

## A model for the signal transmission performance in MV cables for power line communication

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**Abstract-** *The aim of this paper is the development of a theoretical model of medium voltage (MV) cables in the frequency range 50-200 kHz which can be easily implemented in the Simulink® environment. Two transmission line configurations, line-ground and line-line were considered. The model requires the knowledge of the transmission channel parameters in the frequency domain. Thus, a characterization of MV cables in the two transmission line configurations by means of experimental measurements was performed on commonly used MV cables, RG7H1R, of different sections, 95 mm<sup>2</sup> and 185 mm<sup>2</sup> with aluminium core and copper shielded. To validate the model a comparison between the attenuation constant  $\alpha$  measured and the one simulated for both the configurations under study was carried out.*

### I. Introduction

Since early '70s of the 20<sup>th</sup> century the Power Line Communication (PLC) has been applied for the management and control of high voltage (HV) transmission networks. Subsequently the PLC applications is also enlarged to the low voltage (LV) power line networks, because of the huge development of PLC in home applications [1-2].

Recently, the application of PLC to MV power networks has been taken into account. The network management optimization, the monitoring of the system and the operational services are the most important PLC applications for the MV networks [3]. In Europe, the available frequency intervals for communication systems on LV and MV power networks are settled by CENELEC EN 50065-1 [4]. The standard specifies five different bandwidths from 3 kHz to 148 kHz. In Northern America and in Japan the regulation is more permissive because it allows one to use frequencies up to 525 kHz, i.e. up to the AM broadcast threshold [5]. A further reference for PLC systems is the IEEE standard 643 – 2004 [6]. In the case of cable lines, two configurations are mainly used, line-ground and line-line configuration. In the line-ground configuration the signal is injected between a phase and cable shield. The shield is normally connected to the ground at the ends of the line. In the line-line configuration, the signal is injected between two phases of a three-phase power system, or between the phase and the neutral conductor of a single-phase power system. In both cases the signal can be injected by capacitive couplers or inductive couplers [6]. In literature, different studies have been presented on the behaviour both of HV and MV overhead lines and on LV cables at high frequency. On the other hand, there are few studies on the behaviour of MV cable lines [7-8]. The models proposed are mainly based on Bergeron's model, used also in this work [1-9].

The aim of this paper is to present a model of the transmission system, developed in Simulink® environment. The model requires the knowledge of the per unit length parameters of the transmission channel in the frequency domain. MV cable constructors give the per unit length resistance and capacitance specifications only at 50 or 60 Hz. Thus, it is necessary to perform a characterization of MV cables by means of experimental measurements [10].

The very friendly and few expensive software used for the development of this model is the main advantage of this paper. A further contribution is represented by the experimental characterization of the MV cable parameters for the 50 – 200 kHz frequency range which can be used by the cable constructors in adding at the 50 Hz specifications.

In this paper, firstly the theoretical model is presented. Secondly, the measurement of the per unit length resistance, inductance, capacitance and conductance parameters is described in the case of the line-line configuration. The measurements were carried out on two unipolar MV shielded cables type RG7H1R, of 185 mm<sup>2</sup> and 95 mm<sup>2</sup> cross-section with aluminum core and copper shielded. Finally, the model has been validated by comparing the measured and simulated attenuation constant  $\alpha$  for both the configurations under study.

### II. Theoretical model

In literature the methods used to simulate and to study the transmission line behavior are different [1-9]. Most of them are obtained from the time dependent telegrapher's equations which are for the elementary line transmission cell the following:

$$\frac{\partial v(x,t)}{\partial x} + R' i(x,t) + L' \frac{\partial i(x,t)}{\partial t} = 0 \quad (1)$$

$$\frac{\partial i(x,t)}{\partial x} + G' v(x,t) + C' \frac{\partial v(x,t)}{\partial t} = 0 \quad (2)$$

In these equations  $x$  denotes the longitudinal direction of the line and  $R'$ ,  $L'$ ,  $G'$  and  $C'$  are the per unit length resistance ( $\Omega/m$ ), inductance (H/m), conductance (S/m) and capacitance (F/m) respectively.

In the time domain the most numerical method applied to solve the telegrapher's equations is the Bergeron one [1-9]. Usually,  $G'$  is neglected and only the distributed series resistance  $R'$  is considered to take into account losses in the line. Therefore, the input parameters required by the model are the reference frequency, the resistance  $R'$ , the inductance  $L'$  and the capacitance  $C'$ . The electric parameters are all frequency dependent and a variation law versus frequency can be obtained by experimental measurements.

### III. Experimental set-up and measurement results

The impedance and admittance measurements were carried out with a vector network analyzer (VNA) by Rohde & Schwartz, operating in the frequency range 9 kHz - 20 GHz. The frequency range investigated is 50-200 kHz according to the EN 50065-1, thus including the fixed CENELEC range 95 kHz - 148.5 kHz. The measurements were carried out in the case of two unipolar MV shielded cables type RG7H1R with aluminum core, of different cross-sections, i.e. 185 mm<sup>2</sup> and 95 mm<sup>2</sup>. The experimental set-up is described in a previous work of the authors [10]. The measurements were performed for two different line configurations: the core-shield for single cable and the core-core transmission mode for two cables.

The results were memorized by the VNA as sequence of complex data (2-dimensions vector), of the type:

$$\dot{Z}_{sh}(f) = \text{Re}(\dot{Z}_{sh}(f)) + j \text{Im}(\dot{Z}_{sh}(f)) \quad (3)$$

$$\dot{Y}_0(f) = \text{Re}(\dot{Y}_0(f)) + j \text{Im}(\dot{Y}_0(f)) \quad (4)$$

where  $f$  is the frequency [Hz],  $\dot{Z}_{sh}$  and  $\dot{Y}_0$  are the impedance measured when the line terminations are short-circuited and the admittance measured when the line terminations are opened, respectively. From the real and imaginary parts of  $\dot{Y}_0(f)$  the line transversal parameters values,  $G'(f)$  and  $C'(f)$ , are derived. Similarly, from the real and imaginary parts of  $\dot{Z}_{sh}(f)$  the line longitudinal parameters values,  $R'(f)$  and  $L'(f)$ , are derived.

For a transmission line with losses, it is well known that the propagation constant  $\gamma$  is calculated as follows:

$$\mathbf{g} = \mathbf{a} + j\mathbf{b} = \sqrt{(R' + j\omega L')(G' + j\omega C')} \quad (5)$$

where  $\alpha$  is the attenuation constant (in Np/m) and  $\beta$  is the phase constant (in rad/m).

In order to evaluate the attenuation constant, the real part of the propagation constant is deduced as follows:

$$\mathbf{a} = 8686 \text{ Re} \left( \sqrt{(R' + j\omega L')(G' + j\omega C')} \right) \quad (6)$$

where in this case the attenuation constant is in dB/km

In the following figures (1-2), the measurement results of  $\alpha$ , for both a single cable system and a double cable system vs frequency are shown. The attenuation constant values have been computed neglecting  $G'$  in agreement with the model assumption.

### IV. Model validation

The model used for the simulation of a MV cable behaviour in the frequency domain, was implemented in Simulink® by means of the distributed parameter line block of the Power System library. In figure 3 the Simulink® model in the case of line-ground configuration is shown whereas in figure 4 the Simulink® model in the case of line-line configuration is presented.

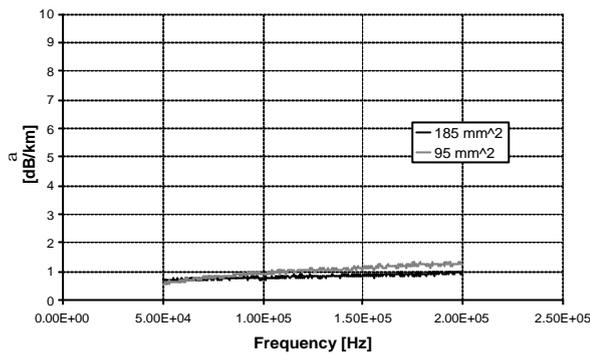


Figure 1. Attenuation constant  $\alpha$  vs. frequency for a single cable ( $G'$  neglected).

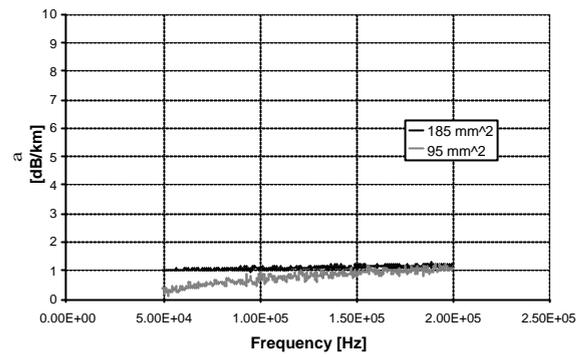


Figure 2. Attenuation constant  $\alpha$  vs. frequency for a double cable system ( $G'$  neglected).

It was simulated a 3 km line energized by a sinusoidal voltage source for both the configuration studied. The working frequency is variable from 50 kHz to 200 kHz with 5 kHz steps. The line was terminated at both ends with a 50  $\Omega$  resistance, to simulate the input impedance of the network analyzer.

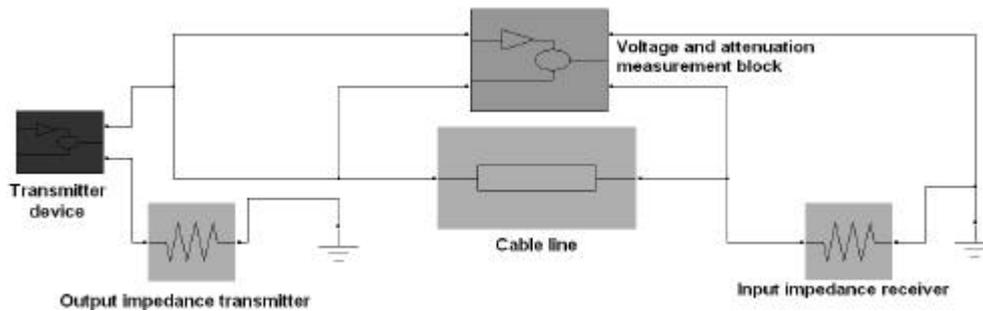


Figure 3. The Simulink® model for the line - ground configuration.

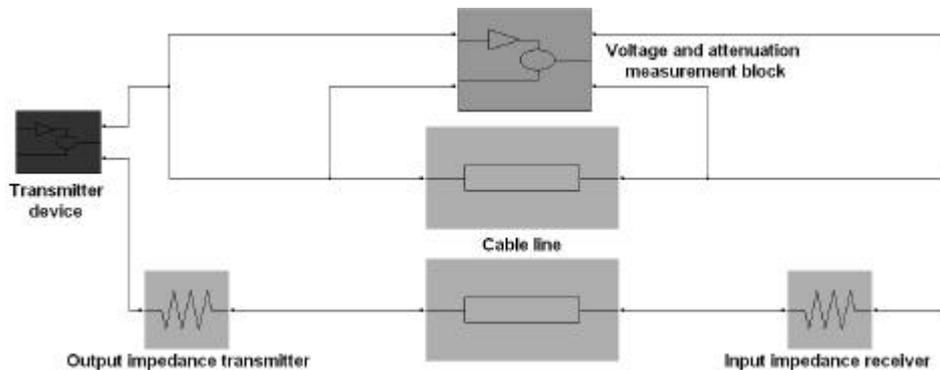


Figure 4. The Simulink® model for the line - line configuration.

The input parameters required by the model are the reference frequency, the resistance  $R'$ , the inductance  $L'$  and the capacitance  $C'$ . The electric parameters are all frequency dependent and a variation law versus frequency was obtained by the experimental measurements. The per unit length resistance  $R'$  versus frequency trend, obtained for the line-ground configuration and shown in fig.6, was fitted by the following second-order polynomial function:

$$R'(f) = A_R f^2 + B_R f + C_R \quad (7)$$

As for the per unit length parameters  $L'$  and  $C'$  versus frequency trends a fitting with constant values was obtained, as follows:

$$L'(f) \approx L \quad (8)$$

$$C'(f) \approx C \quad (9)$$

The coefficients  $A_R$ ,  $B_R$ ,  $C_R$ ,  $L$  and  $C$  are reported in Tables 1 and 2.

Cable	$A_R$ [O/(m*Hz <sup>2</sup> )]	$B_R$ [O/(m*Hz)]	$C_R$ [O/m]
1 x 95 Al	-2.000*E-13	9.000 *E-8	-0.0015
1 x 185 Al	-3.000*E-14	1.000*E-8	0.0047

Table 1.  $R'$  coefficients for a single cable system

Cable	$L$ [H/m]	$C$ [F/m]
1 x 95 Al	2.500*E-7	2.000*E-10
1 x 185 Al	1.400*E-7	2.500*E-10

Table 2.  $L$  and  $C$  values for a single cable system

In the case of the line-line configuration, the behaviour of the per unit length parameters versus frequency was similar to the one obtained in the line-ground configuration. In Tables 3 and 4 the relative coefficients to the electric parameters  $R'$ ,  $L'$  and  $C'$ , according to (7), (8) and (9), are reported.

Cable	$A_R$ [O/(m*Hz <sup>2</sup> )]	$B_R$ [O/(m*Hz)]	$C_R$ [O/m]
1 x 95 Al	-3.000*E-13	2.000 *E-7	0.0023
1 x 185 Al	-9.000*E-15	2.000*E-8	0.0055

Table 3.  $R'$ -coefficients for a double cable system

Cable	$L$ [H/m]	$C$ [F/m]
1 x 95 Al	4.730*E-7	1.110*E-10
1 x 185 Al	2.680*E-7	1.550*E-10

Table 4.  $L$  and  $C$  coefficients for a double cable system

In order to validate the model, the attenuation  $\alpha$ , evaluated by the simulation, was compared with the one obtained by the measurements. Figures 5 and 6 show the comparison in the case of a single cable configuration (95 mm<sup>2</sup> and 185 mm<sup>2</sup> respectively). In the case of a double cable configuration the comparison results are shown in Figures 7 and 8 (95 mm<sup>2</sup> and 185 mm<sup>2</sup> respectively).

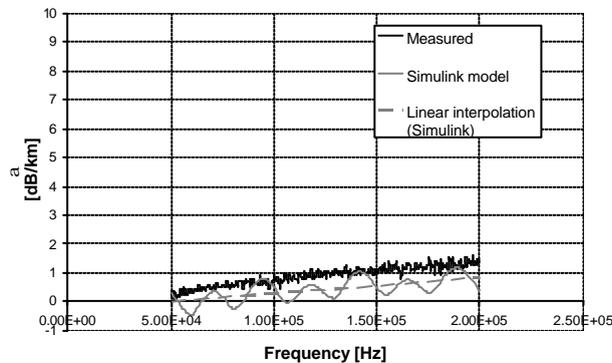


Figure 5. Measurement and simulation results of the attenuation constant  $\alpha$  vs frequency for the 95 mm<sup>2</sup> cross-section cable in the single cable configuration.

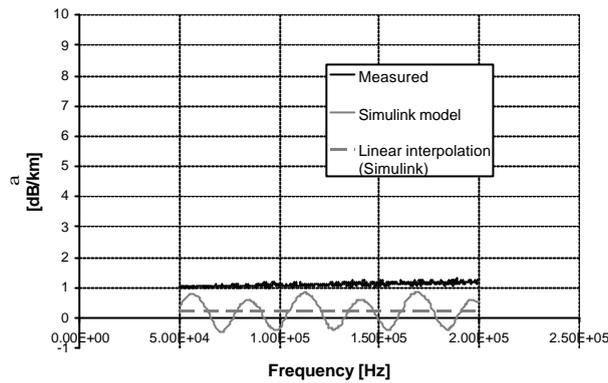


Figure 6. Measurement and simulation results of the attenuation constant  $\alpha$  vs frequency for the 185 mm<sup>2</sup> cross-section cable in the single cable configuration.

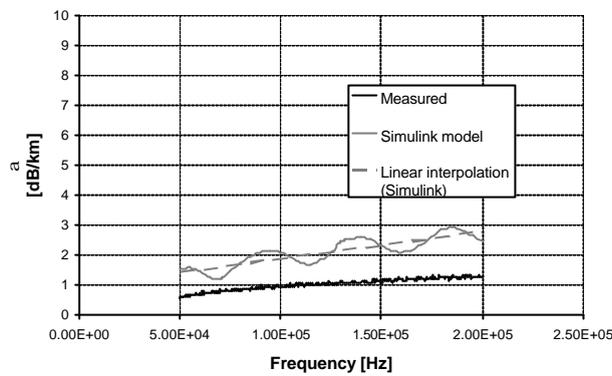


Figure 7. Measurement and simulation results of the attenuation constant  $\alpha$  vs frequency for the 95 mm<sup>2</sup> cross-section cable in the double cable configuration.

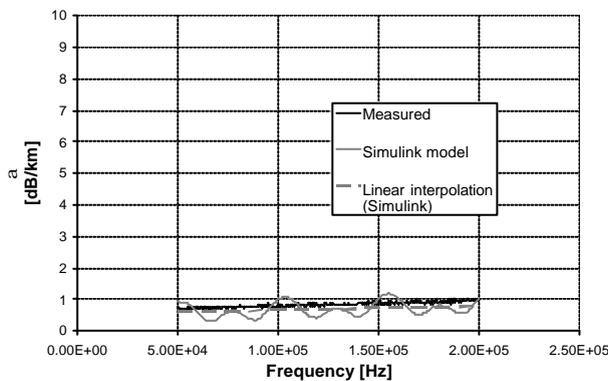


Figure 8. Measurement and simulation results of the attenuation constant  $\alpha$  vs frequency for the 185 mm<sup>2</sup> cross-section cable in the double cable configuration.

## V. Conclusions

In this work paper it has been proposed a simple distributed parameters MV cable model in the frequency domain. Two case studies are considered: line-ground and line-line transmission configurations. The main advantage of the proposed model is that it can be easily implemented in the Simulink® environment. On the contrary, the model requires the knowledge of the per unit length parameters of the transmission channel in the frequency domain. Thus, it was necessary to perform a characterization of MV cables in the two line configurations by means of experimental measurements. The model was validated by comparing the measured and simulated attenuation constant  $\alpha$  for both the configurations under study. The results demonstrate a good agreement between the measurement results and the simulation results mainly for the double cable transmission mode.

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