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Response of Power Lines as PLC Channels

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Abstract

This paper deals with the response of power lines as communication channels. For this purpose, we simulated and analyzed the frequency response of resistance, inductance, capacitance and conductance parameters for three power lines: one solid core and two stranded core. Thereafter, we simulated and analyzed the frequency and length response of the power line as PLC channel for narrowband systems. Beginning with an $R´$, $L´$, $C´$, and $G´$ distributed parameter model of a power line as transmission line through two-port network theory; we obtained that expression of the parameters in frequency function and the transfer function of power lines depend on frequency and length. In stranded-core power lines frequency response is observed with less resistance than in solid-core power lines; this is due to geometric characteristics. In the frequency and length response of power lines, higher attenuation was observed in solid-core power lines than in stranded-core power lines. In the frequency and length response of power lines, higher attenuation was observed in solid-core power lines than in stranded-core power lines, being the lines with stranded-core the most suitable for communication among PLC devices without robust modulation and coding schemes.

Key words: PLC channel; power line; frequency; attenuation; mathematical model.

Respuesta de líneas de potencia como canales PLC

Resumen

Este trabajo aborda la respuesta de líneas de potencia como canales de comunicación (PLC por su sigla en inglés). Para esto se modela, simula y analiza la respuesta en frecuencia de los parámetros resistencia, inductancia, capacitancia y conductancia de tres líneas de potencia: una de núcleo sólido y dos de núcleo entorchado. Posteriormente se simula y analiza la respuesta en frecuencia y longitud de las líneas como canales PLC para sistemas de banda angosta. Parte de un modelo de parámetros distribuidos $R´$, $L´$, $C´$, y $G´$ de una línea de potencia como línea de transmisión con teoría de dos puertos; se obtienen los parámetros en función de la frecuencia y las funciones de transferencia de las líneas dependientes de la frecuencia y longitud. Se observa en la respuesta en frecuencia de la línea de núcleo entorchado menor resistencia frente a la línea de núcleo sólido debido a su característica geométrica. En la respuesta en frecuencia y longitud, se muestra mayor atenuación de la señal en la línea de núcleo sólido que en núcleo entorchado. En la respuesta en frecuencia y longitud, se muestra mayor atenuación de la señal en la línea de núcleo sólido que en núcleo entorchado, siendo el tipo de línea de núcleo entorchado el más indicado para comunicar dispositivos PLC sin requerir esquemas de modulación y codificación robustos.

Palabras Clave: Canal PLC, línea de potencia; frecuencia; atenuación; modelo matemático.

Introduction

The systems of power line communications (PLC) use the electrical networks as communication channels, being advantageous against other systems given that PLC do not need additional cabling from what already exists [1][2]; however, the power line was not designed to transport information, and this limits at the physical level the performance of the communication system [3]. The dependence of the characteristics of the PLC channel on the line and the electrical network [4], along with the boom of PLC systems, has attracted interest on the model and computer simulation aimed at designing optimized PLC systems [5].

Among reports aimed at characterization and simulation of PLC systems, we have: [6] which simulates the frequency response of a *VVF* power line (Suganami Electric Wire Co. Ltd), depending on resistance, capacitance, conductance, relative electrical permittivity parameters, and losses in the dielectric up to 30 MHz, and analyzes its behavior in a derivation topology; [7] models and simulates with multi-trajectory theory an underground line in the range from 500 kHz to 20 MHz in a derivation topology; [8] models and simulates an NYM-J 3x2.5 line with multi-trajectory theory to 20 MHz, with a derivation topology and proposes modeling the PLC channel as digital filter; [9] models and simulates with two-port theory CYKY 3x1.5, 3x2.5 and 3x4 lines, dependent on resistance, inductance, capacitance, and conductance parameters up to 1 GHz and analyzes the frequency response of topologies of an electrical network with a CYKY 3x2.5 line.

Reports of PLC systems, besides analyzing frequency response, must analyze length response for different types of lines, given that electrical networks differ in topology, structure, and types of lines [3][10]. Due to this, our work models a power line as transmission line through two-port theory, theoretically describing the parameters of solid-core and stranded-core power lines; simulating a solid-core line and two stranded-core lines, within a range from 3 kHz to 3 MHz, according to resistance, inductance, capacitance, and conductance parameters. Additionally, this work models, simulates, and analyzes the behavior of each type of line as PLC channel in a frequency range from 3 kHz to 3 MHz with power line lengths of 50, 100, 250 and 500 m, and in power line lengths of 10 to 50 m with frequency of 148.5 and 500 KHz, 1 and 3 MHz. This is important in designing PLC narrowband systems because the design does not solely depend on the frequency in the PLC channel but also on the length.

Model of a power line as transmission line

A power line as transmission line is characterized by four *R´*, *L´*, *C´*, and *G´* distributed parameters, where these represent resistance, inductance, capacitance, and conductance, respectively [11]. These are present in a model of distributed parameters in infinitesimal lengths, Dx, of the transmission line (Figure 1.a).

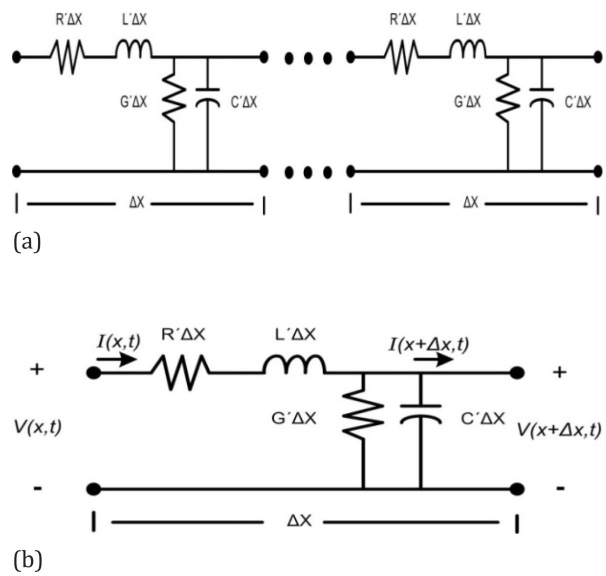

Figure 1. Transmission line model. a) Distributed parameters every Δx. b) Δx transmission line segment.

From the model of an Δx line segment (Figure 1.b), the differential equations of voltage and current are determined along the line, equations 1 and 2 [10]:

$$-\frac{\partial V(x,t)}{\partial x} = R'\cdot i(x,t) + L'\cdot\frac{\partial i(x,t)}{\partial t} \quad (1)$$

$$-\frac{\partial i(x,t)}{\partial x} = G'\cdot V(x,t) + C'\cdot\frac{\partial V(x,t)}{\partial t} \quad (2)$$

where amounts *V(x,t)* and *i(x,t)* denote the instantaneous voltage and current in the *x* position, respectively. Equations 1 and 2 are general equations of a transmission line, expressed in function of the *R´*, *L´*, *C´*, and *G´* parameters. The characteristic impedance (Z_0) and the propagation constant (γ), equations 3 and 4 (respectively), are derived from equations 1 and 2 [9][12]:

$$Z_0 = \sqrt{\frac{(R' + j \cdot w \cdot L)}{(G' j \cdot w \cdot C)}} \quad (\Omega) \qquad (3)$$

$$\gamma = \sqrt{(R' + j \cdot w \cdot L) \cdot (G' + j \cdot w \cdot C)} \quad (\mathrm{m}^{-1}) \qquad (4)$$

with w=2·π·f, where f is the frequency (with units in Hz).

The characteristic impedance and the propagation constant depend on the *R´*, *L´*, *C´*, and *G´*, *f* and parameters, but not on line length [12][13][14].

R´, L´, C´, and G´ parameters for power line

For a pair of solid-core lines, with the following physical characteristics: radius of conductor (a), distance of separation between lines (*D*), electrical conductivity (σ_c), and magnetic permeability (μ_c), surrounded with an electrical permittivity dielectric (ε), magnetic permeability dielectric (μ_ε) and with dissipation factor (*tan δ*), the *R´*, *L´*, *C´*, and *G´* parameters are given by equations 5, 6, 7, and 8, respectively [10]:

$$R' = \frac{\sqrt{\mu_c \cdot f}}{a \cdot \sqrt{\cdot \sigma_c \cdot \pi}} \cdot \frac{D/2 \cdot a}{\sqrt{\left(\frac{D}{2 \cdot a}\right)^2 - 1}} \quad (\Omega/\mathrm{m}) \qquad (5)$$

$$L' = \frac{\mu_e}{\pi} \cosh^{-1}(D/2 \cdot a) + \frac{R'}{2 \cdot \pi \cdot f} \quad (\mathrm{H/m}) \qquad (6)$$

$$C' = \frac{\pi \cdot \varepsilon}{\cosh^{-1}(D/2 \cdot a)} \quad (\mathrm{F/m}) \qquad (7)$$

$$G' = 2 \cdot \pi \cdot \tan\delta \cdot C' \cdot f \quad (\mathrm{S/m}) \qquad (8)$$

When a high-frequency signal flows in a solid-core line, greater signal flow is generated near the surface, this skin effect is characterized by the skin-depth parameter (δ) equation 9 [13]:

$$\delta = \frac{1}{\sqrt{\pi \cdot f \cdot \sigma_c \cdot \mu_c}} \quad (\mathrm{m}) \qquad (9)$$

Due to this phenomenon, the line's cross-section area, where the information signal circulates, diminishes and – consequently – resistance increases with frequency.

Resistance parameter for stranded-core line

For a pair of stranded-core line, the skin surface where the signal flows is modified in geometry due to the presence of *gaps* between the wires comprising it. To calculate to resistance of stranded-core line (*Rc*), must be considered a correction factor (X_R), equation 10:

$$R_C = X_R \cdot R' \quad (\Omega/\mathrm{m}) \qquad (10)$$

where *R'* is given by equation 5. X_R is calculated through equation 11:

$$X_R = \frac{(\cos^{-1}(\frac{r_{wire} - \delta}{r_{wire}}) \cdot r_{wire}{}^2 - (r_{wire} - \delta) \cdot \sqrt{r_{wire}{}^2 - (r_{wire} - \delta)})}{2 \cdot r_{wire} \cdot \delta} \qquad (11)$$

where r_{wire} is the radius of a wire that comprises the stranded-core line [13].

PLC channel model

The model of a power line as PLC channel in two-port network configuration (Figure 2) relates input and output voltages and currents of a line with length , in matrix form, equation 12 [15]:

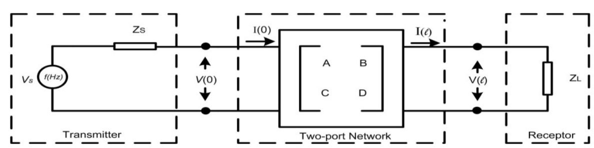

Figure 2. Two-port model of a line connected to a transmitter and a receptor.

$$\begin{bmatrix} V(0) \\ I(0) \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \cdot \begin{bmatrix} V(\ell) \\ I(\ell) \end{bmatrix} \qquad (12)$$

or in equivalent manner, equation 13:

$$\begin{aligned} V(0) &= A \cdot V(\ell) + B \cdot I(\ell) \\ I(0) &= C \cdot V(\ell) + D \cdot I(\ell) \end{aligned} \qquad (13)$$

where *A*, *B*, *C*, and *D* are coefficients that depend on ℓ, γ, and Z_o, which in turn depend o n the *R´*, *L´*, *C´*, *G´*, and *f* parameters, equation 14 [14][16]:

$$\begin{aligned} A &= \cosh(\gamma\ell) \\ B &= Z_0 \cdot senh(\gamma\ell) \\ C &= \frac{senh(\gamma\ell)}{Z_0} \\ D &= \cosh(\gamma\ell) \end{aligned} \qquad (14)$$

The transfer function ($H(f,\ell)$) models the frequency (*f*) and length (ℓ) response as PLC channel through two-port theory, equation 15:

$$H(f,\ell) = \frac{Z_L}{\left[Z_S(C \cdot Z_L + D) + A \cdot Z_L + B\right]} \quad (15)$$

where Z_L and Z_S are the impedance of the transmitter and the receptor, respectively [16].

Simulation and analysis of results

Three lines were used, one solid core and two stranded-core lines; these power lines are used in the electrical networks of *Compañía Energética de Occidente S.A.S. E.S.P.* in the Department of Cauca, Colombia. The Table 1 summarizes relevant physical characteristics of these lines; these characteristics were obtained analytically from the power lines and others taken from [17][18][19]. For the simulations a simple topology without branch was considered; formed by a power line with length variable, besides of a frequency generator connected to starting point of the power line. The simulations are performed according to the standards for narrowband systems [20], because the PLC system tested by the *Compañía Energética de Occidente S.A.S. E.S.P.* uses this frequency range, according the EN 50065-1 [21], particularly the fixed CENELEC band 95 kHz – 148.5 kHz [9], and, this system, operates outdoor over power lines with line lengths from 10 m to 500 m.

The simulation of frequency and length response of these lines was conducted in MATLAB R2012b, and to facilitate reading in figures is identified as a convention: *Al-1350* and *Al-8000* for stranded-core lines, and *Al* for Solid-core line.

Frequency response of R_C, R´, L´, C´, and G´ parameters

Frequency response curves of the R_C, *R´*, *L´*, *C´*, and *G´* parameters are presented, bearing in mind equations 5 to 11, of the three lines from Table 1; Figures 3.a, 3.b, 3.c, and 3.d, respectively.

Table 1. Stranded-core and solid-core lines.

Type of Line / Physical characteristics of Line	Stranded-core line 1*4 +4 AWG Aluminum Al-1350 - Insulator XLPE	Stranded-core line 1*6 +6 AWG Aluminum Al-8000 - Insulator XLPE	Solid-core line 1*8 +8 AWG Aluminum AL - Insulator XLPE
Line diameter – Phase (m)	5.71e-3	4.29e-3	3.26e-3
Relative magnetic permeability (approx.)	1	1	1
Electrical conductivity (S/m)	3.54e7	3.53e7	3.77e7
Relative electrical dielectric permittivity	2.3	2.3	2.3

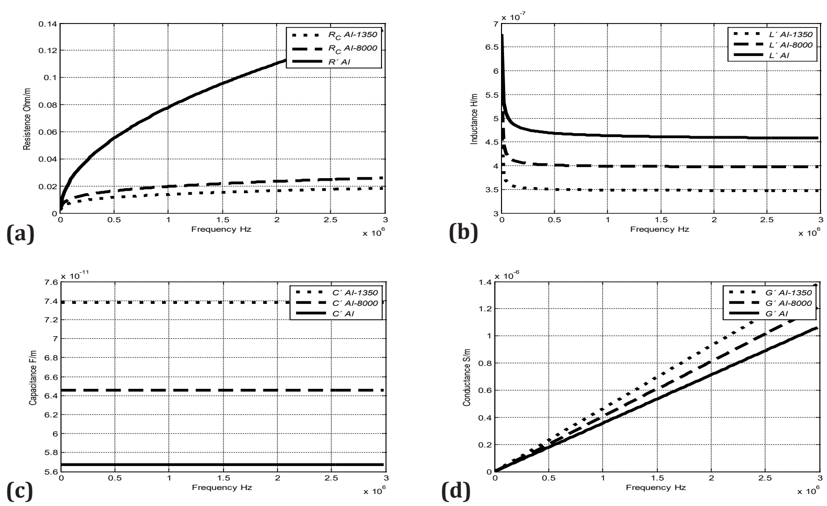

Figure 3. Frequency response of Al-1350 and Al-8000 lines and Solid-core Al line. **a)** Resistance (*R´*). **b)** Inductance (*L´*). **c)** Capacitance (*C´*). **d)** Conductance (*G´*).

Figure 3 shows that resistance for the stranded-core lines is lower than the resistance presented by the solid-core line, which is favorable for PLC purposes, given that in those we can attenuate and stabilize the frequency response in the defined band. The inductance for the stranded-core lines is lower than the inductance presented by the solid-core line, which is favorable for PLC purposes. The capacitance for the Al-1350, Al-8000, and Al line is $7.38x10^{-11}$ F/m, $6.46x10^{-11}$ F/m and $5.68x10^{-11}$ F/m, respectively. The frequency response is constant given that the dielectric relative permittivity (*XLPE*) is independent of frequency for the range of interest [22][18][19]. The conductance for the stranded-core lines is slightly higher than the conductance presented by the solid-core line for frequencies above 500 kHz; however, the difference does not exceed $0.1x10^{-5}$ S/m. The difference in resistance, inductance, capacitance, and conductance in the stranded-core lines is due to their physical characteristics, primarily their diameter.

Frequency response of the transfer function of a PLC channel

Frequency response curves of the magnitude of the transfer function $|H(f,\ell)|$ of the three lines are presented, for the range from 3 kHz to 3 MHz, for four lengths, *l*: 50, 100, 250, and 500 m; Figures 4.a, 4.b, 4.c, and 4.d, respectively.

Figure 4 shows that for the four lengths the response of $|H(f,\ell)|$ presents notches. The effects of reflections in tap (endpoint of the power line) appears in the transfer function in form of notches with fixed frequency spacing [7][9][10]. This notches whose envelope undergoes attenuation that increases progressively with frequency for the three lines. However, the solid-core line (*Al*) experiences greater attenuation than the stranded-core lines and this difference increases progressively with frequency. It is also noted that the attenuation rate increases with line length; thus, according to the simulations for the four line lengths (50, 100, 250, and 500 m), the attenuation rates are summarized in Table 2.

From the aforementioned, it is concluded that the attenuation rate in frequency is greater for the solid-core line than for the stranded-core lines, suggesting that the behavior in frequency of the latter is better than that for the solid-core line.

Length response of the transfer function of a PLC channel

Length response curves of the magnitude of the transfer function $|H(f,)|$ of the three lines are presented, for the range from 10 m to 500 m, for four frequency values: 148.5 kHz, 500 kHz, 1 MHz, and 3 MHz, Figures 5.a, 5.b, 5.c, and 5.d, respectively.

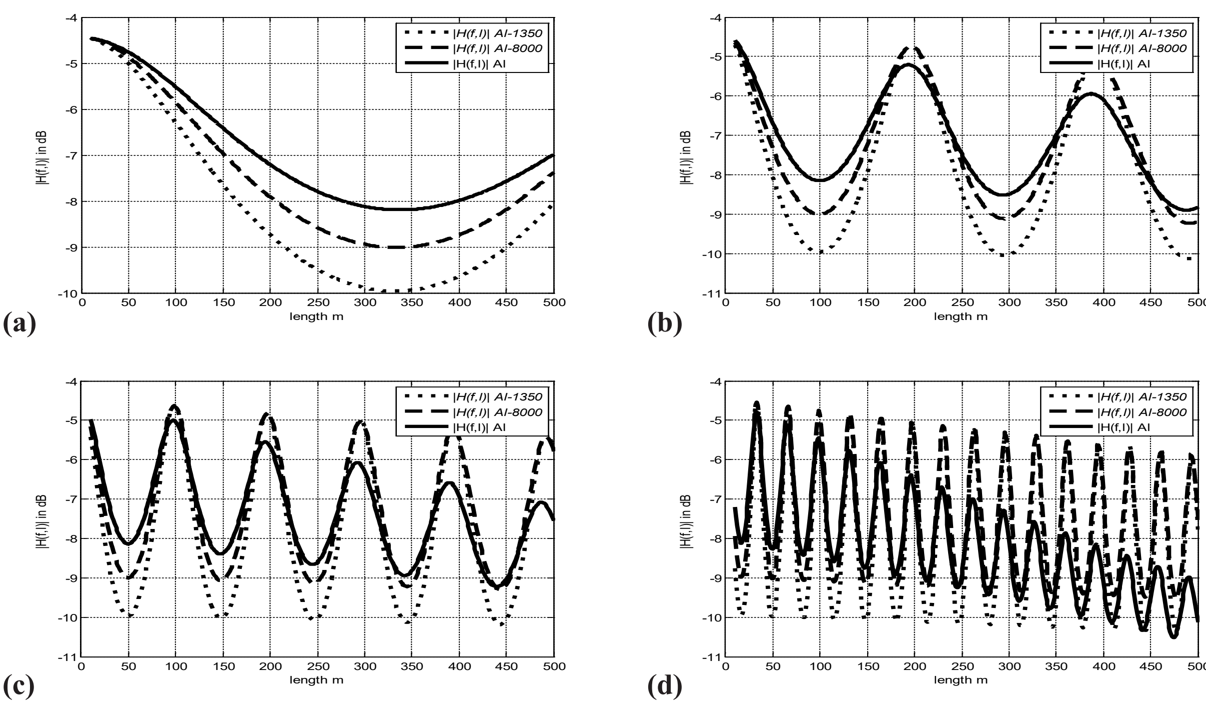

Figure 4. Frequency response of $|H(f,)|$ of the PLC channel model, with Al-1350, Al-8000, and Al stranded-core lines. **a)** *l* = 50 m. **b)** *l* =100 m. **c)** *l* = 250 m. **d)** *l* = 500 m.

Table 2. Attenuation rate in frequency of |*H(f,)*| for four line lengths.

Type of Line	Attenuation dB/MHz (*l* = 50 m)	Attenuation dB/MHz (*l* = 100 m)	Attenuation dB/MHz (*l* = 250 m)	Attenuation dB/MHz (*l* =500 m)
Solid-core Al	0.070	0.194	0.339	0.641
Stranded-core Al-1350/8000	0.028	0.041	0.045	0.120

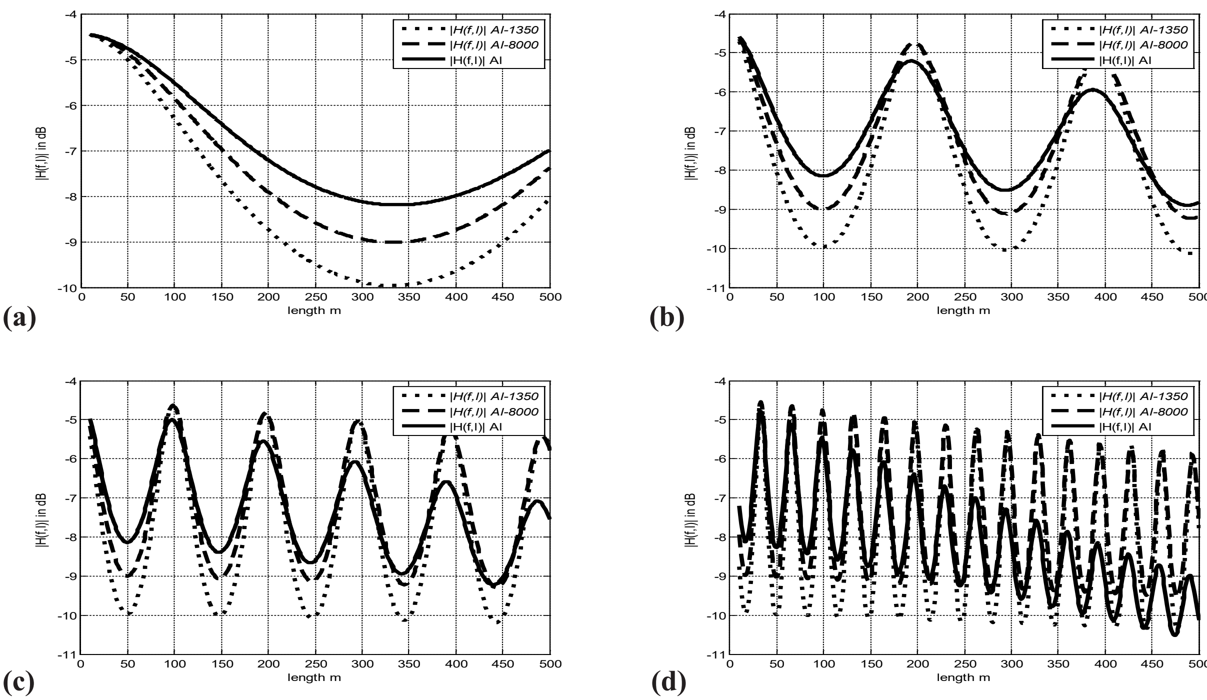

Figure 5. Length response of the magnitude of *H(f,)* of the PLC channel model, with Al-1350, Al-8000, and AL stranded-core lines. **a)** 148.5-kHz frequency. **b)** 500-kHz frequency. **c)** 1-MHz frequency. **d)** 3-MHz frequency.

Figure 5 shows that for the four frequencies the response of |*H(f,ℓ)*| present notches. The notches present an envelope that undergoes with attenuation that increases progressively with length for the three lines. For frequencies higher than 500 kHz, the solid-core line (*Al*) experiences greater attenuation than the stranded-core lines and it can also be seen that the attenuation rate increases with line length, thus, according to the simulations for the four frequencies (148.5 kHz, 500 kHz, 1 MHz, and 3 MHz), the attenuation rates are summarized in Table 3.

From the aforementioned, it is concluded that the attenuation rate in distance is greater for the solid-core line than for the stranded-core lines, for frequencies higher than 500 kHz, suggesting that the behavior in length of the latter is better than that for a solid-core type line.

Table 3. Attenuation rate in length of the |*H(f,ℓ)*| for four frequencies.

Type of Line	Attenuation dB/100 m (*f* = 148.5 kHz)	Attenuation dB/100 m (*f* = 500 kHz)	Attenuation dB/100 m (*f* = 1 MHz)	Attenuation dB/100 m (*f* = 3 MHz)
Solid-core Al	0.745	0.172	0.244	0.407
Stranded-core Al-1350/8000	1.092	0.039	0.048	0.050

Conclusions

We modeled and simulated a solid-core line (*1*8 +8 AWG Aluminum-AL Insulator XLPE*) and two stranded core lines (*1*4 +4 AWG Aluminum Al-1350 and 1*6 +6 Aluminum Al-8000 - Insulator XLPE*) as PLC channels, considering them transmission lines through two-port theory within a frequency range from 3 kHz to 3 MHz and power line length from 10 to 500 m according to resistance, inductance, capacitance, and conductance parameters.

The stranded-core lines present lower resistance to the flow of high-frequency signals against the solid-core line, given the geometric configuration represented through the X_R correction factor.

The magnitudes of the *C´*, *L´*, and *G´* parameters obtained from the lines in question, in spite of the geometric differences of the solid-core line against the stranded-core lines, do not represent great incidence on the capacitive and inductive impedances for PLC purposes.

The frequency response from 3 kHz to 3 MHz with lengths of 50, 100, 250, and 500 m of the transfer function of the PLC channel model of the three lines presents attenuation of 0.070, 0.194, 0.339 and 0.641 dB/MHz for the solid-core line and 0.028, 0.041, 0.045 and 0.120 dB/MHz for the two stranded-core lines, permitting identification of greater attenuation for the solid-core line than for the stranded-core line, showing a notch attenuated with frequency. In turn, the length responses from 10 to 500 m with frequency of 148.5 kHz, 500 kHz, 1 MHz, and 3 MHz of the magnitude of the transfer function of the PLC channel model of the three lines present attenuation of 0.745, 0.172, 0.244 and 0.407 dB/100 m for the solid-core line and 1.092, 0.039, 0.048 and 0.050 dB/100 m for two stranded-core lines, indicating, for frequencies higher than 500 kHz, that the solid-core line presents greater attenuation than the stranded-core lines, showing notches attenuated progressively with line length. Important aspects when designing and implementing a PLC system, according to the application, section of the electric energy distribution network, and the maximum length separating the ends of a PLC system.

Finally, it may be concluded that if a PLC system operates within frequency below of 3 MHz and over distances below 500 m, the attenuation experienced by the signal, under a PLC model in function of the *R´*, *L´*, *C´*, and *G´* parameters of the transmission line, is not critical; thereby, guaranteeing the viability of communication among devices of a PLC system without needing robust modulation and coding schemes.

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