Impact of Ground Resistivity on Transmission Line Electrical Parameters

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Abstract: ***In electric power systems, the overhead transmission lines are designed to transmit the electrical energy from one point to another. The electrical parameters calculations of the transmission lines are very important to the areas concerned to electromagnetic compatibility and transitional processes in power systems. The ground-return parameters of the transmission line passing over one-layered ground (homogenous ground) overestimate the electrical parameters values of the transmission line. Therefore, accurate calculations of the transmission line electrical parameters were performed in this research, taking into account the impact of the ground resistivity. Approximated values of ground resistivity for the most common soil types of homogenous ground in our region were utilized. The behaviors of the ground-return parameters (Carson correction factors) while varying the ground resistivity were explained. As a result, as the ground resistivity increases, the ground-return parameters increase and consequently the overall transmission line electrical parameters.***

Keywords: Transmission Line Electrical Parameters, Ground-Return Parameters, Ground Resistivity, Carson Correction Factors

1. Introduction

The electrical parameters of high-voltage overhead power lines are very important to the research area of transitional processes. These parameters were calculated according to known expressions, based on certain assumptions regarding to the geometry of the overhead transmission line and the physical properties of the system conductors [1-5].

The electrical parameters of the overhead power lines may not consider the ground effect. It means that, these parameters may differ from those calculated in case of the ground-return parameters were taken into consideration. These ground-return parameters depend on the ground dielectric properties. Therefore, the dielectric properties of the ground the overhead power lines pass over must be taken into account [3, 4].

It is known that, the dielectric properties of the ground that affect its return parameters are ground permittivity and ground resistivity [4, 6]. The dielectric permittivity affects the ground-return parameters at high frequencies; otherwise it has no effect [7, 8]. Since the ground dielectric permittivity has no effect at power frequency (50 Hz), only the ground resistivity property is considered in this research.

In 1926 J. R. Carson presented the innovative idea of solving the problem of ground-return parameters [6]. It was based on the assumption that, the power voltage and power current propagate along the line like a wave and the ground has an exact conductivity (ground is not perfect conductive). By developing these ideas, he got equations that express the calculation of return parameters of the homogeneous ground (one-layered ground) [9-11].

The system of two parallel wires with a ground return was taken into consideration by Carson, which is the basic one and its obtained solution may be extended to multi-wired systems [3, 6].

The double-wired overhead line that passes over the homogeneous ground has impedance that consists of two components: one is entirely geometric in nature, while the other is calculated via Carson integration [6, 12, 13, and 14]. The first component was calculated using the overhead line geometric spacing. This component takes into consideration that, the double-wired overhead line passes over a homogenous ground, which is assumed to be superconductive. Therefore, this component does not make any ground contribution to the electrical parameters of the two-wired overhead line [6, 13]. The ground-return impedance is the second component that takes into consideration how the ground influences the two-wired overhead line parameters [12, 14].

This paper discusses the effect of ground resistivity on the ground-return parameters (ground resistance & ground inductance), and consequently their effect on the overall transmission line electrical parameters. Note that, the ground the transmission line passing over is considered as homogenous ground (infinite one-layer ground). The simulated results in this research were performed using MATLAB.

2. Transmission Line Electrical Parameters Considering the Ground as Perfect Conductive

Normally, for transmission lines have distances less than 80 km (short transmission line), it is not important to consider the transmission line capacitance. So in this research, only the resistance and inductance matrices of three-phase transmission line (110 kv) were calculated considering the perfect conductivity of the homogenous ground. In other words, only the geometric nature of the transmission line is taken into account. It means that, no ground contribution to the transmission line electrical parameters.

2.1 Calculation of Transmission Line Resistance

It is known that, the standard DC resistance of a conductor assumes a homogeneous distribution of the current, and therefore the current density is the same at every cross-section point of the conductive layer of the conductor. Skin-effect occurs when alternating current passes through a conductor. It causes the current to be pushed onto the surface of the conductor, which increases its real resistance [15, 16].

For the correction of the skin effect, the correction factor which expresses the ratio between AC and DC resistances as given in [16] were taken into consideration. Therefore, the AC resistance of the conductor of 110 kv transmission line according to [14] is 0.1181 Ω/km per phase at frequency 50 Hz. This resistance expressed in matrix form as shown in formula (1).

$$[R] = \begin{bmatrix} 0.1181 & 0.0 & 0.0 \\ 0.0 & 0.1181 & 0.0 \\ 0.0 & 0.0 & 0.1181 \end{bmatrix}, [\Omega/\mathrm{km}] \quad (1)$$

It is clear that, the resistance matrix [R] of the three-phase transmission line has only the main diagonal values (geometric self-values). It means that, the resistance matrix [R] of the transmission line has no geometric mutual values.

2.2 Calculation of Transmission Line Inductance

To compute the matrix of inductance, consider the geometric configuration presented in [14] for the three-phase overhead transmission line (110 kv) that passing over a homogenous ground as shown in figure (1). This geometric configuration displays unsymmetrical spaces between the three phase conductors of the transmission line.

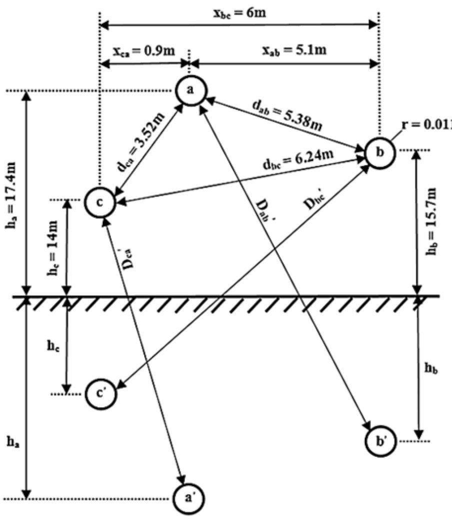


Figure 1: Geometric configuration for three-phase transmission line (110 kv) which has unsymmetrically triangle spacing between conductors

For the derivation of line inductance, fictitious replacement is used in which the ground (as the second electrode) is replaced by a conductor in the ground below the real one, at a depth equal to the height of the conductor above the ground (see figure 1). This method of images can be use independently of the frequency or material constants of conductor and ground [17-21].

Where,
h_a, h_b, and h_c = mean heights of a, b, and c conductors;
x_{ab}, x_{bc}, and x_{ca} = horizontal distances between the conductors a, b, c;
d_{ab}, d_{bc}, and d_{ca} = distances between the conductors a, b, c;
$D_{ab'}$, $D_{bc'}$, and $D_{ca'}$ = distances between the conductors and images of conductors;
a′, b′, and c′ = images of the transmission line conductors a, b, and c respectively.

The transmission line inductance (self & mutual) in case of the ground considered as perfect conductive are calculated according to the following formulae,

$$L_{ii} = \frac{\mu_o}{2\pi} ln \frac{2h_i}{r_i'} \quad (2)$$

$$L_{ij} = \frac{\mu_o}{2\pi} ln \frac{D_{ij}'}{d_{ij}} \quad (3)$$

Where,
L_{ii}, L_{ij} = self and mutual inductances for overhead transmission line; [H/m]
D_{ij}', d_{ij} = distances determine the overhead line's mutual inductance; [m]
$r_i' = r_i e^{-\mu_r/4}$ = effective radius of conductor (i); [m]
μ_o = magnetic permeability for air, which equal to approximately $4\pi \times 10^{-7}$; [H/m]
$\mu_r = 1.0$ = relative permeability for non-magnetic ground

Formulae (2, 3) illustrated that, self-inductance value is directly proportional to the height of the conductor from the ground, while mutual inductance value is inversely proportional to the distance between conductors. Note here that, the distance (d_{ij}) affects the mutual inductance value more than the distance ($D_{ij'}$).

The inductance matrix [L] for the three-phase transmission line according to the geometric data shown in figure (1) and using formulae (2, 3) is given by,

$$[L] = \begin{bmatrix} 1.664 & 0.366 & 0.438 \\ 0.366 & 1.644 & 0.316 \\ 0.438 & 0.316 & 1.621 \end{bmatrix}, [\mathrm{mH/km}] \quad (4)$$

For more comprehending, figure (2) shows the graphical frames of the geometric values for self and mutual inductances in case of the ground considered as perfect conductive.

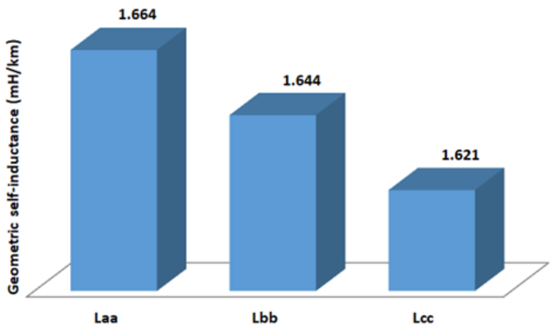
As shown in figure (2), the conductor of phase A has the greatest self-inductance value. It means that, the longest height of the conductor from the ground, the larger its self-inductance value.

It is also shown that, the mutual inductance value between phases A and C is the greatest one. In other words, shorter the distance between the two conductors, larger the mutual inductance between them.

3. Carson Correction Factors for Transmission Line Electrical Parameters

In early research, the ground is considered as a perfectly conductive (ground resistivity equals zero) [22]. However, in reality the ground have a conductivity or resistivity value depending on the soil type. It means that, it is important to correct the values of the transmission line electrical parameters using Carson correction factors.

Note here that, Carson calculations takes into account only the calculation of the ground-return parameters. In other words, only the resistance and inductance have Carson correction factors.



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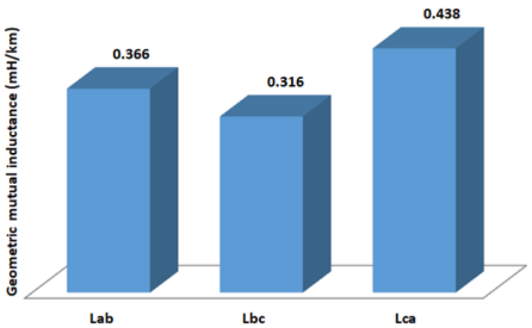

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Figure 2: Graphical frames of geometric values for self and mutual inductances considering the perfect conductivity of the homogenous ground; a) Self-inductance, b) Mutual inductance

Carson correction factors for resistance and inductance (self and mutual) according to [6, 23, and 24] are given by;

$$\Delta Z_{ii} = \Delta R_{ii} + j\Delta X_{ii} = \Delta R_{ii} + j\omega\Delta L_{ii} \quad (5)$$

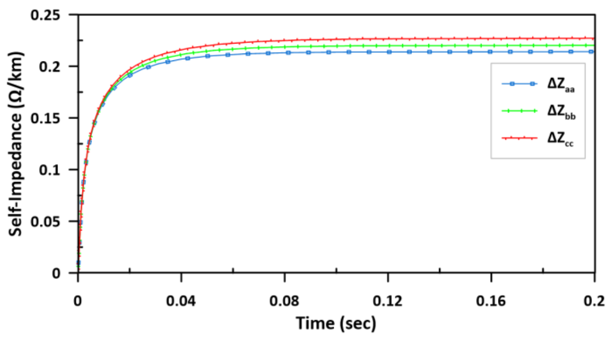
$$= j\frac{\omega\mu}{\pi}\int_0^\infty \frac{exp[-2h_i\lambda]}{\lambda + \sqrt{\lambda^2 + j\omega\mu/\rho}}d\lambda$$

$$\Delta Z_{ij} = \Delta R_{ij} + j\Delta X_{ij} = \Delta R_{ij} + j\omega\Delta L_{ij} \quad (6)$$

$$= j\frac{\omega\mu}{\pi}\int_0^\infty \frac{exp[-(h_m + h_n)\lambda]}{\lambda + \sqrt{\lambda^2 + j\omega\mu/\rho}}cos(x_{ij}\lambda)\,d\lambda$$

Where,
ΔZ_{ii}, ΔZ_{ij} = self and mutual Carson correction factors for transmission line impedance; [Ω/m]
ΔR_{ii}, ΔR_{ij} = self and mutual Carson correction factors for transmission line resistance; [Ω/m]
ΔX_{ii}, ΔX_{ij} = self and mutual Carson correction factors for transmission line reactance; [Ω/m]
ΔL_{ii}, ΔL_{ij} = self and mutual Carson correction factors for transmission line inductance; [H/m]
ω = angular frequency; [rad/s]
μ = magnetic permeability of the ground; [H/m]
ρ = ground resistivity; [Ω.m]
λ = integration variable.

It is clear that, the method of numerical integration is an important feature of Carson calculation method. To use Carson integral, it is necessary to define the instant of time that the integration value becomes constant or stable. To do this, the exact value of the ground resistivity had taken into account. With a ground resistivity equals 100 Ω.m, the behaviors of self and mutual impedances using Carson integral with respect to time are shown in figure (3). It can be seen that, the integration values increasing gradually as the time increases before it have stable values. These stable values are obtained approximately after 0.15 sec for both cases (self-impedance, mutual impedance).



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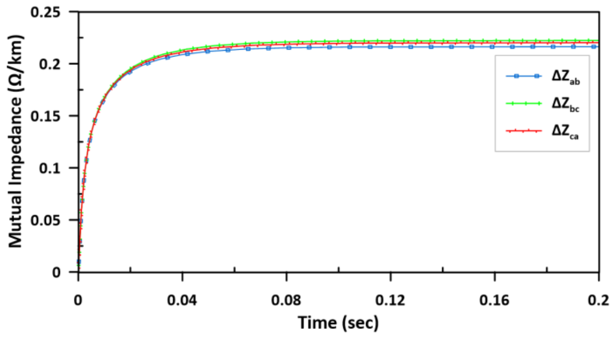

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Figure 3: Behaviors of self and mutual impedances using Carson integral when the ground resistivity equals 100 Ω.m; a) Self-impedance, b) Mutual impedance

As shown in figure (3), phase C has the greatest behavior of self-impedance while phase A has the lowest one. It means that, the shortest height of the conductor from the ground, the larger its self-impedance. At the same time, the mutual impedance between phases B and C has the greatest behavior while between phases A and B has the lowest one. In other words, lesser the sum of heights of two adjacent conductors, larger the mutual impedance between them.

As the exact value of the ground resistivity is used, the transmission line electrical parameters have significant deviations from that obtained in section (2). To clarify it more, the correction factors of the transmission line parameters using Carson formulae expressed in matrix form as following,

$$[\Delta R_g] = \begin{bmatrix} 0.04773 & 0.04781 & 0.04790 \\ 0.04781 & 0.04790 & 0.04799 \\ 0.04790 & 0.04799 & 0.04808 \end{bmatrix}, [\Omega/\text{km}] \quad (7)$$

$$[\Delta L_g] = \begin{bmatrix} 0.6644 & 0.6717 & 0.6842 \\ 0.6717 & 0.6843 & 0.6911 \\ 0.6842 & 0.6911 & 0.7066 \end{bmatrix}, [\text{mH/km}] \quad (8)$$

Then, the overall transmission line resistance and inductance in case of the ground resistivity equals 100 Ω.m are given by,

$$[R_{tot.}] = [R] + [\Delta R_g] \quad (9)$$

$$= \begin{bmatrix} 0.1658 & 0.04781 & 0.04790 \\ 0.04781 & 0.1660 & 0.04799 \\ 0.04790 & 0.04799 & 0.1662 \end{bmatrix}, [\Omega/\text{km}]$$

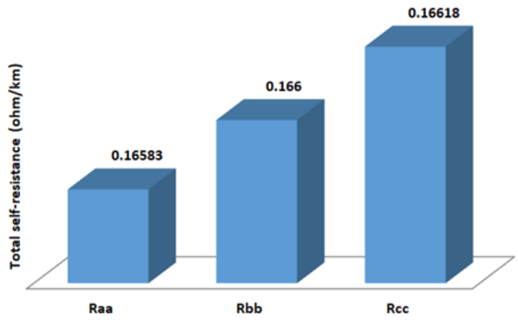
$$[L_{tot.}] = [L] + [\Delta L_g] \quad (10)$$

$$= \begin{bmatrix} 2.329 & 1.038 & 1.122 \\ 1.038 & 2.328 & 1.007 \\ 1.122 & 1.007 & 2.327 \end{bmatrix}, [\text{mH/km}]$$

From the results shown in formulae (9, 10) it is evident that, the calculated values of the total transmission line parameters are significantly different from those obtained using formulae (1, 4). Furthermore, it is obvious that the calculated values of the transmission line inductances (especially mutual inductances) have more deviations than the calculated values of resistances. As a result, the total value of transmission line mutual inductance between phases B and C increased by approximately three times the original value (at ground resistivity equals zero).

To understand the behavior of the overall transmission line parameters, figures (4, 5) show the graphical frames of these parameters in case of the ground resistivity equals 100 Ω.m. As shown in figures (4), the behavior of resistance values follows the behavior of Carson correction factors while the behavior of inductance values follows the geometric behavior (see figures 5).

It should be mentioned that, the electrical parameters calculations are somewhat different in the case of a transmission line whose three-phase conductors arranged in a flat configuration. The geometric configuration of such transmission line in accordance with data given in [5] is shown in figure (6).



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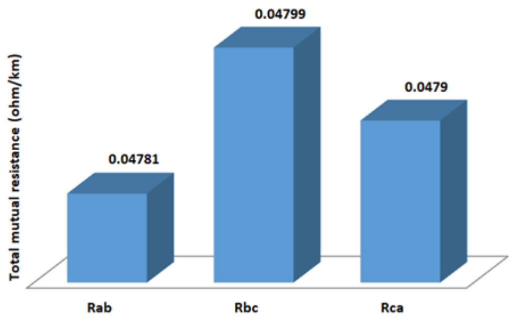

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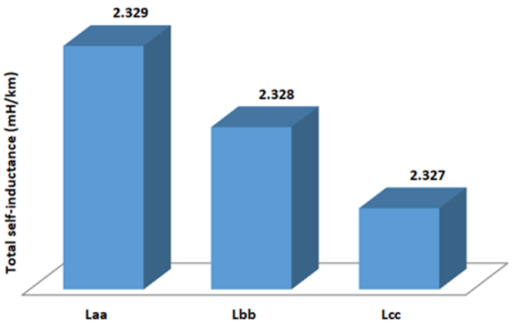
Figure 4: Graphical frames of overall values of transmission line resistance when the ground resistivity equals 100 Ω.m; a) Self-resistance, b) Mutual resistance



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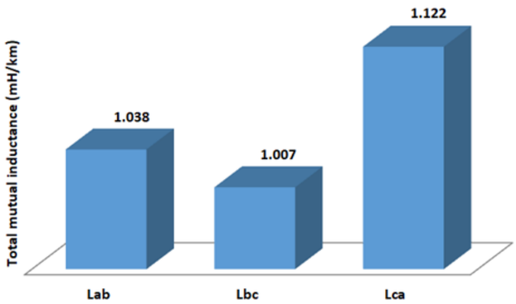

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Figure 5: Graphical frames of overall values of transmission line inductance when the ground resistivity equals 100 Ω.m; a) Self-inductance, b) Mutual inductance

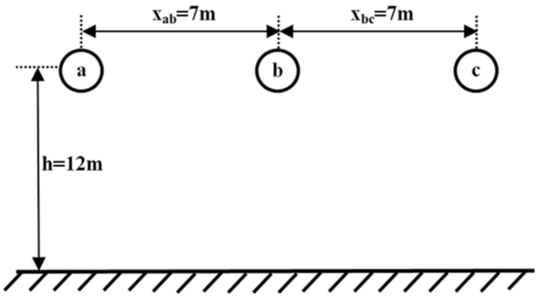


Figure 6: Geometric configuration for three-phase transmission line whose conductors arranged in a flat horizontal shape

Tables (1, 2) show the transmission line electrical resistances and inductances respectively for this case in three forms (geometric parameters, Carson correction factors, overall values) at ground resistivity equals 100 Ω.m. From the results listed in tables (1, 2), the same previous conclusion was got. It is evident that, the overall transmission line electrical parameters have significant deviations from the geometric parameters when the ground resistivity had taken into consideration.

Table 1: Electrical resistances for the case of flat horizontal configuration of three-phase transmission line conductors

Item	*Resistance [Ω/km]*		
	geometric	*correction*	*overall*
R_{aa}	0.07721	0.04829	0.12550
R_{bb}	0.07721	0.04829	0.12550
R_{cc}	0.07721	0.04829	0.12550
R_{ab}	-	0.04828	0.04828
R_{bc}	-	0.04828	0.04828
R_{ca}	-	0.04827	0.04827

Table 2: Electrical inductances for the case of flat horizontal configuration of three-phase transmission line conductors

Item	*Inductance [mH/km]*		
	geometric	*correction*	*overall*
L_{aa}	1.535	0.737	2.272
L_{bb}	1.535	0.737	2.272
L_{cc}	1.535	0.737	2.272
L_{ab}	0.255	0.729	0.983
L_{bc}	0.255	0.729	0.983
L_{ca}	0.137	0.707	0.845

In this case, Carson correction factors for self-parameters are the same because of all the three-phase conductors located at the same height from the ground. Note that, Carson correction factors for mutual parameters have very little divergences due to the different horizontal distances between conductors.

4. Effect of Ground Resistivity on the Ground-Return Parameters

In this section, the influence of ground resistivity variation on the ground-return parameters and consequently the resulting electrical parameters of three-phase transmission line (110 kv) were analyzed.

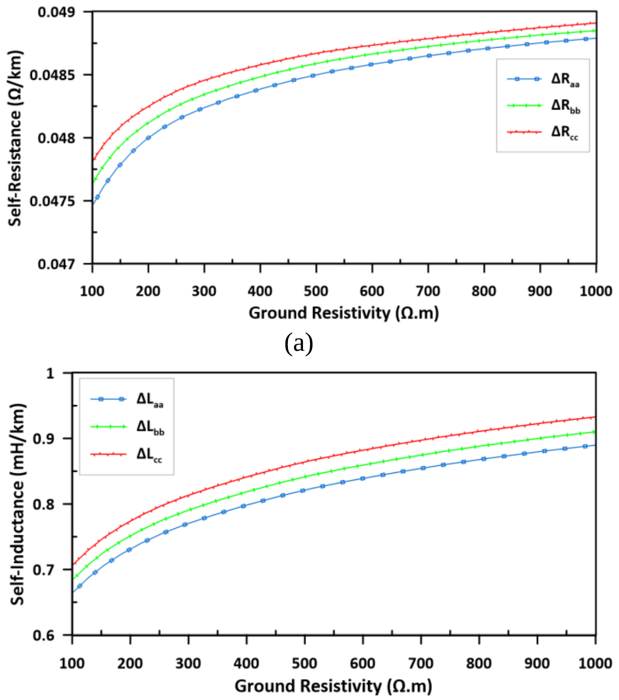
It is very difficult to determine the exact resistivity of the homogenous ground without some expensive geological measurements. These measurements are almost never realized, and therefore approximated values were used [22, 25, and 26]. The resistivity of some of the most common soil types of the homogenous ground that exist in our region are listed in table (3). The values of ground resistivity used in this research were taken in accordance with [25, 27].

Table 3: Ground resistivity for some of soil types of homogenous ground

Soil type	*ρ [Ω.m]*
Clay	100
Silt	150
Loam	250
Sand	1000

Figures (7, 8) show how Carson correction factors were affected while varying the resistivity of the homogenous ground, which consequently affect the overall transmission line electrical parameters (resistance & inductance).

It is clear from figure (7) that, the Carson correction factors of self-parameters (resistance, inductance) increase as the ground resistivity increases.



(a)

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Figure 7: Carson correction factors for self-parameters against ground resistivity; a) Self-resistances, b) Self-inductances

It is evident that, phase C has the biggest Carson correction factor of self-parameters for all values of ground resistivity. As a result, the correction factors of phase C for self-resistance and inductance are approximately0.04916 Ω/km and0.9339 mH/km respectively in case of the ground resistivity equals 1000 Ω.m. It means that, these correction factors of phase C increase the values of self-resistance and inductance by approximately 42% and 58% respectively for the case of sandy soil type of homogenous ground.

Similarly, the Carson correction factors of mutual inductances increase as the ground resistivity increases (see figures 8). As a result, the Carson correction factor for mutual inductance between phases B and C is the biggest (0.9182 mH/km at ground resistivity equals 1000 Ω.m), which increases the mutual inductance value by approximately 290%.

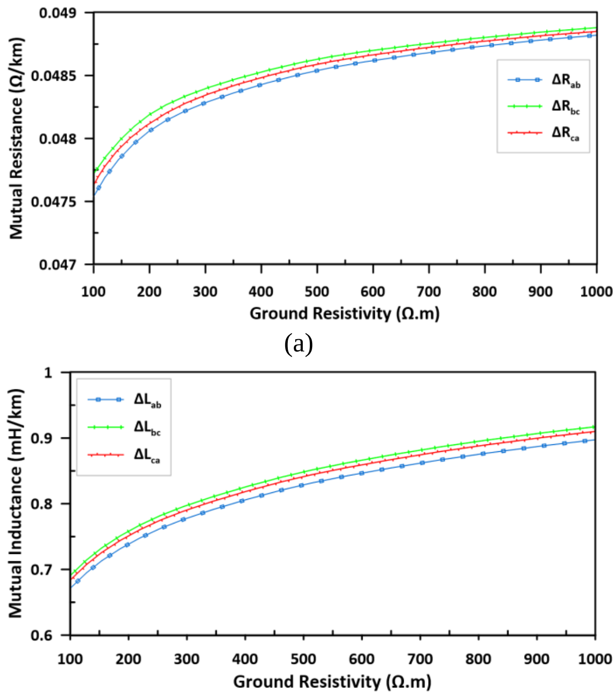

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Figure 8: Carson correction factors for mutual parameters against ground resistivity; a) Mutual resistances, b) Mutual inductances

From the previous results, it is clear that the ground effect on the transmission line electrical parameters increases as the value of ground resistivity increases. This makes sandy soil type have the greatest impact on the transmission line electrical parameters when it compared with other types of soils that listed in table (3).

5. Conclusion

The behavior of the transmission line electrical parameters (resistance and inductance) depends on the geometric configuration of the transmission line conductors and the value of ground resistivity. This value of ground resistivity is varying according to the soil type of the homogenous ground.

Considering the ground resistivity into account, makes it possible to investigate the ground effect on the overall transmission line electrical parameters via calculating the ground-return parameters.

Increasing the ground resistivity, overestimate the ground-return parameters (Carson correction factors) and consequently the overall values of transmission line parameters. This overestimation of ground-return parameters may have an impact on the propagation of electromagnetic waves and transitional voltages in high-voltage power systems.

It is clear that, the resistivity of the ground has a greater influence on the mutual inductance of the transmission line than on its self-inductance. In general, the ground resistivity affects the transmission line inductance more than its resistance.

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