World Academy of Science, Engineering and Technology
International Journal of Electrical and Computer Engineering
Vol:7, No:1, 2013

Soil Resistivity Structure and Its Implication on the Pole Grid Resistance for Transmission Lines

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***Abstract*—**High Voltage (HV) transmission lines are widely spread around residential places. They take all forms of shapes: concrete, steel, and timber poles. Earth grid always form part of the HV transmission structure, whereat soil resistivity value is one of the main inputs when it comes to determining the earth grid requirements. In this paper, the soil structure and its implication on the electrode resistance of HV transmission poles will be explored. In Addition, this paper will present simulation for various soil structures using IEEE and Australian standards to verify the computation with CDEGS software. Furthermore, the split factor behavior under different soil resistivity structure will be presented using CDEGS simulations.

***Keywords*—**Earth Grid, EPR, High Voltage, Soil Resistivity Structure, Split Factor, Step Voltage, Touch Voltage.

I. Introduction

WORLDWIDE high voltage transmission structure requires earthing design to ensure the compliance of the system to the local standards and regulations. Earthing system provides a low resistance pass for fault current, AC induction, and lightning strikes, it also provides a safe touch and step voltage around these pole structures.

Soil resistivity structure is one of the main elements that have a strong impact on the design; the change in the soil resistivity structure could lead to a complex earthing design.

Soil resistivity testing is the process of measuring the conductivity of the soil; the resulting soil resistivity is expressed in ohm-meter.

Soil resistivity structure will aid the designer in determining the surface layer soil resistivity for safety factors determination; also it will provide the deeper soil structure to aid in determining the effect of deep electrodes against shallow ones. [1]

II. Theoretical Study

Soil resistivity plays a vital part in determining the earthing grid resistance; soil resistivity measurement can be carried out using three different methods, Wenner, Schlumberger Array and Driven Rod Method [2], [3]. This paper will discuss the Wenner Method

A. WennerMethod

Wenner Method consists of four electrodes, two are for current injection and two are for potential measurement. Fig. 1 shows the Wenner Method.

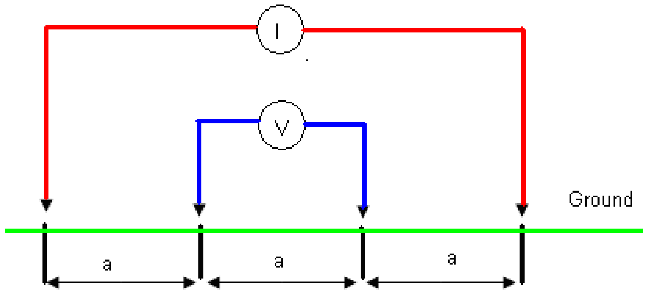

Fig. 1 Wenner four probe arrangement

The soil resistivity formula associated with WennerMethod is shown in equation 1 where R is the resistance measured by the machine, and a is the spacing of the probe

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

Wenner Array is the least efficient from labour perspective since it requires four people to perform the task in a short time. On the other hand it is the best method when it comes to ration of received voltage per unit of transmitted current

III. Soil Resistivity Data

Transmission lines occupy wide areas, they could reach to hundreds of kilometers across the country, and this will expose the base of the pole to different soil structures thus leading to change in soil resistivity on the base of each structure. Depending on the soil structure, many standards state that the base of the pole shall be bonded to an earth grid system less than 10 ohms or less than 30 ohms. (This depends on the location of the pole and the soil resistivity value) [4].

Table I shows the soil resistivity data for various types of ground. It is clearly shown that the soil resistivity could change from 1 ohm to 10000 ohms depending on the location of the electrode. This information should force the designer to survey a soil resistivity structure at the proposed pole location to avoid complex grid designs for these poles and thus to meet the maximum grid resistance as stated by the local authorities and standards [5].

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TABLE I
TYPICAL RESISTIVITY FOR DIFFERENT GROUNDS

Type of Soil or water	**Typical Resistivity (Ω / m)**	**Usual Limit (Ω / m)**
Sea Water	2	0.1 to 10
Clay	40	8 – 70
Ground well and spring water	50	10 – 150
Clay and Sand mix	100	4 – 300
Shale, Slates, Sandstone	120	10 – 1000
Peat, Loam and Mud	150	5 – 250
Lake and Brook Water	250	100 – 400
Sand	2000	200 – 3000
Morane Gravel	3000	40 – 10000
Ridge Gravel	15000	3000 – 30000
Solid granite	25000	10000 – 50000
Ice	100000	10000 - 100000

IV. SOIL RESISTIVITY DATA AND ELECTRODE RESISTANCE

Electrode resistance determination depends directly on the soil structure as shown in equation 2 [6], [7]:

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

If one electrode could not achieve the required resistance level, placing few electrodes in parallel will help in reducing the grid resistance. Equation 3 shows the resistance of the grid formed with few electrodes in parallel [8], [9].

$$R = \frac{\rho}{\pi L}\left(\ln\left(\frac{2L}{b}\right) - 1\right) \tag{3}$$

where

L is the buried length of the electrode

b is the equivalent radius of the electrode at the surface

$$b = (dhsS)^{0.25}$$
$$S = (4h_2 + s^2)^{0.5} \tag{4}$$

where:

d is the diameter of the electrode

h is the buried depth

s is the distance between 2 parallel electrodes

S is the distance from one electrode to the image of the other in meters

V. GRID RESISTANCE COMPUTATION USING IEEE FORMULA

The below calculation is based on a six- meter electrode with the following characteristics:

- Cross section area of 70mm2
- Copper
- Diameter of 0.00944 m

Table II shows the grid resistance of the proposed electrode, based on the information from this table, if the soil resistivity is higher than 50 ohms.m, the 6 meters electrode will not be compliant if the maximum resistance should be less than 10 ohms.

TABLE II
ELECTRODE GRID RESISTANCE FOR VARIOUS SOIL STRUCTURES

Type of Soil or water	**Typical Resistivity (Ω / m)**	**Electrode resistance (Ω)**	
		Calculation	CDEGS
Sea Water	2	0.4	0.37
Clay	40	7.99	7.509
Ground well and spring water	50	9.99	9.38
Clay and Sand mix	100	19.98	18.772
Shale, Slates, Sandstone	120	23.98	22.527
Peat, Loam and Mud	150	29.98	28.159
Lake and Brook Water	250	49.96	46.931
Sand	2000	399.69	375.450
Morane Gravel	3000	599.54	563.17
Ridge Gravel	15000	2997.68	2815.9
Solid granite	25000	4996.13	4693.1
Ice	100000	19984.51	18772

For a soil resistivity of 100 ohm.m, a single electrode of 14 meters should be used to comply with the 10 ohms limitation.

For a soil resistivity of 250ohm.m, in order for a single electrode to meet the 10ohm limitation, a 40 meter electrode should be installed; the 40 meter electrode resistance is computed to be 9.36ohms.

For a soil resistivity of 2000 ohm.m (sand area), a 375 meter electrode should be used to ensure the compliance of the 10 ohms limitation for the grid resistance.

It is clear that for any soil resistivity higher than 100 ohm.m, the single electrode is not the preferred engineering method to comply with the 10 ohms limitation requirement. Multiple electrode systems and possible mesh systems should be used to ensure that it will be cost effective and meet the relevant requirements.

VI. OTHER FACTORS THAT IMPACT ON SOIL STRUCTURE

A study of the soil resistivity for a period of 12 months gives an idea on the soil structure that has to be used during design. As engineers, we should always use the worst case scenario when dealing with human safety. Table III shows the impact of the moisture on the soil resistivity result of a soil. Table IV shows the impact of temperature on the soil resistivity value [9], [10].

TABLE III
VARIATIONS OF SOIL RESISTIVITY WITH MOISTURE CONTENT

Moisture Content	Typical Value of Resistivity (Ω / m)	
% of Weight	Clay missed with Sand	Sand
0	10,000,000	-
2.5	1,500	3,000,000
5	430	50,000
10	185	2,100
15	105	630
20	63	290
30	42	-

TABLE IV
VARIATION OF SOIL RESISTIVITY TEST WITH TEMPERATURE

	Temperature in Degree Celsius	Typical Soil Resistivity Value (Ω / m)
Mix of Sand and Clay with Moisture content of about 15% Weight	20	72
	10	99
	0 water	138
	0 Ice	300
	-5	790
	-15	3,300

These changes in soil with intensive agricultural productions are variable in time and location, a continuous and precise spatially follow up of the soil properties is required when designing an effective earthing system.

VII. CASE STUDY

A new 132kV over head feeder is designed and constructed to support the additional load required at Towfikiya Zone Substation. The feeder uses a Mango conductor and for OHEW, 48 optical fiber is used.

The design is completed based on the following inputs:

- Single line to ground fault is 7000A
- Primary clearance time is 500ms
- Towfikiya earth grid is 0.5ohm
- Labweh earth grid is 0.5 ohm
- The feeder will consist of 20 spans of an average 100 meters per span
- Soil resistivity structure consists of 2 layers, bottom layer of 100 ohm.m and top layer as per Table II

In [13],[14],[15], the split study is determined and CDEGS is used to compute the current that utilizes the grid of each pole, similar approach is followed in determining the split current between the OHEW and Towfikiya earth grid.

Table V shows the allowable touch voltage under different top soils, this calculation is based for a 50kg person and using equation 5 [11], [12]:

$$V_{touch} = \frac{116 + 0.174 C_s \rho_s}{\sqrt{t}} \tag{5}$$

$$C_s = 1 - \frac{0.09\left(1 - \frac{\rho}{\rho_s}\right)}{2h_s + 0.09} \tag{6}$$

where

Cs is the de-rating factor related to surface layer thickness and resistivity

ρ_s is the top surface layer

t is the primary clearance time

TABLE V
ALLOWABLE TOUCH VOLTAGE UNDER DIFFERENT SOIL STRUCTURES

Soil type	Soil resistivity value	**Vtouch (V)**
Sea Water	2.00	164.62
clay	40.00	173.91
Ground Well and Spring Water	50.00	176.35
clay and Sand Mix	100.00	188.58
Shale, slates	120.00	193.47
Peat, loam	150.00	200.80
Lake and Brook water	250.00	225.25
Sand	2000.00	653.13
Morane gravel	3000.00	897.63
Ridge Gravel	15000.00	3831.65
Solid Granite	25000.00	6276.66
Ice	100000.00	24614.26

CDEGS software is used to determine the split factor between the OHEW and Towfikiya earth grid. Run the simulation with different soil structures as stated in Table I, for earth simulation, the transmission pole is changed as per Table II CDEGS data. This split factor represents the percentage of the current that uses the OHEW under a single line to ground fault. Fig. 2 shows the Split factor in respect to the soil structure, it is clearly shown that the same feeder length and set up will have a large difference in the current that uses the OHEW as a return path under different soil structures.

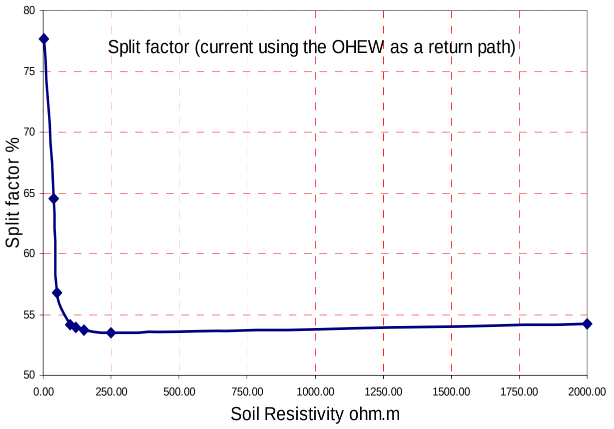

Fig. 2 Current using the OHEW under SLG fault

Fig. 3 shows the relation between the current using the OHEW as a return path under fault condition and the pole grid resistance. It is clearly shown the impact on the current that is returned using the OHEW under different pole grid arrangements.

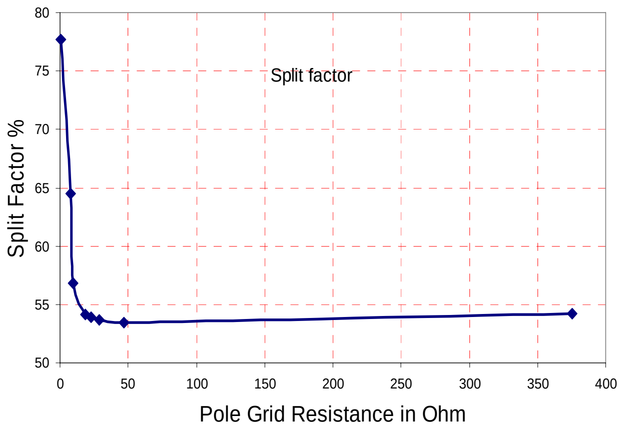

Fig. 3 Split factor in relation to the pole grid resistance

Fig. 3 also shows that for pole grid resistance higher than 30 ohms, there will be almost a neglected impact on the current in the OHEW. CDEGS compute the shunt current

The first three poles from Towfikiya and the last three poles between Labweh are studied. Fig. 4 shows the EPR on the nominated 6 poles compared to the allowable touch voltage as per Table V.

If the EPR is higher than the allowable touch voltage additional study is required. (For more information refer to our publication in [3]).

Using the output in Fig. 4, for example under soil resistivity of 2ohm.m no further study is required, under soil resistivity of 50ohm.m poles 1, 19 and 20 requires a further study to ensure its compliance to the system.

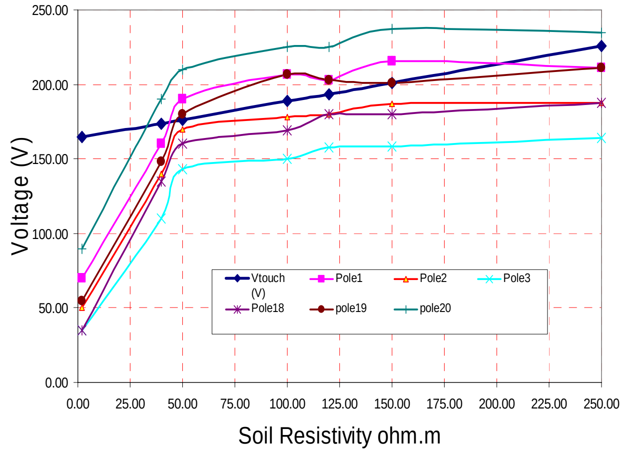

Fig. 4 EPR on the nominated pole against allowable touch voltage

VIII. Conclusion

In conclusion this paper shows how the soil resistivity test condition can play a vital role to facilitate compliance with the relevant standards and regulations. The case taken shows that soil resistivity study at the early stage of the project, could lead to an easier implementation of the design and save both time and budget.

It is clearly shown in this paper that under the nominated six meter electrode per pole, the 10 ohms grid resistance will only be achieved if the soil resistivity is less or equal to 50ohm.m

Even the 10ohm electrode is achieved; the case study shows higher EPR than the allowable touch voltage on poles 1, 19 and 20. It is likely to conclude that it is almost impossible to have a standard pole grid electrode arrangement as every soil structure requires an earthing system study. Moreover, it is not always right to nominate the maximum pole grid resistance as proven, even this value is achieved further analysis is required as the EPR could introduce touch voltage higher than the allowable limits.

IX. Further Consideration

Nowadays transmission poles are located in close distance from pipe lines and any other services, for example, under the Australian standards for a clearance time of 500ms the maximum allowable voltage on the pipe line is 100V for an unskilled person, if the clearance time is higher than 500ms the allowable touch voltage is nominated at 50V. The case study shows that under soil resistivity of 50ohm.m and under pole grid resistance less than 10ohms, the EPR at certain pole can reach over 200V which is twice more than the allowable voltage on pipe line under 500ms clearance time and more than 4 times the allowable voltage under a clearance time higher than 500ms.

This clearly shows the need for an earthing design on each pole adding that it is hard to establish a guide line for standards pole grid arrangement due to many factors involved in the compliance chart.

This paper highlights the importance of using a two-layer soil structure when it comes to determine the earth grid resistance and EPR. Among the five case studies, only in case study number 4, apparent soil resistivity method can be approved.

Using apparent soil structure in cases 1, 3 and 5 will lead to a more expensive system, and using the apparent soil structure in case study 2, leads to a non-compliance system.

This paper also shows that apparent soil resistivity structure can be used when small deviation occurs in the field test data as illustrated in case study number 4.

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