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Displacement Currents Effects on Earth-Return Parameters

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ABSTRACT: The article presents the earth's contribution to self and mutual impedances of double-wired aerial lines passing over a homogenous earth (one-layered earth) due to its importance in electromagnetic compatibility problems in electric power systems. In order to clarify the earth contribution of aerial line impedance, the earth-return parameters (resistance and reactance) for numerous types of earth soil were computed from the point of view of takes into account the longitudinal displacement currents using Wise modification of Carson integration. The most popular earth soil types in our region that takes into consideration in this research are clay, loamy, and sandy soils. In all cases under study, the effect of displacement currents is classified by using the ratio of displacement current density to resistive current density (denoted by k-ratio) that depends on the electromagnetic properties of each earth soil type. Hence, the behaviors of the earth-return parameters for each type of earth soil are mainly explained according to the k-ratio. This research displays how the calculated values of earth-return parameters were affected when the displacement currents were taken into consideration. As a result, the relative differences of these calculated values that got using Wise and Carson calculation methods become noticeable when the k-ratio is greater than 0.1 for all cases under study.

KEYWORDS: Carson integral, Earth-return parameter, EM properties of earth, Displacement currents, Wave propagation, Penetration depth

1. INTRODUCTION

In general, in case of the electromagnetic (EM) properties of the homogenous earth (one-layered earth) were not taken into consideration, the electromagnetic waves assumed to propagate along the overhead transmission lines without distortion and attenuation (propagate with light speed). In other words, the longitudinal displacement currents should be taken into account via including the earth permittivity in calculations. Consequently, the distortion and attenuation of the wave's propagation were taken into account along the long transmission lines [1, 2]. Hence, considering the EM properties of the homogenous earth into account is very important to the research area of electromagnetic compatibility [2].

It is known that, the impedance of double-wired aerial line passing over homogeneous earth consists of two components; one of them has a purely geometric nature and the other is determined using Carson integration [3–6]. The first component determined using the geometrical spacing of the double-wired aerial line. This component takes into account the superconductivity assumption of the homogenous earth the double-wired aerial line passes over. So, this component gives no earth contribution to the two-wired overhead line impedance [1, 3, and 5]. The second component is known as the return impedance of the homogenous earth. It takes into account the contribution of the earth to the two-wired overhead line impedance, that consequently affects waves propagation in earth and switching over-voltages in high-voltage power systems [4, 6].

It is said quite often that, the integration formula given by Carson didn't take into consideration the displacement currents in earth or air. This assumption makes it restricted to frequency range corresponds to the quasi-conductive earth [5]. In other words, neglecting the displacement currents makes restrictions to use Carson integration method in quasi-stationary frequencies band. This assumption is correct only when the earth's relative permittivity is not equal to unity [7]. Sunde integration formula allowed the frequency range to be increased to a higher band. In this formula, Sunde took into consideration only the displacement currents in earth [7, 8].

The range of frequency was extended to cover the quasi-stationary band of frequency by Wise modification of Carson integration. In this modification, Wise took into account the displacement currents in earth and air [9, 10].

This article discusses the impact of earth EM properties and consequently the longitudinal displacement currents on the earth-return impedance ($\Delta Z=\Delta R+j\Delta X$). The EM properties of the earth are represented by the earth resistivity and earth permittivity.

This research is dedicated to the case of two-wired overhead system passing over one-layered earth (homogenous earth). In our region, the most popular earth soil types that used in this study are clay, loamy, and sandy soils.

Obviously, the methods and algorithms used to calculate the earth-return impedance of overhead line in the problems of magnetic interference and electromagnetic compatibility are very important and should have special consideration. These algorithms should provide high adequacy, especially as the accuracy of physical measurements is not sufficient even for practical purposes [11–13]. Therefore, all the calculations in this research were performed using MATLAB and MATHCAD environments for all types of earth soil under study. Uses of two different computing environments is due to monitor and control the accuracy of results, especially since the two environments use different methods of numerical integration calculation.

2. THEORETICAL GROUND

It is known that, Carson’s integration is the first and classic method used to calculate the frequency-dependent parameters of earth (ΔR, ΔX) [3, 6, 14, and 15]. Carson took into account in his study the system of two parallel wires with earth-return, which is the basic one of multi-wired systems [16–19]. The geometric configuration for the double-wired aerial line under study, that passing over homogenous earth (infinite one layer) is shown in figure (1).

In order to take the displacement currents into account, an earth fictitious replacement is employed. In this method, the earth is replaced by a conductor below the real one, at a depth equal to the conductor's height above the earth [20, 21]. Note that, all the earth soil types under study are considered as a non-magnetic ($\mu_r = 1.0$).

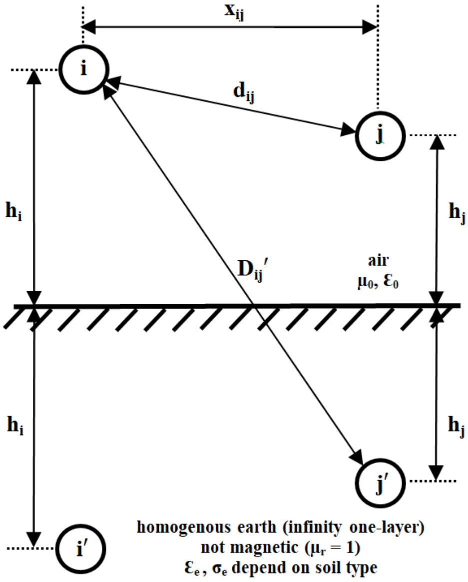


Figure 1. Geometric configuration for the double-wired aerial line under study

where,
h_i, h_j = mean heights of (i) and (j) conductors; [m],
x_{ij} = horizontal distance between conductors (i) and (j); [m],
D_{ij}', d_{ij} = distances that determine the geometric mutual reactance of the double-wired overhead line; [m],
i′, j′ = images of the conductors (i) and (j) respectively.

The earth-return parameters (self and mutual) in case of quasi-conductive mediums that given by Carson integration [3, 20] expressed as following,

$$\Delta Z_{ii}^{Carson} = \Delta R_{ii}^{Carson} + j\Delta X_{ii}^{Carson} \tag{1}$$

$$= j\frac{\omega\mu_0}{\pi}\int_0^\infty \frac{exp[-2h_i\lambda]}{\lambda + \sqrt{\lambda^2 + j\omega\mu_0\sigma_e}}\, d\lambda$$

$$\Delta Z_{ij}^{Carson} = \Delta R_{ij}^{Carson} + j\Delta X_{ij}^{Carson} \tag{2}$$

$$= j\frac{\omega\mu_0}{\pi}\int_0^\infty \frac{exp\left[-\left(h_i + h_j\right)\lambda\right]}{\lambda + \sqrt{\lambda^2 + j\omega\mu_0\sigma_e}}\cos(x_{ij}\lambda)\, d\lambda$$

The earth-return parameters (self and mutual) in case of quasi-stationary mediums that determined by Wise modification of Carson integration [9] have the following forms,

$$\Delta Z_{ii}^{Wise} = \Delta R_{ii}^{Wise} + j\Delta X_{ii}^{Wise} \tag{3}$$

$$= j\frac{\omega\mu_0}{\pi}\int_0^\infty \frac{exp[-2h_i\lambda]}{\lambda + \sqrt{\lambda^2 + \gamma_e^2 - \gamma_a^2}}\, d\lambda$$

$$\gamma_e^2 = j\omega\mu_0(\sigma_e + j\omega\varepsilon_e) \tag{3a}$$

$$\gamma_a^2 = j^2\omega^2\mu_0\varepsilon_0 \tag{3b}$$

$$\Delta Z_{ij}^{Wise} = \Delta R_{ij}^{Wise} + j\Delta X_{ij}^{Wise} \tag{4}$$

$$= j\frac{\omega\mu_0}{\pi}\int_0^\infty \frac{exp\left[-\left(h_i + h_j\right)\lambda\right]}{\lambda + \sqrt{\lambda^2 + \gamma_e^2 - \gamma_a^2}}\cos\left(x_{ij}\lambda\right)\, d\lambda$$

where,
ΔZ_{ii}, ΔZ_{ij} = self and mutual earth-return impedance; [Ω/m],
ΔR_{ii}, ΔR_{ij} = self and mutual earth-return resistance; [Ω/m],
ΔX_{ii}, ΔX_{ij} = self and mutual earth-return reactance; [Ω/m],
γ_e, γ_a = wave propagation constant of earth and air respectively,
$\omega = 2\pi f$ angular frequency; [rad/s],
μ_0 = magnetic permeability for air, which equal to approximately $4\pi \times 10^{-7}$; [H/m],
$\varepsilon_e = \varepsilon_0 \cdot \varepsilon_r$ = permittivity of earth; [F/m],
ε_0 = permittivity of free space, which equal to approximately 8.85×10^{-12}; [F/m],
ε_r = relative permittivity of earth,
σ_e = conductivity of earth; [S/m],
λ = integration variable.

Remember that, Carson integrations (formulae 1, 2) takes into account the displacement currents only when the earth's relative permittivity is equal to unity ($\varepsilon_r = 1$) [7]. It means that, Carson integrations are still adequate just for a limited range of frequency [5].

The inclusion of the earth's relative permittivity ($\varepsilon_r \geq 1$) in the integration of Sunde allows to take into consideration the displacement currents in earth. For this reason, Sunde formulae can be applied in a wider frequency range [7, 8].

The presence of the earth and air permittivities in the integrations of Wise (formulae 3, 4), enables researchers to take into account the longitudinal displacement currents in earth and air. This makes Wise formulae more accurate to use for higher range of frequency [9, 10, and 22].

Note that, all the calculation formulae (Carson and Wise) used in this research are concerned just to the case of homogeneous earth [6, 14, and 23].

3. CLASSIFICATION OF DISPLACEMENT CURRENTS EFFECT

It is known that; the displacement currents effect depends not only on the EM properties of the earth but also on the frequency. It means that, the effect of displacement currents increases with the frequency [17, 24].

The classification of the displacement currents effect leads to easy interpret the behaviors of the earth-return parameters in all soil types under study. It is possible to obtain such classification via using the ratio of displacement current density to resistive current density. This ratio that denoted by (k-ratio) is given as following,

$$k - ratio = \left|\frac{J_d}{J_r}\right| = \left|\frac{j\omega\varepsilon_e E}{\sigma_e E}\right| = \frac{\omega\varepsilon_e}{\sigma_e} \qquad (5)$$

where,

J_d, J_r = densities of displacement and resistive currents; [A/m^2],

E = electric field; [V/m].

From formula (5) it is obvious that, the k-ratio depends on the EM properties of homogenous earth in case of the frequency is constant. The EM properties (permittivity and resistivity) for the most popular dry soil types in our region are listed in table (1) in accordance with [25, 26].

Table 1. Permittivity and resistivity of earth for dry soil types under study

Dry soil type	*ε_e, (F/m)*	*$\rho_e = 1/\sigma_e$, (Ω.m)*
Sand	$4\varepsilon_0$	600
Loam	$5\varepsilon_0$	240
Clay	$6\varepsilon_0$	100

The graphs of frequency against k-ratio using formula (5) for these dry soil types are shown in figure (2). As shown, the behavior for the case of clay soil is the highest one, while the behavior for the case of sandy soil is the lowest one. These behaviors depend on the permittivity and resistivity of each soil type.

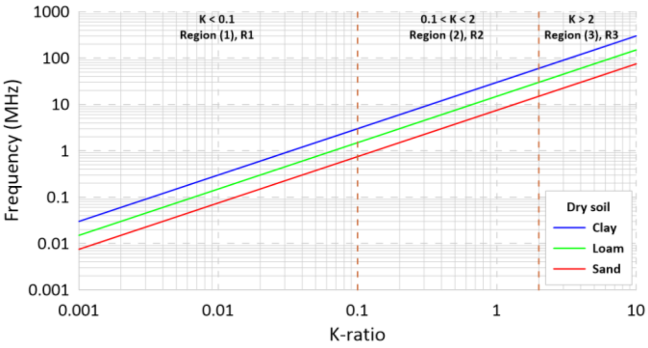


Figure 2. Graphs of frequency against k-ratio for dry soil types under study

From the graphs shown in figure (2), it is very simple to identify the k-ratio and its corresponds frequency or vice versa for each type of earth soil under study. To show the frequency limits of region (1) and region (2) for each dry soil type, table (2) display these limits (f_{R1}, f_{R2}) that correspond to k-ratio = 0.1, 2. These frequency limits depend up on the EM properties of each soil type.

Table 2. Frequency limits correspond to k-ratio = 0.1, 2 for dry soil types under study

Dry soil type	*f_{R1}, (MHz)*	*f_{R2}, (MHz)*
Sand	0.75	15
Loam	1.5	30
Clay	3	60

The effect of displacement currents of each soil type under study may be classified according to the k-ratio as following:

a) If k-ratio is less than 0.1, the displacement currents can be neglected due to their very little values when it compared with the resistive currents (region 1, R1).

b) If k-ratio is more than 0.1 and less than 2, the displacement currents become comparable with the resistive currents and cannot be neglected (region 2, R2).

c) If k-ratio is more than 2, the displacement currents become prevailing and have a significant effect on calculated parameters (region 3, R3).

It should be mentioned that, it is suitable to use Carson formula to calculate the earth-return parameters in region (R1), but is not accurate to use it in regions (R2, R3) when the earth's relative permittivity is more than unity. In contrary, Wise formula is suitable to use in all regions (R1, R2, and R3) due to considering into account all the possible values of earth's relative permittivity ($\varepsilon_r \geq 1$).

4. PENETRATION DEPTH ACCORDING TO EARTH SOIL TYPE

It is known that, the penetration depth (skin depth) defines the distance that EM wave can propagate through the upper-layer of earth before its amplitude has been decayed [24].

Since the earth is considered as perfect conductive in the past ($\sigma >> \omega\varepsilon$), the electromagnetic wave has very high attenuation and consequently very low penetration depth that tends to zero at very high frequencies [27, 28].

In 1926, Carson assumed the earth is not perfect conductive and took into account the exact value of the earth conductivity in his integration method [3]. Consequently, this assumption affects the penetration depth of the electromagnetic wave.

The calculations of penetration depth contribute to understanding the behaviors of the earth-return parameters. Therefore, the calculations of wave's penetration depth for all earth soil types under study are considered in this research. The general expression of the earth penetration depth in accordance with [24, 27] is given by;

$$\delta_e = \frac{1}{\alpha_e} = \frac{1}{\omega\left[\sqrt{\frac{\mu_0 \varepsilon_e}{2}\left(\sqrt{1+\left(\frac{\sigma_e}{\omega \varepsilon_e}\right)^2}-1\right)}\right]} \tag{6}$$

where,

δ_e = wave penetration depth in earth; [m],

α_e = wave attenuation constant; [Np/m].

In this section, the penetration depth calculations for the dry soil types (sand, loam, and clay) were performed using formula (6). The graphs of penetration depth against frequency are shown in figure (3). As shown, the wave's penetration depth decays sharply as the frequency increases until it reaches convergent little values for each earth soil type separately. In other words, as the frequency increases, the wave propagates less distance in earth. Consequently, this can affect the calculated values of the earth-return parameters (see section 5).

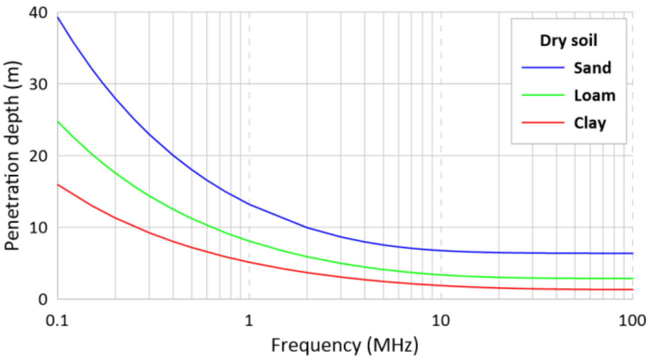


Figure 3. Penetration depth against frequency for dry soil types under study

Obviously, the case of clay soil has the lowest behavior of penetration depth, while the case of sandy soil has the greatest one when comparing all types of dry soil with each other. As a result, the values of penetration depths related to frequency 100 MHz equal to 6.4 m, 2.9 m, and 1.3 m for sandy, loamy, and clay soil types respectively. Hence, the electromagnetic waves can propagate longer distance in case of sandy soil compared with other soil types under study. This means that, the higher the factor ($\rho_e\ \varepsilon_e$), the greater the wave's penetration depth when comparing the dry soil types with each other.

5. EFFECT OF DISPLACEMENT CURRENTS ON EARTH-RETURN PARAMETERS

The main purpose of this section is to compare and analyze the calculated values of the earth-return parameters (self and mutual) that got using Wise and Carson calculation methods. It should be clear that, Wise integral formulae (3, 4) become Carson integral formulae if we consider the displacement currents when relative permittivity equal to unity ($\varepsilon_r = 1$). It means that, Wise integrals are considered as general formulae to compute the earth-return parameters taking into account the effect of the displacement currents when relative permittivity more than or equal to unity ($\varepsilon_r \geq 1$).

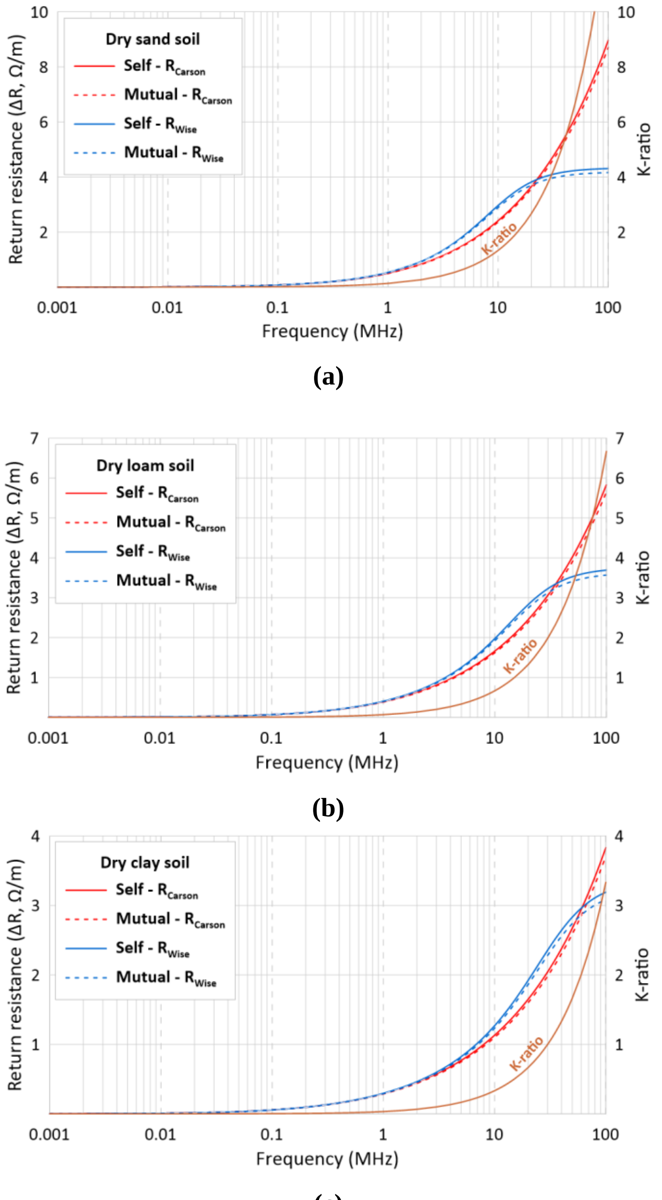
In this section, the calculations were performed using MATLAB and MATHCAD in case of a double-wired aerial line with $h_i = h_j = 8$ m and $x_{ij} = 3$ m passing over dry soil types under study (sandy, loamy, and clay). All the calculated values shown in graphs that obtained using Wise as well as Carson integration are expressed in Ω/m.

Since the case of sandy soil has the lowest frequency corresponds to k-ratio = 0.1 as shown in table (2), so its return parameters have the greatest behaviors in our study. Therefore, sandy soil type is selected as a general case from the cases under study to illustrate the effect of displacement currents on earth-return parameters. The behaviors of earth-return parameters (ΔR, ΔX) are discussed in details in the following subsections.

5.1 Effect of displacement currents on earth-return resistance

The calculated curves of the earth-return resistance (self and mutual) for the case of two-wired overhead line passing over the dry soil types under study are shown in figure (4).

As shown in figure (4), the case of sandy soil has the higher values of earth-return resistance when comparing with other earth soil types. It means that, the higher the factor ($\rho_e\ \varepsilon_e$), the higher the values of earth return-resistance. At the same time, the calculations carried out using Wise and Carson integration methods gave the higher contrast in results for the case of sandy soil. This is because of, the differences in results started to appear earlier at lower value of frequency (0.75 MHz) as displayed in table (2). Therefore, the case of sandy soil is considered as the more comprehensive case under study when it compared with other soil types.



(a)

(b)

(c)

Figure 4. Calculated graphs of earth-return resistance (self and mutual) and k-ratio against frequency for all types of dry soil under study; a) sand, b) loam, c) clay

Note that, to clarify the behaviors of earth-return resistance, the wave's penetration depth makes it easy to understand the nature of these behaviors. Hence, the behaviors of earth-return resistance in case of the double-wired aerial line passing over sandy area are described deeply as following,

a) For k-ratio less than 0.1 (R1, $k < 0.1$), the calculated values of earth-return resistance (self and mutual) increase by a monotonic behavior with the frequency when using both Wise and Carson calculation methods with the same rate (see figure 4a). It means that, the results got using both calculation methods (Wise and Carson) are similar due to the displacement currents have negligible effect in region (1).

b) For k-ratio more than 0.1 and less than 2 (R2, $0.1 < k < 2$), the calculated values using Wise calculation method still increasing monotonically with the frequency as shown in figure (4a). In this region (R2), the displacement currents become comparable with resistive currents. Therefore, the results got using Wise formula has overestimation when it compared with the results got using Carson formula.

c) For k-ratio more than 2 (R3, $k > 2$), the displacement currents have a significant effect. In region (3), the calculated values using Wise formula still increasing monotonically by convergent values due to the convergent little values of the earth penetration depth (see figure 3). As shown in figure (4a), a saturated behavior is observed for the calculated values obtained using Wise formula at high frequencies. That is the reason of why the earth-return resistance using Wise formula has underestimation when it compared with that got using Carson formula. Note that, the results got using Carson formula still increase with higher rate as the frequency increases due to not considering into account the actual values of wave's penetration depth in earth. Whereas Carson assumed in his calculations that, the earth-return resistance is tending to increase to very high value when frequency tends to infinity while the earth penetration depth will tend to zero.

When studying the effect of earth displacement currents on earth-return resistance for the other earth soil types under study (loam and clay), the same behaviors were got but with lower values compared with the case of sandy soil (see figure 4). Note that, the lower behavior for these cases (loam and clay) is due to the higher frequency limits of regions (R1, R2) as shown in table (2).

From the results obtained when using Wise calculation method, it can be seen that the higher the factor (ρ_e ε_e), the earlier the frequency at which a saturated behavior of earth-return resistance was attained.

5.2 Effect of displacement currents on earth-return reactance

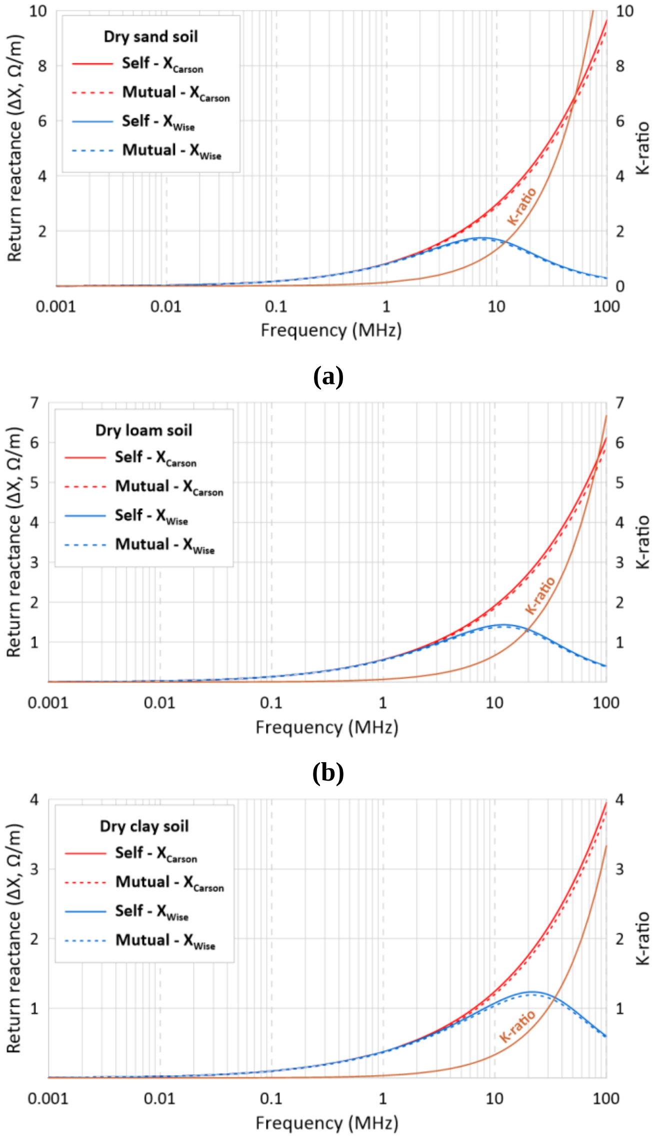
In this subsection, figure (5) shows the calculated curves of the earth-return reactance (self and mutual) for the case of two-wired aerial line passing over the types of dry soil under study. As shown, the behaviors of earth-return reactance are completely different from that obtained in the case of earth-return resistance.

Since the case of sandy soil has the greatest behavior as mentioned previously, the behaviors of its earth-return reactance are described deeply as following,

a) For k-ratio less than 0.1 (R1, $k < 0.1$), the calculated values of earth-return reactance that got using Wise and Carson formulae are the same due to the negligible effect of displacement currents (see figure 5a). It means that, the behaviour of earth-return reactance increasing monotonically with the frequency when using both calculation methods by the same rate.

b) For k-ratio more than 0.1 and less than 2 (R2, 0.1 < k < 2), the calculated values that got using Wise formula increases by a non-monotonic behavior with the frequency due to the effect of the displacement currents. In contrary, the calculated values got using Carson formula still increase by a monotonic behavior with the frequency. Therefore, the contrast between results got using Wise and Carson formulae increases as the frequency increases.

c) For k-ratio more than 2 (R2, k > 2), the earth-return reactance decreases sharply as the frequency increases until it reaches convergent little values due to the significant effect of the displacement currents. While, the results got using Carson formula still increase with the frequency due to his assumption for wave's penetration depth. This leads to more deviations between the results obtained using Wise and Carson formulae.



(a)

(b)

(c)

Figure 5. Calculated graphs of earth-return reactance (self and mutual) and k-ratio against frequency for all types of dry soil under study; a) sand, b) loam, c) clay

In contrary with the case of earth-return resistance, the calculated values of earth-return reactance have underestimation for all frequencies correspond to k-ratio more than 0.1 when using Wise formula.

The same behaviors were got for the cases of double-wired aerial line passing over the other types of earth soil under study (loam and clay), but with lower values compared with the case of sandy soil (see figure 5).

It is seen from the results shown in figures (4, 5) that, the calculated values obtained using Wise or Carson calculation method for the case of self-return parameters have slightly higher values when it compared with that obtained for mutual return parameters. Furthermore, the deviations between results of self or mutual return parameters that got using both calculation methods (Wise and Carson) become noticeable when the k-ratio is greater than 0.1 due to the effect of displacement currents.

Obviously, all previous results present how the calculated values of self and mutual return parameters of earth were affected when the displacement currents were taken into consideration.

5.3 Relative differences of results

To more easily compare the results obtained from the two calculation methods (Wise and Carson), the relative differences (RD) of results were calculated using formula (7).

$$RD = \frac{difference}{Average} x100 = \frac{A_{Wise} - A_{Carson}}{\left[\frac{A_{Wise}+A_{Carson}}{2}\right]} x100 \qquad (7)$$

where,

RD = relative difference of results,

A_{Wise} = calculated value using Wise calculation method,

A_{Carson} = calculated value using Carson calculation method.

Figure (6) shows the graphs of the relative differences of earth-return resistance (self and mutual) for all dry soil types under study. As shown, the relative differences have non-monotonic increase with the frequency for all soil types under study. It means that, the relative differences between Wise and Carson calculations may have monotonic behavior or non-monotonic behavior according to the frequency range used in calculations. Note that, the negative values of relative differences are due to the saturated behavior of the calculated values obtained using Wise calculations at high frequencies, while the calculated values that got using Carson calculations still increasing with the frequency.

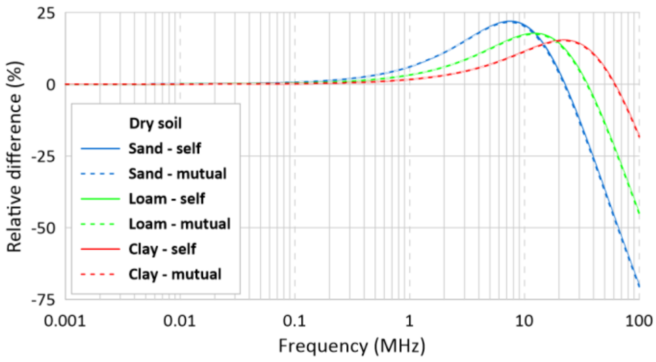


Figure 6. Relative differences of results against frequency for the case of earth-return resistance

Similarly, the relative differences of earth-return reactance (self and mutual) against frequency for all dry soil types are shown in figure (7). As shown, these relative differences decreasing monotonically with the frequency for all soil types under study. It is obvious that, using of Wise calculation method leads to underestimation of results for all frequencies corresponding to k-ratio more than 0.1 due to the effect of displacement currents.

From the results shown in figures (6, 7) it is clear that, the relative differences of the calculated values for self-return parameters have slight variations from that got for mutual return parameters. Furthermore, the case of sandy soil has the greatest relative differences when it compared with the other soil types under study. This is due to; this case has the lowest frequency corresponds to k-ratio = 0.1 at which the differences of results start to appear. It means that, the higher the factor (ρ_e $\mathcal{E}_e$), the greatest the relative differences between results obtained when using Wise and Carson Calculations. In other words, the relative difference behavior of calculated values depends on the EM properties for each soil type.

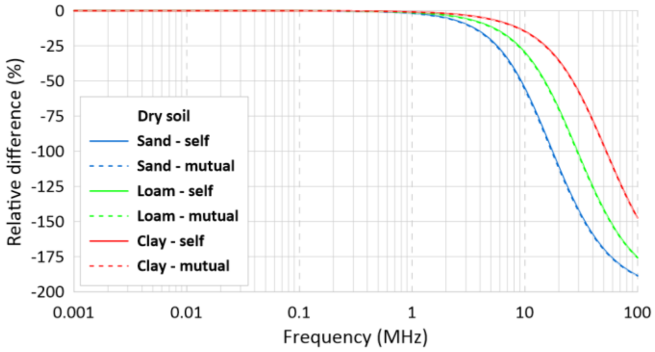


Figure 7. Relative differences of results against frequency for the case of earth-return reactance

To apply this study on wide range of relative permittivity and resistivity of earth, all the previous calculations were re-performed for the cases of wet soil types. The EM properties of earth and frequency limits of regions (R1, R2) for these wet soil types are listed in tables (3, 4).

Table 3. Electromagnetic properties of earth for wet soil types

Wet soil type	*$\mathcal{E}_e$, (F/m)*	*ρ_e, (Ω.m)*
Sand	$10\mathcal{E}_0$	300
Loam	$15\mathcal{E}_0$	120
Clay	$18\mathcal{E}_0$	50

Table 4. Frequency limits of regions (R1, R2) for wet soil types

Wet soil type	*f_{R1}, (MHz)*	*f_{R2}, (MHz)*
Sand	0.6	12
Loam	1	20
Clay	2	40

From the calculated results we found that, the same previous behaviors for the cases of dry soil types were got but at lower ranges of frequency (see table 4). It means that, the cases of wet soil have lower calculated values of earth-return parameters and consequently higher relative differences of results that got using Wise and Carson calculations methods. This is due to the lower value of earth resistivity for the case of wet soil when it compared with the case of dry soil for each soil type separately.

Finally, generalizing all the previous calculations performed in this research on three-phase transmission systems will be more complicated due to the mutual coupling between phases.

CONCLUSIONS

For problems concerned to electromagnetic compatibility in power systems, it is very important to take into account the earth's contribution of the double-wired aerial line impedance. In other words, the displacement currents should be taken into account when determining the earth-return parameters. Whereas, these displacement currents have an effect, that cannot be neglected when the k-ratio is greater than 0.1. In order to compute the earth-return parameters, Wise calculation method takes into account the relative permittivity of earth that makes it more accurate to use in high frequency ranges.

Considering the calculations of wave's penetration depth into account makes it easy to understand the behaviors of the earth-return parameters. It is clear from the results that, as the value of the factor (ρ_e $\mathcal{E}_e$) increases, the electromagnetic wave can propagate longer distance in earth. It means that, the wave's penetration depth is affected by the electromagnetic properties of earth that depend on soil type and consequently this affects the calculated values of earth-return parameters.

When taking the displacement currents into account it can be seen that, the higher the factor (ρ_e $\mathcal{E}_e$), the earlier the frequency, at which the relative differences of earth-return parameters become noticeable or the convergent values of these parameters begin to appear. Furthermore, non-monotonic behaviors of relative differences for the calculations of earth-return resistance were observed, while the calculations of earth-return reactance have monotonic behaviors.

It should be mentioned that, the cases of wet soil have the same behaviors that obtained for the cases of dry soil but at lower ranges of frequency. It means that, the cases of wet soil have lower calculated values of earth-return parameters and consequently higher relative differences due to their lower earth resistivity.

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