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INFLUENCE OF SOIL CHARACTERISTICS ON THE IMPEDANCE OF ABOVEGROUND AND BURIED WIRES IN MULTILAYER HORIZONTAL SOIL MODEL ENVIRONMENTS

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ABSTRACT

The influence of soil parameters (resistivity, permittivity, permeability and thickness of the soil layers) on the longitudinal impedance of aboveground and buried wires is presented for the first time for arbitrary horizontal multilayer soil models based on a rigorous and general solution developed by the authors. Detailed computation results are presented for typical stratified earth with different layer parameters. The results show marked differences in the earth return impedances when compared to the case of homogeneous soils. The analysis shows the influence of each parameter and reveals that layer thickness, resistivity and permeability are significant factors to the longitudinal impedance, especially for buried wires.

KEY WORDS

Wire impedance, overhead wires, buried wires, multilayer soils

1. Introduction

The self impedance and mutual impedance of overhead and buried wires are critical parameters for circuit analysis inductive interference in communication circuits, pipelines and railway tracks from near-by power lines or extensive electrified structures, and to analyze faults, harmonics, and transients in power lines. Extensive experimental data on the mutual impedance of earth return circuits indicate that assuming the earth as a homogenous medium usually introduces errors in the analysis [1, 2]. With a two-layer model, a satisfactory agreement with experimental results is obtained much more frequently than with a uniform soil model. Geographical studies also indicate that the earth is not uniform or homogeneous, but quite often can be approximated as a layered structure. Therefore, the assumption of homogeneous uniform soil in the calculations of line parameters may introduce errors in the analysis.

Typically the external self impedance of a conductor and the mutual impedance between conductors are required. The former is the voltage drop along a conductor caused by a unit current flowing in the conductor. The mutual impedance Z_{ij} is the voltage drop along conductor *i* caused by a unit current flowing in conductor *j*. Both the self impedance and the mutual impedance are influenced by the earth environment.

In 1926, J. R. Carson [3] in the US and F. Pollaczek [4] in Germany almost simultaneously published a method for determining the frequency-dependent impedance considering the effect of earth return current for overhead lines and buried cables, respectively. Their solution, called the Carson/Pollaczek model or Carson's method, does not consider the effect of displacement current, and is limited to semi-infinite homogeneous soil models. At a later stage, in 1934, W. H. Wise [5] extended the analysis and took into account the effect of the displacement current when the relative permittivity of the earth and air are not equal. In 1965, Mullineux and Reed [6] showed that Carson's integral solution could be derived by using a double Fourier transform, and at the same time, they generalized the method to allow the relative permeability to be other than unity, which was not permissible in the analysis by Carson and Pollaczek. In 1966, L. M. Wedepohl and R. G. Wasley [7] using the double-integration method solved the field equation for the self and mutual impedance of an overhead multi-conductor system with a two layer soil model, and obtained an integral similar in form to that derived by Wise [5]. In 1968, E. D. Sunde [8] also gave a solution for the two-layer case. In 1973, M. Nakagawa et al [9] using W. H. Wise's method developed a solution for the longitudinal impedance of overhead transmission lines above a soil model consisting of three horizontal layers. Later in 1976, M. Nakagawa and K. Iwamoto [10] calculated the earth return impedance of overhead lines for a multi-layer soil model. However, M. Nakagawa et al [9, 10] still used W. H. Wise's assumption in which the current has a pure imaginary propagation constant.

Very recently, the authors developed a rigorous and general method that does not require the assumption of a pure imaginary current propagation constant and that takes into account the presence of a horizontal, multi-layer soil with arbitrary layer thicknesses, resistivities, permeabilities and permittivities [11]. In this paper, a parametric analysis is carried out based on this new method to determine the effects of soil parameters on the longitudinal self and mutual impedances of aboveground and buried conductors.

Figure 1 shows a typical configuration of a group of horizontal conductors running parallel to the X axis, and located in the air or buried in different layers of a multi-layer earth having arbitrary thicknesses and material characteristics.

The main objective of this parametrc analysis is to determine the influence of each layer characteristics parameter on the conductor self and mutual impedances as a function of frequency.

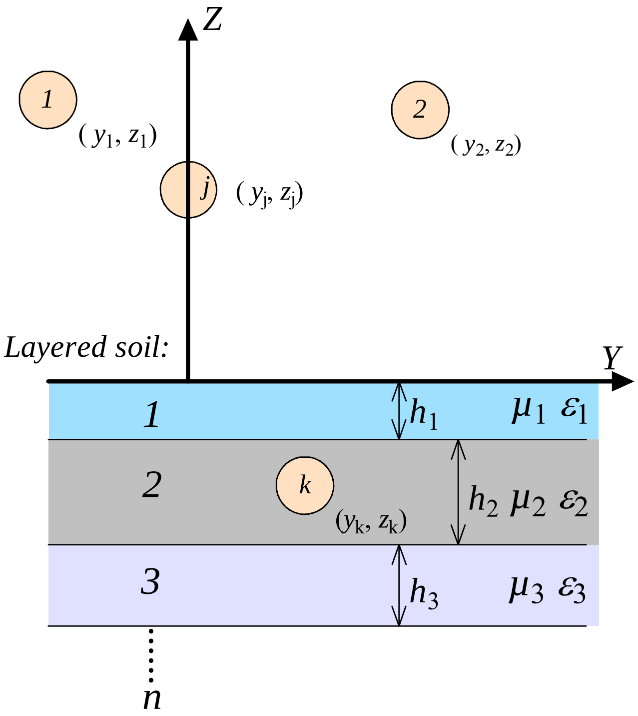

Figure 1. Conductors Parallel to the Earth Surface Located in Air and in a Horizontal Multilayer Soil

2. Effect of Soil Parameters on the Self and Mutual Impedances

2.1 Effects of Soil Stratification Structure

To illustrate the effects of soil stratification on the longitudinal impedance of overhead or buried conductors, the self and mutual impedances of conductors are calculated for several soil models, i.e., uniform, two-layer, three-layer and four-layer models as shown in Table 1.

The relative permittivity and permeability of the soil layers are assumed to be 1 in all cases, unless stated otherwise in the description of each specific case.

In the following cases, in order to clearly demonstrate the effects of soil stratification on the external impedance, the resistivity of the conductor is assumed to be $1 \cdot e^{-10}$ times that of annealed copper at 20˚C. Consequently, the internal impedance of the conductors is not included in the self impedance computation results. The radius of the conductors is 0.01 m for all cases.

Table 1
Soil Models

Soil Type	Layer No.	Resistivity (Ω-m)	Thickness (m)
Uniform	1	100	Infinite
Two-layer	1	100	1
	2	500	Infinite
Three-layer	1	100	1
	2	500	5
	3	200	Infinite
Four-layer	1	100	1
	2	500	5
	3	10	1
	4	200	Infinite

Figure 2 shows the magnitude of the self impedance of a conductor located 10 m above the earth surface for the four soil models shown in Table 1. For a conductor buried at 0.5 m below the earth surface, the magnitude of the self impedance is shown in Figure 3.

For two conductors located 1 m above ground and separated by 5 m, the magnitude of the mutual impedance is shown in Figure 4. If the two conductors are buried at 0.5 m below the earth surface and separated by 5 m, the magnitude of the mutual impedance is illustrated in Figure 5. The mutual impedance between an overhead conductor located at 0.5 m above ground and a buried conductor located at 0.5 m below the earth surface is also calculated. The results are shown in Figure 6.

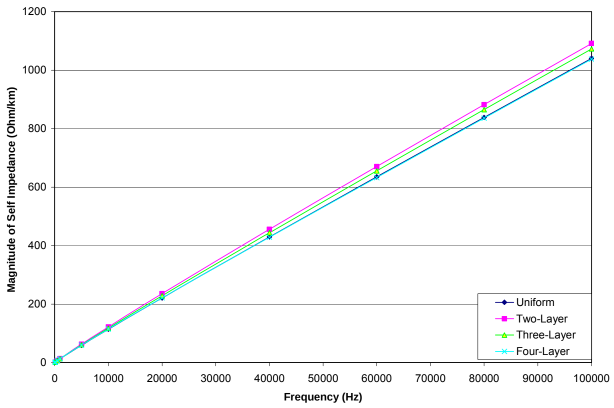

Figure 2. Magnitude of the Self Impedance of an Overhead Conductor for Different Soil Models

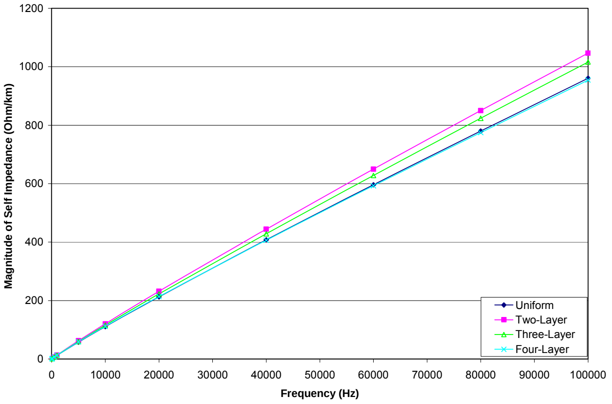

Figure 3. Magnitude of the Self impedance of a Buried Conductor for Different Soil Models

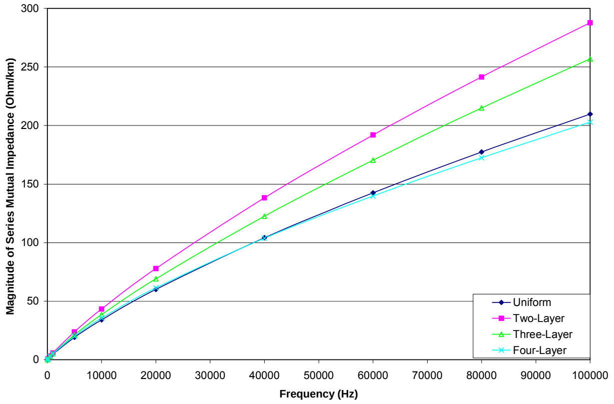

Figure 4. Magnitude of the Longitudinal Mutual Impedance of Overhead Conductors for Different Soil Models

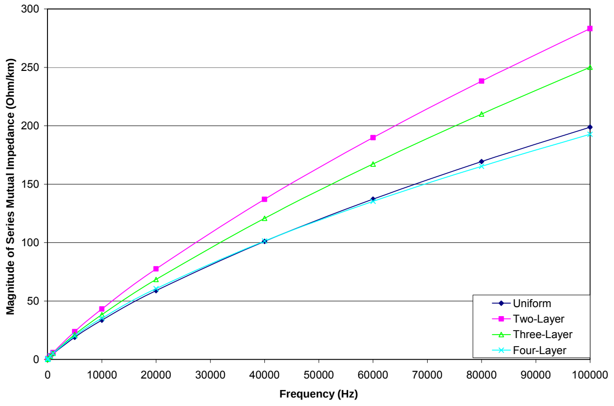

Figure 5. Magnitude of the Longitudinal Mutual Impedance between Buried Conductors for Different Soil Models

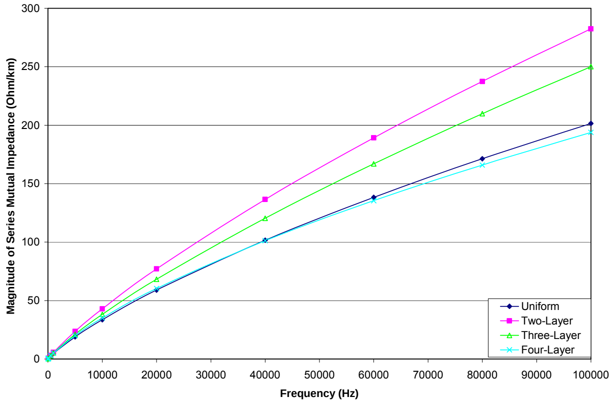

Figure 6. Magnitude of the Longitudinal Mutual Impedance between Overhead and Buried Conductors for Different Soil Models

The effect of soil stratification on the frequency-dependent self impedance and mutual impedance of overhead and buried conductors is clearly demonstrated in Figures 2 to 6. As expected, the longitudinal impedance increases with frequency. From Figures 2 to 6, we can see that as the soil model changes from uniform to a two-layer one with a larger bottom layer resistivity, the longitudinal impedance increases accordingly. For three-layer soil models, the longitudinal impedance decreases as the bottom soil resistivity decreases. However, because the soil resistivities of the middle and bottom layers are higher than the soil resistivity of the uniform soil model, the longitudinal impedance curve lies somewhere between the uniform soil model and the two-layer soil model curves. As for the four-layer soil model, due to the existence of the third layer with a lower soil resistivity than the uniform soil model resistivity, the longitudinal impedance curve approaches the uniform model curve. Figures 2 to 6 also demonstrate that the effect caused by soil stratification gets stronger with frequency, and the effect on the mutual impedance is more significant than for the self impedance.

2.2 Effect of Layer Thickness

Due to seasonal variations, the resistivity and thickness of the top soil layer changes with the temperature and moisture content in the soil.

In the following we assume a rather dry 500 ohm-m uniform soil model which is subject to a sudden heavy rain in summer. And assume that the thickness of the top wet layer changes with the rain fall level. A low over high two-layer soil model with a top layer resistivity of 10 Ω-m and a bottom layer resistivity of 500 Ω-m is selected to simulate the effects of the wet top layer thickness.

The magnitude of the self impedance of a conductor located 10 m above ground or buried at 0.5 m below the earth surface of this soil model are shown in Figures 7 and 8, respectively.

A uniform soil model with a soil resistivity of 10 Ω-m is also shown in Figures 7 and 8, as a limit case for the two-layer model. From Figures 7 and 8, it can be seen that the self impedance decreases when the thickness of the top wet layer increases. When the top layer thickness reaches 5 m or more, the self impedance curve for the two-layer model approaches that of the uniform soil limit case.

It looks like for a low resistivity layer, there is an effective thickness beyond which the rest soil characteristics have little influence on the results as if the good surface conducting layer shields the rest of the soil.

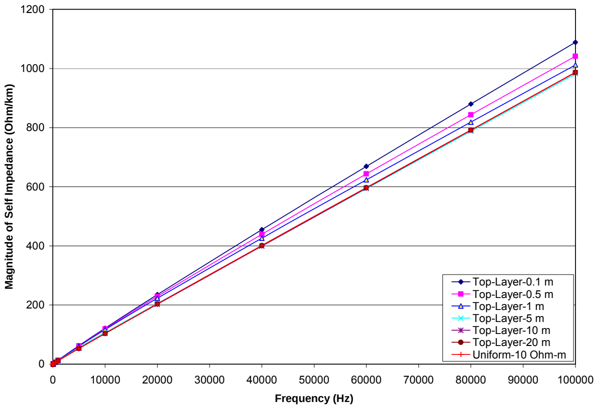

Figure 7. Effect of the Top Layer Thickness on the Magnitude of the Self Impedance of an Overhead Conductor in Low/High Soil Model

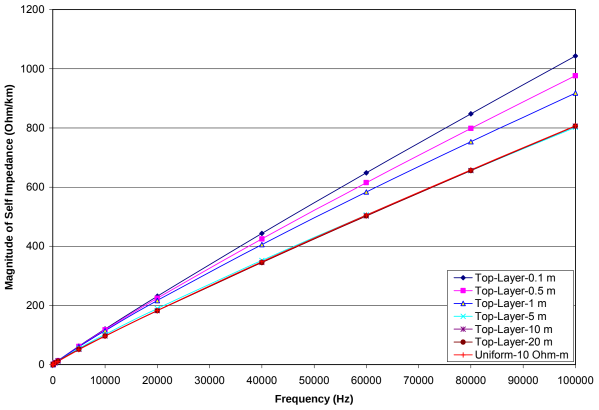

Figure 8. Effect of the Top Layer Thickness on the Magnitude of the Self Impedance of a Buried Conductor in Low/High Soil Model

From Figures 7 to 10, it also can be seen that the effect of the top layer thickness is more significant for the buried conductor than for the overhead conductor.

Similarly, in winter the resistivity of the top soil in northern countries increases dramatically because of the frozen water present in the soil. The thickness of the frozen layer changes with the temperature. A high over low two-layer soil model with a top layer resistivity of 2000 Ω-m and a bottom layer resistivity of 500 Ω-m is selected to simulate this effect.

The self impedance of a conductor located 10 m above ground and at 0.5 m below the earth surface is shown in Figures 9 and 10, respectively. A uniform soil model with a soil resistivity of 2000 Ω-m is also shown in Figures 9 and 10, as a limit case for this two-layer model.

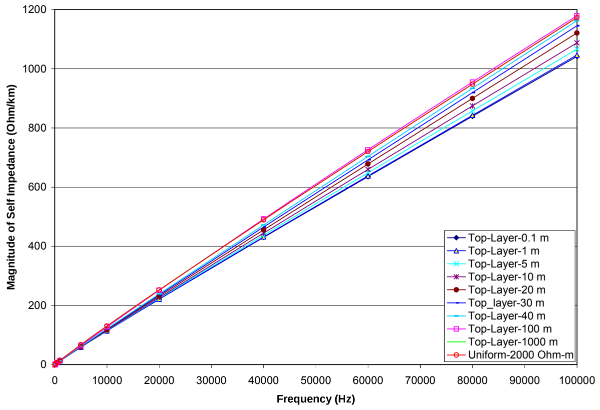

Figure 9. Effect of the Top Layer Thickness on the Magnitude of the Self Impedance of an Overhead Conductor in High/Low Soil Model

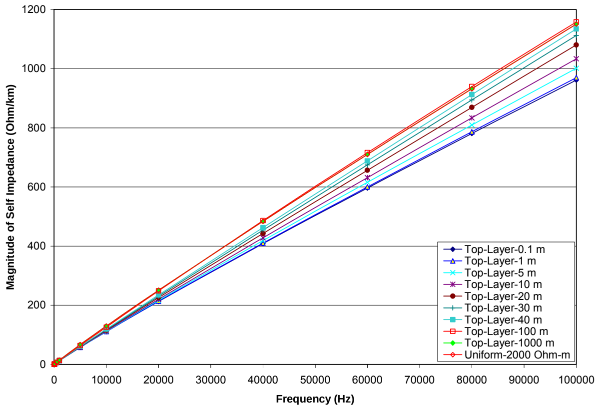

Figure 10. Effect of the Top Layer Thickness on the Magnitude of the Self Impedance of a Buried Conductor in High/Low Soil Model

The results show that the self impedance increases with the top layer thickness. In this case, results comparable to those obtained with the uniform soil are obtained only for a top layer thickness greater than 100 m suggesting that high resistivity surface layers are more “transparent” than the low resistivity ones.

2.3 Effect of Soil Permeability

Transmission lines or communication circuits may traverse ferromagnetic regions with large soil permeabilities. This effect is simulated with a two-layer soil model like the one used in Section 2.1, but with a different permeability for the top soil layer. The effect of the soil permeability on the magnitude of the self impedance for a conductor located at 10 m above ground or at 0.5 m below the earth surface is shown in Figures 11 and 12, respectively. In the figures, μ is the relative permeability of the top soil layer. The relative permeability of the bottom layer is taken as 1.

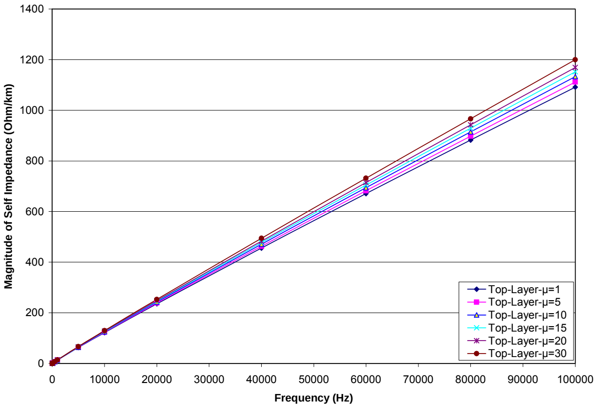

Figure 11. Effect of the Soil Permeability of the Top Soil Layer on the Magnitude of the Self Impedance of an Overhead Conductor

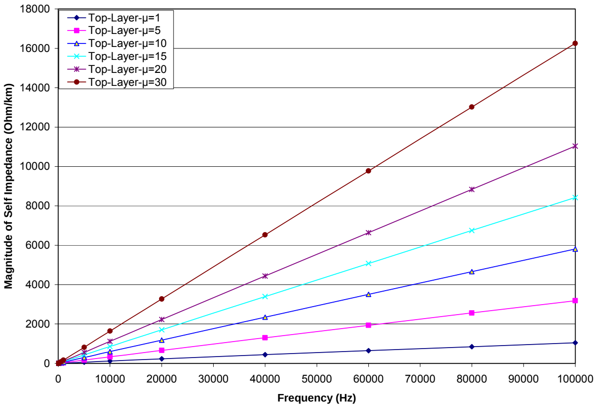

Figure 12. Effect of the Soil Permeability of the Top Soil Layer on the Magnitude of the Self Impedance of a Buried Conductor

From Figures 11 and 12, it can be seen that the self impedance of the overhead or buried conductor increases with the permeability of the top soil layer. This effect is especially pronounced for the buried conductor, for which the effect of permeability on the impedance should not be neglected

2.4 Effect of Soil Permittivity

The water content in the soil not only affects the resistivity, but also the permittivity. In order to get a clear picture of this effect, simulations have been made for low over high (10 Ohm-m over 500 Ohm-m) and high/low (1000000 Ohm-m over 500 Ohm-m) two-layer soil models. The thickness of the top layer is 20 m. The relative permittivity of the top layer is varied between 1 and 80. Figures 13 and 14 show the results for a conductor located 10 m above ground or at 0.5 m below the earth surface, respectively.

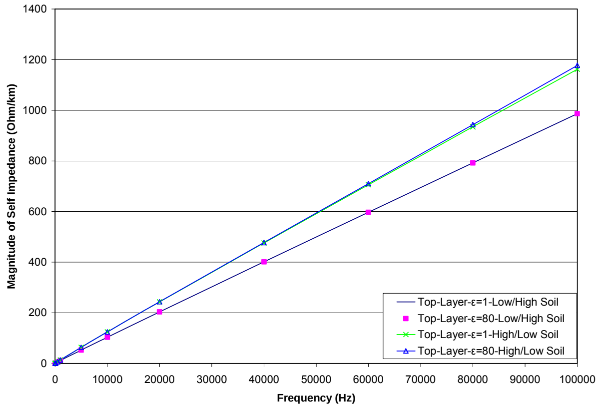

Figure 13. Effect of the Soil Permittivity of the Top Soil Layer on the Magnitude of the Self Impedance of an Overhead Conductor

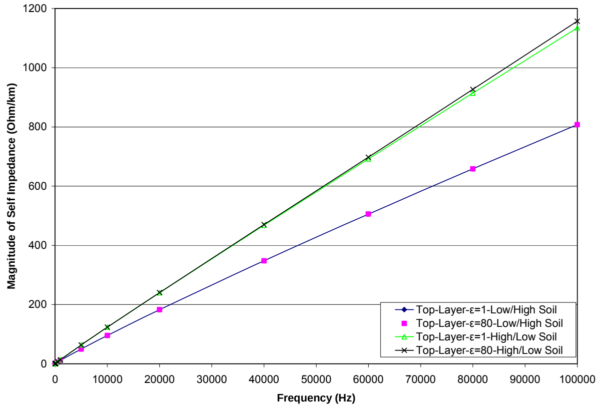

Figure 14. Effect of the Permittivity in the Top Layer on the Magnitude of Self Impedance of a Buried Conductor

In Figures 13 and 14, it can be seen that when the permittivity of the top soil layer increases from 1 to 80, the self impedance of the overhead conductor or the buried conductor changes very little for the high over low two-layer soil model, and remains essentially constant for the low over high two-layer soil model.

3. Conclusion

This paper clearly demonstrates the influence of soil stratification on the longitudinal impedance of conductors located above ground and buried in the soil. The effects of the resistivity, permeability and thickness of the soil layers were examined for several multi-layer horizontal soils.

The results show that the longitudinal impedance of conductors can be affected significantly by the layered structure of the soil, especially for buried conductors.

Acknowledgements

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