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Soil Resistivity Cut off Value and Concrete Pole Deployments in HV Transmission Mains

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Abstract**—**The prologue of new High Voltage (HV) transmission mains into the community necessitates earthing design to ensure safety compliance of the system. Concrete poles are widely used within HV transmission mains; many retired transmission mains with timber poles are being replaced with concrete ones, green transmission mains are deploying concrete poles. The earthing arrangement of the concrete poles could have an impact on the earth grid impedance also on the input impedance of the system from the fault point of view. This paper endeavors to provide information on the soil resistivity of the area and the deployments of concrete poles. It introduce the cut off soil resistivity value ρ_{SC}, this value aid in determine the impact of deploying the concrete poles on the earthing system. Multiple cases were discussed in this paper.

Keywords**—**Soil Resistivity, HV Transmission Mains, Earthing, Safety.

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. Also earth grid system on high voltage transmission poles provides a safe path for lightning strike.

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 [1].

HV infrastructure are fed by transmission mains, concrete poles form important element of the line infrastructure, concrete poles are either reinforced concrete or a pre-stressed concrete, both these poles are considered conductive, these pole have the ability to carry current, the steel within the concrete pole bond the over head earth wire (OHEW) on top of the pole to the earth grid of the pole. The fault current will flow in the steel of the pole, the section of the concrete pole buried underground form an important part of the earth grid. Under different soil resistivity value, replacing timber poles with concrete one will reduce the grid resistance and enhance the EPR at the pole. This soil resistivity value called the cut off soil resistivity. Determining this cut off soil value will aid in determine if replacing the timber poles with concrete ones will have any negative impact on the earth grid.

This paper discusses the cut off soil resistivity value and how it assists designers during transmission mains refurbishing and new ones.

Replacing an aged timber poles with concrete ones could lead to increase the grid resistance of the poles which will lead to higher EPR, also this will have an impact on the split factor of the system, under this condition; more current will flow into the earth grid of the faulted substation.

Under green protect, and under certain soil resistivity, the section of the concrete pole buried under ground provide similar resistance to a single electrode system under timber poles approach.

This paper shows how can the designer assess where the impact on the earthing system will occur after deploying concrete poles instead of timber ones, also it discusses the impact on the transmission mains input impedance as seen from the fault location.

II. Theoretical Study

As conversed earlier, earthing system provides a safe environment for workers and people, transmission mains structure form part of the earthing system, the OHEW of an over head line assist in reducing the earth potential rise (EPR) at the substation [2]-[4], transmission mains earthing system design consist of:

- Soil Resistivity Structure Computation
- Earth Grid determination on the base of each pole
- Split factor at the HV substation
- Computation of the current flowing in the pole earth grid

The steel within the concrete pole are made continuous, the design of the pole allow for the OHEW to be connected to the furrow of the pole, also the earth grid of the pole will 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 part of the pole underground form part of the earth grid of this pole. The earth grid of the pole consist of the grid formed by the section of the pole buried underground and by the electrodes system installed at the bottom of the pole. The resistivity value of this combined grid depend on many factors such a soil resistivity of both the concrete and the soil surrounding the pole.

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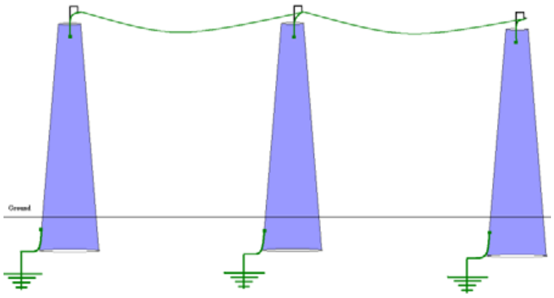

Fig. 1 OHEW and earth grid connection on concrete pole

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. Higher moisture content or increased electrolyte concentration can lower the resistivity and increase the conductivity. Soil resistivity values typically range from about 2 to 10000 Ω·m, but more extreme values are not unusual.

Table I shows the different type of soil and its typical soil resistivity. It is rare to find an area where it consist of one type of soil, usually the soil structure consist of multiple layers. From a soil resistivity perspective, it is acceptable to use two layers when determining the earth grid assessment.

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 most three popular methods to perform soil resistivity test are [5], [6]:

- Wenner Method
- Schlumberger Array
- Driven Rod Method

The wenner method is the most popular one, Fig. 2 shows Wenner method arrangement, the soil resistivity formula related to Wenner method is shown in (1).

$$\rho = 2\pi a R \quad (1)$$

where

R is the resistance measured by the machine,

a is the spacing of the probe

Determination of the soil structure allows for the earth grid computation, the earth grid of a transmission poles usually consist of single electrode, (2) shows the computation of the earth grid of an electrode, if single electrode is no sufficient to achieve the required grid resistance value, multiple electrodes are placed in parallel to reduce the earth grid [7].

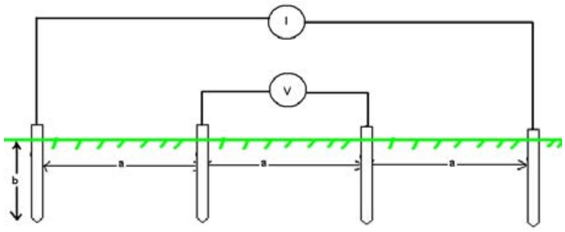

Fig. 2 Wenner Method for Soil Resistivity Test

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

where

L is the buried length of the electrode in meters

d the diameter of the electrode in meters

The section of the pole buried under ground has a grid resistance as shown in (3),

$$Z_{Pole-UG} = \frac{\rho_C}{2\pi L}\left(\ln(r_1) - \ln(r_0)\right) + \frac{\rho_S}{2\pi L}\left(\ln(4L) - 1 - \ln(r_1)\right) \quad (3)$$

where:

ρ_C is the concrete resistivity

ρ_S is the soil resistivity

r_0 is the radius of an equivalent cylindrical represents all steel within the concrete pole

r_1 is the concrete pole radius

L is the length of the steel

This paper divided the deployments of concrete poles into three types:

1. Concrete poles replacing timber ones
2. Concrete poles for new transmission mains

A. Concrete Poles Replacing Timber Ones

Under the situation where the timber poles are replaced with concrete ones, the existing earth grid of the timber poles will be in parallel with the section of the concrete pole buried underground. Equation (4) represents the new grid resistance of the concrete pole. Should be noted that (4) stand under the assumption that the existing earth grid connected to the concrete poles at the ground level.

$$Z_{Pole-Grid} = \frac{Z_g\left(\rho_C \ln\left(\frac{r_1}{r_0}\right) + \rho_S\left(\ln\left(\frac{4L}{r_1}\right) - 1\right)\right)}{2\pi L Z_g + \rho_C \ln\left(\frac{r_1}{r_0}\right) + \rho_S\left(\ln\left(\frac{4L}{r_1}\right) - 1\right)} \quad (4)$$

where

Z_g is the existing timber pole earth grid resistance

Under this condition, the earth grid at the base of the concrete poles is always lower than the existing earth grid resistance for the timber pole.

The resistance seen from the OHEW connection point on top of the concrete pole is not always lower to the one under timber pole, (5) represents the cut off soil resistivity value as defined in this paper. Depending on where the soil resistivity value stands from ρ_{CS} value, the concrete pole impedance as seen from the OHEW connection point could be lower or higher to the one from the timber pole.

$$\rho_{CS} = \frac{5Z_g^2P^2 - 2\pi Z_g\rho_C\left(LN\left(\frac{4L_P}{r_0}\right)-1\right) - \rho_C^2 LN\left(\frac{r_1}{r_0}\right)\left(LN\left(\frac{4L}{r_0}\right)-1\right)}{\rho_C\left(LN\left(\frac{4L}{r_1}\right)-1\right)\left(LN\left(\frac{4L}{r_0}\right)-1\right)} \quad (5)$$

where

P is the total length of the concrete pole

If the soil resistivity $\rho_S \succ \rho_{CS}$ the resistance as seen from the OHEW connection point under concrete poles is higher to the one under timber pole, therefore less current will flow into the earth grid system which means lower EPR. (Pole Grid Resistance is always lower to the one under timber pole, refer to (4)). It also should be noted that under this condition, more current will flow into the faulted substation earth grid and less current into the OHEW system.

If $\rho_S \prec \rho_{CS}$ the resistance as seen from the OHEW connection point under concrete pole is lower to the one under timber pole, therefore, higher fault current will flow in the concrete pole earth grid system, earthing assessment under this condition is required. It should be noted that under this condition, less current will be injected into the faulted substation earth grid and more current will use the OHEW system.

B. New Transmission Mains with Concrete Poles

Numerous utilities set a maximum earth grid resistance to be connected to their poles (usually timber poles). In Australia this value vary between 10 and 30 ohms depend on the soil resistivity of the area. As conversed earlier, the section of the concrete poles buried in the ground form part of the earth grid, under certain soil resistivity value, the base of the concrete poles achieve the required earthing under these utilities. Assume the required earth grid resistance is Z_{g1}, (6) represents the cut off soil resistivity value that determine if the concrete pole on its own capable of achieving the required resistance

$$\rho_{CS} = \frac{2\pi L Z_{g1} - \rho_C \ln\left(\frac{r_1}{r_0}\right)}{\ln\left(\frac{4L}{r_1}\right)-1} \quad (6)$$

If $\rho_S \succ \rho_{CS}$ the concrete pole not capable under its own to achieve the required resistance, if $\rho_S \prec \rho_{CS}$ the concrete pole capable of achieving the required grid resistance on its own.

Many utility have a standard earth grid arrangement for timber pole, usually the grid consist of an electrode of L_e length and d diameter, (7) represent the cut of soil under this condition

$$\rho_{CS} = \frac{\rho_C LN\left(\frac{r_1}{r_0}\right)}{L \times LN\left(\frac{8L_e}{d}\right) - L_e \times LN\left(\frac{4L}{r_1}\right) - (L + L_e)} \quad (7)$$

Under this condition, if $\rho_S \succ \rho_{CS}$ the concrete pole section buried underground resistance is lower than an electrode of L_e length and d diameter.

From (7) it is possible to use concrete on an electrode to lower its resistance under high soil resistivity, if $\rho_S \succ \rho_C$ (the soil resistivity is higher than the concrete resistivity) concrete encase the electrode will reduce its resistance. It should be noted, for a high soil resistivity area, it is possible to reduce the electrode resistance as it is only in concrete if the radius of the concrete encase is 1.48 the length of the electrodes. This based on theoretical study, experimental results is in progress for verification.

C. Cut Off Soil Resistivity Value and Split Factor

The split factor of the substation is depending on the input impedance of the transmission line as seen from the fault and the earth grid resistance value of the substation. Under infinite transmission main line, (8) or (9) can be used to determine the input impedance [8], [9].

$$Z_{in} = 0.5Z_{gw} + \sqrt{Z_{gw}Z_{Pole}} \quad (8)$$

$$Z_{in-NEEC} = \frac{0.5N(N+1)Z_{gw}Z_{Pole} + Z_{Pole}^2}{\frac{N(N^2-1)}{6}Z_{gw} + NZ_{Pole}} \quad (9)$$

where

N is the total number of poles

Z_{gw} is the self impedance of the OHEW of the average span

Z_{Pole} is the pole resistance as seen from the OHEW connection

It should be noted that transmission line to be considered infinity, it is length should satisfy (10):

$$L\sqrt{\frac{Z_S}{Z_{pole}}} \geq 2 \quad (10)$$

where:

Z_S is the OHEW self impedance for average span

Both these equations rely on the pole resistance; therefore, replacing timber poles will have an impact on the input impedance depending on the relation between the cut off soil value and the soil resistivity.

Increase in the pole resistance will lead to an increase in the input impedance, (11) shows the split factor computation, it is clear how the increase in the pole resistance will impact on the split factor of the system.

$$S_f = \frac{Z_{in}}{Z_{in} + Z_{g-sub}} \tag{11}$$

From (11), under the condition where the concrete poles is replacing timber ones, if the soil resistivity is higher than the cut off soil value, the split factor will increase which lead to more fault current into the substation earth grid. Equation (12) shows the relation between the substation ground current and the split factor

$$I_{Grid} = S_f \times I_{Fault} \tag{12}$$

III. Case Study Computation

This paper discussed three different case studies as detailed bellow:

1. Replacing timber poles with concrete ones
2. Installing new concrete poles
3. Use concrete encase on electrode to reduce its resistance under high soil resistivity

A. Case #1 Input

An existing transmission line connecting two substation required refurbishing due to its timber pole condition; the existing timber poles have an earth grid resistance of 10 ohms. The new concrete poles have the following details:

1. 20 meters concrete poles
2. 15% in the ground
3. 0.05m is the radius of the combined steel
4. Concrete pole diameter is 0.7 m
5. Concrete soil resistivity is 30 ohm.m
6. Two soil Resistivity values, 50 and 750 ohm.m

B. Case #2 Input

A new transmission main is under construction, the required earth grid resistance for each pole is 10 ohms, the concrete poles have the following details:

1. 20 meters concrete poles
2. 15% in the ground
3. 0.05m is the radius of the combined steel
4. Concrete pole diameter is 0.7 m
5. Concrete soil resistivity is 30 ohm.m
6. Two Soil resistivity were used, 30 and 70 ohm.m

C. Case #3 Input

An existing transmission mains located within high soil resistivity area, the required grid resistance is 10 ohms. The pole are consisted of timber one, single electrode shall be installed due to the confined area. The followings are the input for the computation:

1. Electrode length is 6 meters
2. Soil resistivity value vary between 10 and 100 ohm.m
3. Electrode have a diameter of 0.01
4. Concrete resistivity is 30 ohm.m
5. Concrete encase has 150mm diameter

In case #1 assessment, (5) were used to compute the cut off soil resistivity value,

$$\rho_{CS} = 529.58\Omega.m$$

Equation (4) was used to compute the earth grid resistance for the concrete poles with the existing earth grid under 50ohm.m soil resistivity condition.

$$Z_{Pole-Grid-50ohm.m} = 4.95\Omega$$

The total impedance as seen from the OHEW connection was computed to be 6.7 ohms, this value is lower to the 10 ohms under timber pole arrangement.

Equation (4) was also used to compute the grid resistance for the concrete pole under 750 ohm.m soil resistivity,

$$Z_{Pole-Grid-750ohm.m} = 9.12\Omega$$

The total impedance as seen from the OHEW connection was computed to be 10.86 ohms, this value is higher than the timber pole condition, which mean lower current will use the concrete pole under this condition. (it should be noted that the EPR is depend on $Z_{Pole-Grid}$ and the current that use the concrete pole)

In case #2, (6) was used to compute the cut off soil resistivity value:

$$\rho_{CS} = 51.33\Omega.m$$

For soil resistivity 30 ohm.m, the pole grid resistance value based on the buried section of the concrete pole was computed to be 7.13 ohms and for the 70 ohm.m soil resistivity, the pole grid resistance was computed to be 12.5 ohms.

In case #3, Fig. 3 shows the electrode resistance without concrete encase and with concrete encase for different soil resistivity, it proves that for soil resistivity higher to concrete resistivity, concrete encase will lead to lower electrode resistance

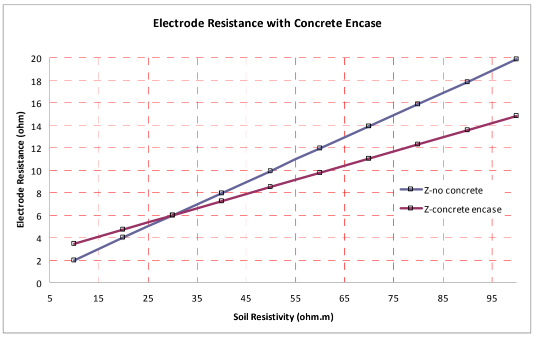

Fig. 3 Electrode resistance under concrete encasement

Increase the concrete encase diameter will reduce the resistance of the electrode, Fig. 4 shows the electrode resistance under different concrete encase with 50 ohm.m soil resistivity.

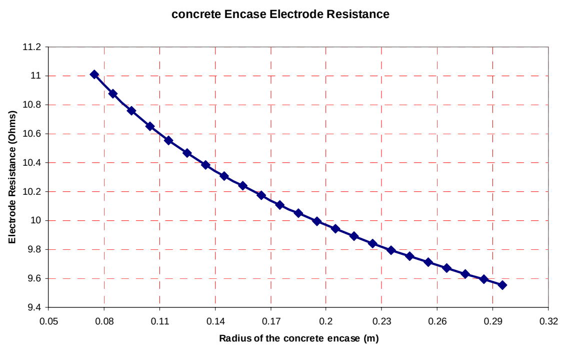

Fig. 4 Electrode Resistance under different concrete encase radius

IV. Conclusion

This paper provides important information when it comes to concrete poles deployments. It shows the important of soil resistivity analysis before the deployment of the concrete structures.

This paper introduce the soil resistivity cut off value and its relation to the concrete poles deployments, the example of this paper proves that by knowing ρ_{CS} will assist in determine the impact on the earth grid due to concrete pole installation. Based on this paper, it is possible to complete a preliminary assessment using the soil resistivity field data to determine where the impact will occur on the earthing system due to concrete pole deployment.

Also it shows how it is possible to reduce the resistance of an electrode by concrete encase the electrode, increasing the radius of the concrete encase will degrease the resistance of the electrode.

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