GIS) comprises concrete foundations along with a horizontal grounding grid and vertical grounding rods. The concrete foundations in substations are generally located under power transformers, gas insulated switchgear equipment, control panels, protection relays and various auxiliary equipment. The design of grounding system is critical for compact GIS installations located in high resistivity soils. In such substations, these foundations can be used as additional vertical grounding rods and are connected to the horizontal grounding grid of the substation. In the present study, an analytical model has been developed to calculate ground resistance, Ground Potential Rise (GPR), and step/touch potentials of the grounding system used for GIS. The current distribution across the horizontal grid is also analysed for a fault current of 40 kA (rms). In order to evaluate effect of design of vertical grounding rods on ground potential rise, different configurations are considered. Further, influence of concrete foundations on above performance parameters has been studied by considering various soil resistivities and grid spacing. Finally, the design of grounding system has been validated by comparing touch and step potentials with the permissible levels as per IEEE-80.

1 INTRODUCTION

Gas Insulated Substations (GIS) have found a broad range of applications in power systems because of their high reliability, easy maintenance, limited space requirement etc. GIS modules are based on the principle of complete encapsulation of energized (live) parts in grounded metallic enclosures. The metallic enclosure, in GIS, also shields live parts from external pollution. In conventional Air Insulated Substation (AIS) the closest ground is the earth surface [1]. Compressed SF_6 gas at a pressure of 100 kPa to 650 kPa is employed as an insulating medium between the grounded encapsulation and the energised parts in GIS.

The grounding system of a high voltage substation comprises a horizontal grounding grid and vertical grounding rods [2]. The resistance of grounding grid depends on different parameters such as resistivity of soil, resistivity of crushed rock / high resistive coating, area of grounding grid, depth of the grid, mesh size of grid / grid spacing, number of grounding rods, area of ground conductors etc. Prior to installation of substation, it is necessary to measure soil resistivity during different weather conditions. Layer of crushed rock (gravels, high resistance layer) is often spread above the grounding grid to increase the contact resistance between the soil and feet of the personnel in substations. The grounding system is conventionally extended over the entire substation switchyard and sometimes beyond its surrounding fence. The design of grounding grid becomes difficult, especially, when soil resistivity is high and area of grounding grid is limited, as in the case of compact gas insulated substations. Grounding grid with cross elements ensures safe surface potentials such as step and touch voltages. Surface potentials have been effectively controlled by deeper grounding rods, introduction/ increase of ground wells and by using low resistivity soil /clay [3].

The horizontal grounding grid is generally located at 0.5 to 0.8 m below the ground plane and is connected to the vertical grounding rods. The depth to which the rods are inserted into the ground and their quantity are based on soil resistivity and area of grounding grid. Low resistance of grounding grid provides low potential which appear on the grounding system in the event of a short circuit or a lightning stroke [4]. There are concrete foundations along with horizontal grounding grid and vertical grounding rods. For the optimisation of ground / grid resistance and surface potentials it is important to utilize the concrete foundations used for the substation installation. Concrete has natural moisture content and can be considered as a semi-conductive material whose resistivity is in the order of 30 to 90 Ω-m. Due to large contact surface areas between concrete and soil, low ground resistances can be achieved.

2 ANALYTICAL MODEL

Figure 1 shows the horizontal grounding grid along with the vertical grounding rods. Grounding grid is considered to be laid at a depth of ‘h” from the level ground plane. The length of grounding rod is Lg. The length and width of grid are “L” and “W” respectively. "D" is uniform grid spacing. N_L and N_W are number of nodes (intersections) on length and width of grounding grid respectively.

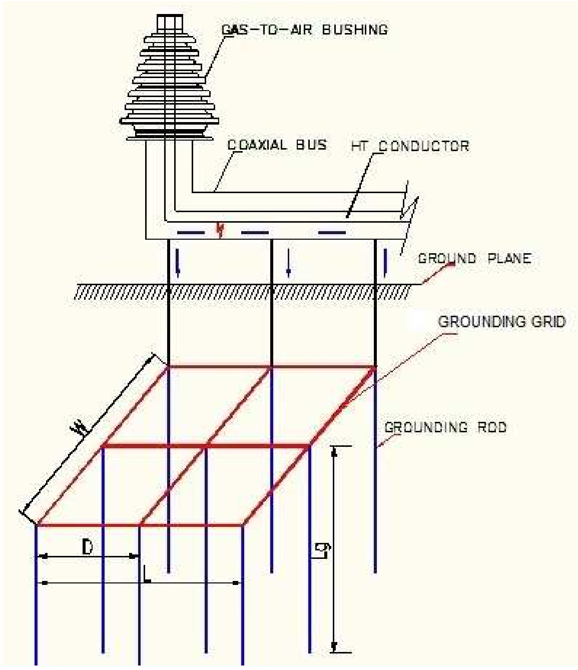

Figure 1: Grounding system for a GIS

The following three surface potentials are important to understand while designing the grounding system:

1. Ground potential rise (GPR); the maximum voltage that a substation grounding grid attains relative to a distant grounding point or potential of remote earth. GPR is product of ground resistance (R) and grid current (I_G).
2. Step Voltage (V_s); the difference in potential experienced by a person bridging a distance of 1m with feet (average step length), without contacting any other grounded object.
3. Touch potential (V_t); the potential difference between the GPR and the surface potential at the point where a person is standing and the touch/ contact on a grounded structure/equipment.

The following main parameters are considered for the calculation of surface potentials:

1 Grid Current, I_G
2 Fault Clearance Time, T_F
3 Maximum Ambient Temperature, T_a
4 Maximum Allowable temperature, T_m
5 Depth of Grid, h
6 Depth of high resistivity Layer, h_s
7 Resistivity of soil, ρ
8 Resistivity of top layer, ρ_s
9 Area of ground conductor, A
10 Length of Ground rods, L_g
11 Grid spacing, D
12 Length of Grid, L
13 Width of Grid, W

In order to provide safety to the operating personnel, the design of grounding system is optimized by keeping touch and step potentials well below the permissible levels as recommended in standards (IEEE-80). These potentials are calculated by means of the following equations [3]:

$$E_s = \frac{(1000 + 6C_s\rho) * 0.116}{\sqrt{T_F}} \quad (1)$$

$$E_t = \frac{(1000 + 1.5C_s\rho) * 0.116}{\sqrt{T_F}} \quad (2)$$

Where, E_s and E_t are tolerable step and touch voltages in volts and

T_F = Fault clearance time, sec.
C_s is calculated using following relation:

$$Cs = 1 - 0.106 * \left[\frac{1 - \frac{\rho}{\rho_s}}{0.106 + 2h_s}\right] \quad (3)$$

Grid Resistance, R has been calculated using following equation:

$$R = \frac{\rho}{L_T} + \frac{\rho}{\sqrt{20A_g}}\left(1 + \frac{1}{1 + h\sqrt{\frac{20}{A_g}}}\right) \quad (4)$$

Where, A_g is Area of grounding grid.
L_T is total length of grounding conductor including grid and rods.
Touch and step potentials of a particular grounding system have been calculated by using following equations:

$$V_s = \frac{\rho I_g K_s K_{is}}{L_h + 1.15L_v} \quad (5)$$

$$V_t = \frac{\rho I_g K_m K_{it}}{(0.75 * L_h) + (0.85L_v)} \quad (6)$$

Where, V_s and V_t are calculated step and touch voltages respectively.
K_s and K_m are spacing factors for step and touch voltages.
K_{is} and K_{it} are correction factors for step and touch voltages.
L_h is length of horizontal grid conductor.
L_v is length of vertical grounding rod conductor.
The ground resistance with concrete foundations is calculated by using following equations:

$$R_c = \frac{0.2\rho}{\sqrt[3]{V}}\,\Omega \quad (7)$$

$$R_g = \frac{R_c.R}{R_c + R}\,\Omega \quad (8)$$

V is volume of the concrete foundation. R_c and R_g are concrete foundation resistance and over all ground / grid resistance respectively. The number of concrete foundations that are made under substation depends on configuration of GIS, soil conditions, area of grid and dynamic loading of different equipment. In the present study, the average size of the foundation is considered to be about 0.8x0.8 m^2 and the depth of foundation is up to 3.0 m. A single concrete structure has enclosed conductors that are welded among themselves and then connected to grounding grid. The length of this conductor could be more than 10 m and the same have been considered for analysis. Figure 2 shows the grounding grid with concrete

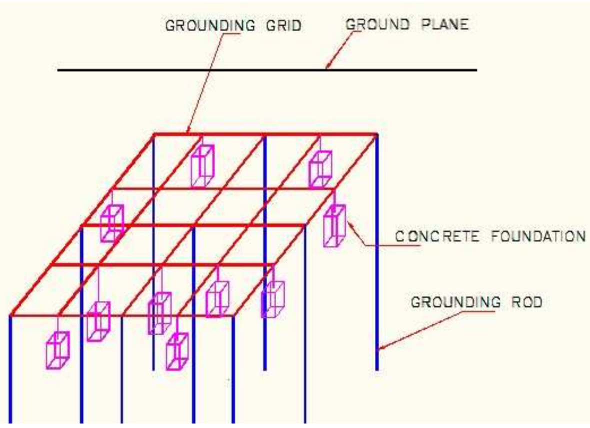

Figure 2: Grounding Grid of a GIS with Concrete Foundations.

foundations in GIS. By means of eq. 7, the foundation resistance in soil can be calculated. A single foundation resistance is in the order of 20 Ω. It is also important that the foundation under transformer is very large and foundation resistance is only few ohms depending on size of transformer. From eq. 8, with increase of number of concrete foundations, grid resistance can be reduced substantially. Interestingly, resistance of a grounding rod is also in the order of 10 to 20 Ω depending on its length and is comparable to concrete foundation resistance. In other words, foundations play an important role in substations when its resistivity is comparable to soil resistivity.

3 RESULTS AND DISCUSSIONS

The grounding grid is represented by means of an equivalent RLC circuit and the current distribution as well as GIS enclosure voltages are calculated using PSCAD software. For a fault current of 40 kA, the current distribution in the horizontal grid is highly non-uniform. When the current calculation is made along length of the grid, it is evident that currents at the middle and outer meshes are high compared to in-between meshes (refer Figure 3). Surface potentials get created because of the differential currents in the mesh and it is a matter of concern for the operating personnel and the connected sophisticated electronic equipment. The current distribution is again found to be function of number of grounding rods and their location in the grid. At the same time, with increase of number of grounding rods, the ground potential rise or grid resistance decreases (refer Figure 4). As GPR is a function of grid resistance for a particular fault current, it is important to optimise the same by novel techniques. The overall grid resistance is found to be affected by soil resistivity, area of the grid and length of grounding grid conductor. The effect of grid spacing on ground resistance is only marginal.

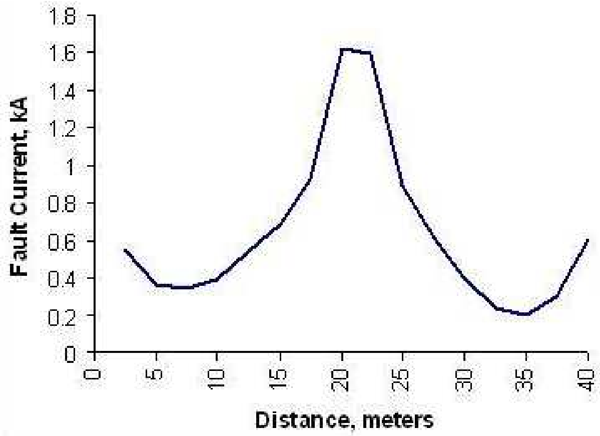

Figure 3: Current Distribution along the length of the grounding grid.

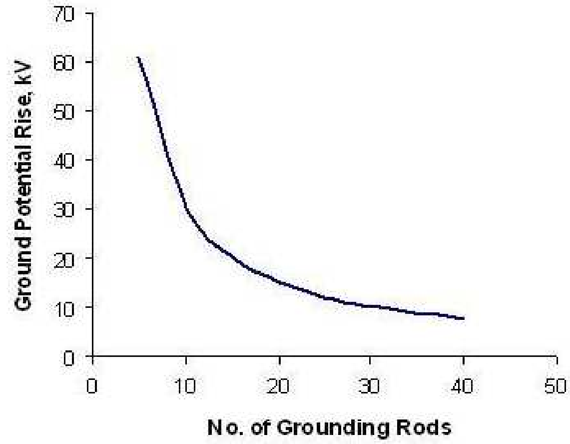

Figure 4: Effect of number of Grounding rods on Ground Potential Rise (GPR).

The touch and step potentials mainly depend on grid spacing, length of grounding rods, number of grounding rods along with soil resistivity. The effect of number of grounding rods on these potentials has been analysed for a grounding grid of 40 m x 30 m with grid spacing of 1.5 m (refer Figure 5). From the figure, it is evident that with increase of number of grounding rods, surface potentials can be reduced well below to tolerable levels. Here, length of grounding rod is considered to be 6 m and soil resistivity of 100Ω-m. For particular grid spacing, the touch potentials can be reduced more effectively than step potentials when number of grounding rods is in the order of 20 to 30. With increase of number of grounding rods further, effect on touch potential is only marginal. The same has been confirmed for longer lengths of grounding rods up to 12 m. More clearly step voltage can be reduced by increasing grid spacing as well as total length of the grounding rods. With increase of grid spacing touch voltages increase notably. Hence, there is an optimised grid spacing for a particular soil resistivity for which both touch and step potentials are well below tolerable levels. It is also understand that at higher soil resistivity, the grid spacing must be as low as possible to limit surface potentials.

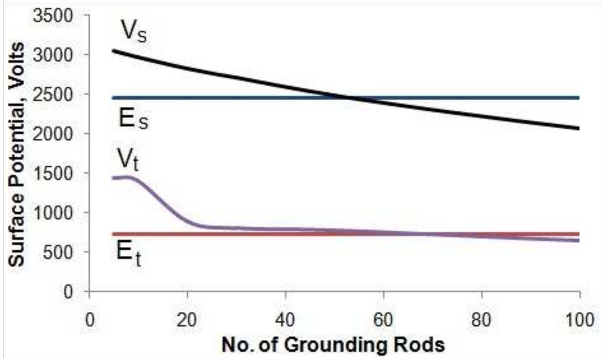

Figure 5: Variation of Surface Potentials for different number of grounding Rods.

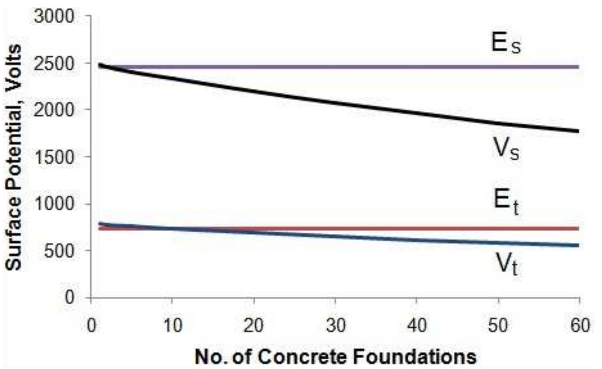

Figure 6: Variation of Surface Potentials for different number of concrete foundations.

In practice, it is very difficult to design grounding system for compact gas insulated substations that are to be installed in locations where soil resistivity is high. At the same time, area of the grid is limited. In this situation, the grounding rods can not be increased beyond certain extent. Thus, surface potentials and grid resistance of the substation can be limited only by connecting the grounding grid to the existing concrete foundations. Figure 6 shows the variation of surface potentials for different number of concrete foundations. It is interesting to see that the step and touch voltages can be reduced to the order of 28 to 30% by using these foundations. At the same time, the grid resistance could be reduced from 1.27 to 0.38 Ω for

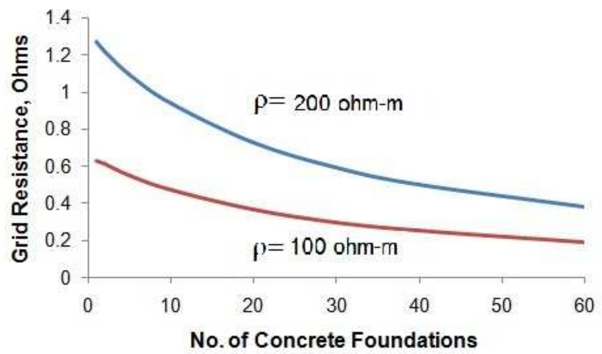

Figure 7: Variation of Grid Resistance for different number of Concrete Structures.

grounding grids located with soil resistivity of 200Ω-m (refer Figure 7). The reduction in grid resistance is found to be significant whatever may be the resistivity of soil. It is also important to note that for high resistivity soils, diameter of grounding grid conductor, thickness of high resistivity crushed layer, length of grounding rods, number of grounding rods have to be increased substantially in order to limit surface potentials to safe levels. Moreover, the earth pipes / pits are also used by BHEL in substations to limit the surface potentials during fault conditions. By using conventional grounding techniques, the GPR for limited area grids are in the order of few tens of kV. However, by using concrete foundations and ground pipes, GPR can be reduced to well below 5 kV, which improves safety to operating personnel and reliability of secondary equipment in substations.

4 CONCLUSION

An analytical approach has been developed to calculate the ground resistance, touch and step potentials of substation ground during a fault. The effect of different parameters on performance of the grounding system used for gas insulated substations has been analyzed and found that the analysis is useful for its design. The importance of concrete foundations in limiting surface potentials and grid resistance is also analysed for a gas insulated substation during a fault condition. The study emphasizes need for the optimization of grounding system parameters such as length of grounding rods, number of grounding rods and grid spacing for compact gas insulated substations built on high resistivity soils and short plinths.

5 ACKNOWLEDGMENTS

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