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HV substation earth grid commissioning using current injection test (CIT) method: Worst case scenario determination

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Abstract
The existing of the High Voltage (HV) infrastructure creates a unique set of safety circumstances. The earthing system is one of the main elements to mitigate any unsafe conditions. Commissioning the earth grid certifies that the implemented system fulfills to the pertinent necessities. This paper endeavors to present vital information on how to perform the earth grid commissioning of an HV infrastructure. This paper will minutiae the minimum needs to guarantee the test will symbolize the actual fault case that the design was based on. A flow chart diagram is established and presented in this paper, which allows the determination of the most suitable injection route. The results of the case study are discussed, and the results are shown in this paper.

Keywords: Earth grid; EPR, Fault current distribution; High voltage; OHEW; Split factor; Transmission mains earth grid.

1. Introduction
Electrical infrastructure upgrade is required to meet the demands increase. The upgrade could be in the form of refurbishing existing infrastructure or installing an additional one. The new infrastructure involves the installation of new transmission lines and new substations. These new assets could be located within proximity to the residential area. Also, part of these infrastructures could be accessible to the generic public. Mishandling HV infrastructure can cause damages to properties and may inflict injuries and be fatal. High voltage infrastructure necessitates earthing design to guarantee the safety and the acquiescence of the system to confined standards and regulations. Earthing system presents a safe working environment for workers and people passing by during a fault or malfunction of the power system.
During the design stage of the earth grid, the designer collects all the possible information from soil resistivity, services in the area, and the layout of the proposed substation. This information may not be very accurate thus it will not symbolize the real case. For example, it is hard to obtain an accurate soil resistivity structure to represents the local area. Therefore, numerous designers follow the single layer structure approach, while others follow the two-layer soil structure approach [1, 2]. The output of these two approaches provides a slightly different earthing system data. Also, within a developed area, it is not possible for the designer to capture the entire existing infrastructure during the design stage. This condition forces the requirements to commissioning the design earthing grid prior the commissioning of the HV infrastructure. During the earthing system commissioning, the tester simulates the actual fault

that represent the worst case scenario. The low-frequency current injection test is used to commissioning and test the integrity of the installed earthing system [3].

The current injection test simulates a fault condition by injecting an offset frequency [4]. It is important to choose the injection path where the worst case scenario is presented. The works in [5] show the critical of the injection path. Also, the works show the critical of the overhead earth wire (OHEW) when it comes to fault current distribution.

The works in this paper endeavour to provide information in regards to the fault current distribution under substation fault, as well as feeder fault. This information helps determining the injection path that represents the worst case scenario. The correct path ensures accurate measurements for the step, touch and transfer voltages. A case study is included.

2. Theoretical study

The works in this paper enhances the CIT diagram as per [5]. The updated diagram is shown in Figure 1. The works in this section focus on the analysing the fault current distribution to determine the correct path that represents the worst case scenario. The CIT is based on injecting current and measure the voltage rise due to the injection current magnitude. Figure 2 represents the CIT injection circuit.

Under substation fault and the presence of the auxiliary path, the fault current splits into two sub-currents [6]:

- Substation grid current
- Auxiliary path current

2.1 Substation current

Equation 1 represents the substation current under the presence of the auxiliary path:

$$I_g = I_f \delta_f \tag{1}$$

where: I_g is the substation grid current, I_f is the fault current, δ_f is the split factor as defined in equation 2 [7].

$$\delta_f = \frac{\left(1 - \frac{z_{gw}}{z_s}\right) Z_{OHEW-in}}{Z_{OHEW-in} + Z_g} \tag{2}$$

where: z_{gw} is the mutual impedance between the faulted phase and the auxiliary path, z_s is the auxiliary path self-impedance, Z_g is the faulted substation earth grid resistance, $Z_{OHEW-in}$ the input impedance of the auxiliary path.

Figure 3 shows the split current circuit under the presence of the OHEW. The input impedance of the OHEW depends on its condition:

- Finite or Infinite Line
- Continuous or non-continuous line

Under a finite system, the source substation grid resistance is taken into consideration during the calculations of the input impedance. Based on existing research, the infinite length of the OHEW can be found using equation 3 [8].

$$l\sqrt{\frac{z_s}{z_p}} \succ 2 \tag{3}$$

where: z_s is defined by $z_s = \frac{Z_s}{L_s}$, z_p is defined by $z_p = Z_p L_s$, Z_p is the pole grid resistance in ohms, Z_s is the OHEW self-impedance per span length in ohms.

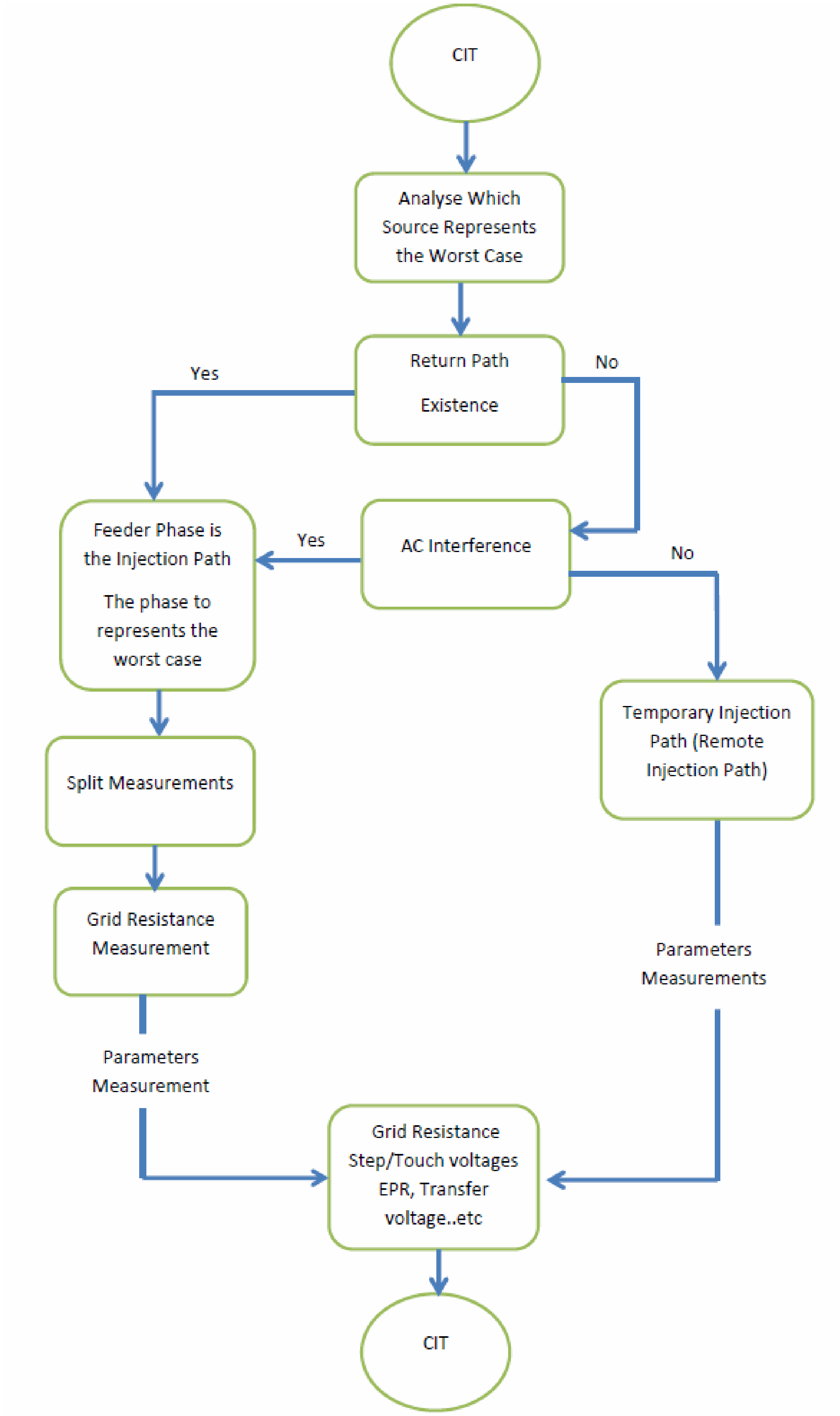

Figure 1. Current injection test diagram

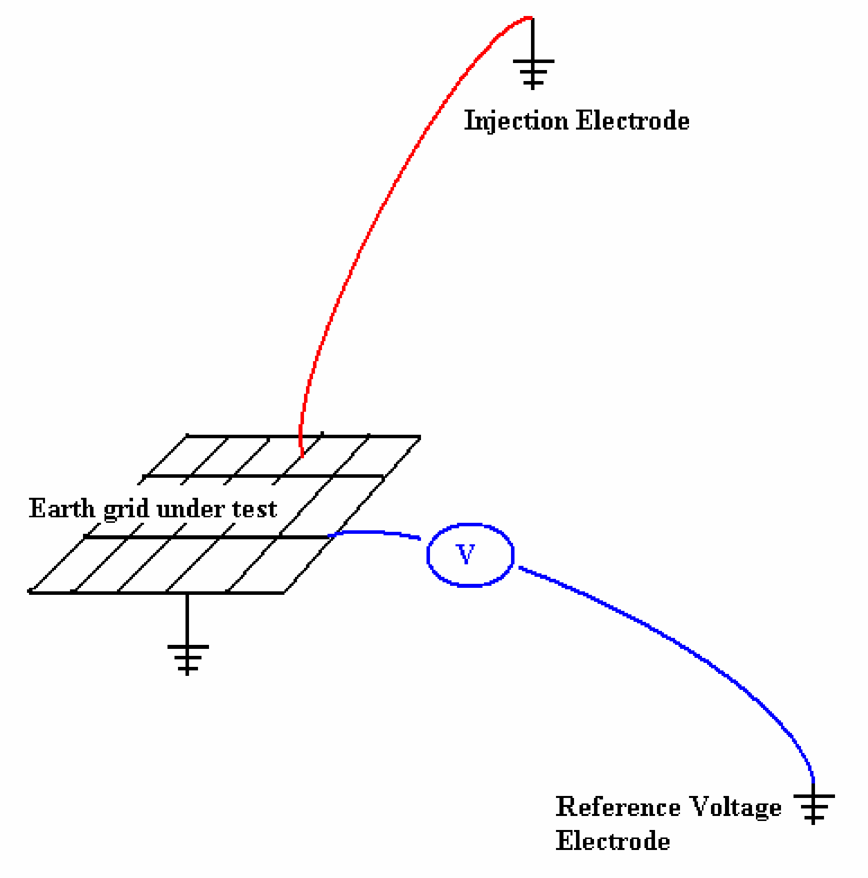

Figure 2. Current injection test layout for grid resistance determination

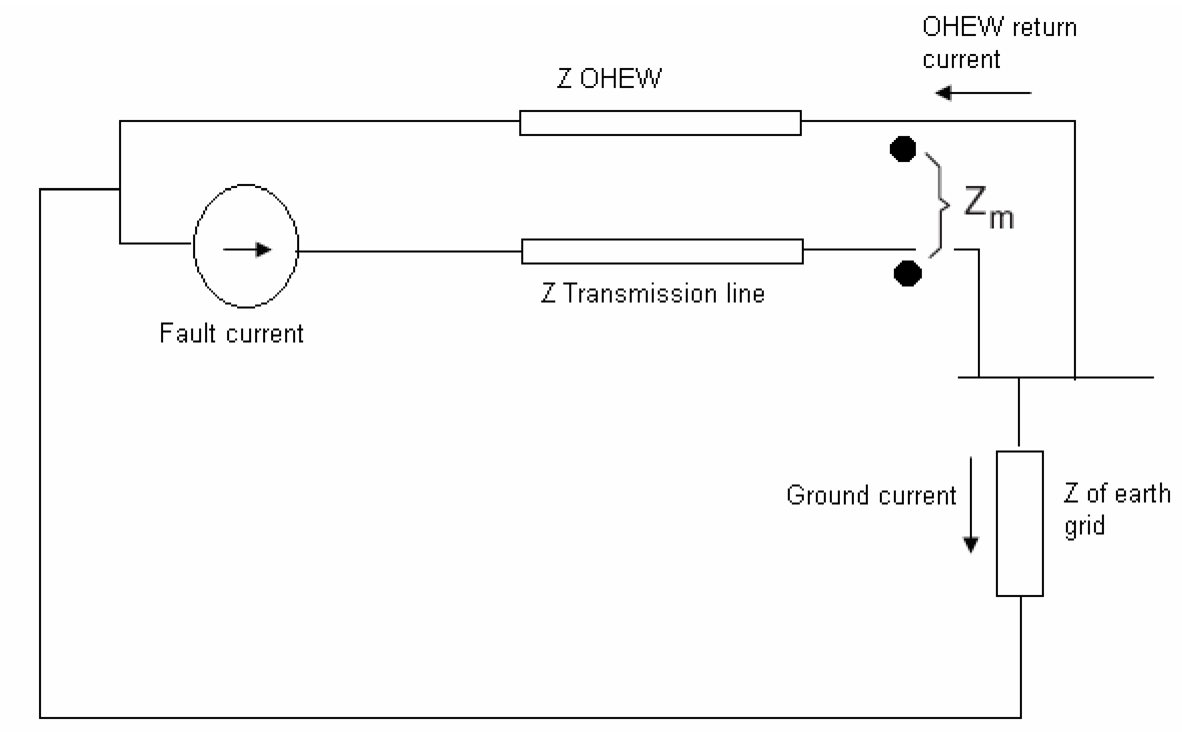

Figure 3. HV transmission main with return path

Under the finite continuous condition, the second substation grid system is part of the input impedance. Equation 4 can be used to calculate Z-neec and the input impedance can be found using equation 5.

$$Z_{e-NEEC} = \frac{0.5N(N+1)Z_s Z_P + Z_P^2}{\frac{N(N^2-1)}{6} Z_s + NZ_P} \quad (4)$$

$$Z_{input} = Z_{e-neec} // (Z_{s2} + Z_{g2}) \quad (5)$$

where: N is the number of poles, Z_{s2} is the OHEW self-impedance for the last span before the substation in ohms, Z_{g2} is the source substation earth grid resistance in ohms.

Under the finite non-continuous condition, equation 4 can be used to compute the input impedance. Under the infinite system, the fault at the substation cannot see the earth grid of the source; it can only see a section of the OHEW system. Equation 6 can be used to compute the input impedance.

$$Z_\infty = \frac{Z_s}{2} + \sqrt{\frac{Z_s^2}{4} + Z_s Z_p} \quad (6)$$

In practice, $Z_s \prec\prec Z_P$ therefore, the input impedance of an infinite line can be expressed in equation (7).

$$Z_\infty = \frac{Z_s}{2} + \sqrt{Z_s Z_p} \quad (7)$$

Based on equations 1 to 7, the substation current can be estimated, and the path for the worst case scenario can be finalised.

2.2 Transmission pole current

The fault current split into the OHEW input system as shown in the previous section. Figure 4 shows the fault current distribution along the transmission line OHEW.

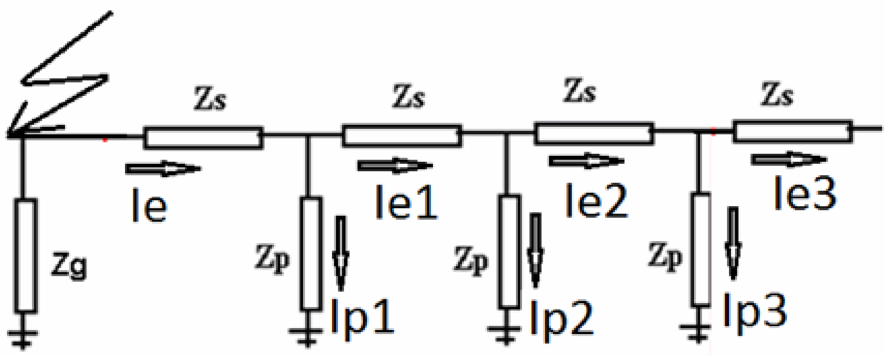

Figure 4. Fault current distribution along the OHEW system

According to [9, 10], the current remaining in the OHEW and doesn't discharge to the ground at the pole grid is found using equation 8:

$$I_{OHEW-remain} = I_f \frac{z_{gw}}{z_s} \quad (8)$$

According to [11], the pole grid current can be found using equations 9 and 10 for an infinite condition:

$$I_{P1} = \frac{\delta_e \left(1 - \frac{z_{gw}}{z_s}\right) Z_{OHEW-in}}{Z_{OHEW-in} + Z_P} I_f \quad (9)$$

$$I_{Pn} = \left[\frac{Z_P}{Z_{OHEW-in} + Z_P}\right]^{n-1} I_{P1} \quad (10)$$

where: n is the pole numbers where the line is still under infinite condition. It is noted that n cannot be less than 1. δ_e is the OHEW split factor [12], Z_P is the pole grid resistance in ohms.

Please note: equations 8, 9 and 10 are for the case where the fault is on the line where OHEW is present and infinite. The discharge current under this condition can be found using equation 11:

$$I_{discharge} = I_f \frac{Z_g \left(1 - \frac{z_{gw}}{z_s}\right)}{Z_{OHEW-in} + Z_g} \quad (11)$$

For a substation that has one line with OHEW and another line without OHEW, a fault at the substation due to the line with no OHEW forces the current magnitude to be discharged on the line with the OHEW as per equation 12:

$$I_{discharge} = I_f \frac{Z_g}{Z_{OHEW-in} + Z_g} \quad (12)$$

Based on equations 11 and 12, the worst case scenario on transmission poles is presented for a fault located on the other feeding line with no OHEW. For example, 110/11kV zone substation, the 110kV has a return OHEW (continuous) with 7kA SLG fault current. The 11kV in the field has no Return Path and 3kA fault current.

During the 11kV fault, the substation grid current is 3kA. However, under 110kV fault, the substation grid current is 7kA multiplied by the Split Factor. For split factor of 0.4, the substation grid current is 2.8kA which is lower than the 11kV fault contribution. However, if the split factor is 0.6, the substation grid current under the 110kV fault is 4.2kA which is higher than the 11kV fault contribution.

It should be noted, where the substation Grid current for the 110kV fault is 4.2kA, the 11kV fault contribution which is presented by the 3kA, could represents the worst case scenario for the transmission poles located within the finite length of the substation. Furthermore, the route location of the 11kV and the location of the fault play an important part to determine the behavior of the fault current under 11kV fault.

3. Theoretical study discussion

From the theoretical study, it is identified that the worst case scenario for substation can be different to the transmission line. When a substation earth grid is commissioned with one of the fault sources has an OHEW while the second one without the OHEW, equation 13 can be used to assist in determining the worst case scenario:

$$I_{f-no-OHEW} = I_{f-with-OHEW} \left(1 - \frac{z_{gw}}{z_s}\right) \quad (13)$$

where: $I_{f-no-OHEW}$ is the fault current from the source without the OHEW, $I_{f-with-OHEW}$ is the fault current from the source with the OHEW.

To determine $\left(1-\frac{z_{gw}}{z_s}\right)$, the following steps can be followed:

- Complete the current injection test using the line with the OHEW
- Measure the substation grid resistance and the input impedance of the OHEW
- Measure the substation earth grid current
- Use equations 1 and 2 to determine $\left(1-\frac{z_{gw}}{z_s}\right)$

If equation 14 is valid, the worst case scenario for the transmission line under substation fault is represented by the fault on the feeder without the OHEW. Otherwise the worst case scenario is presented by the fault sourced by the transmission line with the OHEW.

$$I_{f-no-OHEW} \succ I_{f-with-OHEW}\left(1-\frac{z_{gw}}{z_s}\right) \tag{14}$$

The worst case scenario for the substation is represented by the fault on the feeder without the OHEW if equation 15 is valid:

$$I_{f-no-OHEW} \succ I_{f-with-OHEW}\frac{\left(1-\frac{z_{gw}}{z_s}\right)Z_{OHEW-in}}{Z_{OHEW-in}+Z_g} \tag{15}$$

Determining the worst case scenario ensures accurate measurement of the actual step, touch and transfer voltages which leads to accurate comparisons with the allowable safety limits as detailed in section 4. Furthermore, the enhanced diagram aid in determining the correct path when it comes to AC interference study if applicable. The works in [5], contain more information regarding the diagram in Figure 1.

4. Safety requirements

The measured touch and step voltage shall be assessed against the allowable safety limits. The step and touch voltage can be determined from the two equations 16 and 17. These two equations are calculated using the resistance of a 50Kg person when assessing the public access area. Equations 18 and 19 calculate step and touch voltage using a 70Kg body weight [13, 14].

$$V_{touch}=\frac{116+0.174C_s\rho_s}{\sqrt{t}} \tag{16}$$

$$V_{step}=\frac{116+0.696C_s\rho_s}{\sqrt{t}} \tag{17}$$

$$V_{touch}=\frac{157+0.236C_s\rho_s}{\sqrt{t}} \tag{18}$$

$$V_{touch}=\frac{157+0.942C_s\rho_s}{\sqrt{t}} \tag{19}$$

$$C_s=1-\frac{0.09\left(1-\frac{\rho}{\rho_s}\right)}{2h_s+0.09} \tag{20}$$

where: *Cs* is the derating factor relating to surface layer thickness and resistivity, ρ_s is the top surface layer, *t* is the primary clearance time.
Determining the soil structure can be done by measuring the soil conductivity using Wenner method [15, 16]
EPR contour can be determined using the maximum EPR and the measured voltage in Figure 5. Equation 21 represents the maximum EPR and equation 22 represents the EPR contour. This process can be repeated for different directions to ensure that accurate data is obtained to draw the EPR contour of the tested earth grid. Figure 5 represents the EPR contour computation; the EPR is high at the substation and decreases as the distance from the tested grid increases.

$$EPR = I_{Grid} \times Z_{grid} \tag{21}$$

$$EPR_{contour} = EPR_{\max} - V_{fig5} \tag{22}$$

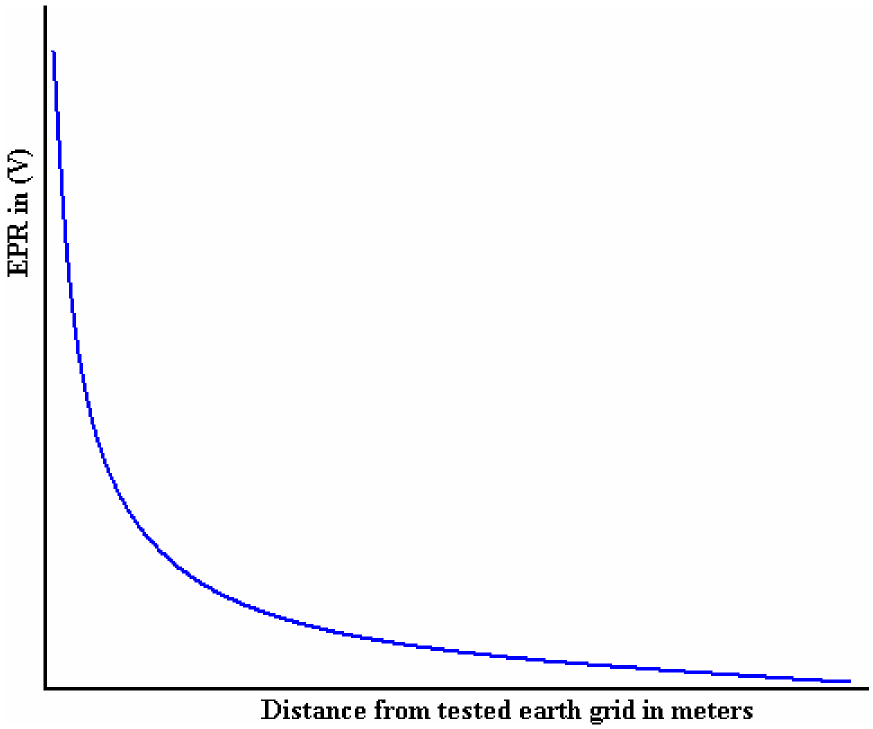

Figure 5. EPR contour against the separation distance

5. Case study
A new zone substation “A” is being constructed. The zone substation is fed by a single 132kV transmission line. Two distribution feeders are going out of the substation. Below are the characteristics of the design:

- Transmission Single Line to Ground Fault Current is 6kA
- Distribution line Single Line To Ground Fault Current is 3.8kA
- Substation earth grid of 0.2 ohms
- Clearance times; both faults on transmission and distribution lines has 500ms clearance time
- Two Soil Resistivity structures is uniform; 100 ohm.m
- Delta configuration is used for the transmission pole conductor arrangement

Follow the paper works, the current injection test was arranged for the transmission line, the substation grid resistance and the OHEW input impedance were measured, the magnitudes of these resistances are shown below:

$Z_g = 0.21 \qquad Z_{OHEW} = 0.89$

Substation grid current was measured to be 3.125kA

The following computation is obtained by using equations 1 and 2: $\left(1-\frac{z_{gw}}{z_s}\right)=0.643$

Applying equation 13: $6\times 0.643=3.86\succ I_{f-no-OHEW}$

Based on this analysis, the worst case scenario for the transmission pole under substation fault is presented by the transmission line fault. However, the substation fault worst case scenario is shown by the distribution fault. It is assumed that the entire distribution fault current only utilizes the substation earth grid as a return path to the source transformer. This assumption represents a conservative approach. For the substation analysis, the step and touch voltages as well as the EPR contour should be scaled to reflect the distribution fault. In this case, the injection current is 8A, the substation grid current was measured to be 4.17A. Therefore, the associated measured touch voltage should be multiplied by a factor of 911 to simulate the distribution fault. Please note, for the transmission line fault, the factor is 750.

6. Conclusion

This paper proves the importance of choosing the right injection path when completing a CIT for HV infrastructure. Depending on the HV feeding arrangement and its route surrounding infrastructure, the CIT route shall be determined to ensure that the test represents the worst case scenario otherwise the results are no accurate. This paper introduces the CIT diagram which aid in assessing and determining the correct injection path. The case study shows the importance of using the proposed diagram and how it leads to more accurate results

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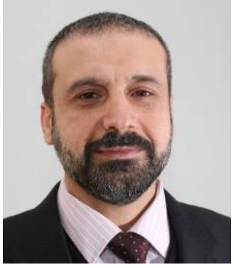

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