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# Wood Poles Earthing System in Practical case of 132kv

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---------------------------------------------------***ABSTRACT***:---------------------------------------------------
*Now a days, there are many software design packages that can do all necessary Over Head Lines calculations. However, it is required to appreciate the engineering behind any software, as it is important to understand what is happening and feed in the engineering knowledge. This paper is being able to propose the application of a standard design as the earth system of each wood pole cable termination towers, which allow a 132kV cable to connect two sections of wood pole construction 132kV overhead line between two 132kV Substations.The Lightning affects conductors in specific discrete event. There is no condition information as such on which to base conductor lifetime.*

***Key words***: *Earthing, Wood Poles, Lightning, Pole Power Line, Electricity Regulations.*
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## I. INTRODUCTION:

Originally, wood poles were designed as per the 1947 Electricity Commissioners" Regulations, which stipulated they had to have a factor of safety of 3.5 with a wind pressure of 8lb/ft2 (380N/m$^2$) and 3/8 in (9.5mm) radial ice on the conductors ate 22$^o$F (-5.6$^o$C). Todays, under the 1988 Electricity Supply regulations, the criterion is that the pole must be fit for purpose. This gives the design engineer much more latitude in his pole design and has led to environmental approach details in ENATS 43-40(www.energynetworks.org, 2020)(Wareing, 2002).

This paper is be able to propose the application of a standard design as the earth system of each wood pole cable termination towers (wood poles), which allow a 132kV cable to connect two sections of wood pole construction 132kV overhead line between two 132kV Substations. Changes or extensions to the earth system may be necessary to allow the line to be put into service without delays, these should be proposed.

**The methodology design procedure in BS EN 50522 9 (Earthing of power installations exceeding 1 kV a.c.)(BSI, 2012), Figure NA.7 may be considered in this paper but it may not be in details, figure 1.**

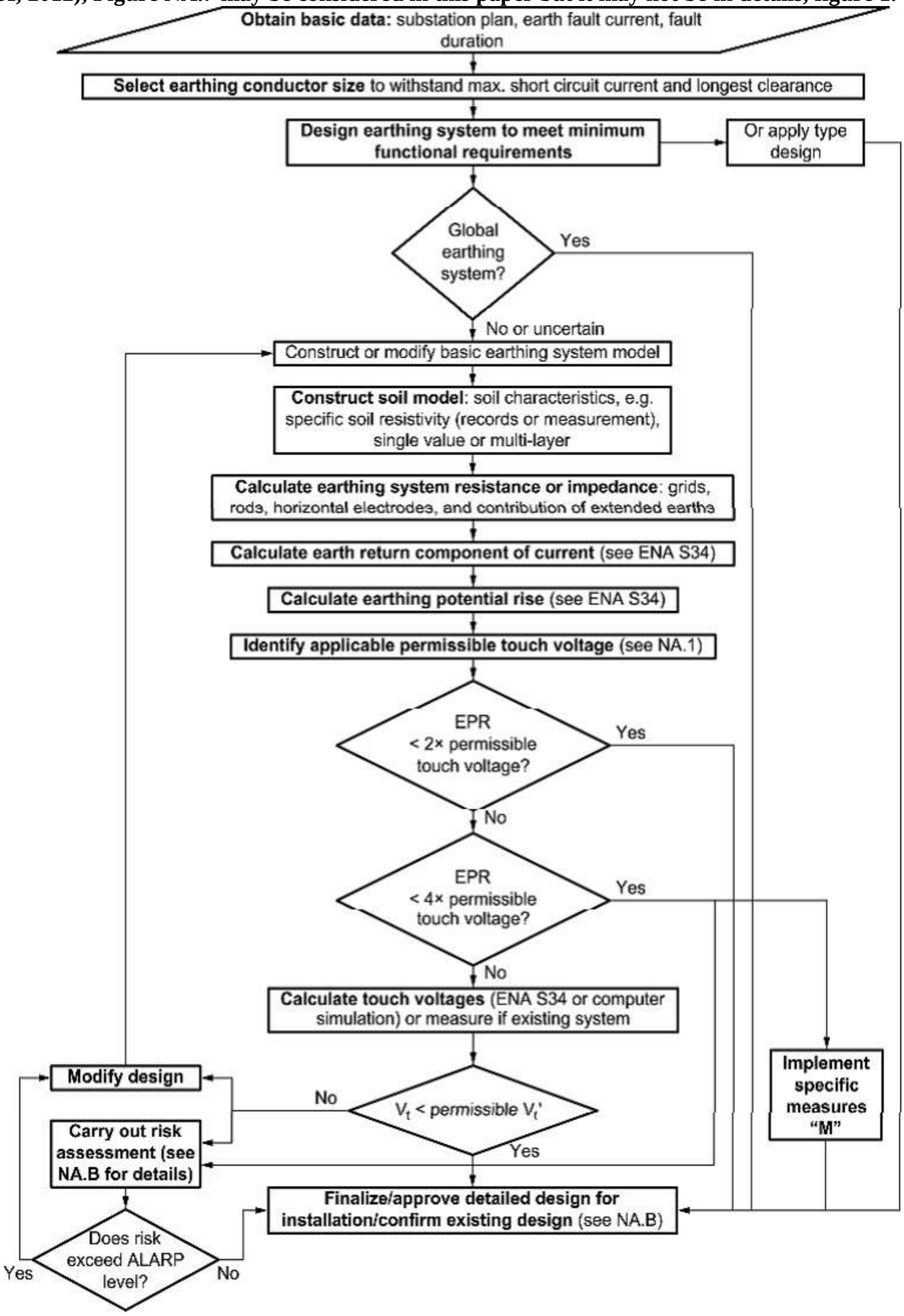


**Figure 1:** Design methodology in BSEN 50522, Figure NA 7

## II. LITERATURE REVIEW:

Lightening can affect overhead lines, either by:
* Direct strike, causing the lightning strike current to travel along the conductors until a route to earth is found.
* An indirect strike where a voltage surge is induced in the line by the magnetic field associated with a strike to an objector ground near the line(McCombe, J. and HAIGH, F. R., 1966).

Neither a direct nor indirect strike to a line will cause conductor damage directly, except in extremely rate rare occasions in the case of a direct strike with a high strike current (>100 kA), where localised heating at the struck point may be sufficient to cause strand failure. This has sufficiently low probability not to be as part of a condition assessment(Goven, 1988).

**2.1 The Standard (Basic) Earth System with Practicable Extensions:**
**Earth Electrode impedances:**
The final earth system impedance for each termination TPA and TPB (Terminal Pole) must not exceed 10 Ω for lightning protection because of the presence of SPD (spectral power distribution) the lightning condition will apply.
A standard minimum earth system for TPA and TPB is shown below:

An earth system will be pole top bonding conductors connected by earth conductors to an arrangement of buried earth conductor that encompasses all 4 poles of the terminal structure by at least 1 metre to ensure that step voltage and any touch potential are reasonably controlled. Four rods of length 2.4m are added at the corners to take the advantage of any better ground below the surface level, improving the high frequency performance for SPD and withstand periodic dry conditions. The outline dimensions will be of the order 5m × 5m. The grid is divided into symmetrical 2.5m square meshes, as in figure 2.

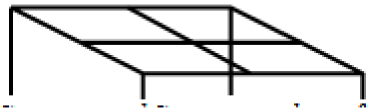

**Figure 2:** The Symmetrical Square meshes of the earth grid

Average effectiveresistivityat electrodedepth forTPA =45 Ω-m
Average effectiveresistivityat electrodedepth forTPB=55 Ω-m
Becauseofthesimilarvaluesasasimplificationtheaveragevaluemaybeusedfor allelectrodescalculations.

$$r = \sqrt{\frac{Area}{\pi}} = \sqrt{\frac{5 \times 5}{\pi}} = 2.82\ m$$

(Theradiusofasolidcircularplatehavingthesame areaas the earthgrid)

$$R_G = \frac{\rho}{4r} + \frac{\rho}{L}$$

Where " ρ "is the soil resistivityin (Ω.m), and Lis thelength of thetotal buried conductors ofthegrid in (m).

$$L = (5 \times 6) + (4 \times 2.4) = 39.6\ m$$

$$R_A = \frac{45}{4 \times 2.82} + \frac{45}{39.6} = 5.125\ \Omega$$

$$R_B = \frac{55}{4 \times 2.82} + \frac{55}{39.6} = 6.265\ \Omega$$

- **Calculation of zero impedance fault at TPA:**

EF current component from direction $A = 3.8\ A$

$$\therefore Z_{SA} = \frac{(132 \times 10^3)/\sqrt{3}}{3.8 \times 10^3} = 20.055\ \Omega$$

EF current component from direction $B = 6.7\ A$

$$\therefore Z_{SB} = \frac{(132 \times 10^3)/\sqrt{3}}{6.7 \times 10^3} = 11.375\ \Omega$$

Combine the two impedances as parallel impedance for a combined source impedance$Z_{ST}$:

$$Z_{ST} = \frac{Z_{SA} \times Z_{SB}}{Z_{SA} + Z_{SB}} = \frac{20.055 \times 11.375}{20.055 + 11.375} = 7.258\ \Omega$$

As a check total EF current $I_{EFT} = \frac{(132\times10^3)/\sqrt{3}}{7.258} = 10499.8 \cong 10.5\ KA$
The earth resistance at terminal "A" $R_A = 5.125\ \Omega$, and that at terminal "B" $R_B = 6.265\ \Omega$
The combined earth resistance:

$$R_{ET} = \frac{5.125 \times 6.265}{5.125 + 6.265} = 2.819\ \Omega$$

The corrected total earth fault current:

$$I_{EFT} = \frac{(132 \times 10^3)/\sqrt{3}}{2.819 + 7.258} = 7562.79 \cong 7.563\ KA$$

Neglecting cable effects, the present day EPR of the cable will be:
$EPR = 7.563 \times 2.819 = 21.32\ KV$
Applying 1.2 factor for the future network:
Future $EPR = 1.2 \times 1.1 \times 21.32 = 28.1424\ KV$
The EPR will obviously need to be reduced to a credible value and since the 132KV cable has not been installed, horizontal electrode could be considered to adjust earth fault current.
Minimum possible earth grid resistances are:

$$R_{A(minimum)} = \frac{45}{4 \times 2.82} = 3.9894\ \Omega$$

$$R_{A(minimum)} = \frac{55}{4 \times 2.82} = 4.876\ \Omega$$

Even it a very extensive (fine mesh) earth grid is installed, the EPR will be high because of high resistance of the electrodes $R_A$ and $R_B$. Thus a horizontal electrode will be considered.

At this moment, cable ducts are installed from terminal pole TPB up to point 50m from TPA. Thus connecting a horizontal electrode to the earth grid of TPA is suitable to reduce the earthing resistance and EPR. The cable terminal TPA will be extended with 50m horizontal electrode buried with cable ducts with cable ducts without suffering time delay. At the same time, the grids at both terminals TPA and TPB will be divided into symmetrical 1 $m^2$ meshes.

- **Calculation of Earthing Conductors Cross-section:**

For fault currents which are interrupted in time (t) less than 5 seconds the cross-section (A) of the earthing conductors or earth electrodes shall be calculated from the following formula (from 60949:1988):

$$A = \frac{I}{K}\sqrt{\frac{t}{ln(\frac{\theta_f + \beta}{\theta_i + \beta})}}$$

Where: I is the required current rating, $\theta_i$ is the initial temperature in C˚, $\theta_f$ is the final temperature in C˚ and the values of K and $\beta$ are constants depending on the conductor material.
BS 7430 recommends the maximum temperature rise of types of joints bolted, brazed or welded. The maximum recommended conductor temperature for a bolted connection is 250 C˚. Using copper conductors to carry fault current of 25kA for 3sec and the initial temperature 30 C˚.
For copper, $K = 226\ A/mm^2$ and $\beta = 234.5\ C^{\circ}$

$$A = \frac{25000 \times 0.7}{226}\sqrt{\frac{3}{ln(\frac{250 + 234.5}{30 + 234.5})}} = 172.4\ mm^2$$

(The cross-section of copper electrodes and conductors in earthing system).

Typically company standards for 132KV plant for 25KA, 3 seconds rating is 40mm × 6mm strip as a single conductor will be used in earth grids in TPA and TPB and in the horizontal electrode in TPA. Figure 3 illustrate the earth electrode at TPA.

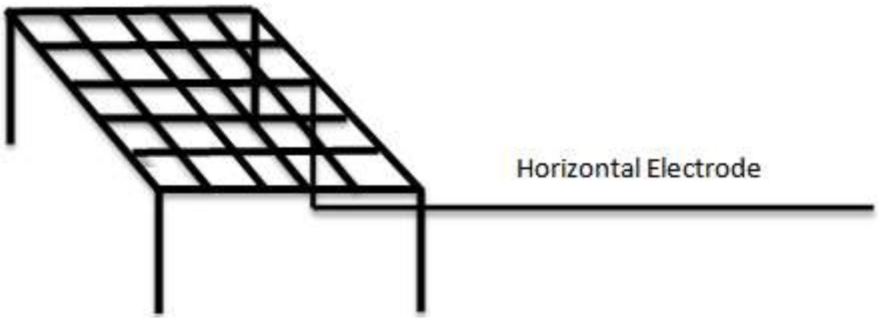


**Figure 3**: Infill Electrode

The resistance of horizontal electrode can be calculated using the following formula:

$$R_{EH} = \frac{\rho}{\pi L}(ln\frac{2L}{d})$$

Where is "$\rho$" the average soil resistivity in (Ω.m), $L$ is the length of earth strip in meters and d is half of the width of a strip conductor in meters. Because of the short cable route, average effective ground resistivity of the cable route may be assumed the average of TPA and TPB measurements.

$$\therefore \rho = \frac{45+55}{2} = 50\ \Omega.m$$

$$R_{EH} = \frac{50}{\pi \times 70}\left(ln\frac{2\times 70}{0.04/_2}\right) = 2.013\ \Omega$$

In this case, will:

$$L = (6\times 5 + 6\times 5) + (4\times 2.4) = 69.6\ m$$

$$\therefore R_{AG} = \frac{45}{4\times 2.82} + \frac{45}{69.6} = 4.63\ \Omega$$

$$\therefore R_{BG} = \frac{55}{4\times 2.82} + \frac{55}{69.6} = 5.67\ \Omega$$

$$R_A = \frac{R_{AG}\times R_{EH}}{R_{AG}+R_{EH}} = \frac{4.63\times 2.013}{4.63+2.013} = 1.4\ \Omega$$

$$R_B = R_{BG} = 5.67\ \Omega$$

The combine earth resistance $R_{ET} = \frac{R_A\times R_B}{R_A+R_B} = \frac{1.4\times 5.67}{1.4+5.67} = 1.123\ \Omega$

The corrected total Earth Fault Current ( $I_{EFT}$):

$$I_{EFT} = \frac{V_{ph}}{Z_{ST}+R_{ET}} = \frac{132\times 10^3/\sqrt{3}}{7.258+1.123} = 9.093\ KA$$

With neglecting cable effects, the present EPR of the cable will be:

$$EPR = I_{EFT}\times R_{ET} = 9.093\ \times 1.123 = 10.211\ KV$$

- **Applying 1.2 factor for future current:**

$$EPR = 1.2\times 1.1\times 10.211\ = 13.4785\ KV$$

Adjust Earth Fault Current sources:

$$future\ total\ earth\ fault\ current = 1.2\times 10.5 = 12.6\ KA$$

$\therefore$ Future total sources $Z_{SB} = \frac{132\times 10^3/\sqrt{3}}{12.6\times 10^3} = 6.05\ \Omega$

- **Future source terminal A and B:**

$$Z_{SA2} = Z_{SA1}\times\frac{Z_{SB}}{Z_{ST}} = 20.055\ \times\frac{6.05}{7.258} = 16.717\ \Omega$$

$$Z_{SB2} = Z_{SB1}\times\frac{Z_{SB}}{Z_{ST}} = 11.375\ \times\frac{6.05}{7.258} = 9.482\ \Omega$$

For checking future source total impedance:

$$Z_{ST2} = \frac{Z_{SA2}\times Z_{SB2}}{Z_{SA2}+Z_{SB2}} = \frac{16.717\ \times 9.482}{16.717\ + 9.482} = 6.05\ \Omega$$

1- **Cable calculation:**

The type of 132KV cable circuit will have a major impact on the design of the associated cable terminal earth systems. The circuit cables laid for 500m in 200 ducts between TPA and TPB. The ducts are laid in trefoil in trench 2m deep as in figure 4.

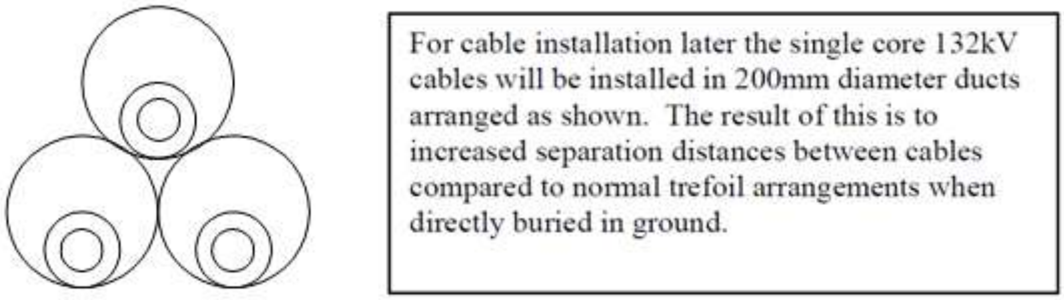


**Figure 4**: Cable Details

The calculation method is based on procedure in ENA S34. First, we need to calculate self-impedance of the cable sheath for an average effective ground resistivity of the cable route( $\rho$).The average ( $\rho$) of TPA and TPB resistivity is measure, because of short cable route.

$\therefore \rho = \dfrac{45+55}{2} = 50\ \Omega/m$

Self-impedance of the three cable sheaths $Z_{CS,S}$ :

$$Z_{CS,S} = R_{CS} + \left[5\pi^2 + (j20\pi \times ln\frac{S_e}{d_m}\right] \times 10^{-3}\ \Omega/Km$$

When $S_e$ is earth return distance in ground $= 9.32\sqrt{\rho(\Omega.m)} = 9.32\sqrt{50} = 659\ \Omega.m$

"$d_m$" Geometrical mean radius of the three cable sheaths (GMR).

"GMR" of the three single core cable sheaths $\sqrt[3]{GMR_1 \times GMD_1{}^2}$

$GMR_1$ Average screen radius = 46.1 mm = 0.0461 m

$GMD_1$ Of the three single core cable sheaths $\sqrt[3]{D_{1-2} \times D_{2-3} \times D_{1-3}} = D = 200mm \cong 0.2m$

$GMR = \sqrt[3]{0.0461 \times 0.2^2} = 0.1226\ m$

$$\therefore\ Z_{CS,S} = 0.0218 + \left[5\pi^2 + (j20\pi \times ln\frac{659}{0.1226}\right] \times 10^{-3}$$

$Z_{CS,S} = 0.0218 + [5\pi^2 + (539.697] \times 10^{-3}$

$Z_{CS,S} = 0.0218 + [541.9488\lfloor 84.78^\circ] \times 10^{-3} = 0.544\lfloor 82.49^\circ\ \Omega/Km$

$Z_{CS,S} = 0.544\lfloor 82.49^\circ\ \times 0.5 = 0.272\lfloor 82.49^\circ = 0.0356 + j0.2697\ \Omega$

Also the mutual impedance between phase and cable sheaths$Z_{P-CSM}$:

$Z_{P-CSM} = \left[5\pi^2 + (j20\pi \times ln\dfrac{S_e}{d_m}\right] \times 10^{-3}\ \Omega/Km$

Where $d_m$ = geometrical mean distance between a phase conductor and the three cable sheaths (GMD).

$GMD$ Of the three single core cable sheaths $\sqrt[3]{D_{1-2} \times D_{2-3} \times D_{1-3}} = D = 200mm \cong 0.2m$

$Z_{P-CSM} = \left[5\pi^2 + (j20\pi \times ln\dfrac{659}{0.2})\right] \times 10^{-3} = 0.511\lfloor 84.46^\circ = 0.04935 + j0.5089\ \Omega/Km$

$\therefore Z_{P-CSM} = 0.511\lfloor 84.46^\circ\ \times 0.5 = 0.02467 + j0.2543 = 0.256\lfloor 84.46\ ^\circ\ \Omega$

The TPA and TPB ($R_A$ and $R_B$) earth system will be connected via three single core cable sheaths as illustrate in figure 5. An earth fault can occur in the cable section, in the terminal tower TPA or TPB and external on the line at other earthed points near source A or B.

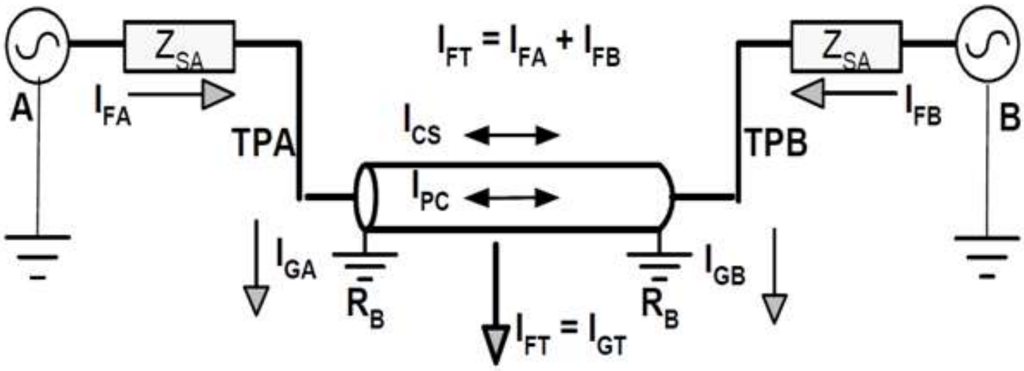


**Figure 5:** The Circuit connection between the two stations A and B

The total fault current $I_{FT}$ is calculated with components from source "A" $I_{FA}$ and source "B" $I_{FB}$. Depending on where an earth fault (EF) occurs, components of the total fault current $I_{FT}$ will flow in a phase conductor $I_{PC}$, cable sheaths $I_{CS}$ and ground $I_{GA}$ and $I_{GB}$ in electrodes in $R_A$ and $R_B$ and there will be different levels of EPR.

In fact, a fault on TPA or TPB will produce the most onerous EPR conditions and a lower EPR effect can be produced by an internal cable fault. An external earth fault will generally produce a lower fault current in one of

the cable phases and a lower EPR caused by induced current flowing in the cable sheath.

The diagram (Figure 6) describe below the equivalent three cable sheaths with electrode at each terminal pole coupled to the particular phase conductor that may carry earth fault current with a self-impedance and a mutual impedance.

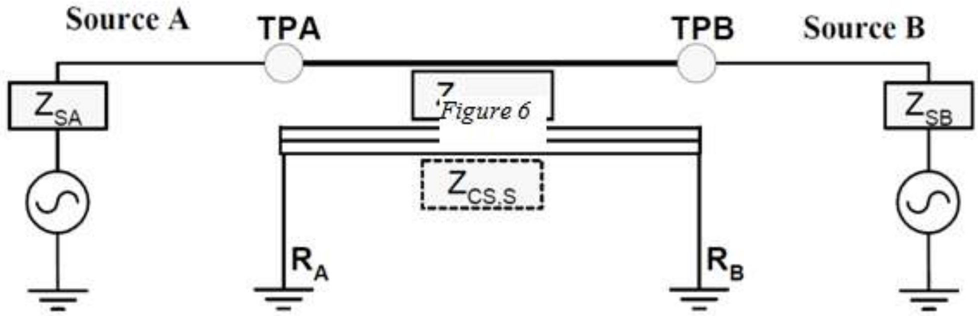


Figure 6

Fault current distribution can be analysed by treating the A and B source of fault current independently. For a fault at one end of the cable such as TPB, the ground current in the electrode $R_B$ can be treated as two superimposed currents (using superposition theorem). One current will be the ground current from source "A" $I_{FAGB}$ in electrode $R_B$ with source "B" replaced by its source impedance as in figure 7.

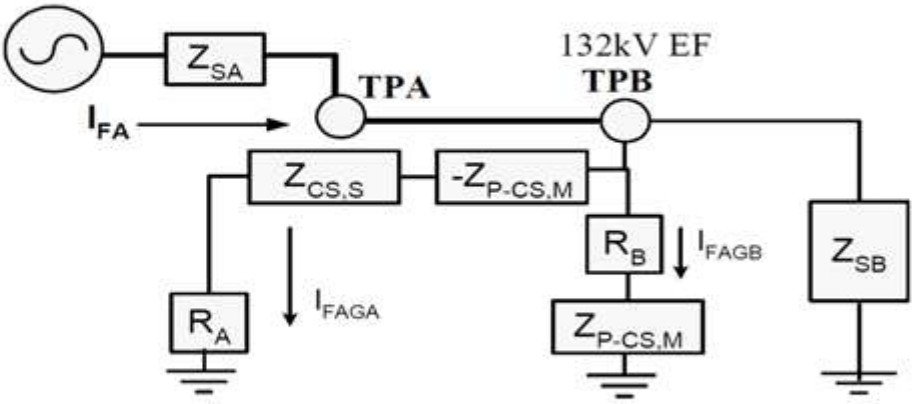


**Figure 7:** The source A in electrode at TPB

The other current will be the ground current from source "B" $I_{FAGB}$ in $R_B$ with source "A" replaced by its source impedance as in figure 8. Currents in $R_B$ from source "A" and source "B" can be added to provide the total fault ground current through the electrode $R_B$ and then EPR at TPB can be calculated. In the similar way, the total fault ground current in electrode $R_A$ can be calculated and then EPR at TPA can be calculated.

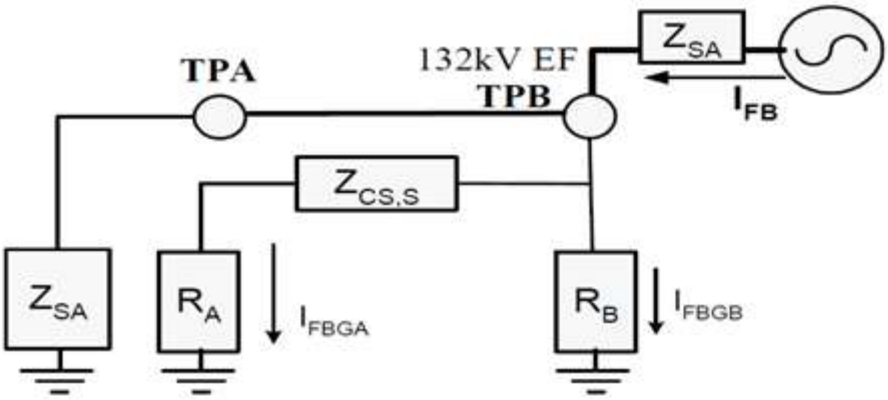


**Figure 8**: The source B in electrode at TPA

1) **The fault at TPA:**

A fault at TPA with Source "B" fault current will pass source "B" current via the cable phase to the remote end fault with mutual impedance to cable sheaths. The fault impedance from TPA to ground has three parallel branches as describe below.

$$\frac{1}{Z_{F-GB}} = \frac{1}{1.4} + \frac{1}{0.0356 + j0.2697 - 0.02467 - j0.2534 + 5.67} + \frac{1}{16.717} = 0.95 - j0.0005\ m\Omega$$

$$Z_{F-GB} = \frac{1}{0.95 - j0.0005} = 1.0525 + j0.0006 \cong 1.0525\ \Omega$$

The total fault current from source:

$$I_{FB} = \frac{V_{Ph}}{Z_{SB} + Z_{F-GB}} = \frac{132 \times 10^3 / \sqrt{3}}{9.482\ + 1.0525} = 7.234\ KA$$

$$EPR_{A1}(TPA) = I_{FB} \times Z_{F-GB} = 7.234\ \times 1.0525 = 7.614\ KV$$

Current from source B in electrode $R_A$:

$$I_{FA1} = \frac{EPR_{A1}}{R_A} = \frac{7.614}{1.4} = 5.44\ KA$$

A fault at TPA with Source "A" fault current will not pass source "A" current via the cable phase to the fault end and there is no mutual impedance coupling to cable sheaths. The fault impedance from TPA to ground has three parallel branches as shown below.

$$\frac{1}{Z_{F-GA}} = \frac{1}{1.4} + \frac{1}{0.0356 + j0.2697 + 5.67} + \frac{1}{9.482} = 0.995 - j0.0083\ m\Omega$$

$$Z_{F-GA} = \frac{1}{0.995 - j0.0083} = 1.005 + j0.008355 \cong 1.005\ \Omega$$

The total fault current from source:

$$I_{FA} = \frac{V_{Ph}}{Z_{SA} + Z_{F-GA}} = \frac{132 \times 10^3 / \sqrt{3}}{16.717 + 1.005} = 4.3\ KA$$

$$EPR_{A2}(TPA) = I_{FB} \times Z_{F-GB} = 4.3 \times 1.005 = 4.3215\ KV$$

Current from source B in electrode $R_A$:

$$I_{FA2} = \frac{EPR_{A1}}{R_A} = \frac{4.3215}{1.4} = 3.0868\ KA$$

2) **The fault at TPB:**

A fault at TPB with Source "A" fault current will pass source "A" current via the cable phase to the fault end and there is mutual impedance coupling to cable sheaths. The fault impedance from TPA to ground $Z_{F-GA}$ has three parallel branches as describe blow.

$$\frac{1}{Z_{F-GB}} = \frac{1}{5.67} + \frac{1}{0.0356 + j0.2697 - 0.02467 - j0.2543 + 1.4} + \frac{1}{9.482} = 0.971 - j0.0077\ m\Omega$$

$$Z_{F-GB} = \frac{1}{0.971 - j0.0077} = 1.009 + j0.0079 \cong 1.009\ \Omega$$

Total fault current from source "A":

$$I_{FB} = \frac{V_{Ph}}{Z_{SA} + Z_{F-GA}} = \frac{132 \times 10^3 / \sqrt{3}}{16.717 + 1.009} = 4.299\ KA$$

$$EPR_{B1}(TPB) = I_{FA} \times Z_{F-GA} = 4.299\ \times 1.009 = 4.34\ \mathrm{K}V$$

Current from source A in electrode $R_B$:

$$I_{FB1} = \frac{EPR_{B1}}{R_B} = \frac{4.34}{5.67} = 0.765\ KA$$

A fault at TPB with Source B fault current will not pass source B current via the cable phase to the fault end and there is no mutual impedance coupling to cable sheaths. The fault impedance from TPB to ground has three parallel branches as illustrate below.

$$\frac{1}{Z_{F-GB}} = \frac{1}{5.67} + \frac{1}{0.0356 + j0.2697 + 1.4} + \frac{1}{16.717} = 0.909 - j0.126\ \Omega$$

$$Z_{F-GB} = \frac{1}{0.909 - j0.126} = 1.079 + j0.15 = 1.079\ \Omega$$

Total fault current from source "B":

$$I_{FA} = \frac{V_{Ph}}{Z_{SB} + Z_{F-GB}} = \frac{132 \times 10^3 / \sqrt{3}}{9.482 + 1.079} = 7.216\ KA$$

$$EPR_{B2}(TPB) = I_{FA} \times Z_{F-GA} = 7.216 \times 1.079 = 7.786\ KV$$

Current from source B in electrode $R_B$:

$$I_{FB2} = \frac{EPR_{B2}}{R_B} = \frac{7.786}{5.67} = 1.373\ KA$$

∴ Total current in $R_A$ is:

$$I_{FAT} = I_{FA1} + I_{FA2} = 5.44\ + 3.0868 = 8.5268\ KA$$

∴ Total current in $R_B$ is:

$$I_{FBT} = I_{FB1} + I_{FB2} = 0.765 + 1.373\ = 2.138\ KA$$

**∴ The EPR at (TPA) and EPR at (TPB):**

$$\therefore EPR\ at\ (TPA) = I_{FAT} \times R_A = 8.5268\ \times 1.4 = 9.9268\ KV$$

$$EPR\ at\ (TPB) = I_{FBT} \times R_B = 2.138 \times 5.67 = 12.12246\ KV$$

2- **Identification of permissible touch voltage:**

The permissible touch voltage can be identified from figure NA.2. The permissible touch voltage, with additional resistance 2150Ω and protection will not exceeding 200msec to operate and disconnect the fault point from source, is 1570V.

According to the design methodology in BSEN 50522 (Figure NA.7), the earthing system design can be finalized when EPR permissible touch voltage. But I could not achieve that with an earth grid of dimensions 5m × 5m. Also running of parallel horizontal conductors in cable ducts can be considered, but these would be close together then there would be the problem of overlapping in addition of minor effect on the resistance and then on the EPR. Parallel horizontal electrodes normally have significant overlap of resistance area and not effective to reduce resistance. Ideally to be effective to reduce resistance parallel electrodes should be separated by their parallel lengths.

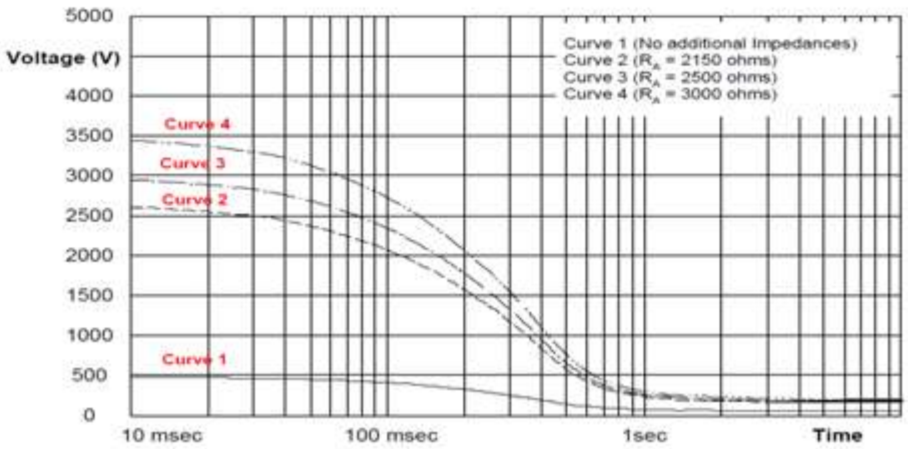


**Figure 9:** Figure NA.2 UK Permissible Touch voltages with Additional Resistances

Also from figure NA.5: the permissible step voltage, with additional resistance of 8600Ω and protection will not exceed 200msec, is 130kV.

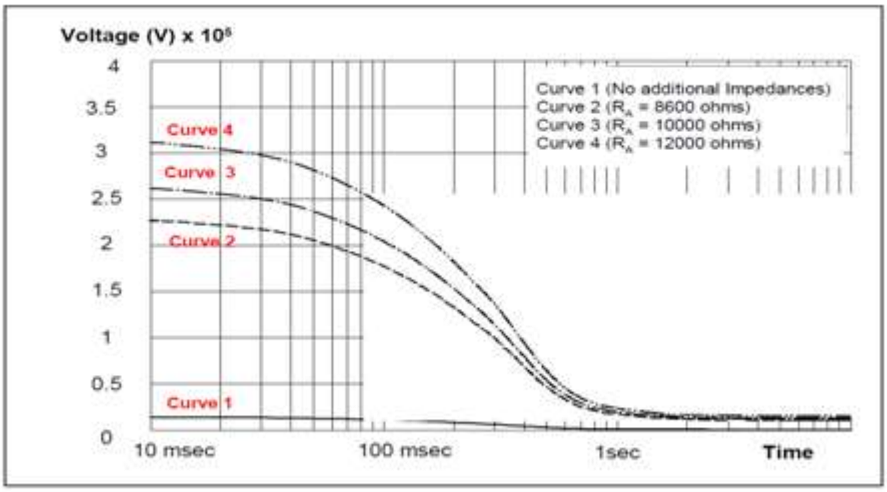


**Figure 10:** Figure NA.5 UK Permissible Step voltages with Additional Resistances

**a) Calculation of touch voltages:**

UK practice uses the following formula to calculate the touch voltage ( $V_T$):

$$V_T = \frac{\rho V}{\pi R L}\left[\left(ln\sqrt{\frac{h}{d}}\right) + \left(\frac{1}{2h} + \frac{1}{D+h} + \frac{1-0.5^{n-2}}{D}\right)\right]K_i$$

Where: $\rho$ effective ground resistivity (Ω.m)
V = EPR
R = Earth grid resistance (Ω)
L = total length of buried conductor (m)
D = spacing between buried parallel conductors (m)
d = diameter of buried conductors or equivalent (d = width/π) (m)
h = depth of the earth grid (m)
n = number of paralleled buried conductors
$K_i = (0.15n + 0.7 = 1.6)$ (UK practice)

$n = 6, and\ d = \frac{40}{\pi} = 12.7mm$

L = the total length of electrode in the grid, excluding rods. (The rods are included in$K_i$)

$L = (6 \times 5) + (6 \times 5) = 60\ m$

- **Touch voltage at TPA and TPB:**

$$V_{TA} = \frac{45 \times 9.9268 \times 10^3}{\pi \times 4.63 \times 60}\left[\left(ln\sqrt{\frac{0.6}{0.0127}}\right) + \left(\frac{1}{2 \times 0.6} + \frac{1}{1 + 0.6} + \frac{1 - 0.5^4}{1}\right)\right] \times 1.6 = 3540.75\ \ volt$$

$$V_{TB} = \frac{55 \times 12.12246 \times 10^3}{\pi \times 5.67 \times 60}\left[\left(ln\sqrt{\frac{0.6}{0.0127}}\right) + \left(\frac{1}{2 \times 0.6} + \frac{1}{1 + 0.6} + \frac{1 - 0.5^4}{1}\right)\right] \times 1.6 = 4315.43\ \ volt$$

**b) Calculation of Step Voltage:**

The calculation of step voltage $V_s$ is based on the definition that this is the voltage over 1m of surface diagonally outwards from a corner of a grid. The expression used in BS7354 is:

$$V_s = \frac{\rho V}{\pi RL}(\frac{1}{2h} + \frac{1}{D + h} + \frac{1 - 5^{n-2}}{D})K_i$$

The parameters of this expression are the same as that for the touch voltage.

- **Step voltage at TPA and TPB:**

$$V_{SA} = \frac{45 \times 9.9268 \times 10^3}{\pi \times 4.63 \times 60} \times \left(\frac{1}{2 \times 0.6} + \frac{1}{1 + 0.6} + \frac{1 - 0.5^4}{1}\right) \times 1.6 = 1.962\ KV$$

$$V_{SB} = \frac{55 \times 12.12246 \times 10^3}{\pi \times 5.67 \times 60} \times \left(\frac{1}{2 \times 0.6} + \frac{1}{1 + 0.6} + \frac{1 - 0.5^4}{1}\right) \times 1.6 = 2.396\ \text{K}V$$

- **Calculation of the "hot zone":**

Hemispherical formula will be used to calculate the hot zone contour around an earth grid.

For the 132kV system, the hot zone is defined by a 1700V ground contour ($V_s = 1700\ V$) at a distance X from the footprint of the earth grid.

$$V_X = \frac{r}{X}EPR$$

That $V_X$ Is the voltage on the ground surface outside the electrode at a point X from the centre of the electrode.

$V_X = 1700V$ For the 132kV hot zone contour calculations.

r = radius of hemispherical electrode.

EPR = Earth Potential Rise

For an electrode of resistance (resistance of the earth grid)$R_E$:

$$r = \frac{\rho}{2\pi R_E}$$

**1- At TPA:**

$$r = \frac{45}{2 \times \pi \times 4.63} = 1.5469\ m$$

$$V_X = \frac{r}{X}EPR$$

$$1700 = \frac{1.547}{X} \times 9.9268 \times 10^3$$

$$\therefore X = \frac{1.547}{1700} \times 9.9268 \times 10^3 = 9.03\ m$$

The radius of hot zone contour from the centre of TPA earth grid.

The hot zone of the earth grid at TPA will not reach the roadway or buildings because they are a distance 150m from TPA.

**2- At TPB:**

$$r = \frac{55}{2 \times \pi \times 5.67} = 1.5433\ m$$

$$V_X = \frac{r}{X}EPR$$

$$1700 = \frac{1.5433}{X} \times 12.12246\ \times 10^3$$

$\therefore X = \frac{1.5433}{1700} \times 12.12246 \times 10^3 = 11\, m$

The radius of hot zone contour from the centre of TPB earth grid.

The hot zone of earth electrode at TPB will not arrive the building in industrial area A because TPB is 60m from the nearest building. Also the hot zone of TPB will not reach the industrial area B because it is at 18m from the security metal fence of this area.

3- **Potential gradients above and near buried Horizontal Electrode:**

There is formula in BS7430 cover "n" horizontal electrodes for appropriate calculations and for a single conductor this formula becomes:

$$E_P = \frac{2\, ln(v_i + \sqrt{(v_i{}^2 + 1)}}{ln(\frac{L^2}{hd})}$$

When $v_i = \frac{L}{2(h^2+r^2)}$

Where:

$E_P$ is the potential rise of the ground surface at a point "P" as per unit value of electrode potential rise EPR, "L" is the length of horizontal electrode (in m), "r" is the distance from the ground surface vertically above the conductor centre to point p on the ground surface (in m) at right angles to conductor, "d" is the equivalent diameter of horizontal electrode (in m) $= 2\omega/\pi$, "$\omega$" is the width of strip conductor and "h" is the depth of conductor from the ground surface vertically above it.

The horizontal electrode is used at TPA only.

$E_P$= EPR at TPA =16.265kV

The total length of the horizontal electrode is 70m and it consists from two parts as it is shown in figure 11.

For the part of 10m length:

$L = 10\, m$

$h = 2.4 + 0.6 = 3\, m$

$d = 2\frac{\omega}{\pi} = \frac{2 \times 0.04}{\pi} = 0.02456\, m$

$r$ Is the centre point of TPA that a distance 150 m from the roadside.

$$v_i = \frac{L}{2\sqrt{(h^2 + r^2)}} = \frac{10}{2 \times \sqrt{(3^2 + 150^2)}} = 0.033$$

$$E_P = \frac{2\, ln(v_i + \sqrt{(v_i{}^2 + 1)}}{ln\left(\frac{L^2}{hd}\right)} = \frac{2\, ln(0.033 + \sqrt{(0.033^2 + 1)}}{ln\left(\frac{10^2}{3 \times 0.02546}\right)} = 0.0092\ p.u.$$

$\therefore$ The voltage at the road side $= 0.0092 \times 9.9268 \times 10^3 = 91.33\ volt$

And for the part of 40m length:

$L = 60\, m$

The industrial area A is at a distance of 150m from the horizontal electrode (r = 150m).

$$v_i = \frac{L}{2\sqrt{(h^2 + r^2)}} = \frac{60}{2 \times \sqrt{(3^2 + 150^2)}} = 0.19996$$

$$E_P = \frac{2\, ln(v_i + \sqrt{(v_i{}^2 + 1)}}{ln\left(\frac{L^2}{hd}\right)} = \frac{2\, ln(0.033 + \sqrt{(0.033^2 + 1)}}{ln\left(\frac{60^2}{3 \times 0.02546}\right)} = 0.00613\ p.u.$$

$\therefore$The voltage at the nearest building in the industrial area A

$$= 0.00613 \times 9.9268 \times 10^3 = 60.85\ volt$$

The hot zone of the horizontal electrode will not reach the roadway or buildings in the industrial area.

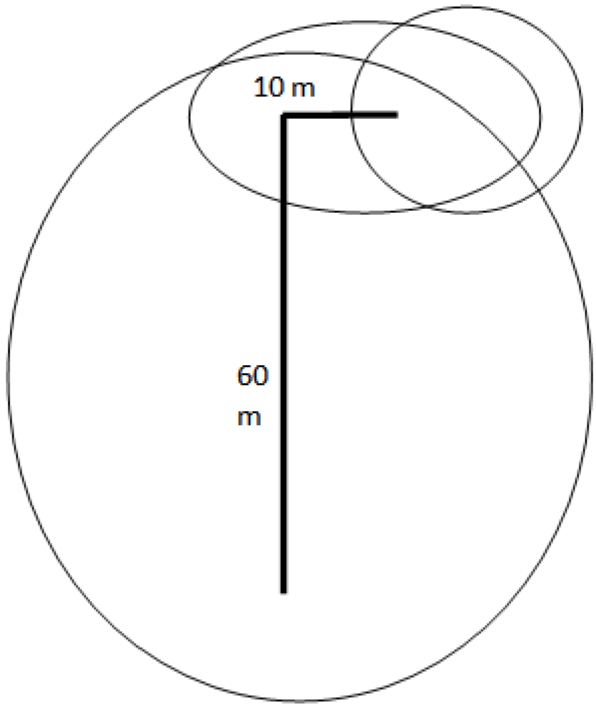


**Figure 11**: The Hot Zone Contours at TPA

4. Special Considerations:

At both TPA and TPB locations, the stay wires are within the hot zone because the distance from the earth electrode and the grounded terminals of the stay wires is 14m.

At TPA location, the centre point of the 4 poles of TPA is a distance 150m from nearest building in industrial area A and 150m from roadside. Thus using hemispherical formula to calculate the voltage gradients at these locations:

$$V_X = \frac{r}{X} EPR$$

From nearest building in industrial area A:

$$\therefore V_{150} = \frac{1.5469}{150} \times 9.9268 \times 10^3 = 102.37 \ volt$$

From roadside area A:

$$and \ \ V_{150} = \frac{1.5469}{150} \times 9.9268 \times 10^3 = 102.37 \quad volt$$

At TPB location, the centre point of the 4 poles of TPB is a distance 60m from nearest building in industrial area A and 18m from the metal security fence of industrial area B.

From nearest building in industrial area A:

$$\therefore V_{60} = \frac{1.5469}{60} \times 12.12246 \times 10^3 = 312.54 \ volt$$

From the metal security fence of industrial area B:

$$and \ \ V_{18} = \frac{1.5469}{18} \times 12.12246 \times 10^3 = 1014.79 \ volt$$

Thus all these locations are out of hot zone of the earth grid.

**5. Transferred voltage and current to Low Voltage equipment:**

The SSB will have electrode which is used to earth 11kV equipment and the LV neutral. There are no service or LV supply points are located near TPA while TPB is 100m from the nearest 11kV/LV distribution substation SSB.

Assuming a reasonable maximum value for the remote electrode of 10Ω at SSB which is used to earth the LV neutral.

The following diagram Figure 12 shows two separated electrodes $E_1$ of TPB and $E_2$ of SSB with a voltage $V_{2OC}$ appearing on the LV neutral point earth electrodes as an open circuit voltage.

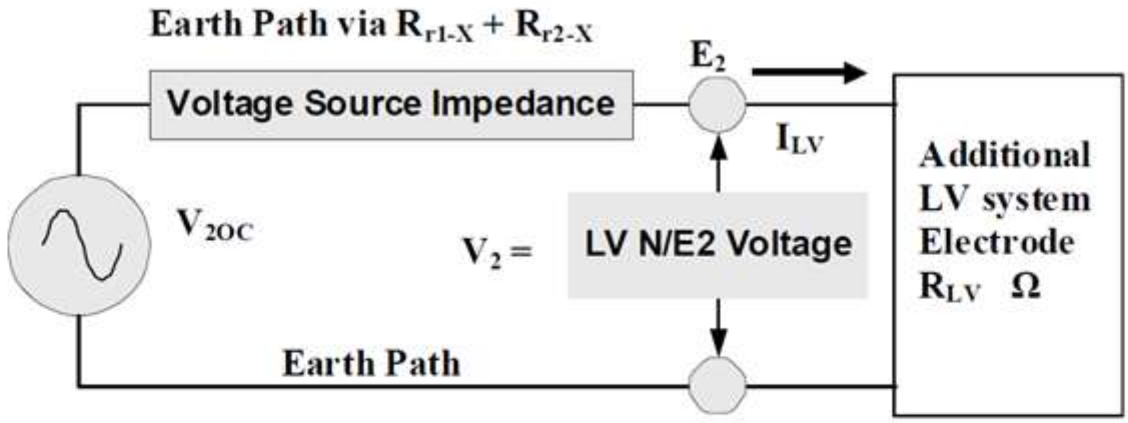


**Figure 12:** Circuit of Separated Electrodes E_1 of TPB and E_2 of SSB

Using hemispherical formula to calculate the open circuit voltage $V_{2OC}$ at the LV electrode $E_2$ because an earth fault at TPB of an earth electrode $R_B$.

$$V_X = \frac{r}{X} EPR$$

$$\therefore V_{2OC} = \frac{1.5469}{100} \times 12.12246 \times 10^3 = 187.5\ volt$$

The resulting voltage ($V_{2OC} = 187.5\ volt$) will be impressed on the LV neutral point and on protective conductors of the small isolated LV systems.

The resistance of the LV electrode $E_2 = 10\ \Omega$:

$$r = \frac{\rho}{2\pi R_E}$$

Radius of hemispherical electrode $E_1$at TPA:

$$r_1 = \frac{45}{2 \times \pi \times 4.63} = 1.5469\ m$$

Radius of hemispherical electrode $E_2$ at SSB:

$$\therefore r_2 = \frac{50}{2 \times \pi \times 10} = 0.796\ m$$

$X_1$: Distance $E_1$ to overlap point X with $E_2$:

$$X_1 = \frac{S}{1 + \frac{r_2}{r_1}}$$

When S is the centre to centre separation distance between electrodes $E_1$ and $E_2$:

$$X_1 = \frac{100}{1 + \frac{0.796}{1.5469}} = 66.025\ m$$

$X_2$: Distance $E_2$ to overlap point X with $E_1$:

$$X_1 = \frac{100}{1 + \frac{1.5469}{0.796}} = 33.975\ m$$

Resistance between electrode $E_1$ and overlap point X:

$$R_{r1-X} = R_{E1}\left(1 - \frac{r_1}{X_1}\right) = 5.67\ \left(1 + \frac{1.5469}{66.025}\right) = 5.8\ \Omega$$

$$R_{r2-X} = R_{E2}\left(1 - \frac{r_2}{X_2}\right) = 10\ \left(1 + \frac{0.796}{33.975}\right) = 10.234\ \Omega$$

The Total resistance between $E_1$ and $E_2$ :

$$R_{r1-X} + R_{r2-X} = 5.8 + 10.234 = 16.034\ \Omega$$

## III. CONCLUSIONS:

**-Sufficient Earth Electrode for Ground Current Rating:**

There is a formula in BS7340, BS 7354 and EA TS 41 – 24 to calculate the sufficient of the earth electrode for current rating. This formula depends on calculating of the current density taking into consideration resistivity of the ground and duration of current in the electrode. This formula as follows:

$J = 10^3 \sqrt{\frac{57.7}{\rho t}}$

Where: J= current density in the electrode ($A/m^2$).

$\rho$ = ground resistivity ($\Omega.m$)

t = duration of fault current in the electrode (seconds).

- **At TPA:**

$J = 10^3 \sqrt{\frac{57.7}{45 \times 3}} = 653.76 \ A/m^2$

Total earth fault current at TPA:

$$I_{FAT} = 8.5268 \text{ KA}$$

The current in the horizontal electrode:

$$I_{HE} = 8.5268 \times \frac{4.63}{4.63 + 2.013} = 5.94 \text{ KA}$$

The current in earth grid of electrode at TPA:

$$I_G = 8.5268 - 5.94 = 2.58 \text{ KA}$$

For 1 meter length of the electrode:

$I_{1m} = 1 \times 2 \times (0.04 + 0.006) \times 653.76 = 60.1459$ A

The length of the buried conductors in the grid only:

$L = (12 \times 5) + (4 \times 2.4) = 69.6$ m

$I = 69.6 \times 60.1459 = 4186.15$ A (Less than $I_G$ ).

The horizontal electrode:

$I = 70 \times 60.1459 = 4211.76$ A (Less than $I_{HE}$ ).

**The result:**

The size of 40mm × 6mm Earth Electrode at TPA is sufficient for ground current rating for the grid, however it is required to increase the electrode size for the horizontal electrode.

- **At TPB:**

The total earth fault current at TPB: 2.138 KA

$J = 10^3 \sqrt{\frac{57.7}{55 \times 3}} = 591.352 \ A/m^2$

The ground current for the electrode at TPB:

$I_{GB} = 69.6 \times 2 \times (0.04 + 0.006) \times 591.352 = 3786.545$ A(Bigger than earth fault current)

**The result:**

The size of Earth Electrode (40mm × 6mm) at TPB is adequate for ground current rating.

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