CHAPTER 2

BASICS OF GROUNDING AND GROUNDING DESIGN

It is essential to understand the meaning and objective of the grounding system in the power system. The effectiveness of design of grounding system is directly related to the understanding of the subject. Similarly the concept of Ground Potential Rise (GPR) and different dangerous potential of the substation are to be understood before moving towards the designing concept of grounding system.

Besides above differences between grounding system of GIS and AIS need to be understood.

2.1 **Grounding**: Grounding means providing an electrical or conductive connection to the mass of earth. The use of grounding is necessary for all parts of power system i.e. generation, transmission and distribution system. [1-5].

There are two types grounding:

(a) Neutral Grounding

(b) General Grounding

The Objectives of Neutral Grounding are:

(1) To reduce the voltage stresses due to switching and lightning surges.

(2) To control the fault currents to satisfactory values.

The objectives of General Grounding system include [1-5] :

1. To provide a low resistance return path for fault current which further protects both working staff and equipment installed in the substation.

2. To prevent dangerous GPR with respect to remote ground during fault condition.

3. To provide a low resistance path for power system transients such as lightning and over voltages in the system.

4. To provide uniform potential bonding / zone of conductive objects within substation to the grounding system to avoid development of any dangerous potential between objects (and earth).

5. To prevent building up of electrostatic charge and discharge within the substation, which may results in sparks.

6. To allow sufficient current to flow safely for satisfactory operation of protection system.

Earlier, the design motive was to get minimum value of earth resistance of grounding mat of substation. However, the modern design practices also focus on the importance of control of step and touch potential within allowable limits. The designing of grounding system depends on the soil resistivity model chosen for the substation soil & the design of grounding system may become inaccurate if average value of resistivity measured is taken in the design calculation especially when the variation of resistivity of different probe distance is more than 25 %. It is advisable to use two layer soil models in such cases [1, 2, 3].

The pictures of Gas Insulated and Air Insulated Substation are shown in figure 2.1 figure 2.2 respectively.

Fig 2.1 High Voltage Gas Insulated Substation

Fig 2.2 Air Insulated Substation and Switchyard with Gravel Surface

2.2 Accidental Ground Current

For dc and 50Hz ac the current path is usually assumed from one hand of human being to both feet and current path between the feet. The value of internal resistance of the human body for the design purpose is considered between 500 Ω to 3000 Ω as recommended in many research [1-3].

The assumptions with respect to the resistances which appear in series with circuit made by the resistances of various parts of human body are given below:

1. Contact resistances of hands and feet are considered to be negligible.

2. Resistances of Gloves and shoes are taken as negligible.

As mentioned 1000 Ω may be considered as the resistance of a human body between hand and feet and also between two hands, or between the feet of human being, is used for designing purpose i.e. $R_B = 1000\ \Omega$.

It is pertinent to mention here that current flowing between feet is far less fatal than hand-to-foot currents. It has been revealed that to get the same impact the ratio of above mentioned currents is as high as 25:1.

However, the following facts may be taken care of:

1. A potential appearing between the two feet might result in a fall of human being on the ground which may cause flow of high current through the heart area. The intensity of fatalness depends on the duration of fault and the possibility of another successive fault current through body especially during auto reclosing of the circuit.

2. Working staff might be doing maintenance work or resting in a position which is prone to fatal current through heart portion during fault.

2.3 Equivalent Circuit for Accident in Substation

Using the above value of body resistance, the tolerable potential which may appear between any two points of contact within substation can be determined [1].

The parameters which are used shown in figure 2.3 are given below:

I_b = the body current in ampere

R_B = the body resistance in Ω

U = the effective potential in volt

I_f = the fault current in ampere

I_g = the grid current in ampere

R_g = the grid resistance in Ω

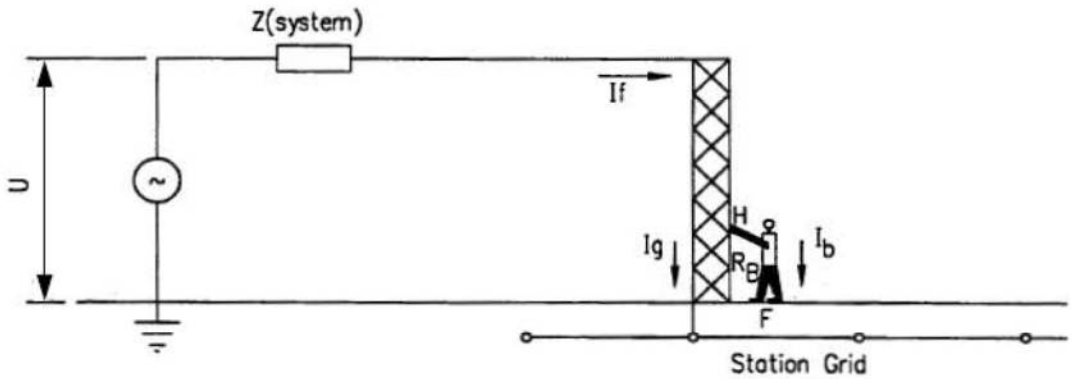

Fig 2.3 Flow of Current through the Body of Working Staff during Fault

Fig. 2.3 depicts that the situation of discharging the fault current I_f to the station grid and at the same time one of the working staff is touching a metallic structure at point H in the substation. Terminal H is at the same potential as the ground grid and terminal F in the circuit is the small area on the surface of the substation that comes in contact with the person's two feet. Thevenin theorem helps us to give simple network of terminals (H,F) of figure 2.3 as shown in figure 2.4.

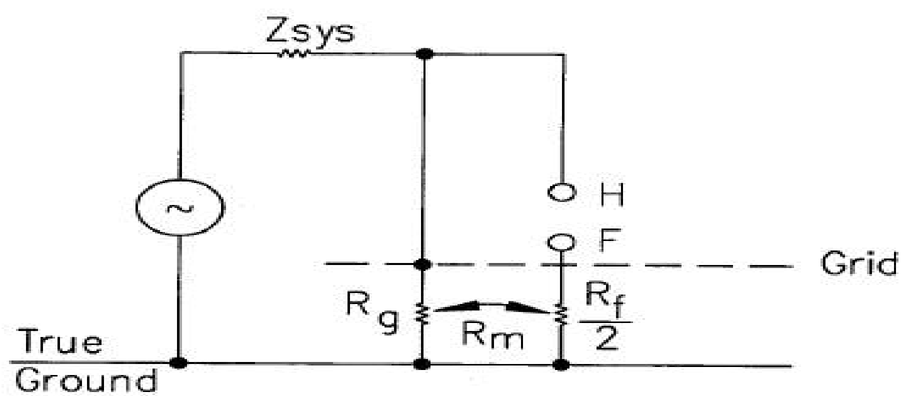

Fig 2.4 Different Resistances of Circuit for Touch Voltage

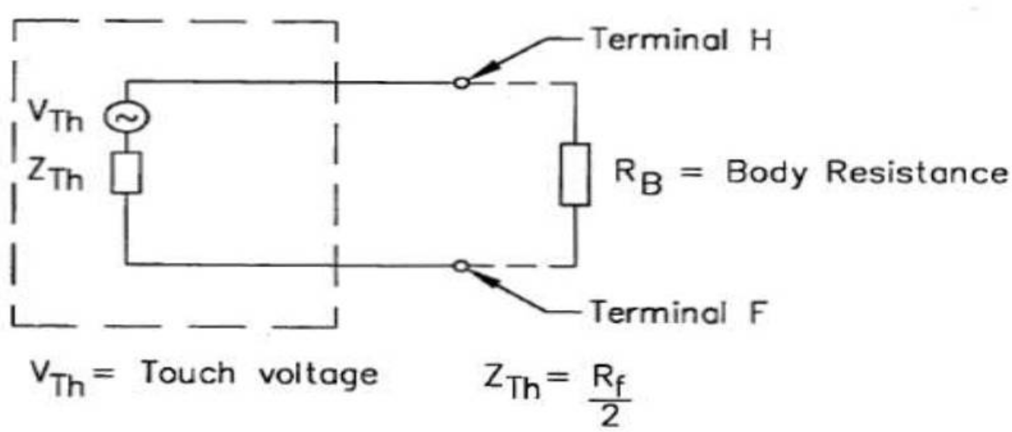

Figure 2.5 Thevenin Equivalent for Touch Voltage

The Thevenin voltage V_{Th} in the above figure 2.5 is the potential between two contact points H and F when the working staff has been removed from the circuit. The Thevenin impedance Z_{Th} in the circuit is the impedance of the system measured between terminals H and F with short circuiting of potential sources of the network as shown above. The current I_b, which flows through the body of working staff as shown in figure 2.3 is given by [1] :

$$I_b = \frac{V_{Th}}{Z_{Th}+R_B} \quad \textbf{(2.1)}$$

With the help of this circuit, touch voltage appearing between hand of the person and the feet may be calculated as per equation 2.2 [1] below:

$$Z_{Th} = \frac{R_f}{2} \quad \textbf{(2.2)}$$

Figure 2.6 depicts the flow of the fault current I_f to the grounding grid of the substation & Thevenin Equivalent for the step potential calculation as shown in figure 2.7.

With the help of this circuit, step voltage appearing between feet of a person may be calculated as per equation 2.3 [1] below:

$$Z_{Th} = 2R_f \quad \textbf{(2.3)}$$

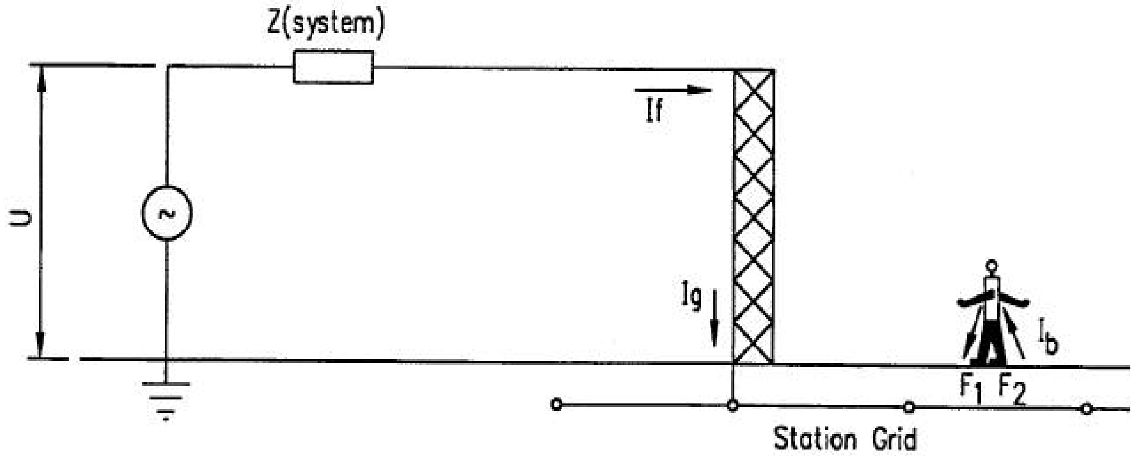

Fig 2.6 Different Resistances of Circuit for Step Voltage

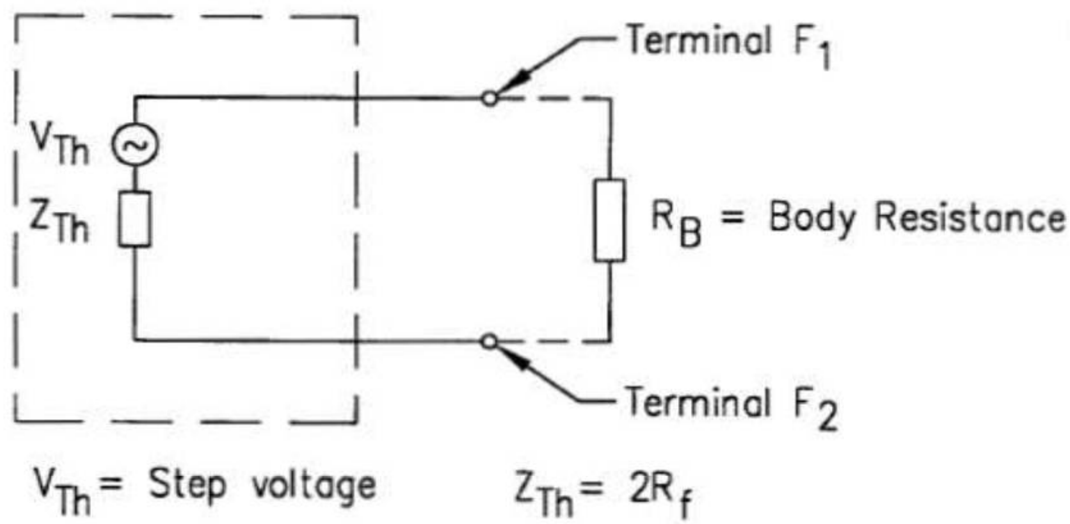

Fig 2.7 Thevenin Equivalent for Step Voltage

For making the analysis easy, the human foot may be assumed as a conducting metallic plate having a radius of 0.08m [1]. The contact resistance of shoes, socks, etc., is not taken into account and usually neglected. With small approximation, equations for Z_{Th} can be re written as follows:

$$R_f = \frac{\rho}{4b} \qquad \textbf{(2.4)}$$

Where ρ = Resistivity of the soil

For touch voltage calculation

$Z_{Th}= 1.5\rho$ **(2.5)**

For step voltage calculation

$Z_{Th}= 6.0\ \rho$ **(2.6)**

The tolerable total equivalent voltages are given by:

$E_{touch} = I_b\ (R_B+1.5\rho)$ **(2.7)**

$E_{step} = I_b\ (R_B+6.0\rho)$ **(2.8)**

The equations 2.7 and 2.8 shall be changed into equation 2.9 & 2.10 and 2.11 & 2.12 respectively if we are using surface material with resistivity ρ_s.

The maximum tolerable voltages for step and touch situations which may appear in the substation can be calculated as per IEEE 80.

1. 50kg person:

$$E_{touch,50} = (1000 + 1.5C_s\rho_s) \times \frac{0.116}{\sqrt{t_s}} \quad \textbf{(2.9)}$$

2 70kg person:

$$E_{touch,70} = (1000 + 1.5C_s\rho_s) \times \frac{0.157}{\sqrt{t_s}} \quad \textbf{(2.10)}$$

3 50kg person:

$$E_{step,50} = (1000 + 6C_s\rho_s) \times \frac{0.116}{\sqrt{t_s}} \quad \textbf{(2.11)}$$

4 70kg person:

$$E_{touch,70} = (1000 + 6C_s\rho_s) \times \frac{0.157}{\sqrt{t_s}} \quad \textbf{(2.12)}$$

Where

E_{touch} is the permissible touch potential (V)

E_{step} is the permissible step potential (V)

Cs is the derating factor for resistivity of gravel or other material ρ_s is the resistivity of the soil (Ω-m) t_f is the maximum time taken by relays for complete isolation of system (s).

This derating factor can be calculated by Equation 2.13 given below [1]:

$$C_s = 1 - \frac{0.09\left(1 - \frac{\rho}{\rho_s}\right)}{2h_s + 0.09} \qquad \textbf{(2.13)}$$

ρ is the resistivity of soil of substation

h_s is the height of the surface layer of grounding grid (m)

2.4. Concept of GPR and Dangerous Voltages in Substation

Ground potential rise (GPR) is a matter of great concern and it is one of the important factor for design of grounding system. When heavy fault current flows to ground it results in the Potential gradient in the substation i.e. the potential difference is highest at the point where the fault current enters the ground, and declines gradually with increase in the distance from the point of discharge of current in the ground.[1-5].

The change of voltage with change in distance may create a potential difference between two points so that a person could get a shock due to step or touch potential as explained earlier. Any metallic part connected to the substation ground grid, such as control and metering cables, rails, fences, or metallic conduits, may also be energized at the some high potential in the substation which itself may be fatal to people working outside the substation.

Many factors which are responsible for the level of shock in the human body include fault current, soil resistivity, moisture content in the soil, ambient temperature and shock duration.

At points away from the grounding electrode or grounding mat, the potential rise decreases. The voltage profile as shown in figure 2.8 around the electrode or grounding grid is given by the following equation:

$$V_r = \frac{\rho I}{2\pi r_x} \quad \textbf{(2.14)}$$

where

r_x = a point from the center of the electrode or ground grid (meters).

V_r = the voltage at distance from the ground grid or electrode (volts)

ρ= the resistivity of substation soil (Ω·m).

I = fault current (amperes)

This case is a simplified system of power system whereas actual grounding systems are more complex than a single electrode system as different soil models may affect the impact of shock or hazard.

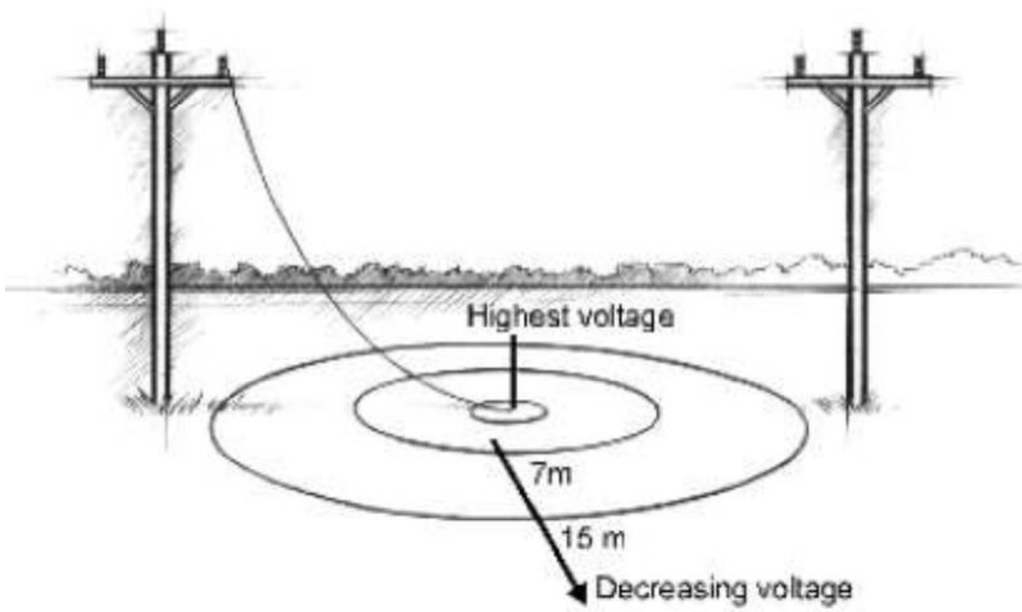

Fig 2.8 Concept of Voltage Gradient

The six dangerous voltages which are being faced in the substation [1] are depicted in figure 2.9 :

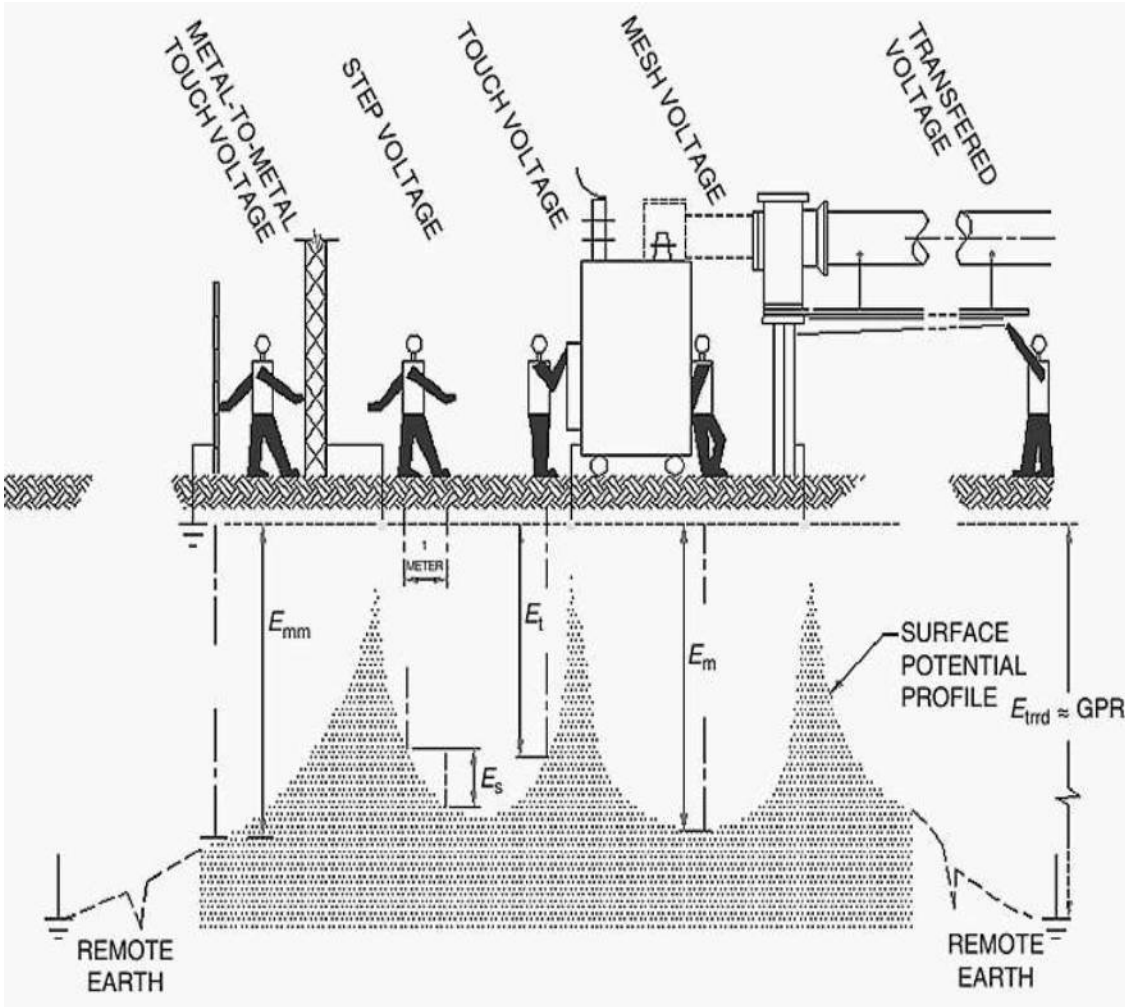

Fig 2.9 Six Dangerous Voltages in Substation

2.5 Fault Current and Maximum Grid Current

To design grounding system of any substation difference between fault current and maximum grid current to be understood. The maximum grid current may be defined as the worst case wherein maximum earth fault current would flow via the grounding grid back to source, known as I_F. This is explained by the figure 2.10 shown below.

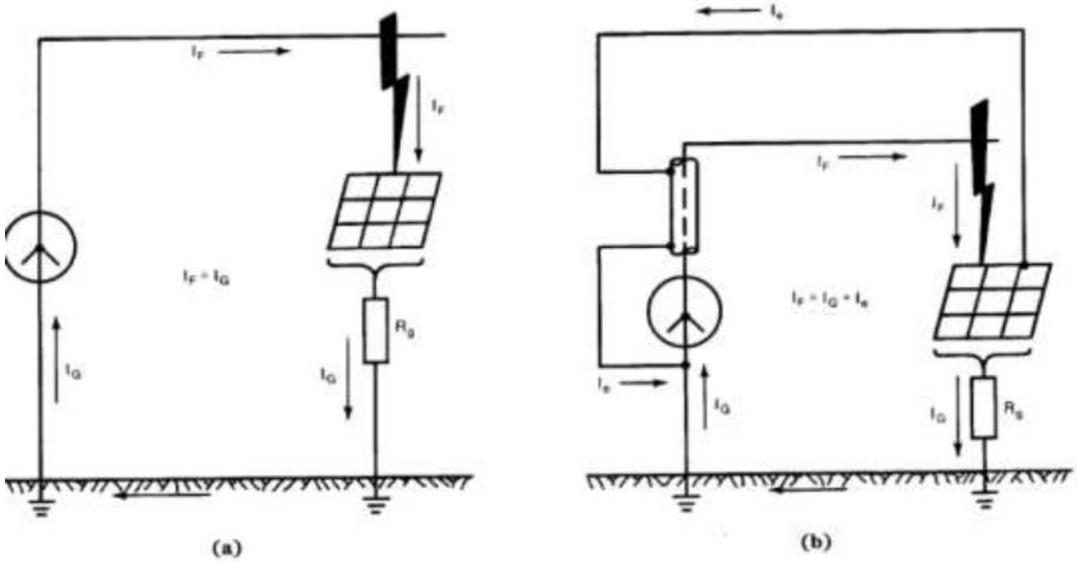

Fig 2.10 Fault Current and Max Grid Current in Substation

(A) Current Division Factor

As mentioned above the earth fault current may or may not flow back to the source through substation grounding grid. A portion of the earth fault current may flow back to the source via overhead earth conductor, buried metallic pipes or cables sheath. Therefore a current split factor S_f need to be taken into account for this return path to the source [1-5]. To make the design conservative a current division factor of $S_{f=}$ 1 is usually used in the designing of grounding grid of substation.

The symmetrical grid current I_g is given by:

$$Ig=I_F S_f \qquad \textbf{(2.15)}$$

(B) Decrement Factor (D_f)

Due to asymmetry of fault current there is dc current present in the circuit during short circuit condition. This decrement factor is calculated by equation 2.16 given below [1].

$$D_f = \sqrt{1 + \frac{T_a}{t_f}\left(1 - e^{\frac{-2t_f}{T_a}}\right)} \qquad \textbf{(2.16)}$$

Where,

D_f = decrement factor

t_f = duration of the ground fault (s)

T_a = constant for dc offset

$T_a = (X/R)(1/2\pi f)$

Where X/R is the reactance to resistance ratio of the substation or network

f= network frequency (Hz)

Also, the table given in IEEE -80 may be used [1] to find D_f .

TABLE 2.1 X/R OF NETWORK AND DECREMENT FACTOR

FAULT DURATION, t_f		DECREMENT FACTOR, D_f			
Seconds	Cycles at 60 Hz	X/R=10	X/R=20	X/R=30	X/R=40
0.0083	0.5	1.576	1.648	1.675	1.688
0.05	3	1.232	1.378	1.462	1.515
0.10	6	1.125	1.232	1.316	1.378
0.20	12	1.064	1.125	1.181	1.232
0.30	18	1.043	1.085	1.125	1.163
0.40	24	1.033	1.064	1.095	1.125
0.50	30	1.026	1.052	1.077	1.101
0.75	45	1.018	1.036	1.052	1.068
1.00	60	1.013	1.026	1.039	1.052

The maximum value of grid current I_G is finally given by equation 2.17 shown below [1]:

$$I_G = I_g D_f \qquad \textbf{(2.17)}$$

The maximum value of GPR is given by [1] equation 2.18.

$$GPR = I_G R_g \qquad \textbf{(2.18)}$$

Where,

GPR= the ground potential rise (V)

I_G = maximum value of grid current of substation

R_g = the resistance measured or calculated for grounding grid.

2.6 Step Potential and Touch Potential

During an earth-fault in the substation the earth fault current flows from the fault-point to earth via the metallic path having certain total resistance R. This flow of fault current (I_f) flowing through resistance R causes a voltage drop V = I_fR. This voltage drop results in a voltage-gradient along the substation floor during the earth faults. This voltage gradient should be held in safe limits by proper design of station Grounding system.[1-5]

An operation maintenance person is subjected to 'step potential' and 'Touch Potential' during an earth-fault in the substation as shown in figure 2.11 below.

The Step Potential and touch Potential depend upon the following aspects:

1. Earth fault current, I_f
2. Duration of earth fault, t_f
3. Fault current flowing through body, I_b
4. Values of body resistances, R_b

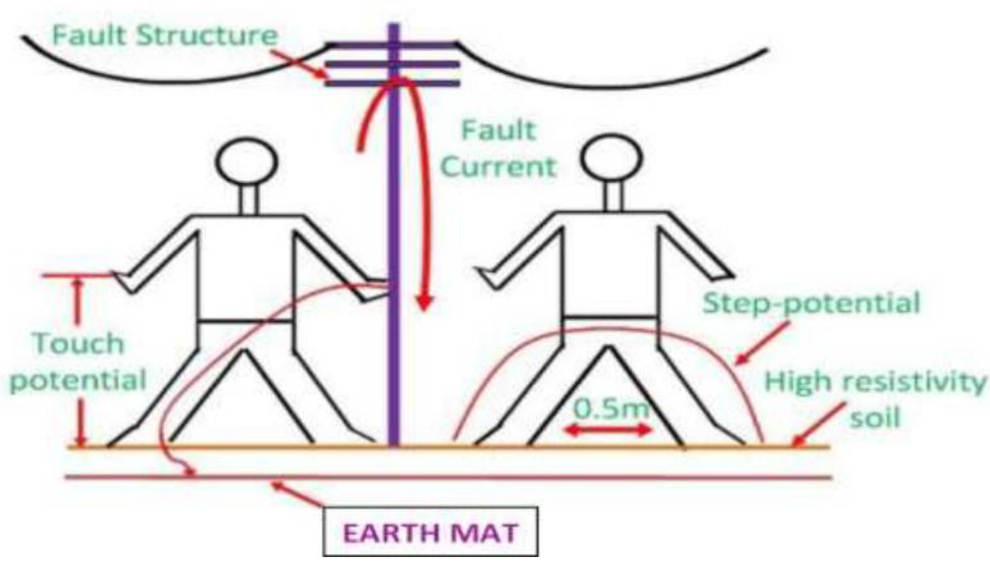

Fig 2.11 Touch Potential and Step Potential

Besides above touch potential, in case of GIS, may be felt between metals of GIS structure i.e. between the two points within the same structure or between two structures as shown in figure 2.12

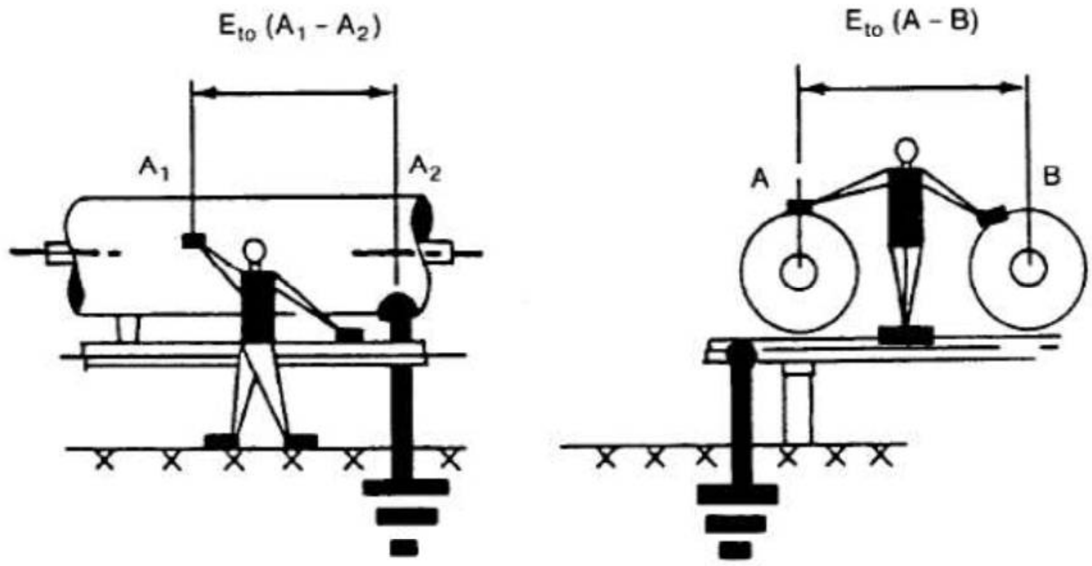

Fig 2.12 Possible Touch Potential in Case of GIS

The step and touch potentials with and without potential gradient control are shown in the figure 2.13 and actual grounding of GIS in the field is shown in figure 2.14 below.

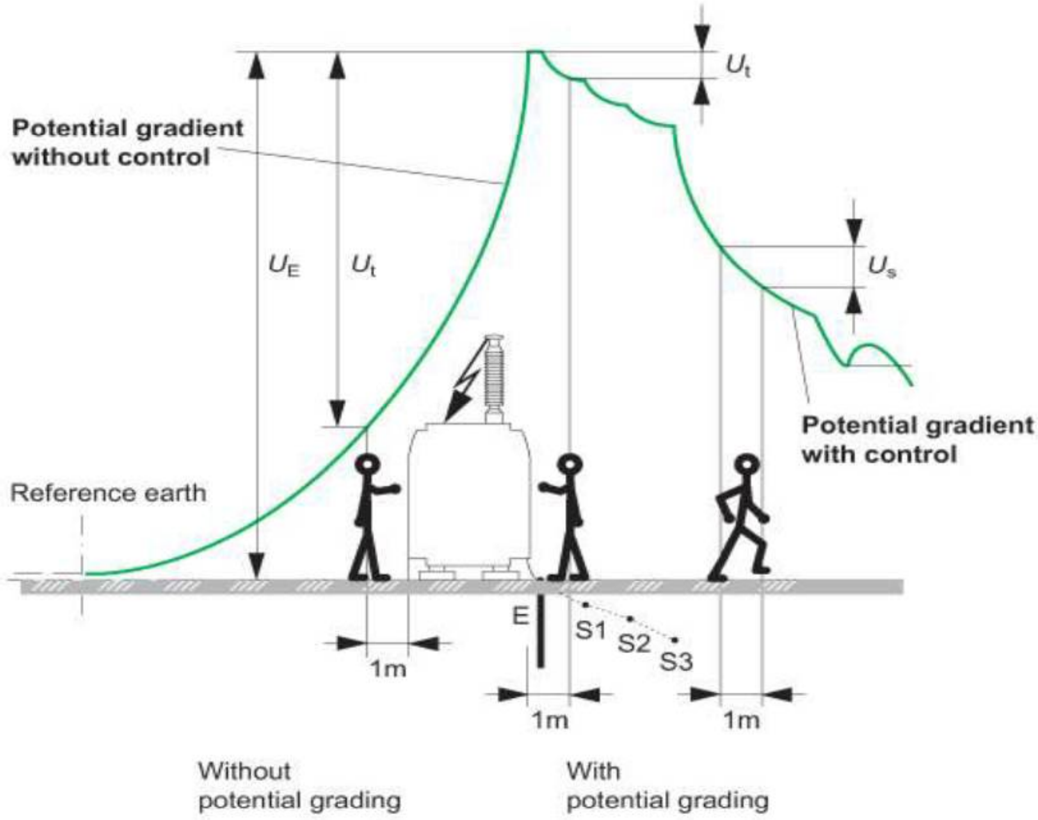

Fig 2.13 Potential Grading for Step and Touch Potential

Fig 2.14 Actual Grounding of GIS

2.7 Different Parts of Grounding System

A typical grounding system [3,4,5] for a substation consists of the followings:

(a) A ground mat (grid) formed by mild steel bars buried in the ground at a depth of about 0.65 meter in a horizontal plane as shown figure 2.15 below . The crossings are welded as shown. The grid covers the entire substation area and sometimes a few meters beyond the fencing of the substation area.

(b) Electrodes driven vertically into the ground at several locations. These electrodes are joined or welded to the ground mat.

(c) Grounding risers are used for making interconnection between the equipment structures or bodies and the grounding grid. These are usually clamped or welded or brazed.

(d) Grounding strips for the transformer neutrals, equipment bonding.

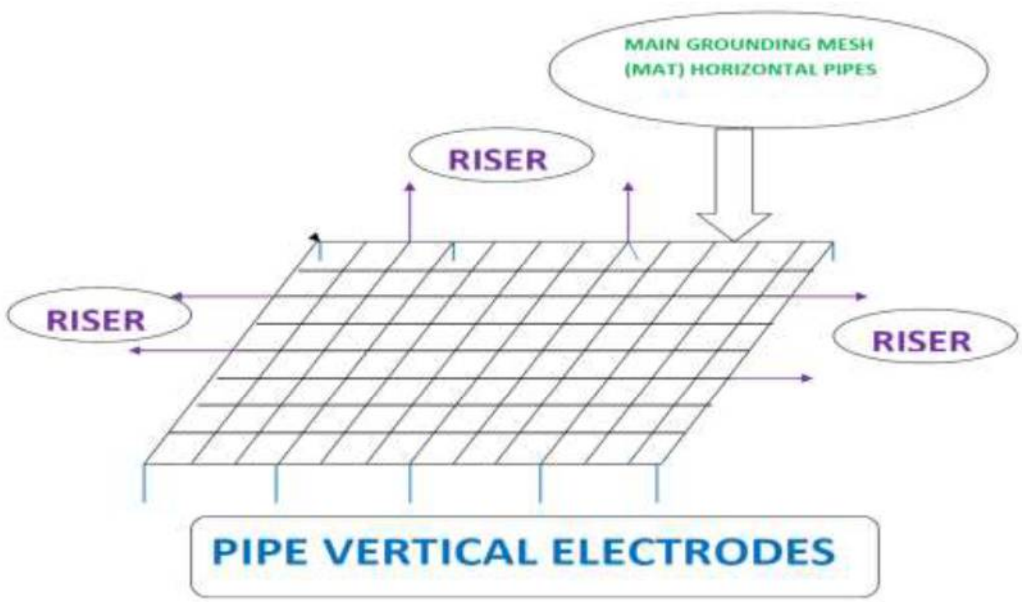

Fig 2.15 Grounding Mat of the Substation

2.8 Need of the GIS

The demand for electrical energy are increasing day by day and problem faced by utilities to find space for commissioning of new substation forcing them to explore the new technology. Gas Insulated Substations (GIS) may cater the need of growing demand of electrical energy with minimum requirement of space and high degree of reliability of supply. Presently GIS of up to 800 kV have been developed and are being widely used [2,3].

GIS have many economic advantages such as a minimum space requirement of only 10% of the space required by a conventional station. GIS have no risk of fire or explosion or contamination due to leakage of oil. They generate no noise and have no radio interference. They offer a very high degree of operational reliability and are easy to maintain in view of the above advantages. It has been found that GIS offer the most economic solutions for the following:

1. An urban and industrial area where space is a constraint and pollution is a problem.

2. Mountainous areas where site preparation, attitude, show and ice are major problems.

3. Coastal areas where pollution problems associated with salt are unavoidable.

4. Underground substations are preferred where the cost of preparing the site for the substation is very high.

5. Areas where aesthetics is a major concern like landscaping and mobile substations for use in mines etc.

Fig 2.16 Actual View of GIS Substation

GIS grounding needs a special care compared to AIS grounding, understanding of the system requirement in totality and specific interface requirement with GIS needs to be taken care by power engineer for correct functioning of the switchgear. Power frequency grounding requirement in AIS and GIS are not different, however a special care with touch voltage requirement may be suitably accessed. High frequency transient requirements are taken care by proper interfacing & following manufacturer's recommendations. These transients may results in the ground potential rises of very small duration and very high magnitude and these further becomes the reason of development of electromagnetic interference (EMI) in the GIS. Actual view of GIS substation is shown in figure 2.16 above.

2.9 Difference of Grounding in AIS & GIS

With many air insulated substations in service, electrical engineers are well conversant with grounding procedures and requirements of Air Insulated Substation, but when it comes for Gas Insulated Substation this is still a mystery to be solved.

2.9.1 Return Currents: In AIS, air is used as an insulating medium hence there are exposed conductors, while in GIS conductors are enclosed within the bus ducts which are made of metal. There will be enclosure/return currents which will be in opposite phase compared to the main current. There are some special considerations given for this current in GIS. The same need is absent in AIS. Aluminium enclosures have lower resistivity compared to steel hence have a better earthing performance.

2.9.2 **Equipment Grounding:** In AIS every equipment is grounded with the main grounding mat with two separate grounding risers. In GIS too, multi point earthing system is adopted to have a control on return currents and to control the magnetic field around GIS.

GIS with continuous enclosures give superior performance to non-continuous enclosure or the enclosures having external separate connectivity. Electrically continuous enclosure enhances safety requirement & reliability. The number of points to be earthed will be recommended by GIS manufacturer.

2.9.3 **Transient Enclosure Voltages (TEV):** On operation of any isolator, circuit breaker there is generation of transient enclosure voltages, due to the dielectric breakdown in SF6 gas, which is generally having a rise time of 3 to 20 nanosecond. However, as these voltages are high frequency voltages (up-to 100MHz, dominant range 20 to 40MHz) & have a very short duration, this does not cause harm to human beings. However there is some special care which needs to be taken to deal with this kind of voltages, especially at discontinuities like GIS to transformer / reactor connection & GIS to cable interface.

2.9.4 **Modification in the main mat spacing:** Special consideration is given to main mat spacing in GIS hall which is not the case in AIS. The spacing is reduced in line with manufacturer recommendation. Main mat is also bonded with floor reinforcement & this helps for better performance during earthing of transient high frequency wave.

2.9.5 **Touch Voltage requirement:** As mentioned in IEEE-80 (2000), for a conventional substation it is very easy to calculate the touch voltages based on the analytical formula. However for a GIS a phase to earth fault which is near to GIS installation needs attention.

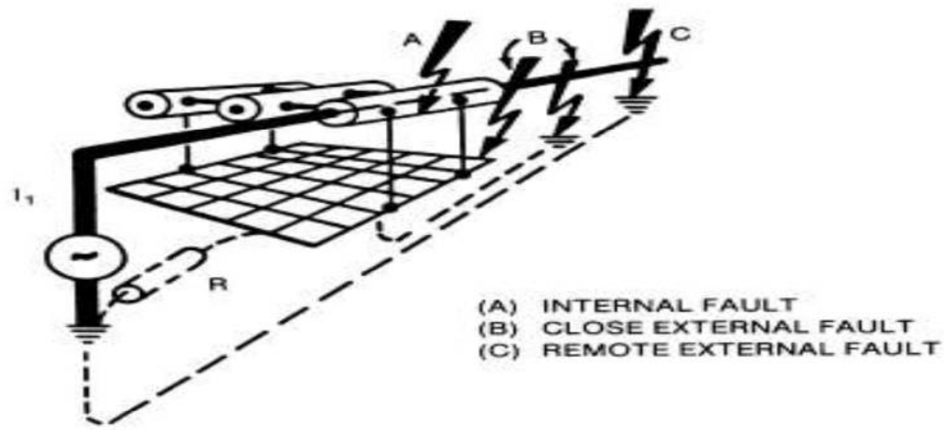

Fig 2.17 Typical Fault Conditions in GIS

The case of typical fault situations in GIS is shown in figure 2.17 above.

2.10 Enclosures Induced Currents

The shielding effectiveness of the bus enclosure is determined by its impedance, which governs the circulation of induced currents.

By choosing separate enclosures for each phase in the GIS, the magnitude of the enclosure current and its and direction can be controlled as this depends on the size of the enclosures of GIS, the phase spacing between the buses in the GIS and the method of interconnection between the enclosures.

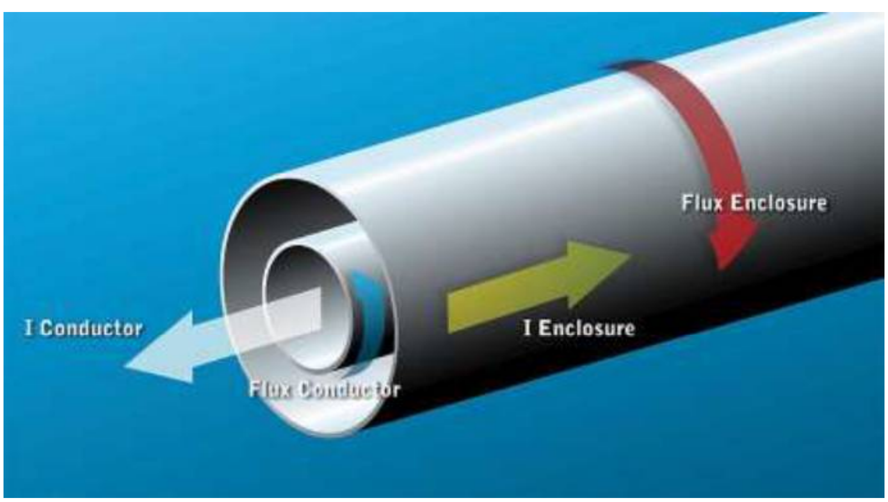

Fig 2.18 Enclosure Current in GIS

For GIS equipments' with continuous enclosures, the current in the main bus conductors cause induced voltage in the enclosures surrounding the main bus conductors. This voltage in the enclosures further produces a longitudinal flow of current in the enclosures. It is pertinent to mention here that this current in the enclosures is almost equal to current in the main bus bar conductors but in opposite direction. The magnetizing current lags this enclosure current by 90 degree.

For GIS with non-continuous design, there are no paths available for enclosure currents. So, there are productions of non-uniform voltages which cause local currents to flow in different isolated section of the enclosures. The patterns of these local currents are non-uniform. Because of such characteristics or properties, the non-continuous design is generally considered less advantageous than that of the continuous type. As such, it is not currently used by the industry.

2.11 Grounding of GIS Structure and Enclosures

GIS structure is made of metal and circulating current present in the enclosures due to flow of current in the main conductors of the enclosures is a matter of great concern. This problem can be solved by multiple bonding and grounding of GIS enclosures. This may be useful in controlling dangerous touch and step potentials within the GIS area [1,3].The grounding methods of GIS enclosures are shown in figure 2.19 and figure 2.20 respectively.

Fig 2.19 Grounding of GIS Enclosures-1

To control the unwanted impacts noticed due to induced currents, the following points may be kept in mind:

a) All structures and enclosures of switchgears should be at kept ground potential.

b) Designing of grounding of enclosures of GIS should be such that no significant potential differences appear between enclosures of switchgears of different bays/sections or supporting structures.

c) Sheath of power cables should be connected to the grounding grid system with grounding connectors or leads that are separated from the GIS enclosures.

d) Enclosure return currents of GIS should not be allowed to flow through any current transformers installed in the circuit.

Fig 2.20 Grounding of GIS Enclosures -2

2.12 Grounding of foundations of GIS

As the path taken by the fault current is mainly influenced by the location (position) of conductive or metallic materials which are present or buried in the surface/ soil ground where equipments are installed. There is need to pay special attention to this area of GIS grounding which may cause discontinuities within grounding system [1].

In the Gas Insulated Substation, a major portion of the substation is usually covered by foundations which are made of concrete which will results in the irregularities in the path taken by fault current. For such cases monolithic slab made of steel enforced gives good results as it also works as an auxiliary mat of grounding system.

In case of a slab of continuous type in the substation, the steel of this slab should be tied to main grounding mat so that there is no potential difference between GIS enclosures and steel in the foundations.

The foundation in the GIS substation may act as auxiliary grounding system provided that the flow of heavy fault current will not lead to deterioration of the steel in the slab i.e. due to local overheating or due to erosion of bond between concrete and steel.

2.13 Some further considerations are [3]:

a. All cables should be shielded and earthed.

b. Cables with separate function should be routed in separate cable trenches.

c. Star point of CT & PT is to be formed at only one point only. This will avoid galvanic coupling of current from earthing network to the control cable core.

d. All enclosures of GIS should be earthed at several points to the earth bus through the base frames of the GIS. All conduits and cable sheaths should be earthed to earth bus available in control cubicles and marshalling boxes.

e. Spacing of earth mat in the GIS hall may be adjusted as per manufacture's recommendation. It should be bonded with floor reinforcement for better performance of transient high frequency singles. Similarly all earthing risers should be bonded to floor reinforcement.

f. Shielded cables should be earthed at one end only.

g. In order to control the circulation of enclosure current beyond regular path, power cable sheath should be earthed directly without involving the enclosure in the earth path. To provide this isolation, cable termination design should have provision of an isolating air gap or some suitable insulating materials are used.

h. Proper care should be taken to ensure that current transformers mounted on GIS do not carry the enclosure return current.

i. Wherever there are discontinuities in enclosure/changes in the medium e.g. at cable terminations or transformer connections, special care should be taken to limit very fast transient over voltages and to avoid circulating currents in CB and transformer tanks.

j. GIS cable terminations and other discontinuities in the enclosure are significant sources of Transient Earth Potential Rise phenomenon. The isolation between the directly earthed power cable sheath and the enclosure may give rise to Transient Potential Rise phenomenon. Particular attention should be given to limit it.