Effect of Impedance Approximate Formulae on Frequency Dependence Realization

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***Abstract*— The accuracy of frequency-dependent line models is affected by the equations that define the line characteristic admittance, Y_c, and its propagation factor, A. Therefore one can see that any model is also dependent on the assumptions adopted in the evaluation of the circuit series impedance, Z, namely the formulation of the internal conductor and the ground return impedances. The complexities of the exact representation of these parameters have led investigators to propose approximate formulae, and several of these are available in the technical literature. Even though the impact of such formulae have been studied in the context of the value of the impedance throughout the frequencies of interest, this work examines their effects on the frequency domain functions, i.e. Y_c and A and on their corresponding syntheses. This paper reports several possibilities that have been tested, such as: Wedepohl's approximations for conductor internal impedance, complex plane and double complex plane for the ground return impedance in overhead circuits, and ground approximations for underground cables. The approximate functions are compared with the theoretical ones using Bessel functions and Carson equations, in the case of overhead transmission lines, and Bessel functions and Pollaczek equations, in the case of underground cable systems.**

***Index Terms*— Frequency-Dependent Transmission Line Models, Electromagnetic Transients**

I. Introduction

It is well known that electromagnetic transient simulations are very important for the design of insulation levels of power systems, for the investigation of operational problems such as transformer energization, design overvoltage control devices, and for the analysis of many other phenomena. Accurate frequency-dependent transmission line models have been developed both for long lines [1] and short line sections [2], and clearly the reliability of such models will depend on the accuracy of the parameters in which they are based.

Transmission systems can be precisely represented by the characteristic admittance Y_c and propagation factor A, which are calculated from series impedance Z and shunt admittance Y, as follows:

$$A = \exp(-l\sqrt{Z \cdot Y})$$
$$Y_c = Z^{-1}\sqrt{Z \cdot Y} \tag{1}$$

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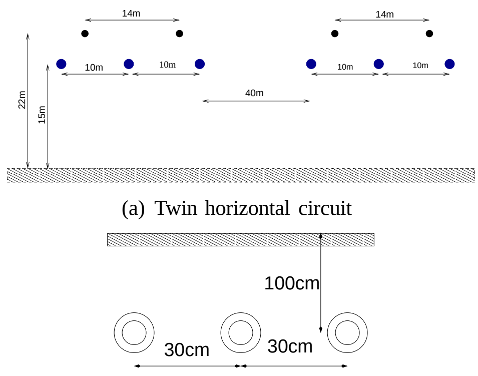
where l is the length of the transmission line or cable. The correct evaluation of the series impedance involves Bessel expressions and numeric solution of integrals which together with the matrix exponentiation and squaring cause both Y_c and A to be non-analytical functions in the frequency domain. Most EMTP-type programs use approximate expressions thus introducing errors. Besides, the frequency dependence is synthesized via fitting approximations of the frequency domain behavior using rational functions, and this increases the errors.

The technical literature has presented several possibilities for the representation of conductor internal and ground return impedances. Wedepohl's formulation for solid and tubular conductor [3] was considered for the internal conductor impedance. For the ground return impedance there are, in fact, two distinct sets of approximations, one for Carson's integral and other for Pollaczek's. The ground impedance of overhead lines was represented using the complex ground plane [4] and the double complex plane [5]. Wedepohl's approximations [3] using the γ (Euler) constant was considered to represent the ground effect in underground systems. A variant of Ametani proposition [6], with Bessel functions and the complex plane, and the formulation proposed by Saad et al. [7] were also adopted.

It should be emphasized that although the impact of the above approximate formulae is to some extent well-known, there has not been many reports concerning the overall impact of these approximations in the actual frequency domain realization. This work intends to fill this gap by qualifying and quantifying the errors involved in typical transmission lines configurations. Two networks were considered, an untransposed 25km twin horizontal overhead line and a 10km untransposed underground cable system, both shown in Fig. 1. Ground resistance of 100Ω.m was considered.



(a) Twin horizontal circuit

(b) Underground Cable

Fig. 1. Line configurations

A brief summary of all combinations analyzed in this paper is presented in table I.

TABLE I
EVALUATED FORMULAE

	Internal Impedance	Ground Impedance	Label
Overhead Line	Bessel	Carson	B-C
	Bessel	Double Complex Ground Plane	B-N
	Wedepohl	Complex Ground Plane	W-D
	Wedepohl	Double Complex Ground Plane	W-N
Underground Cable	Bessel	Pollaczek	B-P
	Bessel	Ametani	B-A
	Bessel	Saad	B-SA
	Wedepohl	Wedepohl	W-W

Bessel-Carson and Bessel-Pollaczek combinations for overhead lines and underground systems, respectively, were adopted as references in this work. Instead of using a series expansion for the infinite integral involved in Carson's and Pollaczek's formulae, a numerical evaluation via Gauss-quadrature was used.

An analysis of the impact of approximate formulae on the rational fitting is also carried out. A columnwise realization was used for the fitting [8].

II. Frequency Domain Analysis

A. General Aspects

The frequency dependence in the characteristic admittance and propagation factor is due basically to the skin effect in the conductors and in the ground impedance. The system impedance Z can be divided in two parts, Z_{int} and Z_{ext}, where Z_{int} represents the internal conductor impedance and Z_{ext} is composed by the ideal external impedance plus the ground return. These parameters have the form $R + j\omega L$, where both R and L are frequency dependent. The system admittance, $Y = G + j\omega C$, can be determined directly from Maxwell potential matrix. Usually the conductance G is considered constant at some default value [2], but some recent experimental work [9] has indicated some new typical values. The capacitance C is frequency independent.

B. Overhead Lines

When phase conductors of an overhead line can be considered cylindrical, with external radius r and resistivity ρ_c, Z_{int} is a diagonal matrix having elements given by [6]:

$$z_{int_{ii}} = \frac{\eta_c \rho_c}{2\pi r} \frac{I_0(\eta_c r)}{I_1(\eta_c r)} \tag{2}$$

where $\eta_c = \sqrt{j\omega\mu_0/\rho_c}$ and $I_0(.)$, $I_1(.)$ are modified Bessel functions of order 0 and 1, respectively.

In 1973, Wedepohl and Wilcox [3] proposed the following approximation for the conductor internal impedance:

$$z_{int_{ii}} \approx \frac{\eta_c \rho_c}{2\pi r} \coth(0.777\eta_c r) + \frac{0.3565\rho_c}{\pi r^2} \tag{3}$$

The relative error of this approximation has a maximum value of 4% for the resistance, when $\eta_c r = 5$, and 5% for the reactance, when $\eta_c r = 3.5$. The error declines for frequencies above these limits and is practically constant for low frequencies, as shown in Fig. 2.

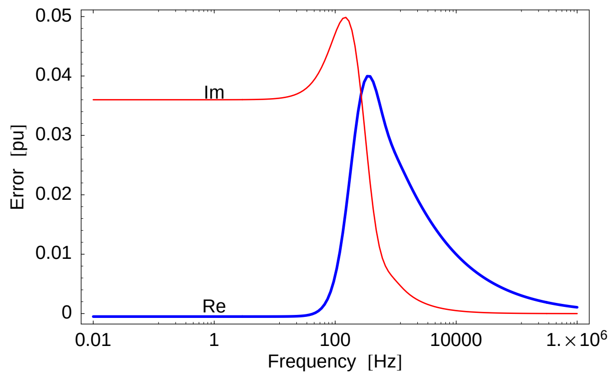


Fig. 2. Error in internal impedance using Wedepohlt's formula

The ground return impedance was originally formulated by Carson in the 1920's as an infinite integral. Equations (4) and (5) show the self and mutual elements of the external impedance matrix.

$$z_{ext_{ii}} = j\frac{\omega\mu_0}{2\pi} \ln\frac{2h_i}{r_i} + \frac{\omega\mu_0}{\pi} J_s \tag{4}$$

$$z_{ext_{ij}} = j\frac{\omega\mu_0}{2\pi} \ln\frac{d'_{ij}}{d_{ij}} + j\frac{\omega\mu_0}{\pi} J_m \tag{5}$$

where h_i is the vertical distance between conductor i and ground, d'_{ij} is the distance between conductor i and image of conductor j, d_{ij} is the distance between conductors i and j, J_s and J_m are given by (6) and (7), respectively.

$$J_s = \int_0^\infty \frac{e^{-2h_i\lambda}}{\lambda + \sqrt{\lambda^2 + \eta^2}}\, d\lambda \tag{6}$$

$$J_m = \int_0^\infty \frac{e^{-(h_i+h_j)\lambda}}{\lambda + \sqrt{\lambda^2 + \eta^2}} \cos d_{ij}\lambda\, d\lambda \tag{7}$$

where $\eta = \sqrt{j\omega\mu/\rho}$ and ρ is the ground resistivity.

In 1981, Deri et al. [4] presented a scientific justification for Dubanton's proposal to represent the ground by considering a complex return plane situated at a distance $p = 1/\eta$. Thus the elements of Z_{ext} are the following:

$$z_{ext_{ii}} \approx j\frac{\omega\mu_0}{2\pi} \ln\frac{2(h_i + p)}{r_i} \tag{8}$$

$$z_{ext_{ij}} \approx j\frac{\omega\mu_0}{2\pi} \ln\left(\sqrt{\frac{x_{ij}^2 + (h_i + h_j + 2p)^2}{x_{ij}^2 + (h_i - h_j)^2}}\right) \tag{9}$$

where x_{ij} is the horizontal distance between conductors i and j.

In 1996, Noda [5] introduced the concept of the double complex return plane. Equations (10) and (11) show the elements of the external impedance matrix.

$$z_{ext_{ii}} \approx j\frac{\omega\mu_0}{2\pi} \left\{ A' \ln\frac{2(h_i + \alpha p)}{r_i} + B' \ln\frac{2(h_i + \beta p)}{r_i} \right\} \tag{10}$$

$$z_{ext_{ij}} \approx j\frac{\omega\mu_0}{2\pi}\left\{A'\ln\left(\sqrt{\frac{(h_i+h_j+2\alpha p)^2+x_{ij}^2}{(h_i-h_j)^2+x_{ij}^2}}\right)\right.$$
$$\left.+B'\ln\left(\sqrt{\frac{(h_i+h_j+2\beta p)^2+x_{ij}^2}{(h_i-h_j)^2+x_{ij}^2}}\right)\right\} \quad (11)$$

where $A' = 0.131836$, $\alpha = 0.26244$, $B' = 1 - A'$ and $\beta = 1.12385$. For typical overhead line configurations, where the distance between conductors is less than the distance between conductors and images, the errors of this approach are about 1% for both resistance and reactance, in a frequency range up to 1MHz.

C. Underground Cables

The core internal impedance of a solid underground cable is identical to (2). Internal surface sheath impedance, the mutual impedance between layers and the external surface sheath impedance are given by (12), (13) and (14), respectively [6].

$$z_{sh_{int}} = \frac{\rho\eta}{2\pi r_2}\frac{I_0(\eta r_2)K_1(\eta r_3)+K_0(\eta r_2)I_1(\eta r_3)}{I_1(\eta r_3)K_1(\eta r_2)-I_1(\eta r_2)K_1(\eta r_3)} \quad (12)$$

$$z_{sh_m} = \frac{\rho}{2\pi r_2 r_3}\frac{1}{I_1(\eta r_3)K_1(\eta r_2)-I_1(\eta r_2)K_1(\eta r_3)} \quad (13)$$

$$z_{sh_{ext}} = \frac{\rho\eta}{2\pi r_3}\frac{I_0(\eta r_3)K_1(\eta r_3)+K_0(\eta r_3)I_1(\eta r_2)}{I_1(\eta r_3)K_1(\eta r_2)-I_1(\eta r_2)K_1(\eta r_3)} \quad (14)$$

Impedances due to conductor insulation layer are the following:

$$z_{ins_1} = \frac{j\mu\omega}{2\pi}\ln(\frac{r_2}{r_1}) \quad (15)$$

$$z_{ins_2} = \frac{j\omega\mu}{2\pi}\ln(\frac{r_4}{r_3}) \quad (16)$$

In the equations above, r_1 is the most internal radius of a single-core cable, r_2 is the sheath internal radius, r_3 is the sheath external radius, r_4 is the outermost cable radius, $K_0(.)$ and $K_1(.)$ are Bessel functions and μ is the permeability of the insulation.

Wedepohl and Wilcox [3] also presented approximate hyperbolical expressions for (12), (13) and (14):

$$z_{sh_{int}} \approx \frac{\rho\eta\coth(\eta(r_3-r_2))}{2\pi r_3} - \frac{\rho}{2\pi r_2(r_2+r_3)} \quad (17)$$

$$z_{sh_m} \approx \frac{\rho\eta}{\pi(r_2+r_3)}\text{csch}(\eta(r_3-r_2)) \quad (18)$$

$$z_{sh_{ext}} \approx \frac{\rho\eta\coth(\eta(r_3-r_2))}{2\pi r_3} + \frac{\rho}{2\pi r_3(r_2+r_3)} \quad (19)$$

The expressions above present suitable accuracy just when the condition $(r_3-r_2)/(r_3+r_2) < 1/8$ is respected, which is true for transmission systems. The errors associated with (17), (18) and (19) are larger than those from the case of the cylindrical conductors.

For underground cables the ground return impedances are given by Pollaczek's integral. Equations. (20) and (21) show the expressions for self and mutual impedances.

$$z_{g_{ii}} = \frac{\rho\eta^2}{2\pi}\left[K_0(\eta r_4) - K_1(\eta D_c) + J_s\right] \quad (20)$$

$$z_{g_{ij}} = \frac{\rho\eta^2}{2\pi}\left[K_0(\eta d) - K_1(\eta D) + J_m\right] \quad (21)$$

where $D_c = \sqrt{r_4^2+4h_i^2}$, $d = \sqrt{x_{ij}^2+(h_i-h_j)^2}$, $D = \sqrt{x_{ij}^2+(h_i+h_j)^2}$ and h_i is the depth of conductor i. The expressions of terms J_s and J_m are the following:

$$J_s = \int_{-\infty}^{\infty}\frac{e^{-2h_i\sqrt{\lambda^2+\eta^2}}}{|\lambda|+\sqrt{\lambda^2+\eta^2}}e^{jr_4\lambda}d\lambda \quad (22)$$

$$J_m = \int_{-\infty}^{\infty}\frac{e^{-(h_i+h_j)}\sqrt{\lambda^2+\eta^2)}}{|\lambda|+\sqrt{\lambda^2+\eta^2}}e^{jx_{ij}\lambda}d\lambda \quad (23)$$

Approximate formulations for ground impedance representations in underground systems are also proposed in [3] as:

$$z_{g_{ii}} \approx \frac{j\omega\mu}{2\pi}\left[-\ln(\frac{\gamma\eta r_4}{2})+\frac{1}{2}-\frac{4\eta h_i}{3}\right] \quad (24)$$

$$z_{g_{ij}} \approx \frac{j\omega\mu}{2\pi}\left[-\ln(\frac{\gamma\eta d}{2})+\frac{1}{2}-\frac{2\eta h_{ij}}{3}\right] \quad (25)$$

where γ is the Euler's constant and $h_{ij} = h_i + h_j$. The above expressions are valid only when $|\eta d| < 0.25$, for mutual impedances and when $|\eta r_4| < 0.25$ for self impedances. In most cases, the approximations present suitable results up to approximately 100kHz. For the case under analysis in this work, Fig. 1(b), the limit is around 190kHz.

Eliminating η from the numerator of Pollaczek's integral, (22) and (23) become similar to (6) and (7). This approximation, proposed by Ametani [6], is valid only when $|\lambda| \gg |\eta|$, e.g. for frequencies below few kHz. The concept is interesting since it makes possible to represent Pollaczek's integral by any method of ground representation for overhead systems. In this work, the complex plane was adopted for the integral impedance representation.

In 1996, Saad, Gaba and Giroux [7] presented an analytical formulation for Pollaczek's integral in a approach similar to the one proposed by Deri et al. [4] for overhead lines. Ground return impedances are then the following:

$$z_{g_{ii}} \approx \frac{\rho\eta^2}{2\pi}\left[K_0(\eta D)+\frac{2e^{-2\eta h_i}}{4+\eta^2 r_4^2}\right] \quad (26)$$

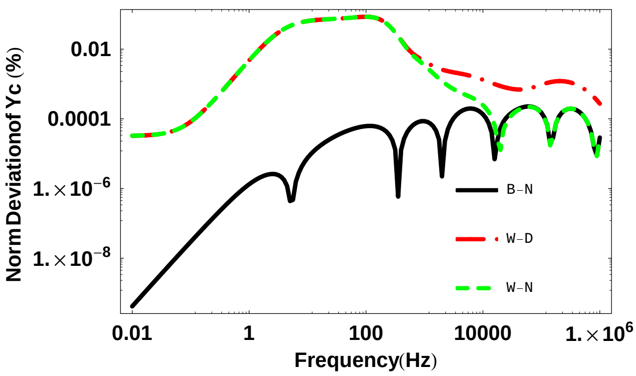
$$z_{g_{ij}} \approx \frac{\rho\eta^2}{2\pi}\left[K_0(\eta d)+\frac{2e^{-\eta h_{ij}}}{4+\eta^2 x_{ij}^2}\right] \quad (27)$$

III. Approximations Evaluation

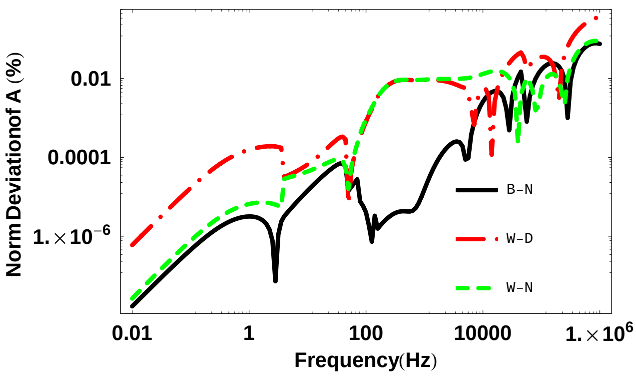
Instead of using the rms-error for the comparison of the approximations, a relative Euclidian norm deviation was adopted. The relative norm deviation RND between a matrix M and its approximation M_{approx} is defined by:

$$RND(\%) = \frac{||M|| - ||M_{approx}||}{||M||} \cdot 100 \qquad (28)$$

Fig.3 presents the results obtained for the overhead line. The labels for each case are as defined in Table I. Fig.3(a) shows the relative norm deviation of the approximations B-N, W-D and W-N for Y_c. It can be seen that W-D and W-N have the same behavior for low frequencies, where the referred ground impedance approximations are similar. For high frequencies, equivalence between W-N and B-N can be understood by evaluation of Fig.2. The maximum RND of W-D and W-N, around 0.01%, occurs in a frequency range where Wedepohl's skin effect formulation is less accurate. For higher frequencies the errors of all approaches lie around 0.0001%. The relative norm deviation of A is presented in Fig.3(b). As occurs with Y_c, W-D and W-N are similar for lower frequencies while W-N and B-N are equivalent for the higher range. Unlike the characteristic admittance, where the maximum occurs at a medium frequency range, the RND of the propagation factor is essentially monotonic and reaches 0.01%.



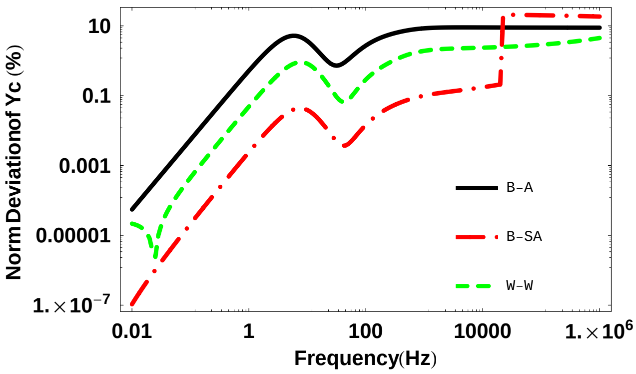
(a) Y_c



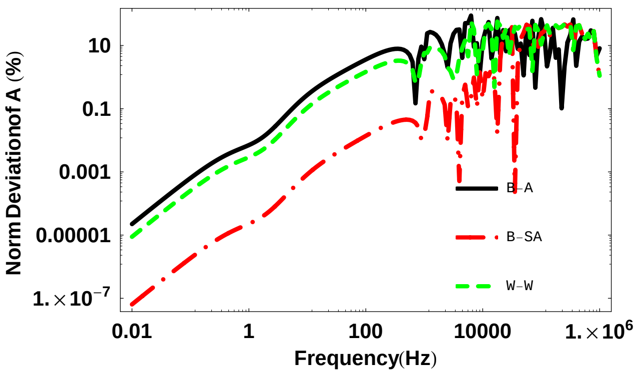
(b) A

Fig. 3. RND for the overhead line

Fig.4 presents the results obtained for the underground cable system. Fig.4(a) shows the relative norm deviation of approximations B-A, B-SA and W-W for the characteristic admittance, while Fig.4(b) shows the RND for the propagation factor. Both functions are essentially monotonic. It is interesting to note that as the limit of validity of the approximation proposed by Saad et al. is reached, the norm deviation grows considerably. The maximum relative norm deviation observed in both Y_c and A is around 10%.



(a) Y_c



(b) A

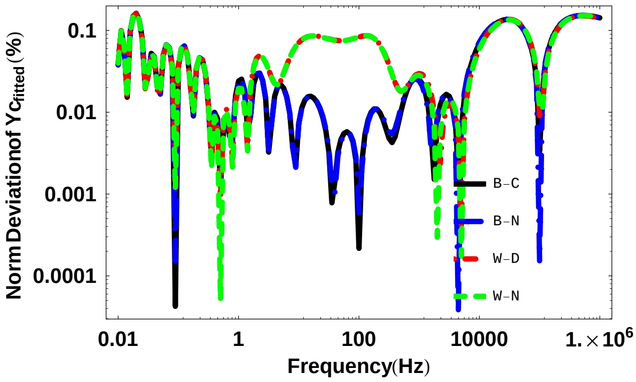
Fig. 4. RND for the underground cable system

IV. Associated Fitting Errors

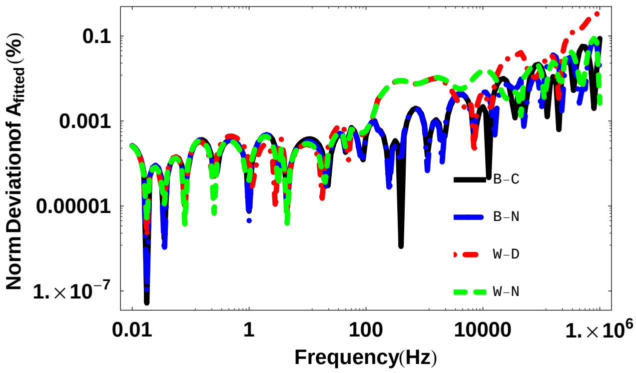
The analytical expressions of Y_c and A are determined by fitting of the values calculated at discrete frequency intervals, using the approximations for the series impedance Z, presented in the previous section. In the case of the overhead line, the functions are fitted with 14 and 20 poles, respectively. In fact, the propagation factor is represented as $A = P{\cdot}e^{-j\omega\tau_{min}}$, where P is the fitted function. The constant τ_{min} represents the propagation time of the light. In the case of the underground system, Y_c is adjusted with 14 poles and A, with 60.

Fig.5 presents results obtained for the overhead line. Fig.5(a) shows the RND of the analytical approaches of the characteristic admittance. Except for a small frequency range, all the formulations seem to have the same behavior. Maximum relative norm deviation verified is around 0.1%.

B-N and B-C frequency responses are similar along the interval considered. As the errors associated with the sampled points calculated through B-N formulation are very small, see Fig.3(a), the fitting process of these approaches tends to be similar. Table II shows the poles of Y_c obtained via B-C and B-N. Note that all poles are real. Fig.5(b) presents the RND of the analytical approaches of the propagation factor. Again, the formulations seem to have the same behavior, the RND grows with the frequency and reaches a maximum value of 0.1%.



(a) Y_c



(b) A

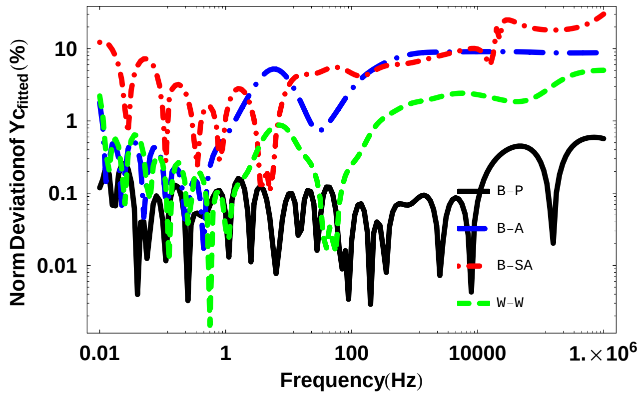
Fig. 5. Norm deviation for the overhead line

TABLE II

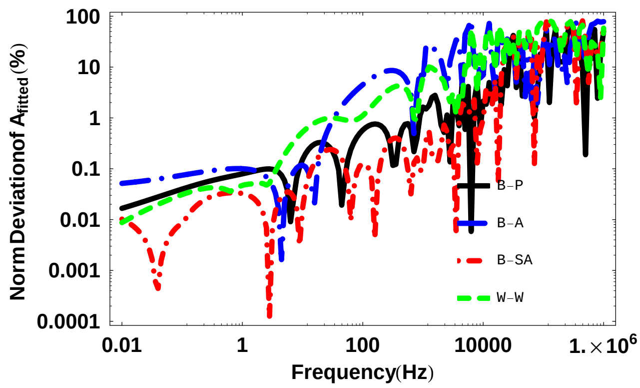
POLES OF $Y_{c_{fitted}}$ VIA B-C AND B-N

B-C	B-N
-408374364.74170172	-400923988.26259589
-605097.60163416585	-593437.88132365642
-71372.876471927666	-69961.27460756748
-9279.2901002227263	-9076.6479568636969
-1342.6802483546169	-1340.6988055710492
-649.44520831251805	-649.8154470133162
-120.51723481008322	-120.64577317400777
-21.68020862601421	-21.687516283587396
-14.43430212256432	-14.421068913548226
-6.5087694343448703	-6.500506711281858
-2.298123862089732	-2.2963366511997578
-0.73077282375599184	-0.73037382224039582
-0.20999237321733702	-0.20991118916314944
-0.045914327198933937	-0.045901636480344982

Fig.6 presents results obtained for the underground cable. Fig.6(a) shows the analytical approximations of the characteristic admittance. The maximum RND verified is around 10%. Fig.6(b) presents the approximations of A. It can be seen that the relative norm deviation grows with frequency and reaches a maximum of 100%. As shown in Fig. 7, high frequency module oscillations make it hard to obtain good fitting for A in underground systems.



(a) Y_c



(b) A

Fig. 6. Norm deviation for the underground cable system

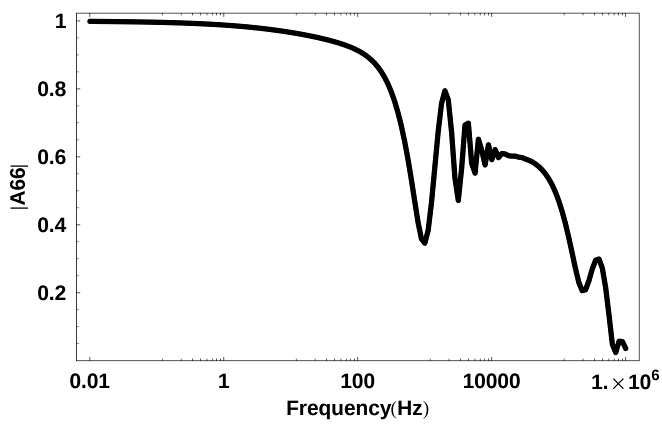


Fig. 7. Element A(6,6) of the underground system calculated via B-P

V. Conclusions

This paper analyzed influence of approximated skin effect and ground return impedance formulations on frequency response of Y_c and A. Functions were fitted by a columnwise realization. Two typical network configuration were evaluated, an overhead twin horizontal circuit and an underground cable system. Earth resistivity of 100Ω.m was adopted.

For the overhead system, errors of the approximations seem to be negligible when compared to the ones associated with the fitting process. The same occurs with the propagation factor of the underground cable system. For its characteristic admittance, errors of approximations and of the analytical functions seems to be very similar.

In the case of the overhead network, the behavior of the fitted approximations is very suitable, as the maximum relative norm deviations observed are around 0.1 % to both Y_c and A. There is practically no difference among the approaches analyzed. In the case of the underground system, RND introduced by B-A, B-S and W-W formulations for Y_c are considerable, maximum values are around 10 %, while the one associated with the B-P method is about 1 %. The same does not occur for A, when all maximum deviations are around 100 %. For studies involving underground systems, the authors strictly recommend the use of B-P formulation for network modeling.

This work has adopted typical numbers of poles in the fitting process of Y_c and A. It is worth to say that errors associated to frequency response of these functions would be smaller than those presented if more poles had been taken. However, it can mean numerical oscillations in time domain.

Although a ground resistivity of 100Ω.m was used in both cases, results not shown in the paper indicate that for higher ground resistivity the behavior of the approximations is essentially the same. However, a substantial change was observed on the analytical approximations of the propagation factor of the underground system, the maximum RND, which is 100% when ρ = 100Ω.m, decreases to 10% when ρ = 1000Ω.m.

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