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Analysis of ground return impedance calculation methods for modeling of underground cables for lightning studies

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Abstract: Analysis of lightning transients in cable systems necessitates accurate calculation of ground return impedances (GRIs) in high-frequency regions. EMT-type programs used for transient analyses incorporate various methods for calculation of GRI. Most of these methods include assumptions and approximations, the validity of which needs to be questioned at high frequencies. In particular, the common approximation of the neglecting effect of displacement currents should be reviewed. The purpose of this paper is to evaluate commonly used GRI calculation methods in terms of their accuracy and validity in high-frequency regions. In this study, GRI calculation methods are analyzed and compared, the effect of displacement currents is evaluated, and validity ranges of the basic calculation formula (Pollaczek formula) are discussed. It is shown that for high-resistivity and high-permittivity soil cases, the effect of displacement currents must be taken into account in high-frequency regions. Most default calculation routines in EMT-type programs neglect this effect. Therefore, it is very important to review and understand the calculation methods used in EMT-type programs before employing them in high-frequency transient analyses. Moreover, it is shown that in most of the practical cases the basic calculation formula (Pollaczek formula) is valid for the frequency range of interest for lightning studies.

Key words: Cable modeling, cable transients, ground return impedance

1. Introduction

Underground cables are widely used in transmission and distribution networks to transmit power between different parts of a system. The metallic sheaths (or armors) of these cables are generally connected to grounding systems on both sides of the cable. Such a connection between independent grounding systems may contribute positively to the overall grounding performance of connected systems by creating a path for sharing grounding current.

The effect of cable sheaths on a grounding system's performance has been evaluated mainly for power frequencies [1,2]. However, these analyses have hardly been extended to high-frequency regions for lightning studies [3]. This is partly due to difficulties encountered in the modeling of cables in high-frequency regions. Among many other difficulties, the calculation of ground return impedance (GRI) can be considered an important one.

Transient analyses of cable systems are generally conducted using so called EMT-type programs. These programs utilize different methods for the calculation of GRI, which are based on certain assumptions and approximations. Before selecting a program and a GRI calculation method for the analysis of lightning transients, it is important to assess their performance in high-frequency regions.

The purpose of this paper is to evaluate commonly used GRI calculation methods in terms of their

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accuracy and validity in high-frequency regions and to point out possible sources of errors by using available method selections in EMT-type programs.

In this paper, firstly, the basic theory behind the calculation of GRI will be presented and its importance for cable transients in a high-frequency region will be described. Secondly, GRI calculation methods will be reviewed and their accuracies in a high-frequency region will be assessed. Finally, basic assumptions used in GRI calculations will be reviewed and their validity limits in a high-frequency region will be evaluated.

Although only EMTP-ATP and PSCAD/EMTDC programs are reviewed within the scope of this study, other programs can be evaluated using the discussions provided. Additionally, the analysis is limited to single-core underground medium voltage cables, which are mainly used in distribution systems, but the results are pertinent to similar cable systems.

2. Cable modeling: basic theory

A single core cable can be represented with a distributed parameter circuit as given in Figure 1.

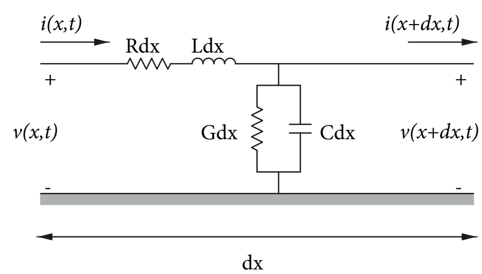

Figure 1. Equivalent distributed parameter circuit of a single core cable.

By applying Kirchhoff's current and voltage laws, converting into frequency domain, and arranging for a multiconductor system of N conductors (core, sheath, armor, etc.), the following equations can be obtained (telegrapher's equations):

$$-\frac{d(V)}{dx} = [Z]\,(I)\,, \tag{1}$$

$$-\frac{d(I)}{dx} = [Y]\,(V)\,, \tag{2}$$

where (V) and (I) are the voltage and current vectors, respectively. $[Z]$ and $[Y]$ are the series impedance and shunt admittance matrixes, respectively.

Focusing on impedance calculations, the series impedance matrix in Eq. (1) can be decomposed into internal and external impedance (i.e. ground return impedance) matrixes as follows:

$$[Z] = [Z_{internal}] + [Z_{external}]\,. \tag{3}$$

Internal impedance is related to electromagnetic fields inside the cable, whereas external impedance is related to fields in the ground surrounding the cable. Details on forming these impedance matrixes are not presented here; instead, related textbooks are referenced [4,5]. For high frequencies, elements of the external impedance matrix become dominant and internal impedance elements become negligible [6,7]. Therefore, only the external impedance matrix will be analyzed in this study.

The external impedance matrix consists of ground return self-impedance and mutual impedance elements. Self-impedance accounts for the voltage developed on the cable's outermost conducting layer due to cable internal currents, whereas mutual impedance accounts for voltage developed on the same layer due to mutual induction from adjacent cables.

General formulae for ground return impedances of underground cables for the configuration given in Figure 2 have been derived by Pollaczek, as follows [8]:

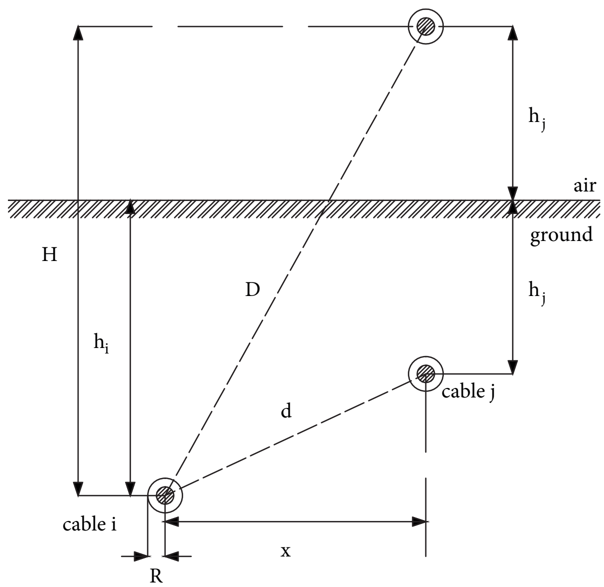

Figure 2. Geometric configuration of two cables.

$$Z_{g-mutual} = \frac{j\omega\mu_0}{2\pi}\left\{K_0(md) - K_0(mD) + \int_{-\infty}^{+\infty} \frac{e^{-H\sqrt{\alpha^2+m^2}}}{|\alpha| + \sqrt{\alpha^2+m^2}} e^{jx\alpha} d\alpha\right\}, \tag{4}$$

$$Z_{g-self} = \frac{j\omega\mu_0}{2\pi}\left\{K_0(mR) - K_0(m\sqrt{R^2+4H^2}) + \int_{-\infty}^{+\infty} \frac{e^{-2h\sqrt{\alpha^2+m^2}}}{|\alpha| + \sqrt{\alpha^2+m^2}} e^{jR\alpha} d\alpha\right\}, \tag{5}$$

$$m = \sqrt{j\omega\mu\ /\rho}, \tag{6}$$

where $Z_{g-mutual}$ is the ground return mutual impedance (Ω/m), Z_{g-self} is the ground return self-impedance (Ω/m), m is the propagation constant (1/m), ρ is the resistivity of the ground soil (Ωm), μ is the permeability of the soil (equal to permeability in free space μ_0) (H/m), α is the integration variable, $K_0(x)$ is the modified Bessel function of the second kind and zero order, R is the outer radius of the cable, h is the burial depth of the cable, and x is the horizontal distance between cables.

The Pollaczek formula is based on the assumptions that the displacement currents are negligible and the quasistatic TEM mode of propagation is effective. The validity of these assumptions will be analyzed in the next section. In this section, we follow these assumptions, and all following arguments will be made on this basis.

The GRI formula, provided by Pollaczek, includes an integral part (the so-called Pollaczek integral), which is very difficult to solve numerically. Therefore, several approximation methods have been proposed by several researchers to calculate GRI with acceptable precision.

3. Ground return impedance calculation methods

The following subsections describe a number of GRI calculation methods, proposed as an approximate solution for Eqs. (4) and (5). Please note that the notation given in the original papers has been changed in order to develop a consistent representation.

3.1. Carson's approximation

For low frequencies, where $|m| << |\alpha|$, the exponential term $\sqrt{\alpha^2+m^2}$ in the Pollaczek integral reduces to $|\alpha|$. With this reduction, the Pollaczek integral becomes equal to Carson's earth return impedance formula, which is commonly used for overhead lines [9,10].

$$Z_{g-mutual} = \frac{j\omega\mu_0}{2\pi}\left\{K_0(md) - K_0(mD) + \int_{-\infty}^{+\infty}\frac{e^{-H|\alpha|}}{|\alpha| + \sqrt{\alpha^2 + m^2}}e^{jx\alpha}d\alpha\right\} \tag{7}$$

$$Z_{g-self} = \frac{j\omega\mu_0}{2\pi}\left\{K_0(mR) - K_0(m\sqrt{R^2+4H^2}) + \int_{-\infty}^{+\infty}\frac{e^{-2h|\alpha|}}{|\alpha| + \sqrt{\alpha^2 + m^2}}e^{jR\alpha}d\alpha\right\} \tag{8}$$

Using this approximation, Carson's infinite series or asymptotic expansion can be used, which make the calculation of GRI much easier.

This approximation gives accurate results (error $< 5\%$) up to 10 kHz. However, after this frequency, the error produced by the approximation increases significantly and reaches up to 20% at 1 MHz [10].

This approximation is the default method implemented in EMTP-ATP, and no alternative method is provided within the program. Considering the frequency range of lightning surges, which can go up to several MHz [11], it can be concluded that the usage of EMTP-ATP for lightning transient analyses of underground cables is not appropriate.

1. **Wedepohl and Wilcox approximation**

Wedepohl and Wilcox approximated ground return impedance formulas as follows [12]:

$$Z_{g-mutual} = \frac{j\omega\mu_0}{2\pi}\left\{-\ln\left(\frac{\gamma md}{2}\right) + \frac{1}{2} - \frac{2mH}{3}\right\}, \tag{9}$$

$$Z_{g-self} = \frac{j\omega\mu_0}{2\pi}\left\{-\ln\left(\frac{\gamma mR}{2}\right) + \frac{1}{2} - \frac{4mh}{3}\right\}, \tag{10}$$

where γ is Euler's constant ($= 0.5772\ldots$).

This approximation method provides a very simple closed form solution to the Pollaczek formula and renders the GRI calculation process uncomplicated.

This method gives accurate results (error $< 0.1\%$) for -md- < 0.25 or -mR-< 0.25. The accuracy of this method is satisfactory up to 100 kHz (error $< 1\%$). However, as the frequency increases, the error increases and reaches up to 25% at 4 MHz [10]. Therefore, this method is considered to be unacceptable for lightning transient analyses.

A modified version of this method is implemented in PSCAD/EMTDC as an option, but details of this version are not provided [13]. Therefore, special care must be taken when using this method in PSCAD/EMTDC.

3.2. Saad–Gaba–Giroux approximation

Saad, Gaba, and Giroux defined an approximated solution to the Pollaczek integral by introducing a new dimensionless integration variable and utilizing Cauchy integral theory. Then, incorporating this approximation into general Pollaczek formulas, the following closed form approximation formulas are achieved [14]:

$$Z_{g-mutual} = \frac{j\omega\mu_0}{2\pi}\left\{K_0(md) + \frac{2}{4+m^2x^2}e^{-Hm}\right\}, \quad (11)$$

$$Z_{g-self} = \frac{j\omega\mu_0}{2\pi}\left\{K_0(md) + \frac{2}{4+m^2R^2}e^{-2hm}\right\}. \quad (12)$$

This approximation shows good agreement with the exact solution, as its relative error is less than 1% for frequencies up to 100 kHz. The error increases for higher frequencies, yet stays below 3% at 1 MHz [14].

This method is provided as a solution option in PSCAD/EMTDC [13] and can be considered to be suitable for lightning transient analyses due to its precise solution, even at high frequencies. However, as will be discussed in the next section, this method neglects the effect of displacement currents, which may lead to high error rates in some circumstances.

3.3. Vance approximation

Vance developed an approximate formula for GRI as follows [15]:

$$Z_{g-mutual} = \frac{\omega\mu_0}{2\pi\gamma_g d}\frac{H_0^1(j\gamma_g d)}{H_1^1(j\gamma_g d)}, \quad (13)$$

$$Z_{g-self} = \frac{\omega\mu_0}{2\pi\gamma_g R}\frac{H_0^1(j\gamma_g R)}{H_1^1(j\gamma_g R)}, \quad (14)$$

$$\lambda_g = \sqrt{j\omega\mu\left(\sigma + j\omega\varepsilon\right)}, \quad (15)$$

where γ_g is the full propagation constant (1/m), σ is the conductivity of the ground soil (S/m), ε is the permittivity of the ground soil (F/m), and H_0^1 and H_1^1 are Hankel functions.

This method considers earth as a lossy medium of infinite thickness around the cable; hence, it omits the air-to-earth interface and neglects the burial depth of the cable. Wait [16] showed that this approach is valid for $\left|2jh\sqrt{\varepsilon\mu_0\omega^2 - j\omega\mu_0\sigma}\right| >> 1$. Therefore, it can be expected that these methods provide more accurate results in a high-frequency region.

An important point to be addressed is that, in contrast to previously mentioned methods, a full propagation constant is used in this method, which means that the effects of displacement currents are taken into account.

This method is not available in either EMTP-ATP or PSCAD/EMTDC. However, due to its simplicity, it can be utilized as an external solution, and results can be incorporated into EMT-type programs by manual processing.

3.4. Petrache approximation

Petrache et al. approximated ground return impedance formulas as follows [17]:

$$Z_{g-mutual} = \frac{j\omega\mu_0}{2\pi}\ln\left(\frac{1+\gamma_g d}{\gamma_g d}\right), \tag{16}$$

$$Z_{g-self} = \frac{j\omega\mu_0}{2\pi}\ln\left(\frac{1+\gamma_g R}{\gamma_g R}\right). \tag{17}$$

Similar to Vance's model, this model neglects the burial depth of the cable and utilizes full propagation constant. This simple approximation has been proven to be very accurate up to 10 MHz [17].

This method is not available in either EMTP-ATP or PSCAD/EMTDC, but it can be used as an external solution function for these programs.

3.5. Theodoulidis approximation

Theodoulidis proposed three separate and independent exact solution alternatives for the ground return impedance formulas in the form of converging series [18]. Among these solutions, the third one provides a rapid and efficient solution to Pollaczek's formula, as given below:

$$Z_{g-mutual} = \frac{j\omega\mu_0}{2\pi}\left[K_0(\gamma_g d) - K_0(\gamma_g D) + 2J_P\right], \tag{18}$$

$$J_P = \frac{H^2 K_0(\gamma_g D)}{D^2} + \frac{2H^2 - D^2}{\gamma_g D^3}K_1(\gamma_g D) - \frac{I_P}{\gamma_g^2 D}, \tag{19}$$

$$I_P = \frac{H^2 - X^2}{D^4}e^{-\gamma_g H}\left(1+\gamma_g H\right) + \frac{\gamma_g^2 x H}{D^2}\int_{H/D}^{1}\left(2\sqrt{1-t^2} - \frac{1}{\sqrt{1-t^2}}\right)e^{-t\gamma_g D}dt. \tag{20}$$

Please note that only the mutual impedance formula is given above. For ground return self-impedance, parameters x, d, and H should be replaced with R, R, and $\sqrt{R^2+4h^2}$, respectively.

This approximation provides an almost exact solution to the Pollaczek formulas, as accuracy can be guaranteed on the order of 10^{-7} for any parameter range [18]. Therefore, in the following sections, this method will be used as the reference solution for the evaluation of the accuracy of other approximation methods.

Similar to the previously mentioned Vance and Petrache methods, the Theodoulidis method is not available in EMT-type programs.

3.6. Other methods

Additional approximation methods have been proposed by other researchers [19,20], but their performances are not notably different from those of the aforementioned methods.

Several researchers proposed solution methods for the direct numerical evaluation of the Pollaczek integral [21–25]. These methods require a considerably higher amount of computations in comparison to the other approximation methods mentioned earlier. However, considering the computational power available today, the usage of numerical solutions is not a problem anymore.

A numerical solution method is implemented in PSCAD/EMTDC as an option, which is claimed to provide an exact solution to the Pollaczek integral. Nevertheless, details or references for this method are not provided [13]; therefore, its performance has not been investigated in the scope of this study.

1. Comparison of ground return impedance approximation methods

In Figure 3, ground return self-impedance of a cable with a radius of 2.3 cm, buried at a depth of 1 m, is calculated in a high-frequency region (0.1–10 MHz) using various approximation formulas. Carson's formula is not taken into account, as it is clearly known to be inappropriate for frequencies higher than several kHz [10].

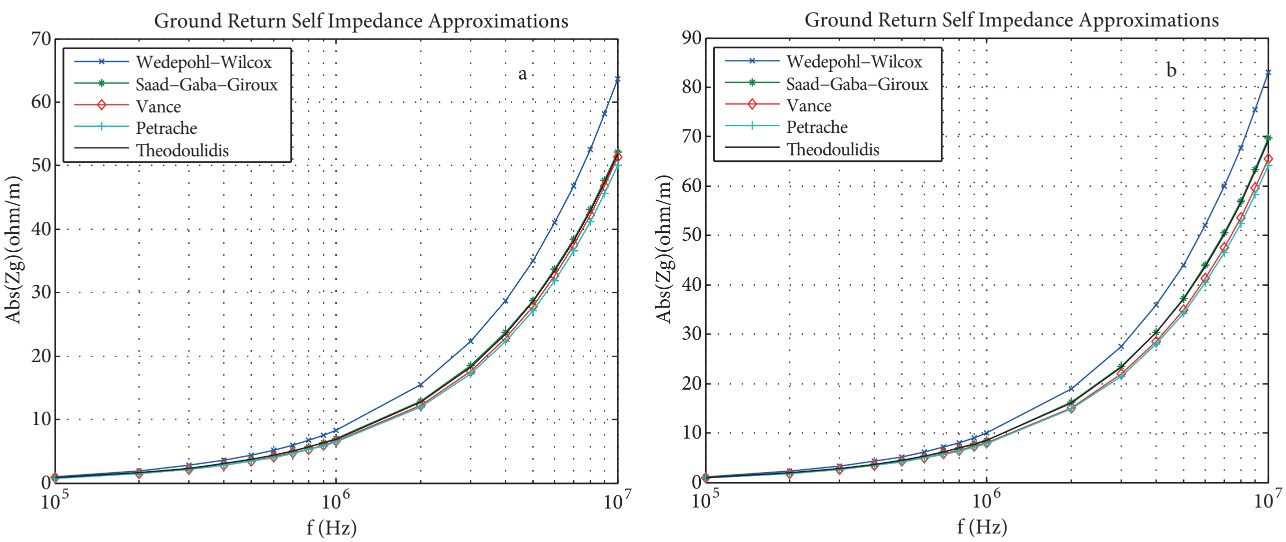

Figure 3. Comparison of ground return self-impedance: a) comparison for $\sigma = 10$ mS/m, b) comparison for $\sigma = 1$ mS/m.

Figure 3 shows that the Wedepohl approximation deviates considerably from other approximation methods after around 1 MHz. Therefore, as noted earlier, this method cannot be used for high-frequency analyses. Other methods provide similar results, which need to be analyzed further.

As mentioned earlier, the Theodoulidis method can be considered as a reference method to evaluate the performance of other approximation methods. In Figure 4, the percentage error levels of the Saad–Gaba–Giroux, Vance, and Petrache methods are evaluated with respect to the Theodoulidis method. Error percentage is defined as follows:

$$Error\ \% = (|Z_{reference} - Z_{approximation}| /\ |Z_{reference}|) \times 100. \tag{21}$$

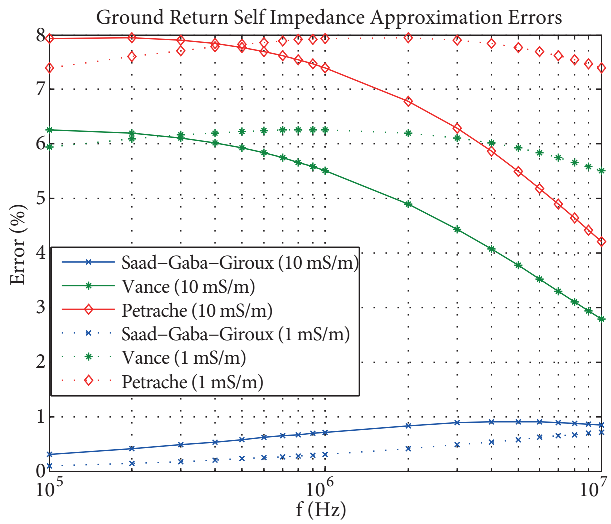

Figure 4. Errors of approximate methods with regards to the Theodoulidis method.

Figure 4 shows that Saad–Gaba–Giroux approximation shows good agreement with the reference method, even at 10 MHz and with very low conductivity soil. Other methods show higher errors, but the error levels are still less than 8%, even at very high frequencies. Therefore, it can be concluded that these three approximation methods provide accurate results in a high-frequency region.

Here, it is important to note that all the calculations and comparisons given above were conducted by neglecting the effect of displacement currents. This assumption affects the accuracy of the approximation methods, especially in a high-frequency region, as will be discussed in the next section.

4. Evaluation of the basic assumptions of the Pollaczek formula

As noted earlier, the Pollaczek formula assumes that the displacement currents are negligible and the quasistatic TEM mode of propagation is effective. In this section, the validity limits of these assumptions will be analyzed.

4.1. Effect of displacement currents

An extended version of Pollaczek's formula was proposed by Sunde [26], where displacement currents are not neglected. Inclusion or exclusion of displacement currents are employed in the definition of the propagation constant. Pollaczek used a propagation constant with low frequency approximation (m), as given in Eq. (6), whereas Sunde proposed the usage of a full propagation constant, as given below [26]:

$$\gamma_g = \sqrt{j\omega\mu\ (\sigma + jw\varepsilon)} = \sqrt{j\omega\mu\sigma - \omega^2\mu\varepsilon}. \tag{22}$$

Full propagation constant γ_g reduces to m when $\omega^2\mu\varepsilon << j\omega\mu\sigma$, that is, when $f << \sigma/2\pi\varepsilon$. For a low-conductivity soil with a conductance of 1 mS/m and a relative permittivity of 1, it can be found that the frequency must be much smaller than 18 MHz in order to apply low-frequency approximation. This frequency limit reduces even further to 1.8 MHz for a relative earth permittivity value of 10. Considering the frequency range of interest for lightning studies, which can be as high as several MHz, it can be said that low-frequency approximation may not be appropriate in all circumstances.

In order to evaluate the effect of low-frequency approximation, the error introduced in the reference method (i.e. the Theodoulidis method) by neglecting displacement currents is given in Figure 5. The cable data used for this analysis are the same as those given previously, and the error percentage is defined as follows:

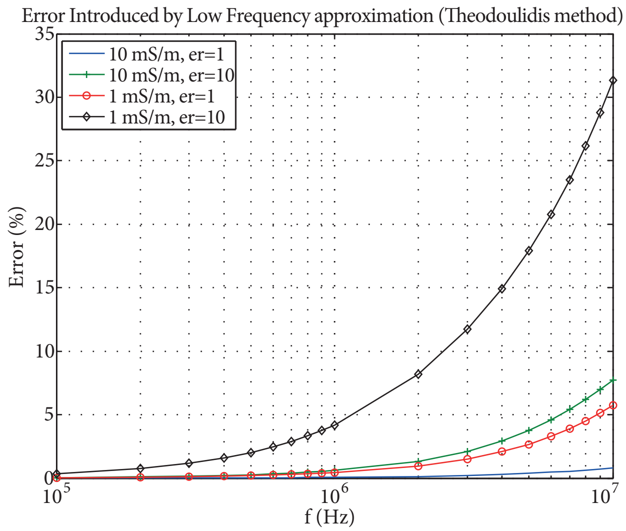

Figure 5. Error introduced by low-frequency approximation.

$$Error\ \% = \left(\left| Z_{g-w/o\ LFA} - Z_{g-w/\ LFA} \right| / \left| Z_{g-w/o\ LFA} \right| \right) x100, \tag{23}$$

where $Z_{g-w/\ LFA}$ and $Z_{g-w/o\ LFA}$ stand for impedances with and without low-frequency approximation, respectively.

Figure 5 shows that the error level increases with lower ground conductivity and higher ground permittivity. This is an expected result, considering the definition of the full propagation constant. Therefore, it can be concluded that the inclusion of displacement currents can have an important effect on impedance calculations, depending on the soil parameters. It is important to note that the impedance value calculated with the full propagation constant turns out to be less than the one calculated with low-frequency approximation. This means that for extreme cases with low ground conductivity and high ground permittivity, actual ground impedance would be considerably less than the value calculated by neglecting the displacement current.

In Figure 6, error levels of the Saad–Gaba–Giroux, Vance, and Petrache methods are evaluated with respect to the Theodoulidis method for various ground conductivity and permittivity values. In low ground conductivity and high ground permittivity cases, the error level of the Saad–Gaba–Giroux method turns out to be very high. This is because this method employs low-frequency approximation, whereas the others use the full propagation constant instead.

The applicability of the Pollaczek formula in a high-frequency region is a matter of separate analysis, where the TEM mode of propagation must be ensured. Consequently, results in a high-frequency region should be carefully evaluated, as they may already be irrelevant due to a violation of basic assumptions.

4.2. Mode of propagation

One of the basic assumptions considered in the Pollaczek formula is a quasistatic TEM mode of propagation, where common mode currents are neglected and only differential mode currents are taken into account [27].

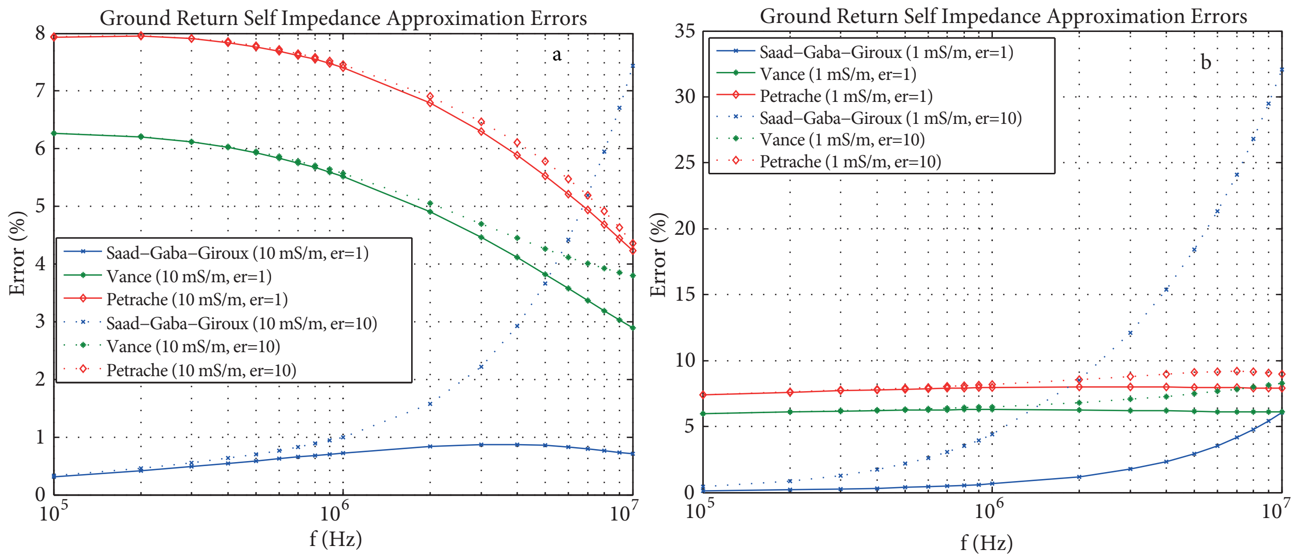

Figure 6. Errors of approximation methods with respect to the Theodoulidis method: a) comparison for $\sigma = 10$ mS/m, b) comparison for $\sigma = 1$ mS/m.

In order to assure the validity of the TEM mode of propagation, both resistive and inductive components of ground return impedance must be positive [28].

In the following analysis, the frequency range for the TEM mode of propagation is investigated by evaluating ground return mutual impedance between two identical cables using the Theodoulidis method. Both cables have an outer radius of 2.3 cm and are buried at a depth of 1 m with 0.5 m of spacing.

Figure 7 shows that the TEM mode of propagation is assured below 10 MHz, which can be considered as a limit frequency for lightning studies. Critical frequency decreases significantly with extended spacing between

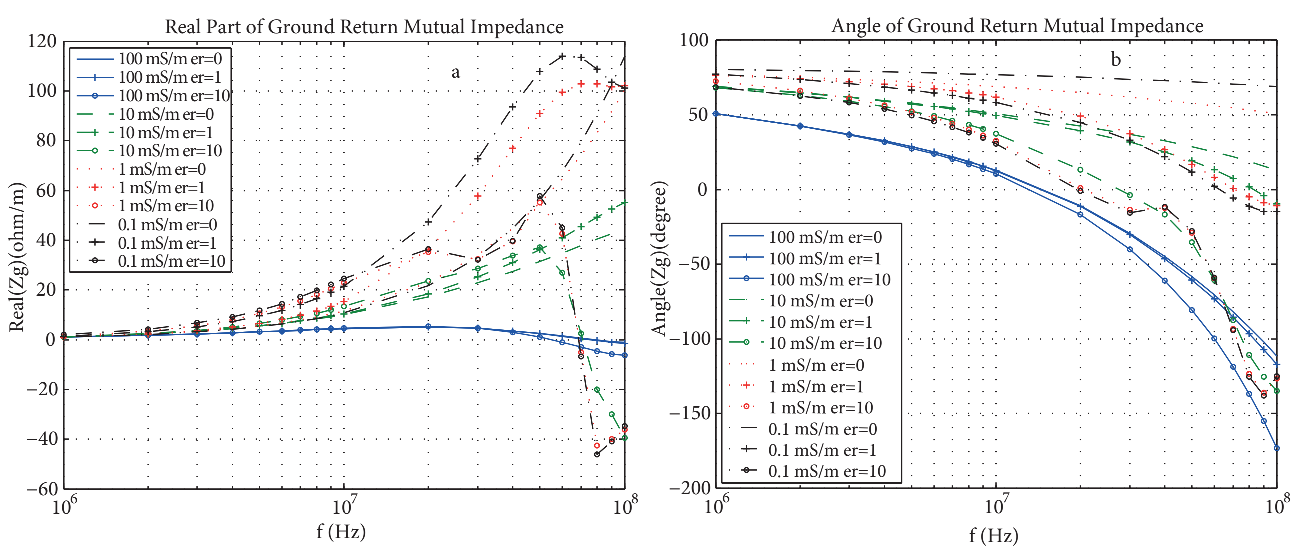

Figure 7. Ground return mutual impedance with the Theodoulidis method: a) real part of the impedance, b) angle of the impedance.

cables. Considering the fact that the cables are laid closely in common practice (e.g., spacing is equal to cable diameter), the critical frequency would be much higher than 10 MHz. Therefore, it can be concluded that the Pollaczek formula is valid for most of the practical cases.

5. Conclusion

Lightning transients are represented with very high frequencies, which may reach up to several MHz. At this frequency range, the ground return impedance of cables becomes dominant. When using EMT-type programs for lightning transient analysis of cables, it is vital to ensure that the GRI calculation method employed is accurate and applicable in a high-frequency region.

In this paper, commonly used GRI calculation methods have been analyzed in terms of their performance in a high-frequency region. It is shown that several very common calculation methods, such as the one incorporated into EMTP-ATP, cannot be used in a high-frequency region.

Furthermore, it is shown that for high-resistivity and high-permittivity cases, neglecting displacement currents yields very high calculation errors. Therefore, calculation methods that exclude the effect of displacement currents by default, such as the ones implemented in PSCAD/EMTDC, may not be appropriate in all circumstances.

The validity limits of GRI calculation methods were also evaluated in the paper. It was shown that in most practical cases the basic GRI calculation formula (Pollaczek formula) is valid for the frequency range of interest for lightning studies.

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