TRAINING IN ELECTRICAL ENGINEERING

Guideline for Earthing of SUBSTATION

VKES
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Guideline for Earthing of Substation

What is earthing
Connecting above ground non conducting metal part to below ground buried metal is earthing or grounding.

Why do we do earthing
Protect human against electric shock, protect equipment from over voltage, provide safe path for lighting currents and prevent accumulation of static charges. When there is a fault large amount of energy is released. It should be diverted to some safe place i.e. earth. While this energy flows, it should not harm anyone nearby. Hence we earth the metallic parts.

What is the Scope of this guideline
This guideline will deal with earthing for protection of human against electric shock in AC substation. Earthing of generator, earthing in industries, earthing of DC substation etc is not dealt in this guideline. Grounding or earthing is also done to protect against overvoltage, prevent stray charges accumulation, provide path for lightning currents. But that not dealt in this guideline. Grounding of electronic instruments referred as instrument earthing or clean earthing is not dealt here. Auto reclosure is not covered.

How to protect a person in a substation against electrical shock
1) Insulate the live conductors (for example cables, or Transformers or breaker contacts etc)
2) Provide clearance between live conductor and earth with help of insulators and metal or concrete support structures
3) Earth all non conducting metal parts (IEEE 80 cover this aspect)

What happens during a fault
During a fault the fault current will flow from live conductor to non conducting metal parts, this may be the outer metallic casing or the metal supports etc. With help of earthing, the fault current flows down to the earth grid.

Why fault take place
A fault takes place: when insulation fails, when support to the live parts fails, when the conductors fall on the ground etc.

What happens when the current flows to the ground or earth
Whenever a current flows in any resistance path, then there is a voltage drop, So when current flows from non conducting metallic part to earth grid, the potential of earth grid and the non conducting metallic part rises. When someone touches that they receive a shock.

How is earthing design of domestic and industrial system different from substation
In industrial system earthing, resistance of earth grid is maintained below some particular value. The design of industrial power system is not covered in this guide hence not explained further.
What happens during a shock
Fault current does not flow directly through the human body, instead fault current develops some potential at the non-conducting metallic surface. When a person touches this surface, some amount of current flow through their body. When the current passes through the body it has different effect at different magnitude.

At what current does a person feel an electric shock and when does a person die

<table>
<thead>
<tr>
<th>Current magnitude (mA)</th>
<th>effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Perception, sensation</td>
</tr>
<tr>
<td>9-25</td>
<td>Painful and cannot move the hands</td>
</tr>
<tr>
<td>60-100</td>
<td>Ventricular fibrillation, heart stops, Death</td>
</tr>
</tbody>
</table>

If person is provided CPR they may survive. If duration reduces the above current can be allowed to increase. The above values are approximate.

What is the current allowed through human body
The main purpose of earthing grid design is to limit the current through the human body below the value which leads to fibrillation or death.

\[ I_B = \frac{k}{\sqrt{t_s}} \]  
(Tolerable body currents)

Where

\[ k = \sqrt{S_B} \]

\( S_B \) is the electrical energy at 50Hz/60Hz human body can allow without fibrillation
This varies depending on the weight of a person. For 50kg person it is 0.01345 J

\[ I_B = \frac{0.116}{\sqrt{t_s}} \]

Hence we can allow the following currents through 50kg human body
116mA for 1sec, 164mA for 0.5sec, 211mA for 0.3sec

What should be the value of \( t_s \)
The duration of current flowing through the body depends on the time for which the fault exists. This depends on the operation of the main protection and backup protection. If the time is not known we can assume 1sec.

What if weight of person is more or less than 50kg
Current reduces for weight more than 50kg and current increases if weight of person less than 50kg. If earthing system is designed for 50kg person and if a person weighs more than 50kg then they are protected. Our assumption is that person below 50kg will not be entering the substation. Some design also use 70kg weight, but it’s better to use 50kg.
What is the value of Resistance for the current through the body
When current flows from metal enclosure to the ground, it comes across the body resistance, gloves and shoes resistance, gravel resistance (below the foot) etc. The resistance of the body alone can be considered as 1000Ω.

What are the paths in which current can flow into human body
1) Hand to foot
2) Foot to foot (rare)
3) Hand to Hand (very rare)
\[ I_B = \frac{V_{th}}{Z_{th} + R_B} \]

\( V_{th} \) can be the voltage between hand to foot (touch voltage) or foot to foot (step voltage)

\( Z_{th} \) will be different when calculating the touch voltage and step voltage.

**Z \( th \) when calculating the touch voltage**

\[ Z_{th} = (Z_s \| R_g) + R_f / 2 \]

\( Z_s \) and \( R_g \) are less compared with \( R_f \)

Hence \( Z_{th} = R_f / 2 \)

**Z \( th \) when calculating the step voltage:**

\[ Z_{th} = 2R_f \]

\( R_f \) Resistance of one foot neglecting the substation grounding impedance

\[ = \frac{\rho}{4b} \] (empirical formula)

\( \rho \) = Earth resistivity, \( b \) = human foot radius (assumed 0.08m)

\( R_f = 3 \rho \)

\[ Z_{th} = R_f / 2 = 1.5 \rho \] (for touch voltage computation)

\[ Z_{th} = 2R_f = 6 \rho \] (for step voltage computation)

**Permissible touch and step voltage**

These are the voltages which will keep the current through the body below the danger level.

\[ E_{touch} = I_B (R_B + 1.5 \rho ) \]

\[ E_{step} = I_B (R_B + 6 \rho ) \]

Where \( I_B \) is the tolerable current through the body

**Correction factor for foot resistance**

Gravel is put on the surface of the substation to increase the foot contact resistance.

\[ R_f = \frac{\rho}{4b} (C_s) \]
\[ C_s = 1 - \frac{0.09(1 - \frac{\rho_s}{\rho})}{2h_s + 0.09} \]

\[ h_s = \text{height of gravel assumed as 100mm} \]

\[ \rho_s = \text{resistivity of gravel, range from 1000 to 5000 \( \Omega \)m} \]

\[ C_s = \text{will be approximately 0.7 to 0.8} \]

**Permissible touch and step voltage with** \( C_s \)

These are the voltages which will keep the current through the body below the danger level.

\[ E_{\text{touch}} = \frac{0.116}{\sqrt{\rho_s}} (1000 + 1.5 \, \rho_s \, C_s) \]

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

Where \( I_B \) is the tolerable current through the body.

**Earthing Grid**

Consist of mesh of horizontal conductors and earth roads penetrating below the ground. The grid material is either copper or Galvanised iron rods or flats. The size depends on the fault current. Depth of laying is approximately 300mm to 600mm below ground level. Number of earthing rods and Spacing of the grid has to be selected by the users. Avoid using copper in an area close to cathodic protection.

![Earthing Grid Diagram](image)

**What needs to be connected to the earthing Grid**

All non-conducting metal parts, transformer body, breakers, isolator structures, Transmission line structures, fence, Generator and Transformer neutrals etc. The connection between the Earth grid and above ground non-metallic parts can be via copper conductor, or GI metal strips. The connection can be by exothermic weld or bolting.
Sizing of earthing grid

\[ A_{mm^2} = \frac{l}{\sqrt{\frac{\sigma \cdot \rho_e \cdot \rho_f}{\sigma + \rho_e \cdot \rho_f}} \ln \left( \frac{k_e \cdot \rho_m}{\rho_e \cdot \rho_f} \right)} \]

\( I \) is in kArms

For copper annealed soft drawn

\[ A_{mm^2} = \frac{l}{\sqrt{\frac{3.42 \times 0.0001}{1 \times 0.00393 \times 1.72}} \ln \left( \frac{234 + 1083}{234 + 20} \right)} = I \times 3.46 \]

Copper undergoes fusing at temperature of 1083 deg C, it is better to restrict the temperature to 250 deg C as copper loses its mechanical strength above this temperature and some joint may get damaged beyond this temperature.

\[ A_{mm^2} = \frac{l}{\sqrt{\frac{3.42 \times 0.0001}{1 \times 0.00393 \times 1.72}} \ln \left( \frac{234 + 250}{234 + 20} \right)} = I \times 5.53 \]

For galvanised iron

\[ A_{mm^2} = \frac{l}{\sqrt{\frac{3.91 \times 0.0001}{1 \times 0.00320 \times 20}} \ln \left( \frac{293 + 419}{293 + 20} \right)} = I \times 14 \]
Fault current distribution ($S_f$)

When a fault occurs the fault current will flow from the fault location back to the neutral of the generator or transformer. Some part of the Fault current goes to the neutral through the earth grid and some part of fault current returns to the neutral through the transmission line earthing conductor. For earthing grid calculation we should consider that part of fault current which goes from the grid to the neutral via the earth. Because it is this current that causes the ground potential rise. The earthing system designed for the actual fault current becomes very conservative and over designed. It is suggested to design the earthing system for the fault current which enters the earth grid.

$$S_f = \frac{l_g}{3I_0}, \quad 3I_0 \text{ is the ground fault current, } l_g \text{ is the grid current which enters the earth}$$

$$S_f = \frac{z_{eq}}{z_{eq} + R_g}$$

$$Z_{eq} = z_2 + \sqrt{z_2 R_t}$$

$Z_{eq}$ is equivalent impedance of the ground wire and tower resistance per span

(Refer IEEE TRANSACTIONS ON POWER APPARATUS AND SYSTEMS VOL. PAS-86, NO. 10 OCTOBER 1967, Analysis of Transmission Tower Potentials, by JANOS ENDRENYI)

$R_t$ is the tower resistance

$$R_t = \frac{\rho}{2\pi r_0}, \quad r_0 \text{ is the radius of the earthing around the tower}$$

Maximum resistance of tower earthing resistance is normally limited to 10Ω

$Z_s$ is the self impedance of the transmission line ground conductor per span
\[ Z_s = r_a + jX_a + \frac{r_e + jX_e}{3} \]

Due to ground wire

Due to zero sequence impedance if phase conductor

Phase A

Phase B

Phase C

Fault Current

Transmission Tower

Earth Grid

Earth Conductor
Fault current division equivalent circuit

\[ r_a = \text{AC resistance of ground conductor} \]

\[ X_a = 0.06327 \ln \left( \frac{1}{GMR \times 0.00328} \right) \quad \text{(self impedance of ground conductor)} \]

\[ r_e = 0.149 \]

\[ X_e = 0.0949 \ln (93310 \times \rho) \]

Above units for resistance and Impedance are in \( \Omega/\text{km} \)

**Decrement Factor**

Fault current consist of DC component in the beginning and this reduces with time. Because of this DC component the peak value of current and RMS value changes. To take this into account the term decrement factor is used.

\[ D_f = \sqrt{1 + \frac{r_a}{t_f} \left(1 - e^{-\frac{t_f}{T_a}}\right)} \]

\[ T_a = \text{DC offset time constant} = \frac{X}{\omega R} \]

\[ t_f = \text{Duration of fault in s} \]

\[ I_G = I_g \cdot D_f \]

\[ I_g = S_f \cdot I_f \]

\[ I_G = \text{RMS equivalent of asymmetrical fault current that enters earth grid} \]

\[ I_g = \text{fault current that enters the earth grid} \]

\[ I_f = \text{RMS value of fault current determined by calculation or simulation} \]
Grid Geometry
The shape of the earthing grid depends on the shape of substation. The depth of the grid will be 0.5 to 1M, the spacing of the grid conductors should be around 3M to 9M. As the grid depth increases, spacing of conductor reduces, area of the grid increases, the overall grid resistance reduces. However this also leads to more cost. Refer the sample calculation in for the substation earthing design example.

Mesh Voltage calculation

\[ E_m = \frac{\rho \cdot K_m \cdot l_G}{l_m} \]

\[ K_m = \frac{1}{2\pi} \left[ \ln \left( \frac{D^2}{16} \cdot \frac{h}{d} \right) + \frac{(D+2h)^2}{8Dd} - \frac{h}{4d} \right] + \frac{k_{ii}}{k_h} \ln \left( \frac{8}{\pi(2n-1)} \right) \]

- \( D \) = Spacing between parallel conductors in m
- \( h \) = Depth of ground grid in m
- \( d \) = Diameter of grid conductor in m

\[ k_{ii} = \frac{1}{(2n)^2} \quad \text{for grid with few ground rods, otherwise } k_{ii} = 1 \]

\[ k_h = \sqrt{1 + \frac{h}{h_o}} \quad (h_o = 1) \]

\[ n = n_a \cdot n_b \cdot n_c \cdot n_d \quad \text{(Factor to take care of shapes of grid)} \]

\[ n_a = \frac{2L_c}{L_p} \quad n_b = \frac{L_p}{4\sqrt{A}} \quad n_c = \left( \frac{L_x \cdot L_y}{A} \right)^{0.7} \quad n_d = \frac{D_m}{\sqrt{l_x^2 + l_y^2}} \]

For square grid \( n_b \cdot n_c \cdot n_d = 1 \), for rectangular grid \( n_c \cdot n_d = 1 \), for L shape grid \( n_d = 1 \),

- \( L_c \) = total length of conductor of horizontal grid (m), \( L_p \) = peripheral length of the grid (m)
- \( L_x \) = maximum length of grid in x direction (m), \( L_y \) = maximum length of grid in y direction (m)
- \( A \) = Area of the grid in \( m^2 \)
- \( D_m \) = maximum distance between any two points on the grid

\[ K_i = 0.644 + 0.148n \]

\[ L_m = L_c + L_R \quad \text{(for grid with few ground rods)} \]

\[ L_m = L_c + \left[ 1.55 + 1.22 \frac{L_r}{\sqrt{l_x^2 + l_y^2}} \right] L_R \quad \text{(for grid with many ground rods)} \]

\( L_r \) = length of each ground conductor, \( L_R \) = length of all ground conductor
Step Voltage calculation

\[ E_s = \frac{\rho K_s I_G}{L_s} \]

\[ K_s = \frac{1}{\pi \rho} \left( \frac{1}{\rho + h} + \frac{1}{\rho (1 - 0.5^n)} \right) \]

\[ L_s = 0.75 L_c + 0.85 L_R \]

GPR- Ground potential rise

When current flows through the earth, the potential increases at each and every location. Earth is a network of RLC circuit, when current flows through this three dimensional network, voltage rises. When a person is standing both his foot experiences different potential, this difference is the step voltage. When a person is touching some object, his hand and foot experience different potential. The difference is the touch voltage. Bird sitting on a transmission line does not get a shock because its entire body is at same potential. In the same way GPR itself is not a problem but the different potential at different parts of body creates problem. GPR can be plotted using computer programs. It is not further studied here. However refer the below curve to get an idea how the GPR distribution appears.

Transferred potential

During fault, the fault current flows through the earth grid and this leads to a ground potential rise (GPR). All metal objects which are connected to the substation earth grid will experience an increase in the potential. Any non conducting metal connected to this earth grid experience a rise in its potential. If the equipment whose non conducting metal is located outside the substation, rise in potential is called transferred potential. Sometimes the transferred potential has led to serious damage of sensitive equipments and has caused fatalities. Hence this subject needs serious study.

Transferred potential affecting 415V LV system: LV system Grounding inside the substation should not be interconnected with the substation grid as the substation GPR will lead to higher voltages in 415V earthing system. Power outlets if any in the switchyard should not be connected to switchyard earthing instead it should be connected to a separate 415V system earthing.
Transferred potential affecting nearby by Rail
Substation has rails installed during the initial commissioning stage. It is better to remove these rails as they may transfer the GPR to some distant location.

Transferred potential affecting nearby Pipelines
If any pipelines are passing near the substation ensure they are not bonded with the substation earth grid

Transferred potential affecting Communication cable screening
All cables, 11kV, 415V, or communication cable may have either an armour or a metal screen. The screen and armour will be earthed at the ends with help of cable glands earth tags. 415V cable armour and control cable screen earthing should not be connected to the substation earth grid.

Control cable which originates at the switchyard marshalling kiosk should not be earthed at the switchyard end. Similarly the armour of any LV cable which provides power supply to the transformer fans should not be earthed at the switchyard end.

Also Isolation transformer can be used to prevent GPR transfer.

Analysis of the problems associated with GPR on communication cables, pipelines, rails etc is not part of this guideline. Detailed analysis will be done separately.

What Causes GPR

Refer below two figures for illustration of how GPR occurs .GPR mainly occurs due to that part of the fault current which flows through the Earth grid. In the below figure, the fault current in green colour is the one which enters the earth grid. This cause a GPR at the respective switchyard.

GPR is not due to the fault current itself but it is due to a portion of the fault current which flows through the earth and enters the earth grid. Fault current which flows through the earth wire of transmission line, current which flows through metal pipelines, or rails or any other metallic infrastructure does not contribute to the GPR, instead these currents bring down the GPR.

There will be no GPR when fault takes place on a bus connected to the secondary of a Transformer, where the Transformer neutral is connected to the substation grid. The fault current flows from the bus to the earth grid and back to the neutral. Fault current does not travel through the earth, hence it does not cause any GPR.
In the above illustration an example of fault on 220kV Transmission line is taken. The fault of 12kA is shown by blue line. It is fed from a line and a 220kV/ 11kV Generator transformer. At the fault location the fault current divides itself and returns back to its source through the ground wire and through the earth. The current flowing through the earth cause GPR at the 220kV/11kV Transformer neutral earthing and at the 220kV substation earthing, which is connected to the 200kV transmission line.

At the 220kV substation the fault current again takes two paths one is through the earthing conductor of the transmission line and the other through the earth. The division of the current can be determined using division factor which has been discussed in the previous paragraph. The fault occurring at some remote end can also create a GPR at the 220kV substation as the fault current flows back to the substation earth grid.

GPR can be computed by, GPR = I_g x R_g

**Grid Resistance**

\[ R_g = \rho \left[ \frac{1}{L_r} + \frac{1}{\sqrt{20A}} \left( 1 + \frac{1}{1+h\sqrt{20/A}} \right) \right] \] (without ground rods)

\[ R_g = \frac{R_1R_2-R_0^2}{R_1+R_2-2R_m} \] (with ground rods and mutual ground resistance between grid and rods)

\[ R_1 = \frac{\rho}{\pi L_c} \ln \left( \frac{2L_c}{a'} \right) + \frac{k_1L_c}{\sqrt{A}} - k_2 \]

Where:
- \( L_c \) is total length of grid conductors in m,
- \( A \) is area of grid in \( m^2 \), \( a \) is radius of conductor in m
- \( k_1, k_2 \) are coefficients refer IEEE 80.

\[ R_2 = \frac{\rho}{2\pi n_R L_r} \left[ \ln \left( \frac{4L_r}{b} \right) - 1 + \frac{2k_1L_r}{\sqrt{A}} (\sqrt{n_R} - 1)^2 \right] \]

Where:
- \( L_r \) is the length of each ground rod in m
- \( b \) is radius of the ground rod in m
- \( n_R \) is the number of ground rods in area \( A \)

\[ R_m = \frac{\rho}{\pi x L_c} \left[ \ln \left( \frac{2L_c}{L_r} \right) + \frac{k_1L_c}{\sqrt{A}} - k_2 + 1 \right] \]

\[ a' = \sqrt{a/2h} \]
Sample Calculations

Sample calculation is performed for cases as mentioned below.
Case 1: 40kA rms fault current without division factor and fault duration of 1sec
Case 2: Fault within substation, with division factor, with decrement factor, duration 300msec
Case 3: Fault on transmission line entering substation, duration 600msec
Case 4: Fault on a 66kV bus of the substation
Case 5: Fault at 11kV Switchgear

Case 1: fault current without division factor and fault duration of 1sec
220kV Design fault level = 40kA rms (ref 1)
Fault duration $t_s = 1$ sec
Resistivity of earth $\rho = 200 \Omega m$
Height of gravel assumed as $h_s = 100mm$
Resistivity of gravel, assume $\rho_g = 2000 \Omega m$

$$C_s = 1 - \frac{0.09(1-\frac{\rho}{\rho_g})}{2h_s+0.09}$$
$$C_s = 1 - \frac{0.09(1-\frac{200}{2000})}{(2 \times 0.1)+0.09} = 0.72$$
$$E_{touch} = \frac{0.116}{\sqrt{t_s}} (1000 + 1.5 \rho_s C_s) = \frac{0.116}{\sqrt{t_s}} (1000 + 1.5 \times 2000 \times 0.72 ) = 366.8 V$$
$$E_{step} = \frac{0.116}{\sqrt{t_s}} (1000 + 6 \rho_s C_s) = \frac{0.116}{\sqrt{t_s}} (1000 + 6 \times 2000 \times 0.72 ) = 1119.2 V$$

Sizing of earthing grid

$$A_{mm^2} = \frac{l}{\sqrt{\left(\frac{TCA}{\rho} \sqrt{\frac{xG}{\rho}} \right) \ln \left(\frac{k_0 + k_m}{k_0 + k_f} \right)}}$$, $l$ is in kA rms

For copper annealed soft drawn

$$A_{mm^2} = \frac{l}{\sqrt{\left(\frac{3.42x0.0001}{1.5 \times 0.00393 \times 1.72} \right) \ln \left(\frac{234+1083}{234+250} \right)}} = l \times 3.46 = 40 \times 3.46 = 138 , \text{ OD}=13.2mm$$

Restrict maximum temperature to 250 deg C due to mechanical strength limitation.

$$A_{mm^2} = \frac{l}{\sqrt{\left(\frac{3.42x0.0001}{1.5 \times 0.00393 \times 1.72} \right) \ln \left(\frac{234+250}{234+250} \right)}} = l \times 5.53 = 40 \times 5.53 =221, \text{ OD}=16.8mm$$

For galvanised iron

$$A_{mm^2} = \frac{l}{\sqrt{\left(\frac{3.93x0.0001}{1 \times 0.00320 \times 2.0} \right) \ln \left(\frac{293+419}{293+293} \right)}} = l \times 14 = 40 \times 14 =709, \text{ OD}=30mm$$
Both copper and iron have their own merits and demerits. It depends on owner’s specification on which one has to be used. Copper has an advantage, it does not get corroded like iron but it is costly. But copper cannot be used where cathodic protection is used. If copper is used then joining of conductors should be done through bracing or exothermic joints. If galvanised iron is used welding needs to be employed. Further calculation will be proceeded with galvanised iron.

Case 1: Fault inside substation with design fault current and duration 1sec

Mesh Voltage

\[ D = \text{Spacing between parallel conductors in } m = 3 \]
\[ h = \text{Depth of ground grid in } m = 0.5; \]
\[ d = \text{Diameter of grid conductor in } m = 0.03 \]
\[ L_c = \text{total length of the conductor of horizontal grid in } m = 13866 \]
\[ L_p = \text{peripheral length of the grid in } m = 580 \]
\[ L_x = \text{maximum length of grid in } x \text{ direction in } m = 160; \]
\[ L_y = \text{maximum length of grid in } y \text{ direction in } m = 130 \]
\[ A = \text{Area of the grid in } m^2 = 20800 \]
\[ D_m = \text{maximum distance between any two points on the grid in } m = 206 \]

\[ k_h = \sqrt{1 + \frac{h}{h_o}} \quad (h_o = 1) \]
\[ = 1.22 \]
\[ n_a = \frac{2L_c}{L_p} = 47.8 \]
\[ n_p = \sqrt{\frac{L_p}{4 \sqrt{A}}} = 1 \]
\[ n_c = \left[ \frac{L_x L_y}{A} \right]^{0.7} = 1 \]
\[ n_d = \frac{D_m}{\sqrt{L_x^2 + L_y^2}} = 1 \]
\[ n = n_a n_b n_c n_d \quad \text{(Factor to take care of shapes of grid)} = 47.8 \]
\[ K_i = 0.644 + 0.148n = 7.72 \]
\[ L_m = L_c + L_r \quad \text{(for grid with few ground rods)} \]
\[ k_{ii} = \frac{1}{(2n)^{\frac{1}{n}}} = 0.7912 \text{ for few ground conductors and nil in periphery and corners} \]

\[ k_{ii} = 1 \text{ for ground conductors throughout} \]
Actual Fault current for fault inside substation was 20.5kA with 6 transmission lines. Fault on Case 2: Fault inside a substation with fault current 20.5kA and duration 100ms

5g1838

Step Voltage

E_m (758) >> E_{touch} (366.8)

Let’s add 500 ground rods of 3M each, \( L_R = 1500, L_T = 3 \)

\[
L_m = L_c + \left[ 1.55 + 1.22 \left( \frac{L_T}{\sqrt{L_c^2 + L_T^2}} \right) \right] L_R = 13866 + \left[ 1.55 + 1.22 \left( \frac{3}{\sqrt{160^2 + 130^2}} \right) \right] 1500 = 16217
\]

\( L_T \) = length of each ground conductor; \( L_R \) = length of all ground conductor

\[
E_m = \frac{\rho K_m K_I I_G}{L_m} = \frac{200 \times 0.17 \times 7.72 \times 40000}{13866} = 758V
\]

There is not much change in the mesh voltage \( E_m \) (648) >> \( E_{touch} \) (366.8)

**Step Voltage**

\[
L_s = 0.75 L_c + 0.85 L_R = 0.75 \times 13866 + 0.85 \times 1500 = 11674
\]

\[
K_s = \frac{1}{\pi} \left[ \frac{1}{I_2 h} + \frac{1}{I_2 + h} + \frac{1}{D} \left( 1 - 0.5^{n-2} \right) \right] = \frac{1}{\pi} \left[ \frac{1}{2 \times 0.5} + \frac{1}{3 + 0.5} + \frac{1}{3} \left( 1 - 0.5^{47.8-2} \right) \right] = 0.515
\]

\[
E_s = \frac{\rho K_s K_I I_G}{L_s} = \frac{200 \times 0.515 \times 7.72 \times 40000}{11674} = 2742V
\]

\( E_s \) (2742) > \( E_{step} \) (1119)

The 40kA fault current considered in this calculation leads to a high GPR value. The fault duration considered as 1 sec may not be the case always as protective relays clear the fault much earlier. Due to these factors the step and touch voltage attained were not below the tolerable limits. In reality the fault current does not attain such a high value. Actual fault level can be calculated including future expansion of the substation. The division factor \( S_f \) also needs to be considered. This is considered in the next case.

**Case 2: Fault inside a substation with fault current 20.5kA and duration 100ms**

Actual Fault current for fault inside substation was 20.5kA with 6 transmission lines. Fault on 220kV bus was highest, hence it considered. Considering future growth of two more bays, fault current contribution of each transmission line was assumed as 3.5KA. Total fault current can be considered as 28KA. For fault inside substation the Bus bar differential protection acts immediately. The Fault duration can be considered as 100ms.
\[ E_{\text{touch}} = \frac{0.116}{\sqrt{f_s}} (1000 + 1.5 \rho_s \ C_s) = \frac{0.116}{\sqrt{0.1}} (1000 + 1.5 \times 2000 \times 0.72) = 1160 \text{ V} \]

\[ E_{\text{step}} = \frac{0.116}{\sqrt{f_s}} (1000 + 6 \rho_s \ C_s) = \frac{0.116}{\sqrt{0.1}} (1000 + 6 \times 2000 \times 0.72) = 3536 \text{ V} \]

**Fault current distribution**

\[ (S_f) = \frac{Z_{eq}}{Z_{eq} + R_g} \]

- **\( R_t \)**: tower resistance = 10Ω

Ground wire: Galvanized stranded steel wire, Strand and wire diameter 7/3.15mm, Total sectional area 54.55 mm², approximate overall diameter 9.54 mm

- \( r_a \): AC resistance of ground conductor = 3.41 Ω/km at 20 deg C

GMR= 2.21\( r \)= 2.21\( \times 1.575 \)=3.48mm= 0.00348M

**\( X_a \)**: reactance of ground conductor

\[ X_a = 0.06327 \ln \left( \frac{1}{GMR \times 0.00328} \right) = 0.06327 \ln \left( \frac{1}{0.00348 \times 0.00328} \right) = 0.72 \text{ Ω/km} \]

- **\( r_e \)**: = 0.149 Ω/km

\[ X_e = 0.0949 \ln (93310 \rho) = 1.588 \text{ Ω/km} \]

\[ Z_s = \left( r_a + \frac{r_e}{3} \right) + j \left( X_a + \frac{X_e}{3} \right) = (3.41+0.149/3) + j(0.72+1.588/3) = 3.46+j1.24 = 3.67 \text{ Ω/km} \]

One span length of 220kV line= 320M =0.32kM

- \( Z_s \) of one span is = 1.176 Ω

\[ Z_{eq} = \frac{Z_s}{2} + \sqrt{Z_s R_t} = \frac{1.176}{2} + \sqrt{1.176 \times 10} = 4.017 \text{ for one transmission line} \]

- \( Z_{eq} \) for 6 present and 2 future transmission lines = 4.017/8 = 0.502

\[ R_g = \rho \left[ \frac{1}{L_T} + \frac{1}{\sqrt{20/\Lambda}} \left( 1 + \frac{1}{1+4h/\sqrt{20/\Lambda}} \right) \right] = 200 \left[ \frac{1}{13866} + \frac{1}{\sqrt{20 \times 20800}} \left( 1 + \frac{1}{1+0.5\sqrt{20/20800}} \right) \right] = 0.629 \]

\[ S_f = \frac{Z_{eq}}{Z_{eq} + R_g} = \frac{0.502}{0.502 + 0.629} = 0.4439 \]

**Computation of \( R_g \) with ground rods**

\[ R_1 = \frac{\rho}{\pi L_c} \left[ \ln \left( \frac{2L_c}{a} \right) + \frac{k_L C}{\sqrt{A}} - k_2 \right] \quad (k_2=4.5, \ k_1=1) \]

\[ a^* = \sqrt{2h} = \sqrt{0.03 \times 0.5} = 0.1224 \]

\[ R_1 = \frac{200}{\pi \times 13866} \left[ \ln \left( \frac{2 \times 13866}{0.1224} \right) + \frac{13866}{\sqrt{20800}} - 4.5 \right] = 0.475 \]
\[ R_2 = \frac{\rho}{2\pi \eta R L_r} \left[ \ln \left( \frac{4 L_r}{b} \right) - 1 + \frac{2k_1 L_r}{\sqrt{A}} (\sqrt{\eta R} - 1)^2 \right] \]

\[ R_2 = \frac{200}{2\pi \times 500 \times 3} \left[ \ln \left( \frac{4 \times 3}{0.015} \right) - 1 + \frac{2 \times 3}{\sqrt{20800}} (\sqrt{500} - 1)^2 \right] = 0.52345 \]

\[ R_m = \frac{\rho}{\pi x L_c} \left[ \ln \left( \frac{2 L_c}{L_r} \right) + \frac{k_1 L_c}{\sqrt{A}} - k_2 + 1 \right] \]

\[ R_m = \frac{200}{\pi \times 13866} \left[ \ln \left( \frac{2 \times 13866}{3} \right) + \frac{13866}{\sqrt{20800}} - 4.5 + 1 \right] = 0.467 \]

\[ R_g = \frac{R_1 R_2 - R_m^2}{R_1 + R_2 - 2R_m} = \frac{0.475 \times 0.523 - 0.467^2}{0.475 + 0.523 - 2 	imes 0.467} = 0.474 \]

\[ S_f = \frac{Z_{eq}}{Z_{eq} + R_g} = \frac{0.502}{0.502 + 0.474} = 0.5143 \]

Decrement factor

\[ X/R \text{ for } 220kV \text{ line } 5.71 \]

\[ T_a = \text{DC offset time constant} = \frac{X}{\omega R} = 0.0187 \]

\[ t_f = \text{Duration of fault in s} = 100 \text{ msec} = 0.1 \]

\[ D_f = \sqrt{1 + \frac{T_a}{t_f} \left( 1 - e^{-\frac{2t_f}{T_a}} \right)} = \sqrt{1 + \frac{0.0187}{0.1} \left( 1 - e^{-\frac{2 \times 0.1}{0.0187}} \right)} = 1.0894 \]

\[ I_G = I_f, \; I_g = S_f \; I_f, \; I_G = S_f \; I_f \]

\[ I_G = 0.5143 \times 28 \times 1.0894 = 15.68 \text{ kA} \]

Mesh Voltage

\[ E_m = \frac{\rho K_m K_l \ell_G}{L_m} = \frac{200 \times 0.17 \times 7.72 \times 15680}{13866} = 296.8 \text{ V} \]

\[ E_m (296.8) < E_{touch} (1160), \]

However few round rods are added close to some equipment like surge arrester, Transformer neutral, isolators etc. Consider 50 ground rods of 3M each, \( L_R = 150 \), \( L_r = 3 \)

\[ L_m = 13866 + \left[ 1.55 + 1.22 \frac{3}{\sqrt{160^2 + 130^2}} \right] 150 = 14101 \]

\[ E_m = \frac{\rho K_m K_l \ell_G}{L_m} = \frac{200 \times 0.17 \times 7.72 \times 15680}{14101} = 291.87 \text{ V} \]

\[ E_m (291) < E_{touch} (1160) \]
Step Voltage

\[ L_s = 0.75 L_C + 0.85 L_R = 0.75 \times 13866 + 0.85 \times 150 = 10527 \]

\[ K_s = \frac{1}{\pi} \left[ \frac{1}{2h} + \frac{1}{D+h} + \frac{1}{D} \left( 1 - 0.5^{n-2} \right) \right] = \frac{1}{\pi} \left[ \frac{1}{2 \times 0.5} + \frac{1}{3+0.5} + \frac{1}{3} \left( 1 - 0.5^{36.7-2} \right) \right] = 0.515 \]

\[ E_s = \frac{\rho K_s K_i I_0}{L_s} = \frac{200 \times 0.515 \times 7.72 \times 15680}{10527} = 1184.39 \text{ V} \]

\[ E_s \ (1184) < E_{step} \ (3536) \]

In case 500 ground rods of 3m each are used as per previous example

\[ L_s = 0.75 L_C + 0.85 L_R = 0.75 \times 13866 + 0.85 \times 1500 = 11674 \]

\[ E_s = \frac{\rho K_s K_i I_0}{L_s} = \frac{200 \times 0.515 \times 7.72 \times 15680}{11674} = 1068 \text{ V} \]

\[ E_s \ (1068) < E_{step} \ (3536) \]

**Case 3: Fault on a Transmission line, with Fault current 10.6kA duration 600ms**

Fault on a Transmission line connected to the substation. Fault current was 10.6kA. The fault duration can be considered as 600 ms taking into account the tripping time of the transmission line relays. The fault current consist of two contribution, 6.1kA from one end of the line and 4.5kA from the substation under study. The GPR in the substation under study is due to a portion of 4.5kA which passes through the earthing grid.

\[ E_{touch} = \frac{0.116}{\sqrt{t_s}} \left( 1000 + 1.5 \rho_s C_s \right) = \frac{0.116}{\sqrt{0.6}} \left( 1000 + 1.5 \times 2000 \times 0.72 \right) = 473 \text{ V} \]

\[ E_{step} = \frac{0.116}{\sqrt{t_s}} \left( 1000 + 6 \rho_s C_s \right) = \frac{0.116}{\sqrt{0.6}} \left( 1000 + 6 \times 2000 \times 0.72 \right) = 1443.6 \text{ V} \]

**Fault current distribution**

\[ Z_{eq} = 4.017 \text{ for one transmission line} \]

\[ R_g = 0.474 \]

\[ S_f = \frac{Z_{eq}}{Z_{eq} + R_g} = \frac{4.017}{4.017 + 0.474} = 0.894 \]
Decrement factor

$X/R$ for 220kV line is 5.71,

$T_a = \text{DC offset time constant} = \frac{X}{\omega R} = 0.0187$

$t_f = \text{Duration of fault in s} = 600 \text{ msec} = 0.6$

$D_f = \sqrt{1 + \frac{T_a}{t_f} \left( 1 - e^{-\frac{2t_f}{T_a}} \right)} = \sqrt{1 + \frac{0.0187}{0.6} \left( 1 - e^{-\frac{2 \times 0.6}{0.0187}} \right)} = 1.015$

Grid Current

$I_G = I_g D_f, \ I_g = S_f I_f, \ I_G = S_f I_f D_f = 0.894 \times 4.5 \times 1.0154 = 4.084 \text{ kA}$

Mesh Voltage

$E_m = \frac{\rho K_m K_l I_G}{L_m} = \frac{200 \times 0.17 \times 7.72 \times 4084}{13866} = 77.3 \text{ V}$

$E_m (77.3) < E_{touch} (473)$

Step Voltage

$E_s = \frac{\rho K_s K_l I_G}{L_s} = \frac{200 \times 0.515 \times 7.72 \times 4084}{10527} = 308 \text{ V}$

$E_s (308) < E_{step} (1443)$

Case 4: Fault on a 66kV bus of the substation.

The Fault current is 14.58kA lesser than 20.5kA fault current at 220kV. Hence this case need not be studied.

Case 5: Fault at 11kV Switchgear.

The Fault current is 19kA and fault duration will be high in order to coordinate with outgoing radial distribution feeders. But step and touch voltage calculation is not applicable for this fault. The fault current flows into the earth grid and enters the neutral of the transformer through the metallic path. Hence Ground potential rise caused by the fault will not be much.
Reference:

- IEEE 80: guide for safety in AC substation grounding
- CEA Transmission planning criteria
- KPTCL Tech Spec for Line survey
- HVPNL Tech Spec
- T&D Handbook
1 - 220kV one and half bus
2 - 220kV/66kV Transformer
3 - 66kV two Main & Transfer
4 - 66kV/11kV Transformer
5 - 11kV Indoor switchgear
6 - 11kV/433V Transformer
7 - 415V Switchgear
8 - Small power DB
9 - Receptacle/Socket
10 - 220kV Double circuit
     Transmission line
11 - 66kV underground cable
12 - 11kV Distribution line

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Earth grid for 415V system
isolated from substation
earth grid to prevent
transfer of potential (GPR)

Switchyard earth grid
designed as per IEEE 80

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220kV/66kV/11kV Switchyard
Earthing arrangement

Vidyuth Kanti Engineering Services
www.vkes.org
Not to scale
Notes:
1) Motor Contribution is taken as 6 times
2) For fault inside the substation, the bus bar differential relay operates within a very short duration of less than 20ms. The fault duration is assumed as 100ms for calculation.
3) For fault on a Transmission line, protection of the line will act. Maximum operating time can be considered as 600 ms including backup.
ABOUT VKES

Vidyuth Kanti Engineering Services is a Bangalore based Startup by Paneendra Kumar BL.

Paneendra kumar BL is a Charted Engineer (UK), Senior member IEEE (USA), Associate member institute of engineers India. Has done Masters in power system from IIT delhi and BE Electrical from RV college of engineering Bangalore. He has 15 years experience in Electrical Engineering of Industrial power distribution, Power plants, Oil and gas, Transmission and Distribution and Power quality. He has published paper in IEEE