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AN EXPERIMENTAL METHOD OF ESTIMATING THE TRANSMISSION CHARACTERISTICS OF POWER-LINE CABLES

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Abstract

A method of estimating the characteristic impedance and propagation constant of power line cables as a function of frequency is presented in this paper. The proposed method includes simultaneous measurements on both end-points of various cables of different lengths and a specifically developed data analysis and estimation algorithm. Experimental results are presented and the method's validity is demonstrated.

1. Introduction

Incited by the increasing demand for high speed data services over any available transmission medium, reliable communications are sought over power line cables. Originally designed solely for power distribution purposes, the power line cables exhibit transmissions characteristics that require the employment of sophisticated modulation and coding techniques in order to confront the adversities of the power line communications (PLC) environment.

The designers of PLC systems require accurate information on the network's behavior, which depends on the cable's transmission characteristics, the network's topology and its termination loading. This fact illustrates the importance of characterizing power line cables, especially in the MHz frequency band.

Several publications have been presented in the literature addressing this complex issue. Important contributions have been made in [1], [2], [3], [4] and [5], but the topic still requires further investigation. It is generally valid to remark that attempting to estimate the cable's primary parameters (R', L', G', C'), using analytical expressions that are based on simplified theoretical models of the cable's physical structure, can often result in inaccurate estimations. Cables with different geometrical characteristics complicate the procedure of creating suitable theoretical models even further. Therefore, in this work we present a general method of estimating the characteristic impedance (Z_0) and the propagation constant (γ) of a cable using experimental measurements and a specifically developed data analysis method.

The paper describes the utilized measurement setup and the calculation steps in Section 2, while the final estimation process of the Z_0 and γ values is discussed in Section 3. Finally, in Section 4 experimental results are presented and verification of the validity of the estimated parameters is performed.

2. Measurement and Data Processing Methodology

The methodology described in this Section primarily attempts to simplify the measurement procedure and dispenses of specifically designed equipment and measurement environments. The basic idea of our approach is that the values of Z_0 and γ determine the transfer function of a network, along with its topology and loading. The simplest possible network consists of a single segment cable. Therefore, by measuring such a network's transfer function and calculating its theoretical equivalent, we can determine the values of Z_0 and γ. Applying this approach on cables of different lengths, we can further improve the estimation of the real values of Z_0 and γ.

Based on this approach, measurements are taken on an experimental set-up involving a signal generator, used to inject a tone signal into the cable under measurement, the cable under test and a two-channel data acquisition system, used for simultaneous waveform acquisition at both cable ends. The procedure consists of simultaneous voltage measurements at both ends of each cable, which are both terminated by impedances of predefined values. The measurements are repeated for tone signals that cover the entire frequency band of interest with a selected frequency step and may be automated using computer-controlled equipment. The values of the terminating impedances are used in the data analysis method and the precision in which their values are defined, affects the estimation accuracy of the Z_0 and γ parameters. Nevertheless, it is not required that the value of these impedances exhibits any relation to the characteristic impedance of the cable.

Each set of measurements includes the two end-point voltages of a cable of particular length for each frequency point in the band of interest. The data analysis method is based on two fundamental steps regarding each frequency point. Initially, the single frequency measurement data are processed using an FFT-based method in order to determine the line's transfer function in terms of amplitude and phase. The calculation is based on the frequency domain ratio of the output to the input voltage at the specific point of the N-point FFT that corresponds to the tone frequency used as input. Provision was made in selecting the data sampling frequency so that the resulting frequency discretization of the N-point FFT precisely associates a specific FFT point to the signal's frequency, since:

$$\delta f = N/F_s \tag{1}$$

where F_s is the sampling frequency.

This procedure is enabled by applying a sufficiently high sampling frequency and performing a suitable time interpolation process to the data, in order to alter their sampling rate to a value that satisfies the requirement described above. This procedure is repeated for various frequencies in order to cover the frequency band of interest. Therefore, by completing this first data processing step, we derive a complex transfer function value for each frequency point.

During the second data processing step, the cable's response is related to its theoretical equivalent. The line's theoretical response is expressed either by considering a multiple reflection environment or a two-port network, depending on the line's length and the frequency of interest. Assuming cable length that is best described by the reflection model in the measured frequency range, we present a diagram of signal propagation as a function of time in Fig.1.

Assuming U_i as the incoming signal at end-point 1, the level of the theoretical frequency domain signals at the two end-points (U_1 and U_2) are calculated according to:

$$U_1 = U_i.[1 + \sum_{i=1}^{L-1}\{\tau_1.{\rho_1}^{(i-1)}.{\rho_2}^{i}.e^{-2i\gamma l}] \tag{2}$$

$$U_2 = U_i.\sum_{i=1}^{L}\{\tau_2.(\rho_1.\rho_2)^{i}.e^{-(2i-1)\gamma l}\} \tag{3}$$

where l is the cable's length, ρ_1, τ_1 and ρ_2, τ_2 are the reflection and transmission coefficients for points 1 and 2, respectively. Consequently, the theoretical transfer function, described as the ratio of the line's output to its input, is given

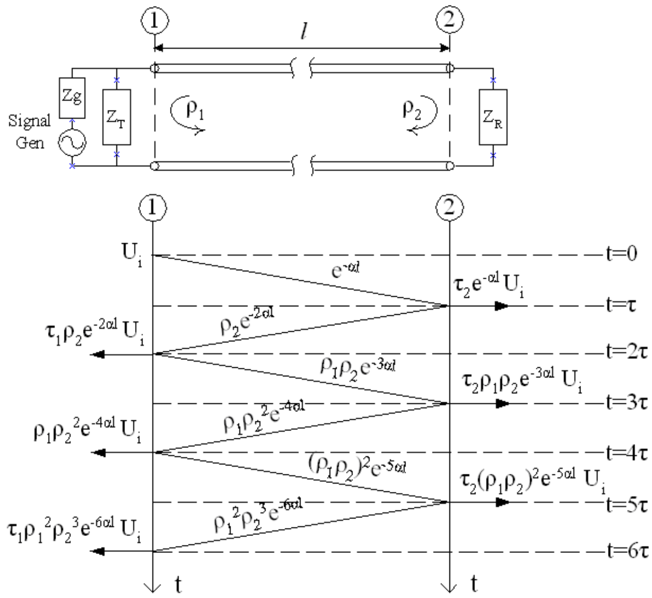

Figure 1: Timing diagram of signal propagation on a cable line.

by:

$$TF_{1-2} = \frac{\sum_{i=1}^{L}\{\tau_2.(\rho_1.\rho_2)^{i}.e^{-(2i-1)\gamma l}\}}{1 + \sum_{i=1}^{L-1}\{\tau_1.{\rho_1}^{(i-1)}.{\rho_2}^{i}.e^{-2i\gamma l}\}} \tag{4}$$

The above expression could be reformed to describe the steady state transfer function when the number of paths tends to infinity, using the following identity:

$$\lim_{L\to\infty}\{\sum_{i=1}^{L} x^i\} = \frac{x}{1-x}\ , \qquad -1 < x < 1 \tag{5}$$

Since, signal components generally tend to decrease faster as the path's length becomes longer, it is valid to assume that $\rho_1\rho_2 e^{-2\gamma l}$ is a complex value inside the unit circle. Therefore, the steady-state transfer function becomes:

$$T = \frac{\tau_2 e^{-\gamma l}}{1 + \rho_2 e^{-2\gamma l}} \tag{6}$$

or equivalently:

$$T = \frac{(\frac{2Z_R}{Z_R+Z_0})e^{-\gamma l}}{1 + (\frac{Z_R-Z_0}{Z_R+Z_0})e^{-2\gamma l}} \tag{7}$$

where Z_R is the receiving-end impedance. This expression directly associates the cable's transmission characteristics to its response and therefore it can be used to determine the properties of the medium when the line's response has been measured.

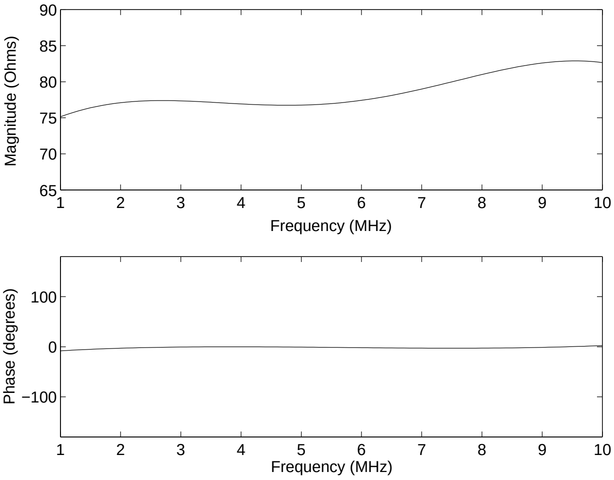

Figure 2: Estimated value of Z_0.

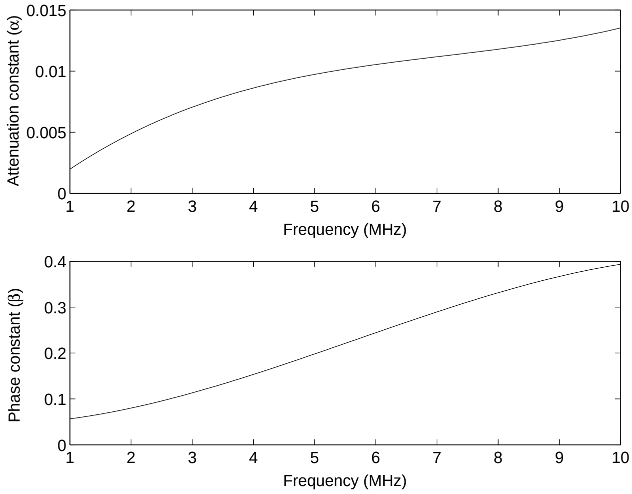

Figure 3: Estimated value of $\gamma = \alpha + j\beta$.

3. Estimation of Cable Transmission characteristics

Estimation of the cable's properties is performed using the transfer function estimates (T_1 and T_2), derived from measurements taken on two cables of different lengths (l_1 and l_2, respectively). Using this two-equation system, a number of possible solutions is calculated for the $[Z_0, \gamma]$ parameters pair. Solution of the system is facilitated through the use of cable lengths that can be expressed as multiples of a common factor.

Not all derived $[Z_0, \gamma]$ values can be considered valid for describing cable properties. Therefore, using a number of logical criteria, the physically meaningless complex solutions are excluded. Such criteria include the following conditions:

- real part$(Z_0) > 0$
- real part$(\gamma) > 0$

During the final stage of the estimation process, it is useful to combine the acceptable solution pairs derived by repeating the process for various pairs of cable lengths. The final values of Z_0 and γ are calculated using a rather *relaxed* intersection of the solution sets. This means that for a particular frequency, the final value of the $[Z_0, \gamma]$ pair is selected, because it is included in every available solution set with only small variations.

To clarify this issue even further, let us consider that one of the solution sets includes the values (Z_0, γ) for frequency f_1. If among the remaining solution sets, we can find a pair of $(Z_0 + \delta Z_x, \gamma + \delta\gamma_x)$, where δZ_x and $\delta\gamma_x$ symbolize the parameters' variations from (Z_0, γ) and x indicates the solution set, and if all variations remain bounded to a predefined threshold, then these selected solutions form a group of acceptable solutions that can be used for deriving the final estimation of the cable's secondary parameters. The pair that minimizes its distance (D) from every other pair in the group is selected as the final pair of properties that describes the cable in that particular frequency point. The distance between Z_0 and every $Z_0 + \delta Z_x$ in the group, consists of both the real part D_{Re} and the imaginary part D_{Im} distance, calculated according to:

$$D_{Re} = \frac{1}{K} \sum_{x=1}^{K} \{|Re\{Z_0\}^2 - Re\{Z_0 + \delta Z_x\}^2|\} \quad (8)$$

$$D_{Im} = \frac{1}{K} \sum_{x=1}^{K} \{|Im\{Z_0\}^2 - Im\{Z_0 + \delta Z_x\}^2|\} \quad (9)$$

where K is the number of the considered solution sets.

4. Experimental Results and Method's Verification

In this section, we present typical experimental results for a common single phase residential power line cable. The cable (HO5VV-F) consists of 3 stranded copper wires of $1.5mm^2$ cross section each and PVC insulation. The measurements were performed on cables of various lengths ($15m, 12m, 21m$ and $36m$) in the frequency band of 1-10 MHz. The cables were terminated with impedances of 75 Ohms at both ends. All possible combinations of two, between the above lengths, were considered in order to form the systems of equations. The final estimated values of Z_0 and γ were derived using the *relaxed* intersection of the solution sets, described in the previous section. The estimation results are presented in Fig.2 for the characteristic impedance and in Fig.3 for the propagation constant.

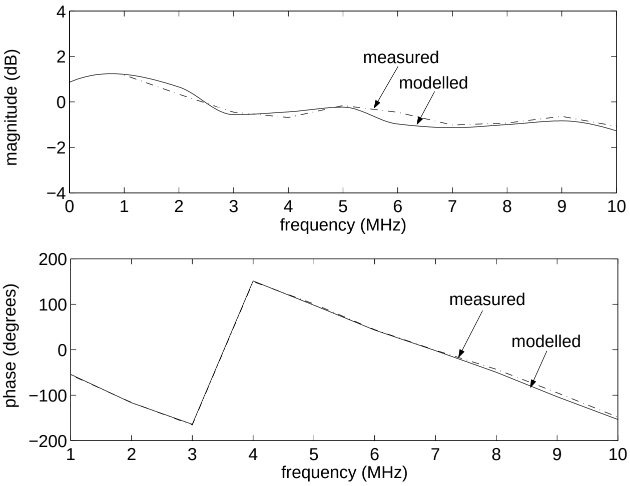

Figure 4: Measured and modelled response of a $22.3m$ cable line.

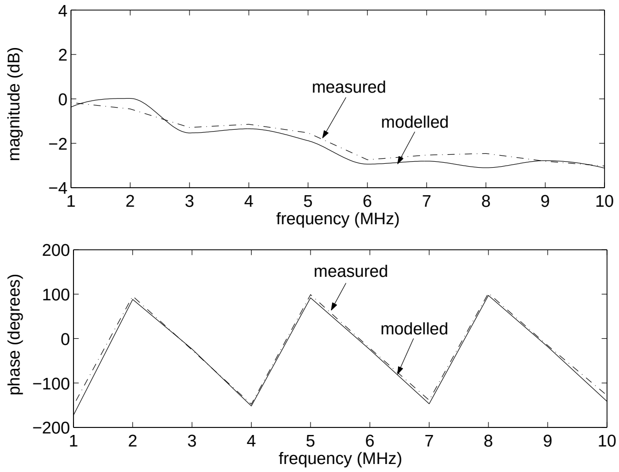

Figure 5: Measured and modelled response of a $53.3m$ cable line.

Verification of the validity of these results was performed using cable lengths that were not included in the estimation process. The measurement procedure was repeated for cables of length $22.3m$ and $53.3m$. The transfer function of each line was estimated using the FFT-based methodology presented in Section 3. Finally, the measured transfer function was compared to the one derived using the theoretical model expressed in (7) and the previously estimated values of the cable's properties. The results of the verification procedure are presented in Figures 4 and 5 for the $22.3m$ and $53.3m$ lines, respectively. It can be observed that the calculated transmission characteristics enable a satisfactory description of the cable's behavior.

The efficiency of the parameters' estimation method is demonstrated further by comparing the response obtained from a small scale power line topology with its modelled equivalent, using the estimated properties of the cable. The topology shown in Fig.6 was constructed using HO5VV-F cables. Network points T_1 and T_3 were used for signal input and output respectively. These network points were terminated by impedances of 100 Ohms. Termination point T_2 was selected for the network's connection to the mains supply (230V AC). In order to isolate the network under measurement from the mains network we connected T_2 to the mains through a power low pass filter with cut off frequency around 1 kHz, whose impedance appears minimal (approximately a short circuit) in the frequency band of interest. The remaining terminations of the network were left as open circuits.

Figures 7 and 8 present the network's measured squared response for two 1 MHz-wide frequency bands, $1-2$ MHz and $7-8$ MHz, respectively. For each frequency band, we also demonstrate the modelled network response, which was analytically calculated using the multipath propagation model presented in [6] . The calculations were performed using the estimated (Z_0, γ) cable values. These results illustrate the ability of the presented methodology to identify the cable's characteristic impedance and propagation constant.

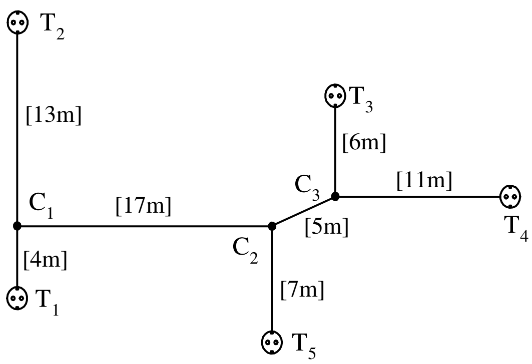

Figure 6: Experimental power line topology.

5. Conclusions

The accurate estimation of the secondary parameters of power cables is vital to the assessment of the transmission characteristics of power line networks. This work presented an experimental method and a data analysis algorithm that allows the estimation of these parameters. The experimental method is based on transfer function measurements of multiple single segment cables, while the data analysis algorithm determines the parameters' values using a solutions' intersection criterion, derived from the measurements of all

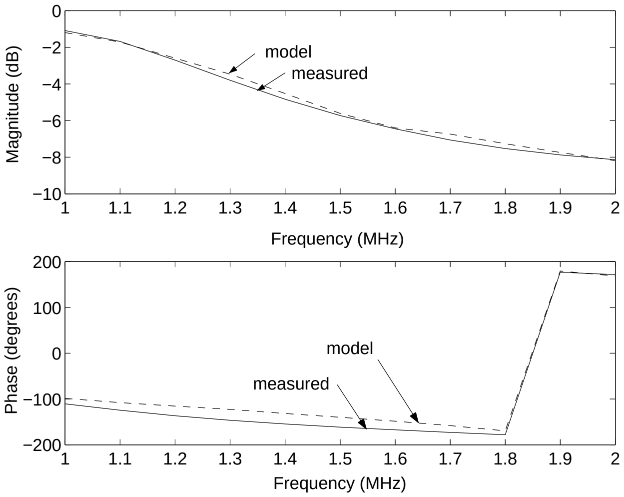

Figure 7: Measured and modelled response of the experimental network (1-2 MHz).

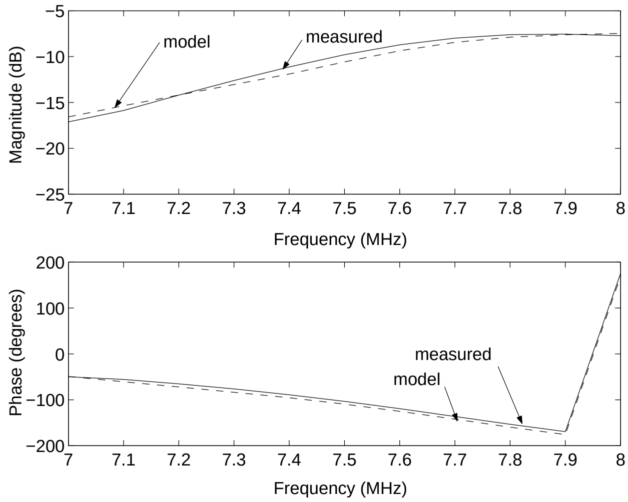

Figure 8: Measured and modelled response of the experimental network (7-8 MHz).

the experiments performed. Various experimental results presented in this paper demonstrate the efficiency of the proposed method.

Acknowledgments

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