

Transmission Mains Earthing Design and Concrete Pole Deployments

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Abstract—The High Voltage (HV) transmission mains into the community necessitate earthing design to ensure safety compliance of the system. Concrete poles are widely used within HV transmission mains; which could have an impact on the earth grid impedance and input impedance of the system from the fault point of view. This paper provides information on concrete pole earthing to enhance the split factor of the system; further, it discusses the deployment of concrete structures in high soil resistivity area to reduce the earth grid system of the plant. This paper introduces the cut off soil resistivity ρ_{sc} when replacing timber poles with concrete ones.

Keywords—Concrete Poles, Earth Grid, EPR, High Voltage, Soil Resistivity.

I. INTRODUCTION

HIGH voltage infrastructure necessitates earthing design to warrant the safety and the acquiescence of the system to the 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. The demand on High voltage (HV) infrastructures is growing due to the corresponding growth in industries and population, mishandling HV infrastructure can cause damages to properties and may inflict injuries and fatalities. Electricity remained the sixth leading cause of injury-related occupational death in USA from 1999 to 2002.

HV infrastructures are fed by transmission mains and concrete poles form an important element of the transmission line infrastructure. These poles are either reinforced concrete or a pre-stressed concrete, considered to be conductive. These poles have the ability to carry current. The earthing design also depends on the connection of the over head earth wire (OHEW) on top of the pole; force this pole to become energized.

This paper discusses the impact on the earthing system when OHEW connected on top of the concrete pole. It analyses the actual grid resistance seeing from the OHEW connection on top of the pole. It compares the total impedance of transmission mains with concrete and timber poles. It provides information on computing the resistance of concrete pole in different soil resistivity structures and also reducing the resistance of an electrode under high soil resistivity exposure.

Many high voltage (HV) infrastructures deploy OHEW for around 10 spans to assist in reducing the earth grid. It reduces the grid current which will reduce the earth potential rise (EPR), the impact on deploying concrete poles to this method

is discussed. It introduces NEEC (National Electrical Engineering Consultancy) approach to compute the input resistance.

Also this paper introduces NEEC cut off soil resistivity value approach which will assist in determining the impact occur by replacing timber poles with concrete ones.

II. THEORETICAL STUDY

As discussed earlier, the earthing system provides a safe environment for workers and people. The transmission mains structure form part of the earthing system, the OHEW assists in reducing the earth potential rise (EPR) at the HV infrastructure.

The transmission mains earthing system consists of:

- Soil Resistivity Structure Computation
- Earth Grid determination on the base of each pole
- Split factor at the HV infrastructure
- Current in the pole earth grid computation

The steels within the concrete pole are made continuous. The design of the pole allows for the OHEW and the earth grid of the pole to be connected to the furrow of the pole. Fig. 1 shows the earthing arrangement of the concrete pole. This connection provides the pole with the ability to carry current, the buried section of the pole form part of the earth grid.

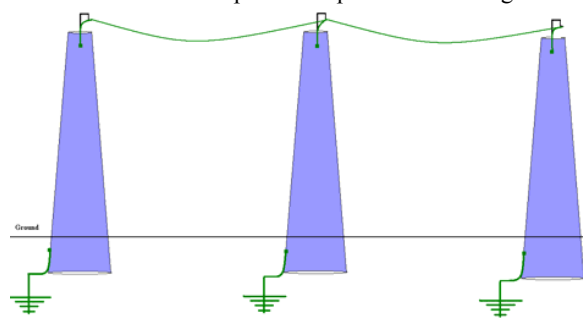


Fig. 1 OHEW and earth grid connection on concrete pole

Soil resistivity is a measure of a soil's ability to retard the conduction of an electric current. The electrical resistivity of soil can affect the rate of galvanic corrosion of metallic structures in contact with the soil. High moisture content or increased electrolyte concentration can lower the resistivity thus increasing the conductivity. Typical soil resistivity values range from about 2 to 10000 Ωm , but other values are not unusual.

Table I shows the different types of soil and their typical soil resistivity values. It is rare to find an area with one type of soil. The soil structure consists of multiple layers. It is

acceptable to use two layers when completing the earth grid assessment [1].

TABLE I
TYPICAL SOIL RESISTIVITY OF VARIOUS TYPE OF SOIL

Type of Soil or water	Typical Resistivity (Ω / m)
Sea Water	2
Clay	40
Ground well and spring water	50
Clay and Sand mix	100
Shale, Slates, Sandstone	120
Peat, Loam and Mud	150
Lake and Brook Water	250
Sand	2000
Morane Gravel	3000
Ridge Gravel	15000
Solid granite	25000
Ice	100000

The earth plays important role in absorbing the fault and malfunction energy of these plants. Soil resistivity structure is the key in this operation. The soil resistivity will establish the conductivity of the ground which determines its capability to form an easy path for the fault or malfunction in the electrical system.

The most three popular methods to perform soil resistivity tests are: [1]

- Wenner Method
- Schlumberger Array
- Driven Rod Method

The wenner method is the most popular one. Fig. 2 shows Wenner method arrangement which the soil resistivity formula related to Wenner method is given as equation 1.

$$\rho = 2\pi aR \tag{1}$$

Where

- R is the resistance measured by the machine
- a is the spacing of the probe

The determination of the soil structure allows for the earth grid computation. The earth grid of a transmission poles consist of single electrodes. The equation 2 shows the computation of the earth grid for the single electrode. If single electrode is not sufficient to achieve the required grid resistance value, multiple electrodes are placed in parallel to reduce the earth grid resistance [2].

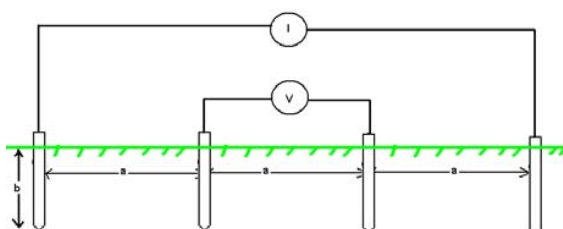


Fig. 2 Wenner Method for Soil Resistivity Test

$$R_g = \frac{\rho}{2\pi L} \left(\ln\left(\frac{8L}{d}\right) - 1 \right) \tag{2}$$

Where

L is the buried length of the electrode in (m)
 d the diameter of the electrode in (m)

The current that flows into the earth grid of the concrete pole, flows through the steel structure of the concrete pole. Therefore the resistance seen from the OHEW connection point includes the resistance of the pole, both parts, above ground and underground part. Fig. 3 shows the resistance equivalent circuit for the concrete pole as seen from the OHEW connection point.

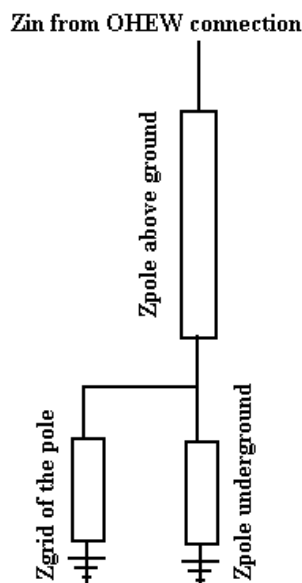


Fig. 3 Equivalent impedance circuit from OHEW

The steel of the underground part of the pole is exposed to the concrete and soil resistivity. Equation 3 can be used to compute the resistance of this section: [3, 4]

$$Z_{Pole-UG} = \frac{\rho_c}{2\pi L} (\ln(r_1) - \ln(r_0)) + \frac{\rho_s}{2\pi L} (\ln(4L) - 1 - \ln(r_1)) \tag{3}$$

Where:

ρ_c = concrete resistivity

ρ_s = soil resistivity

r_0 = radius of an equivalent cylinder represents all steel within the concrete pole

r_1 = concrete pole radius

L = the length of the steel

The total resistance as seen from the OHEW connection can be computed using equation 4:

$$Z_{in-OHEW} = \frac{Z_{P-AG}Z_{p-UG} + Z_{P-AG}Z_g + Z_gZ_{p-UG}}{Z_g + Z_{p-UG}} \quad (4)$$

The total grid impedance of the concrete pole can be computed using equation 5, assuming the grid is connected to the pole at the ground level. Fig. 4 shows the resistance diagram if the earth grid connected to the pole below ground level.

$$Z_{g-total} = \frac{Z_g Z_{p-UG}}{Z_g + Z_{p-UG}} \quad (5)$$

The current that use the pole grid resistance is dependent on $Z_{in-OHEW}$ as seen from the OHEW, depending on the soil resistivity, The presence of the concrete pole could enhance or deteriorate $Z_{in-OHEW}$.

Table II represents the results of $Z_{in-OHEW}$ for a specific concrete and timber poles conditions under different soil resistivity, the input of this table are as shown:

- Concrete resistivity of 30 Ωm
- Soil resistivity as per Table I
- Pole grid consists of 6 meters single electrode
- r_0 is 0.05 m
- r_1 is 0.3 m
- Total length of pole is 20 meters
- Connection point is at the ground level
- 3 meters of UG section

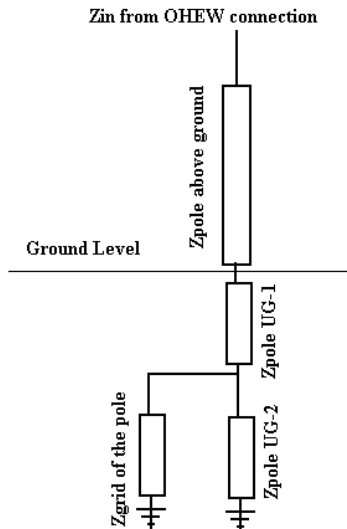


Fig. 4 Ground Grid connection to the concrete pole

TABLE II
Z_{in} FOR TIMBER AND CONCRETE POLE

Typical Resistivity (Ω / m)	Timber Pole $Z_{in-OHEW}$ Ω	Concrete Pole $Z_{in-OHEW}$ Ω
2	0.4	2.1
40	7.99	5.87
50	9.99	6.7
100	19.98	10.9
120	23.98	12.6
150	29.98	15.1
250	49.96	23.4
2000	399.69	169.1
3000	599.54	252.3
15000	2997.68	1251
25000	4996.13	2083
100000	19984.51	8326

Fig. 5 shows the variation of Z_{in} for concrete and timber poles. Based on the example computed in Fig. 5, for soil resistivity lower or equal to 21 ohm.m, the presence of a 20 meter concrete poles increase the Z_{in}

NEEC has introduced the term ρ_{SC} (Soil resistivity cut off value where the presence of the concrete pole enhances the earth grid resistance) and $\rho_{SC} \approx 21\Omega.m$ as shown in Fig. 5. This cut off soil resistivity plays an important role to determine the impact of replacing timber poles with concrete ones. Depending on ρ_{SC} value, the impact could be either on the feeder route or at the substation end.

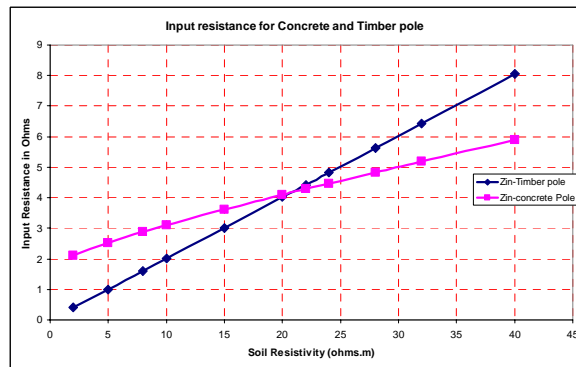


Fig. 5 Z_{in} for concrete and timber pole

The fault current can be divided into sub-currents:

- Current flow in the earth grid
- Current flow in the auxiliary earthing system

Auxiliary earthing system can be represented by Over Head Earth Wire (OHEW) known as a ground wire, and by the cable sheath of the cable. This auxiliary path acts as a path for partial of the fault current, and reduces the current that flow into the ground. The return current value can be determined after calculating the split factor. The split factor determines the percentage of the current that flow into the ground and the

portion that flow into the auxiliary path.

Split factor S_f , is vital to be determined when designing an earthing system that have an auxiliary path for the fault current. Split factor is essential for determining the actual EPR at the substation and gives an indication of the EPR along the auxiliary path. In addition, it ensures the compliance of any transfer voltage or EPR along the auxiliary path. The split factor can be determined using equation 6:

$$S_f = 1 - \left(\frac{Z_{gm}}{Z_{gw}} \right) \quad (6)$$

Where:

Z_{gw} is the self-impedance of the OHEW in Ω/m .

Z_{gm} is the mutual impedance per meter between OHEW and phase conductors in Ω/m .

The Ground current at the substation is determined by equation 7:

$$I_g = S_f \times I_f \quad (7)$$

The auxiliary path current is determined by equation 8:

$$I_e = I_f - I_g \quad (8)$$

The split factor can be calculated using the grid resistance of the substation and the input impedance of the transmission mains, equation 9 shows the relation between these impedances and the split factor:

$$S_f = \frac{Z_{in}}{Z_{in} + Z_{g-sub}} \quad (9)$$

The input impedance represents the total impedance for the OHEW and the pole earth grid, the total impedance as seen by the fault at the substation can be computed using equation 10, this equation stand for an infinite transmission mains:

$$Z_{in} = 0.5Z_{gw} + \sqrt{Z_{gw}Z_{Pole}} \quad (10)$$

For the concrete pole condition, Z_{Pole} can be calculated using equation 4.

NEEC introduces equation 11 which represents the total impedance of the finite line as seen from the fault location, under short run between two substations and under the conditions that the OHEW is bonded at both end, adding the supply substation earth grid resistance in parallel to equation 11 will yield to correct results.

$$Z_{in-NEEC} = \frac{0.5N(N+1)Z_{gw}Z_{Pole} + Z_{Pole}^2}{\frac{N(N^2-1)}{6}Z_{gw} + NZ_{Pole}} \quad (11)$$

Where

N is the total number of sections

N should be satisfy equation 12

$$NL_s \leq L \quad (12)$$

Where

L_s = the section length

L = the infinite length of the transmission mains

Equation 11 yield to more accurate results for the following conditions:

- OHEW installed only for few span along the transmission line from the substation
- OHEW not bonded at both end of the substation for a finite transmission mains

Fig. 6 shows the computation of equation 10 and 11 for set inputs, as the pole number increase, the input resistance decreases. It is possible to estimate the infinite length of the transmission line from Fig. 6.

As discussed earlier, the split factor determines the grid current at the substation also determine the current into the OHEW which related to the EPR, step and touch voltage on transmission mains poles. Fig. 7 shows the relation between Z_{in} and the split factor, by increasing Z_{in} more fault current will be injected into the substation earth grid, by reducing Z_{in} , more fault current will be using the OHEW and pole grid system.

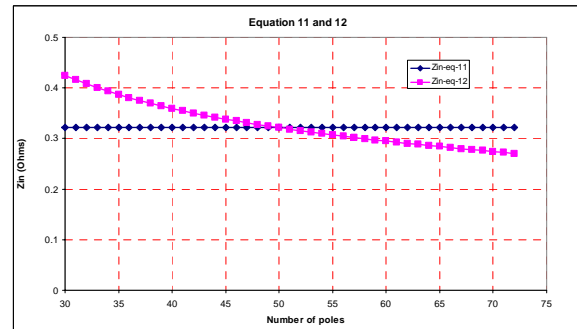


Fig. 6 Computation results for equation 11 and 12

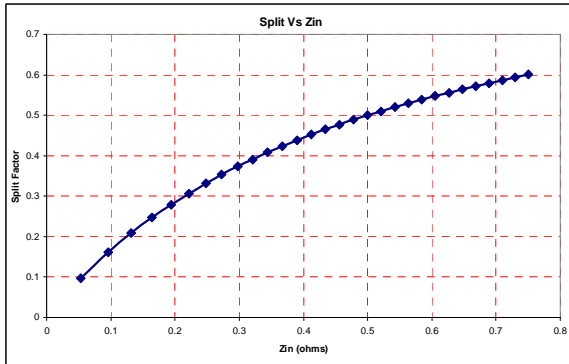


Fig. 7 Split Factor against Z_{in} input of the transmission mains

Replacing timber pole with concrete ones will either increase or decrease the input impedance depending on the soil resistivity value, using the cut off soil resistivity value ρ_{SC} to determine the impact of these concrete poles. (Another publication is being established to discuss the cut off soil resistivity ρ_{SC} for different concrete pole types)

For the example computed in Fig. 5, the following can be derived based on ρ_{SC} :

- If the soil resistivity is bigger than ρ_{SC} less fault current will use the substation earth grid and more fault current use the OHEW system. Assessment on the OHEW shall be completed to ensure this increase of current will not jeopardize the safety of the line
- If the soil resistivity is smaller than the ρ_{SC} , more fault current will use the substation earth grid and less fault current use the OHEW system. Assessment on the substation earth grid is required under this condition to ensure it is safety compliance

III. CASE STUDIES

Two case studies were discussed in this paper as shown below:

Case study 1:

- Substation Earth Grid Resistance of 0.5 ohm
- Primary clearance time 500ms
- SLG (single line to ground) fault current is 3400A
- Overhead feeding arrangement with Overhead earth wire solid bond both end
- Number of poles is 70
- Average soil resistivity of 50ohm.m and 10 ohms.m
- Z_{gw} is 0.01 per span
- 20 meter concrete pole with 3 meters underground
- Timber pole earth grid consist of 6 meter single electrode

Case Study 2:

- Substation Earth Grid Resistance of 0.5 ohm
- Primary clearance time 500ms
- SLG (single line to ground) fault current is 3400A
- Overhead feeding arrangement with Overhead earth for only 10 span
- Number of poles is 70
- Average soil resistivity of 50ohm.m and 10 ohms.m
- Z_{gw} is 0.01 per span
- 20 meter concrete pole with 3 meters underground
- Timber pole earth grid consist of 6 meter single electrode

Using equation 3 to compute the earth grid resistance of the concrete pole section buried underground:

$$Z_{Pole-UG-10\Omega.m} = 4.729\Omega$$

$$Z_{Pole-UG-50\Omega.m} = 9.985\Omega$$

Using equation 2 and 4 to compute the total pole resistance as seen from the OHEW connection point:

$$Z_{in-OHEW-10\Omega.m} = 3.11\Omega$$

$$Z_{in-OHEW-50\Omega.m} = 6.755\Omega$$

$$Z_{pole-timber-10\Omega.m} = 2.01\Omega$$

$$Z_{pole-timber-50\Omega.m} = 10.05\Omega$$

Applying equation 10 or 11 to compute the total impedance of the OHEW, for case study #2, equation 10 cannot be used, only equation 11 can be used

Case study #1

$$Z_{in-CONCRETE-10\Omega.m} = 0.18\Omega$$

$$Z_{in-CONCRETE-50\Omega.m} = 0.264\Omega$$

$$Z_{in-TIMBER-10\Omega.m} = 0.146\Omega$$

$$Z_{in-TIMBER-50\Omega.m} = 0.322\Omega$$

Case study #2

$$Z_{in-CONCRETE-NEEC-10\Omega.m} = 0.34\Omega$$

$$Z_{in-CONCRETE-NEEC-50\Omega.m} = 0.71\Omega$$

$$Z_{in-TIMBER-NEEC-10\Omega.m} = 0.23\Omega$$

$$Z_{in-TIMBER-NEEC-50\Omega.m} = 1.04\Omega$$

Table III represents the split factor under timber and concrete poles for the two soil resistivity input,

TABLE III
SPLIT FACTOR FOR CASE STUDY 1 AND 2

	Timber 10ohm.m	Timber 50 ohm.m	Concrete 10 ohm.m	Concrete 50 ohm.m
	Zin	Zin	Zin	Zin
S_f #1	0.22	0.39	0.26	0.34
S_f #2	0.31	0.67	0.40	0.58

Table IV shows the EPR at the substation based on Table III split factor, the change from timber poles to concrete poles in case study 1 under 10 ohm.m soil resistivity will increase the EPR in order of 20 to 50% depend which formula is used (equation 10 or 11), under soil resistivity of 50 ohm.m replacing timber poles with concrete poles will reduce the EPR at the substation in order of 12 to 20 % depend which formula is used (equation 10 or 11).

For case study 2, replacing timber poles with concrete poles under 10 ohm.m soil resistivity will increase the EPR by 153V and under 50ohm.m will reduce the EPR by 153V.

TABLE IV
EPR DETERMINATION BASED ON TABLE III SPLIT FACTOR

	Timber 10ohm.m	Timber 50 ohm.m	Concrete 10 ohm.m	Concrete 50 ohm.m
	Zin	Zin	Zin	Zin
EPR #1	374	663	442	578
EPR #2	527	1139	680	986

IV. CONCLUSION

This paper provides important information on the impact that will be caused by replacing timber poles with concrete ones. It shows how under different soil resistivity the impact on the earthing system will change when deploying concrete poles.

It introduce the cut of soil resistivity when dealing with concrete poles, also it introduce NEEC total transmission mains impedance formula as seen from the substation under fault.

The case study proves the impact on the EPR of the substation by replacing timber poles with concrete ones. It highlights the importance of reviewing the earthing system to ensure the replacing timber poles with concrete ones will not jeopardize the safety of the earthing system.

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