Design of substation grounding grids

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This project was carried out in the year 2014
قالوا سُبْحَانَكَ لاَ عِلْمَ لَنَا إِلاَّ مَا عَلَّمْتَنَا إِنَّكَ أَنتَ الْعَلِيمُ الْحَكِيمُ 

(التقرير النهائي)
1. Introduction .................................................................................................................. 6
2. Electric shocks and protection .................................................................................. 11
  2.1. Hazard Analysis ..................................................................................................... 11
2.2. A safe grounding design has two objectives: ....................................................... 11
2.3. Soil Characteristics ................................................................................................. 12
2.4. RESISTANCE OF GROUNDING SYSTEMS ....................................................... 14
2.5. Resistance of a Grounding Point Electrode .......................................................... 17
2.7 Resistance of Driven Rods ...................................................................................... 21
3. SUBSTATION GROUNDING SYSTEM ...................................................................... 26
  3.1. PRINCIPLES OF DESIGN OF A SUBSTATION GROUNDING ................... 27
  3.2. NEUTRAL GROUNDING ................................................................................ 30
  3.3. GROUNDING OF LOW-VOLTAGE (LV) SYSTEMS .................................. 33
  3.4. GROUNDING OF GAS-INSULATED SUBSTATIONS .................................. 35
  3.5. Grounding of Enclosures ...................................................................................... 36
  3.5.1. Touch Voltages for GIS ................................................................................. 37
  3.5.2. Transient Impedance of GIS Grounding Grid .............................................. 37
  3.6. Transmission-line tower grounding ..................................................................... 38
  3.7. Safety ground ....................................................................................................... 39
  3.8. Range of Tolerable Currents .............................................................................. 39
  3.9. Tolerable Step, Touch, and Transferred Voltages ............................................. 40
  3.9.1. Electric Shock Hazard in Hospitals ............................................................... 43
3.10. Methods Of Decreasing Ground Resistance ........................................... 43
3.11. Cracks with Low-Resistivity Materials (LRM) ........................................ 44
3.11.1. Chemical Rods .................................................................................. 44
3.11.2. Grounding Augmentation Fill (GAF) .................................................. 46
3.11.3. Cracks with Low Resistivity Materials (LRM) ..................................... 46
4. Experimental setup ..................................................................................... 48
4.1. Introduction ............................................................................................... 49
4.2. Experimental layout .................................................................................. 50
4.3. Touch voltage calculation ......................................................................... 53
4.4. Electric resistivity Measurement by 4 electrode method ......................... 54
4.5. Test procedures ....................................................................................... 57
5. Results And Discussion ................................................................................ 58
5.1. Effect of grid number ............................................................................... 59
5.2. Effect of grid depth .................................................................................. 63
6. Conclusions .................................................................................................. 67
7. Future work .................................................................................................. 67
Table of figure

Figure 2-2- Resistance of different solution ......................................................... 18
Figure 2-3 Current entering ground through a hemispherical electrode .................... 20
Figure 3-1 Step, touch, and transferred voltages near a grounded structure ............... 29
Figure 3-2: Examples of power system neutral grounding ...................................... 32
Figure 3-3 Connection modes of the neutral of the installation and of the frames of the electrical loads ................................................................. 34
Figure 3-4 Example of the various grounding systems included in the same installation 35
Figure 3-5 Chemical Rods ................................................................................. 45
Figure 3-6 Grounding system with explosion and intrinsic cracks ............................ 47

Figure 4-1: photo for Experimental layout ............................................................. 52
Figure 4-2: Experimental layout .......................................................................... 53
Figure 4-3: Electric resistivity Measurement .......................................................... 56
Figure 4-4: Mesh type ......................................................................................... 57

Figure 5-1 Normal profiles of surface potential for 2x2 Mesh with 2 cm depth ........ 60
Figure 5-2 Normal profiles of surface potential for 3x3 Mesh with 1 cm depth Upper part ............................................................... 61

Figure 5-3 Normal profiles of surface potential for 3x3 Mesh with 1 cm depth lower part ............................................................... 62
Figure 5-4 Normal profiles of surface potential for 2x2 Mesh with 1 cm depth .......... 63
Figure 5-5 Normal profiles of surface potential for 2x2 Mesh ................................ 64
Chapter 1

Introduction
1.1. Introduction

Electrical installations require grounding systems, whose geometry may also depend on the footprint of buildings or substations they serve. In most industrial cases, grounding systems consist of grids integrated with rods at each corner. In many cases, if available, non-insulated reinforcing bars in concrete foundations may also serve as vertical ground electrodes. In modern extra-high-voltage and ultrahigh-voltage AC substations, grounding has become one of the dominant problems of system design. It is essential to have an accurate design procedure for the grounding system. Grounding is of major importance to increase the reliability of the supply service as it helps to provide stability of voltage conditions, preventing excessive voltage peaks during disturbances, and also a means of providing a measure of protection against lightning.

It is required that the voltage rise during a fault be kept to low levels. This dictates that ground resistances in high voltage substations must be very low. The most common method of obtaining low values of ground resistance at high-voltage substations is to use interconnected ground grids. A typical grid system for a substation comprises 4/0 bare standard...
copper cable buried at a depth of from 30 to 60 cm parallel to the surface of the earth and spaced in a grid pattern of about 3 to 10 m. At each junction of 4/0 cable, the cables are securely bonded together [1].

grid not only effectively grounds the equipment, but has the added advantage of controlling the voltage gradients at the surface of the earth to safe values for human contact. Ground rods may be connected to the grid to have low values of ground resistance when the upper layer of soil in which the grid is buried is of much higher resistivity than that of the soil beneath.

The best configuration of the grounding grid requires studying the effect of the parameters usually encountered in practice. Such parameters are the length of the grounding grid, the number of meshes in the grid, the diameter of the grounding conductor, the depth of burial of the grid and the effect of using ground rods. It is impractical to investigate the effect of these parameters on full-size grids because of the lack of controlled conditions and variations in soil resistivity at the site. Scale models offer a practical and inexpensive alternative solution. Scale model tests are generally employed to determine grounding resistance and surface potential distributions during grounding faults in the case of complex grounding arrangements where accurate analytical calculations are seldom possible.
The approximate formula for the percentage mesh potential given in Reference [2] indicates that if all dimensions of the grid are reduced by the same factor, the percentage mesh potential remains unchanged. The shape of current and equal potential surfaces are unaltered. Therefore, it is possible to simulate the actual grounding grids with the help of scale models and the potential profiles measured on a model may be used to determine the corresponding potentials on a full-scale Understanding the steps and procedures employed in a good electrical safety program requires an understanding of the nature of electrical hazards. Although they may have trouble writing a concise definition, most people are familiar with electric shock. This often painful experience leaves its memory indelibly etched on the human mind. However, shock is only one of the electrical hazards. There are two others arc and blast.
Chapter 2

Electric shocks

and protection
Electric shocks and protection

2.1. Hazard Analysis

The division of the electrical power hazard into three components is a classic approach used to simplify the selection of protective strategies. The worker should always be aware that electricity is the single root cause of all of the injuries described in this and subsequent chapters. That is, the worker should treat electricity as the hazard and select protection accordingly.

A safe grounding design has two objectives:
• To provide means to carry electric currents into the earth under normal and fault conditions without exceeding any operating and equipment limits or adversely affecting continuity of service.

• To assure that a person in the vicinity of grounded facilities is not exposed to the danger of critical electric shock.

2.2. Soil Characteristics

• **Soil type:** Soil resistivity varies widely depending on soil type, from as low as 1 Ohmmeter for moist loamy topsoil to almost 10,000 Ohm-meters for surface limestone.

• **Moisture content** is one of the controlling factors in earth resistance because electrical conduction in soil is essentially electrolytic.

• **The resistivity** of most soils rises abruptly when moisture content is less than 15 to 20 percent by weight, but is affected very little above 20 percent.

• **The moisture** alone is not the predominant factor influencing the soil resistivity.

• **If the water is relatively pure,** it will be of high resistivity and may not provide the soil with adequate conductivity.

Table 1: Soil Resistivity (ohm-meter)
<table>
<thead>
<tr>
<th>Description</th>
<th>Median</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topsoil, loam</td>
<td>26</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>Inorganic clays of high plasticity</td>
<td>33</td>
<td>10</td>
<td>55</td>
</tr>
<tr>
<td>Fills – ashes, cinders, brine wastes</td>
<td>38</td>
<td>6</td>
<td>70</td>
</tr>
<tr>
<td>Gravely clays, sandy clays, silty clays, lean clays</td>
<td>43</td>
<td>25</td>
<td>60</td>
</tr>
<tr>
<td>Slates, shales</td>
<td>55</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>Silty or clayey fine sands with slight plasticity</td>
<td>55</td>
<td>30</td>
<td>80</td>
</tr>
<tr>
<td>Clayey sands, poorly graded sand-clay mixtures</td>
<td>125</td>
<td>50</td>
<td>200</td>
</tr>
<tr>
<td>Fine sandy or silty clays, silty clays, lean clays</td>
<td>190</td>
<td>80</td>
<td>300</td>
</tr>
<tr>
<td>Decomposed gneisses</td>
<td>275</td>
<td>50</td>
<td>500</td>
</tr>
<tr>
<td>Silty sands, poorly graded sand-silt mixtures</td>
<td>300</td>
<td>100</td>
<td>500</td>
</tr>
<tr>
<td>Clayey gravel, poorly graded gravel, sand-clay mixture</td>
<td>300</td>
<td>200</td>
<td>400</td>
</tr>
<tr>
<td>Well graded gravel, gravel-sand mixtures</td>
<td>800</td>
<td>600</td>
<td>1,000</td>
</tr>
<tr>
<td>Granites, basalts, etc.</td>
<td>1,000</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Sandstone</td>
<td>1,010</td>
<td>20</td>
<td>2,000</td>
</tr>
<tr>
<td>Poorly graded gravel, gravel-sand mixtures</td>
<td>1,750</td>
<td>1,000</td>
<td>2,500</td>
</tr>
<tr>
<td>Gravel, sand, stones, little clay or loam</td>
<td>2,585</td>
<td>590</td>
<td>4,580</td>
</tr>
<tr>
<td>Surface limestone</td>
<td>5,050</td>
<td>100</td>
<td>10,000</td>
</tr>
</tbody>
</table>
2.3. RESISTANCE OF GROUNDING SYSTEMS

The value of resistance to ground of an electrode system is the resistance between the electrode system and another “infinitely large” electrode in the ground at infinite spacing. The soil resistivity is a deterministic factor in evaluating the ground resistance. It is an electro physical property. The soil resistivity depends on the type of soil (Table 2-), its moisture content, and dissolved salts. There are effects of grain size and its distribution, and effects of temperature and pressure. Homogeneous soil is seldom met, particularly when large areas are involved. In most cases there are several layers of different soils. For nonhomogeneous soils, an apparent resistivity is defined for an equivalent homogeneous soil, representing the prevailing resistivity values from a certain depth downward.

The moisture content of the soil reduces its resistivity. As the moisture content varies with the seasons, the resistivity varies accordingly. The grounding system should therefore be installed nearest to the permanent water level, to minimize the effect of seasonal variations on soil resistivity. As water resistivity has a large temperature coefficient, the soil resistivity increases as the temperature is decreased, with a discontinuity at the freezing point.

The resistivity of soil depends on the amount of salts dissolved in its moisture. A small quantity of dissolved salts can reduce the resistivity
remarkably. Different salts have different effects on the soil which explains why the resistivity of apparently similar soil from locations vary considerably (Figure).

Table 0-2  Typical Values Of Resistivity Of Some Soils
Figure (2-2) Variation of soil resistivity with its moisture content
The distribution of grain size has an effect on the manner in which the moisture is held. The finer the grading, the lower will be the resistivity. There is not much experimental work on the effect of pressure, but it is reasonable to assume that higher pressures resulting in a more compact body of earth will result in lower values of resistivity.

2.4. Resistance of a Grounding Point Electrode

The simplest possible electrode is the hemisphere — (figure 2-4) the ground resistance of this electrode is made up of the sum of the resistances of an infinite number of thin hemispheric shells of soil. If a current I flows into the ground through this hemispherical electrode, it will flow away uniformly in all directions through a series of concentric hemispherical shells. Considering each individual shell with a radius x and a thickness dx, the total resistance R up to a large radius r1 would be

\[ R = \int_{r}^{r1} \frac{\rho dx}{2\pi x^2} = \frac{\rho}{2\pi} \left( \frac{1}{r} - \frac{1}{r1} \right) \]
Figure 2-3 Resistance of different solution.
Figure (2-4-a)
Figure (2-4-b)

Figure 0-4 Current entering ground through a hemispherical electrode.
Where \( \rho \) is the earth resistivity. As \( r_1 = \infty \)
\[
R_\infty = \frac{\rho}{2\pi r}
\]
The general equation for electrode resistance is
\[
R = \frac{\rho}{2\pi c}
\]
Where \( c \) is the electrostatic capacitance of the electrode combined with its image above the surface of the earth. This relation is applicable to any shape of electrode.

### 2.7 Resistance of Driven Rods

The driven rod is one of the simplest and most economical forms of electrode. Its ground resistance can be calculated if its shape is approximated to that of an ellipsoid of revolution having a major axis equal to twice the rod’s length and a minor axis equal to its diameter \( d \); then
\[
R = \frac{\rho}{2\pi l} \ln \frac{4l}{d}
\]
If the rod is taken as cylindrical with a hemispherical end, the analytical relation for $R$ takes the form

$$R = \frac{\rho}{2\pi l} \ln \frac{2l}{d}$$

If, however, the rod is assumed to be carrying current uniformly along its

$$R = \frac{\rho}{2\pi l} \left[ \ln \left( \frac{8l}{d} \right) - 1 \right]$$

Table 3 gives approximate formulas for the resistance of electrodes with various shapes.

The resistance of single rod is, in general, not sufficiently low, and it is necessary to use a number of rods connected in parallel. They should be driven as far apart as possible so as to minimize the overlap among their areas of influence. In practice, this is very difficult, so it becomes necessary to determine the net reduction in the total resistance by connecting rods in parallel. One of the approximate methods is to replace a rod by a hemispherical electrode having the same resistance.

The method assumes that each equivalent hemisphere carries the same change. Evaluating their average potential and total charge, the capacitance and hence the resistance of the system can be calculated.
Ground rod

\[
R = \frac{\rho}{2\pi l} \left[ \ln \left( \frac{8l}{d} \right) - 1 \right]
\]

Two ground rods

\[
R = \frac{\rho}{4\pi l} \left[ \ln \left( \frac{8l}{d} \right) - 1 \right] + \frac{\rho}{4\pi S} \left( 1 - \frac{l^2}{3S^2} \right)
\]

- \( S > l \)
- \( S < l \)

\[
R = \frac{\rho}{4\pi l} \left( \ln \left( \frac{32l^2}{dS} \right) - 2 + \frac{s}{2l} - \frac{S^2}{16l^2} \right)
\]

Horizontal strip

\[
R = \frac{\rho}{4\pi l} \left[ \ln \frac{8l^2}{an} + \frac{a^2 - \pi ab}{2(a+b)^2} - 1 + \frac{n}{l} - \frac{n^2}{4l^2} \right]
\]
<table>
<thead>
<tr>
<th>Diagram</th>
<th>Description</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Four-point star" /></td>
<td>Four-point star</td>
<td>$R = \frac{\rho}{8\pi l} \ln \frac{4l^2}{dn} + 2.9 - 2.14 \frac{n}{l} + 2.6 \frac{n^2}{l^2}$</td>
</tr>
<tr>
<td><img src="image2.png" alt="Six-point star" /></td>
<td>Six-point star</td>
<td>$R = \frac{\rho}{12\pi l} \left( \ln \frac{4l^2}{dn} + 6.85 - 6.26 \frac{n}{l} + 7 \frac{n^2}{l^2} \right)$</td>
</tr>
<tr>
<td><img src="image3.png" alt="Ring of wire" /></td>
<td>Ring of wire</td>
<td>$R = \frac{\rho}{2\pi^2 D} \ln \frac{16D^2}{dn}$</td>
</tr>
</tbody>
</table>
Horizontal round plate

\[ R = \frac{\rho}{4D} + \frac{\rho}{8\pi n} \left(1 - 0.036 \frac{D^2}{n^2}\right) \]

Vertical round plate

\[ R = \frac{\rho}{4D} + \frac{\rho}{8\pi n} \left(1 - 0.018 \frac{D^2}{n^2}\right) \]

Table 1 - Approximate formulas for Resistance of Various Electrodes
Chapter 3

SUBSTATION GROUNDING SYSTEM
SUBSTATION GROUNDING SYSTEM

3.1. PRINCIPLES OF DESIGN OF A SUBSTATION GROUNDING

The ground of a substation is very important, as it provides the ground connection for the system neutral, the discharge path for surge arresters, and ensures safety to operating personnel. It also provides a low-resistance path to ground to minimize the rise in ground potential.

The ground-potential rise depends on fault-current magnitude and the resistance of the grounding system.

Low-resistance substation grounds are difficult to obtain in desert and rocky areas. In such cases, the use of grids will provide the most convenient means of obtaining a suitable ground connection. Many utilities add ground rods for further reduction of the resistance. The size of the grid and the number and length of driven rods depend on the substation size, the nature of the soil, and the ground resistance desired.

The practical design of a grid requires inspection of the layout plan of equipment and structures. The grid system usually extends over the entire substation yard and sometimes several meters beyond. To equalize all ground potentials around the station, the various ground cables or buses in the yard and in the substation building should be bonded together by heavy multiple connections and tied into the main station ground.

It is also
necessary to adjust the total length of buried conductors, including cross connections and rods, to be at least equal to those required to keep local potential differences within acceptable limits.

Ground Conductor Size The ground conductor should have low impedance and should carry prospective fault currents without fusing or getting damaged, taking into account future expansion of the connected power system. The size of ground conductor is given by equation (1).

Conductor Length Required for Gradient Control Equation (2) gives the value of the mesh voltage; the value of the step voltage, \( E_{\text{step}} \), is given by the formula (Figure 3-1)

\[
E_{\text{step}} = K_s K_i \rho \frac{I}{L}
\]

where \( K_s \) is a coefficient that takes into account the effect of number, spacing \( S \), and depth \( h \) of burial of the ground conductors.

\[
K_s = \frac{1}{\pi} \left( \frac{1}{2h} + \frac{1}{S+h} + \frac{1}{2S} + \frac{1}{3S} + \ldots \right)
\]
The number of terms within the parentheses is equal to the number of parallel conductors in the basic grid, excluding cross-connections.

The tolerable step voltage with duration $t$, $E_{step}$, which is the voltage between any two points on the ground surface that can be touched simultaneously by the feet, is (IEEE, 1987)

$$E_{step} = \frac{165 + \rho_s}{\sqrt{t}}$$
Where $P_s$ is the resistivity of ground beneath the feet, in ohm-meters, taking its surface treatment into account.

The tolerable touch voltage, $E_{\text{touch}}$ which is the voltage between any point on the ground where a person may stand and any point that can be touched simultaneously by either hand, is

$$E_{\text{touch}} = \frac{165 + 0.25\rho_s}{\sqrt{t}}$$

Equating the value of $E_{\text{mesh}}$ to the maximum value of $E_{\text{touch}}$ yields.

$$\frac{K_m K_i \rho I}{L} = \frac{165 + 0.25\rho_s}{\sqrt{t}}$$

The approximate length of buried conductor required to keep voltage within safe limits is thus.

$$L = \frac{K_m K_i \rho I \sqrt{t}}{165 + 0.25\rho_s}$$

### 3.2. NEUTRAL GROUNDING

Grounding of the neutral points of generators, transformers, and transmission schemes is an important item in the design of power systems.
as it has a considerable bearing on the levels of transient and dynamic over voltages stressing the equipment insulation. It also directly affects the levels of short circuit currents in the power network and, accordingly, the ratings of switchgear needed to cope with them. The methods of system neutral grounding include resistance and low reactance for effective grounding. They also include tuned reactance, solid grounding, and grounding through a high-impedance such as that of a potential transformer ( ). Each of these methods has advantages and limitations. For example, with isolated or high-impedance grounding, excessive vervoltage appear on the system in the case of line-to-ground (L- G) faults. The "healthy" phases acquire transient overvoltages several times higher than the normal peak phase voltage. Also, some contingencies may develop Ferro resonance, causing high power-frequency overvoltages. In both cases, the equipment insulation, if not suitably designed, would be very vulnerable. Further, with the same method of neutral grounding, the magnitudes of fault currents would be so low that only special protective gear could detect them. This type of neutral grounding, however, is favored only in some LV and MV isolated networks where the need of supply continuity is extremely pressing and the equipment insulation is adequate. Neutral grounding through a reactor tuned to match the system capacitance C to ground (= 3wC) neutralizes the system 1 fault currents almost completely.
Thus the fault arc becomes unstable and easily gets extinguished. This method has been in common use in some high-voltage networks in Europe. It helps maintain the continuity of the supply without endangering the system insulation.

For resistance grounding, a resistance of a suitable design is connected between the system neutral point and the grounding electrode group as an addition to the system ground resistance. This technique is suitable for generators, as it helps to maintain their stability by the power consumed during L-G faults; otherwise, the generators might race out of step.

By grounding solidly or through a small reactance, the system overvoltages are limited to their possible minimum. On the other hand, the L-G short circuit currents will be excessive unless the grounding reactor is designed with a suitable magnitude.

Figure 0-2: Examples of power system neutral grounding.
3.3. GROUNDING OF LOW-VOLTAGE (LV) SYSTEMS

The different methods of grounding low voltage systems are:
1. Exposed conductive parts connected to neutral (TN)
2. Grounded neutral (TT)
3. Ungrounded neutral (IT)

The purpose of these three systems is to protect persons and property. They are not identical in dependability of the LV electrical installation with respect to electrical power availability and installation maintenance.

The LV grounding system characterizes the grounding mode of the secondary of the MY/LV transformer and the means of grounding the installation frames. Identification of the system types is thus defined by means of two letters:

- The first one for transformer neutral connection, T for neutral connected to ground and I for neutral isolated from ground (Figure 0-3-a).
- The second one for the type of application frame connection, T for directly connected to the ground and N for connection to the neutral at the origin of the installation, which is connected to the ground (Figure 0-3).

Combination of these letters gives three possible configurations: TT, TN, and IT.
Grounding Systems

Figure 0-3 Connection modes of the neutral of the installation and of the frames of the electrical loads.

The TN system includes several subsystems:

- **TN-C**: if the neutral conductor (N) and protective conductor (PE) are one and the same (PEN).
- **TN-S**: if the N and PE conductors are separate. The use of this system is compulsory for networks with conductors of a cross section less than or equal to 10 mm² Cu.
- **TN-C-S**: use of a TN-S downstream from a TN-C. The opposite is forbidden.

Each grounding system can be applied to an entire LV electrical installation. However, several grounding systems may be included in the same installation, as shown in
3.4. **GROUNDING OF GAS-INSULATED SUBSTATIONS**

The main difference between gas-insulated substations (GIS) and conventional substations is their metallic enclosures. Under faults, these enclosures carry induced currents of significant magnitude. These currents must be confined to specific paths.

**Figure 3-4**

**Figure 0-4 Example of the various grounding systems**
3.5. Grounding of Enclosures

The following requirements should be met to minimize the undesirable effects caused by circulating currents:

1. All metallic enclosures should normally operate at ground voltage level.
2. No significant voltage differences should exist between individual enclosure sections.
3. The supporting structures and any part of the grounding system must not be influenced by the flow of induced currents.
4. Precautions should be taken to prevent excessive currents being induced into adjacent frames and structures.
5. As GIS substations have limited space, reinforced-concrete foundations may cause irregularities in a current discharge path. The use of a simple monolithic slab reinforced by steel serves as an auxiliary grounding device. The reinforcing bars in the foundations can act as additional ground electrodes.
3.5.1. Touch Voltages for GIS

The enclosures of GIS should be properly designed and adequately grounded so as to limit the potential difference between individual sections within the allowable limit of 65-130V during faults (Sverak et al., 1982). The analysis of GIS grounding includes estimation of the permissible touch voltage. Dangerous touch and step voltages within the GIS area are drastically reduced by complete bonding and grounding of the GIS enclosures, and by using grounded conductive platforms connected to the GIS structures.

3.5.2. Transient Impedance of GIS Grounding Grid

The transient impedance of a grounding grid for a commercial 550 kV GIS was measured on site using steep front currents with rise time from 100. From the measured results, it was found that the transient impedance of the grid for those currents is simulated by a series circuit with an inductance and a resistance of 10.1H and 3 n respectively. Over voltages in the GIS due to lightning surges was analyzed using this grounding impedance. It was noticed that:

- The radius of the grid area in which the grounding potential is raised by the injected steep current is very small (1.5 m).
- The grounding impedance of the GIS enclosure can be simulated by attaching the grounding impedance obtained to each grounding point of the GIS enclosure.
• The influence of the grounding impedance connected to the bushing enclosure and the gas circuit breaker enclosure is negligible.

• The isolation of an arrester enclosure end and the grounding impedance of the surge arrester reduce the protecting performance of the surge arrester in the same manner.

3.6. Transmission-line tower grounding

To design and operate a transmission system with a low-outage rating and safety to the maintenance personnel as well as the public, it is necessary to have a suitable grounding system. This can be furnished by overhead ground wires, counterpoises, and by earthling tower bodies and foundations. The degree to which low tower footing resistance can be met depends on local soil conditions. The method used to reduce the equivalent footing resistance and the degree to which this is carried out is a matter of economics. Experience indicates that some means of reducing the footing resistance to an equivalent of 10 n, as measured with the ground wires removed, is more economical than adding extra insulation. Unfortunately, improved grounding cannot be economically effective in the event of direct lightning strokes to phase conductors. The importance of having low tower footing resistance in this case is in avoiding a high rate of back flashovers and thereby improving the conditions for successful fault suppression by ground-fault neutralizers. Ground wires are so located as to shield the line conductors adequately from direct
lightning strokes. Their design is discussed in detail elsewhere. With underground cables the situation is different.

3.7. Safety ground

Safety ground is meant to ensure that persons working with electrical equipment will not be exposed to the danger of electric shocks. Safety of operating personnel requires grounding of all exposed metal parts of power equipment. There is no simple relation between the resistance of the ground system as a whole and the maximum shock current to which a person might be exposed. Thus a low station ground resistance is not in itself a guarantee of safety.

3.8. Range of Tolerable Currents

The effects of an electric current passing through the vital parts of a human body depend on its duration, magnitude, and frequency. Human beings are most vulnerable to currents with frequencies of 50-60Hz. The human body can tolerate slightly larger currents at 5Hz and approximately five times larger direct currents and still larger currents at 3-10 kHz. Currents of 1-6 mA, often termed "let-go currents," although unpleasant to sustain, do not impair a person's ability to control his or her muscles. Currents of 9-25 mA may be quite painful and can make it hard to release energized objects grasped by the hand. For still higher currents, uncontrollable muscular contractions can make breathing difficult.
range of 100 mA ventricular fibrillation, stoppage of the heart, or inhibition of respiration may occur and cause severe injury or death.

To avoid danger from electric shock, one's body should under no circumstances be a part of an electric circuit. There are several means of reducing the hazard of electric shock, including grounding, isolation, guarding, insulation and double insulation, shock limitation, isolation transformers, and employing high-frequency and direct current. The first four methods are normally adopted in high-voltage systems.

3.9. Tolerable Step, Touch, and Transferred Voltages

Using the magnitude of the tolerable body current and the appropriate circuit constants, it is possible to calculate the tolerable potential difference between possible points of contact. The step voltage increases as the closer one gets to the site of a ground fault or to the grounding point. If the enclosure of grounded equipment in which an earth fault has occurred is touched by a person, he or she will be subjected to a potential termed a "touch voltage"

When a person standing within the station area touches a conductor grounded at a remote point, or when a person standing at a remote point touches a conductor connected to the station ground grid, he or she is subjected to a transferred potential. The shock voltage in this case may be equal to the full voltage rise of the ground grid under fault conditions.
The tolerable step and touch voltages with duration’s $t$ for persons weighing 50-70 kg can be estimated as
Step and touch voltages

\[ E_{\text{step}} = [1000 + 6C(\rho_s)] \frac{0.116}{\sqrt{t}} \]

\[ E_{\text{touch}} = [1000 + 1.5C(\rho_s)] \frac{0.16}{\sqrt{t}} \]
3.9.1. Electric Shock Hazard in Hospitals

Increased application of electric instrumentation has greatly increased the risk of electric shock, especially when a patient in a hospital is actually connected into the circuit. The hazard increases when probes or needles are inserted into the body. Sometimes these are placed directly on or inside a heart chamber. Some medical authorities believe that a current as small as 20 ma at 50-60Hz applied directly to the heart can produce ventricular fibrillation. The hazard is increased if pacemakers are used.

3.10. Methods of Decreasing Ground Resistance

Decreasing the ground resistance of a grounding system in high-resistivity soil is often a formidable task. Recently, some new methods have been proposed to decrease ground resistance. Three methods are listed in the following section.
3.11. Cracks with Low-Resistivity Materials (LRM)

This method requires 3 steps: drilling deep holes in the ground, developing cracks in the soil by means of explosions in the holes, filling the holes with lower sensitivity materials (LRM) under pressure. Most of the cracks around the vertical conductors will be filled with LRM, and a complex network of low-resistivity tree-like cracks linked to the substation grid is formed. Field tests show that the optimum span between vertical conductors is in the range of 1.5-2 times the length of the vertical conductor. This method is effective in reducing ground resistances in rocky areas.

3.11.1. Chemical Rods

Chemical rods

Figure 0-5 are electrodes with holes along their length, filled with mineral salts. The specially formulated mineral salts are evenly distributed along the entire length of the electrode.

The rod absorbs moisture from both air and soil. Continuous conditioning of a large area insures an ultra-low-resistance ground which is more effective than a conventional electrode. If the conductive salts are running low, the rod can be recharged with a refill kit. These rods are available in vertical and horizontal configurations. They may be used in rocky soils, freezing climates, dry deserts, or tropical rain forests. They provide stable protection for many years.
Figure 0-5 Chemical Rods
3.11.2. Grounding Augmentation Fill (GAF)

About 95% of the grounding resistance of a given electrode is determined by the character of the soil within a hemisphere whose radius is 1.1 times the length of the rod. It is obvious that replacing all or part of that soil with a highly conductive backfill will facilitate the achievement of a low-resistance ground connection. The greater the percentage of soil replaced, the lower the ultimate grounding resistance.

3.11.3. Cracks with Low Resistivity Materials (LRM)

- This method requires 3 steps:
  - Drilling deep holes in the ground, developing cracks in the soil by means of explosions in the holes, filling the holes with low resistivity materials (LRM) under pressure.
  - Most of the cracks around the vertical conductors will be filled with LRM, and a complex network of low resistivity tree-like cracks linked to the substation grid is formed.
  - Field tests show that the optimum span between vertical conductors is in the range of 1.5-2 times the length of the vertical conductor.
- This method is effective in reducing ground resistances in rocky areas.
- Soil Treatment Alternatives
  - Ground enhancement material
  - Cement-like compound
  - Non-corrosive
  - Extremely conductive
- Installed around the electrode
- Easy installation
- Permanent

Figure 0-6 Grounding system with explosion and intrinsic cracks
Chapter 4

Experimental setup
Experimental setup

4.1. Introduction

Electrical installations require grounding systems, whose geometry may also depend on the footprint of buildings or substations they serve. In most industrial cases, grounding systems consist of grids integrated with rods at each corner. In many cases, if available, non-insulated reinforcing bars in concrete foundations may also serve as vertical ground electrodes.

This complex geometry of the grounding system cannot be exclusively studied analytically. This paper will show a semi analytical method for grounding grids, which uses numerical calculation to solve the set of equations necessary to determine the most significant parameters of grounding grids, such as the ground-resistance, the ground potentials along the soil and the distribution of the ground-fault current along the grid's components (i.e. horizontal wires and rods).
4.2. Experimental layout

The dimensions of the electrolytic tank used for the experiments are 1.70 m x 1.00 m x 1.10 m. The inner surface of the tank is covered by a conducting sheath. Tap water has been used as the electrolyte which serves as an adequately conducting medium and represents homogenous earth. The model grid was supported below the surface of the electrolyte under tension so as to provide a horizontal configuration with the minimum distortion and sag. Nylon fish lines were attached to the grid, at different locations, to maintain the regular shape of the grid. To take measurements, a probe consisting of a copper wire inserted in a plastic tube, for mechanical support, was used. Only the tip of the wire was touching the surface of the water. The probe was supported on a 'T'-shaped wooden frame which rested
on the edges of the tank and could be moved across the surface of the electrolyte at a constant depth in a straight line in any direction over any part of the grid. Scales mounted along the tank edges permitted accurate positioning of the grid and probe.

The experimental layout is shown in Fig. 4-1. An alternating current is used to avoid polarization. The applied voltage to the model is obtained from a 220 AC source through DC power supply.

The magnitude of this voltage is kept constant. During the different tests, by measuring the voltage applied to the model and the current flowing through the electrolyte between the model grid and the return electrode, the effective grid resistance can be obtained. The potential of the test probe with respect to the return electrode is monitored by a voltmeter of a very high internal resistance.
Figure 0-1: photo for Experimental layout
4.3. Touch voltage calculation

\[ E_{touch} = \frac{V_{grid} - V_{min}}{V_{grid}} \times 100 \]
4.4. Electric resistivity Measurement by 4 electrode method

Method of four-electrode probe has been used in soil practices since 1931 for evaluating soil water content and salinity under field conditions (McCorkle, 1931; Edlefsen and Anderson, 1941; Rhoades and Ingvalson, 1971). Halvorson and Rhoades (1976) applied a four-electrode probe in the Wenner configuration to locate saline seeps on croplands in USA and Canada. Austin and Rhoades (1979) developed and introduced a compact four-electrode salinity sensor into routine agricultural practices. A special soil salinity probe, which utilized the same four-electrode principle, was also designed for bore-hole measurements and/or for permanent installations in soils for infiltration and salinity monitoring (Rhoades and Schilfgaarde, 1976; Rhoades, 1979). An electrical cell used to measure electrical conductivity of soil samples, pastes, and suspensions, was also developed based on four-electrode principle (Gupta and Hanks, 1972).

The advantages of electrical conductivity measurements for evaluation of soil salinity led to development of soil salinity classifications using electrical conductivities of soil pastes and suspensions (Richards et al., 1956). Relationships between electrical conductivity measured in-situ with four-electrode probe and conductivity of soil solution or saturated soil paste were developed (Nadler, 1982; Rhoades et al., 1989).
The method of four-electrode probe was also used for evaluation of some other soil properties, such as soil water content (Edlefsen and Anderson, 1941; Kirkham and Taylor, 1949); structure (Nadler, 1991); bulk density, porosity, and texture.

$$\rho_E = \frac{4 \cdot \pi \cdot a \cdot R_W}{1 + \frac{2 \cdot a}{\sqrt{a^2 + 4 \cdot b^2}} - \frac{a}{\sqrt{a^2 + b^2}}}$$

$\rho_E$ = measured apparent soil resistivity (Ωm)
$a$ = electrode spacing (m)
$b$ = depth of the electrodes (m)
$R_W$ = Wenner resistance measured as "V/I"
Figure 0-3: Electric resistivity Measurement
4.5. Test procedures

The grid was first installed and adjusted to the proper depth. The grid was then energised and the voltages and currents were monitored and the grid resistance could be obtained. The probe carriage was aligned over the centre line of the grid. The potential values were recorded at intervals of 2 cm starting from the grid center and ending at approximately 10 cm outside the grid. The positions considered over the area of one quarter of a grid, due to symmetry. The type of mesh are chosen and tested at two different deep Figure 0-4.

Figure 0-4: Mesh type
Chapter 5

Results And Discussion
Results And Discussion

5.1. Effect of grid number

For all grids tested, the applied voltage and current were recorded in addition to the surface potential profiles. The potential profiles were recorded along lines parallel to the side of the grid, and along lines parallel to the diagonal of the grid. The profiles are designated by the distance of that profile from the centre line profile or from the diagonal profile. The location of the profiles was chosen such that maximum and minimum potentials throughout the grid could be determined.
Figure 0-1 Normal profiles of surface potential for 2x2 Mesh with 2 cm depth
The maximum mesh potential is found at the point within the grid boundary where the surface potential is lowest. The mesh potential is then the potential between this point and the grid; it is in fact the touch potential, $E_{touch}$, which would be experienced by a person standing at this point and touching some apparatus connected to the grid. It is generally found in the corner mesh at a point in the center of the mesh.
Figure 0-3 Normal profiles of surface potential for 3x3 Mesh with 1 cm depth lower part
5.2. Effect of grid depth

Figure 0-4 Normal profiles of surface potential for 2x2 Mesh with 1 cm depth
Figure 0-5 Normal profiles of surface potential for 2x2 Mesh with 1 cm depth
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Conclusions

- The resistance of the grid decreases with increasing the number of meshes
- The grid resistance, mesh and step potentials are decreased with increasing the burial depth of grid

Future work

1- Study of the effect with increasing wire diameter.

2- Effect of adding wire rod to the grid.
Reference:

6. Ershевич VV, Крившшин LF, Неклепаев BN, Шеймович VD, Славин GA. CIGRE
In the first We thanks Allah. Our sincere thanks go to Dr. Ghareeb Moustafa, for his guidance, suggestion, continuous encouragement during the progress of this project. Also, we are thanks Dr. Mohammed Al. Shimi for his, advice, assistance and enormous patience throughout this work. Moreover, my thanks go to the staff of the electrical department for their support over the past years.