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Optimal fitting of high-frequency cable model parameters by applying evolutionary algorithms

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ABSTRACT

Due to the widespread use of electronic power converters, low-voltage high-frequency cable models are being increasingly applied in industry, automobile or aeronautics applications among others. It is known that depending on switching frequency, cable configuration and length, transient overvoltage effects comprising a wide frequency range from dc up to several tens of MHz can appear. However, to accurately reproduce the wide-band frequency response, such models often require the use of ladder networks, thus being necessary to adjust the values of a relatively large number of *R*, *L* and *C* components, which is a complex task. This paper is focused to solve this problem, which is done by applying an iterative genetic algorithm (IGA) optimization approach. From a set of experimental short circuit and open circuit tests the high-frequency cable model of a given cable configuration is obtained, whose parameters are fitted by means of the proposed IGA-based method. Finally, the accuracy of the model obtained is validated experimentally by comparing the frequency-domain and time-domain responses through overvoltage predictions of different samples of the analyzed cable.

1. Introduction

Conducted disturbances are boosted in power cable systems fed by switching PWM-modulated power electronic converters [1]. The uninterrupted and fast switching of PWM power converters tends to induce significant transient surges containing steep-fronted impulses that depend on the technology of the semiconductor switches of the electronic power converter. PWM-modulated power converters using IGBTs (insulated gate bipolar transistors) are characterized by short pulse rise times of 100–400 ns [2] and fast switching frequencies in the 2–20 kHz frequency range [3]. Under high switching speed and having substantial distance between the drive and the load, significant voltage overshoot could happen on the load side. The high-frequency performance of power cables intended for PWM (pulse width modulation) applications is of a paramount importance due to the appearance of phenomena such as skin and proximity effects, transient overvoltage or conducted electromagnetic disturbances. To accurately predict such effects, a high-frequency cable model is required. Improved cable models must include low- and high-frequency effects, and must be able to reproduce fast overvoltage transients. Therefore, the development of power systems models to predict electromagnetic transients is gaining importance in view of the numerous studies for both ac and dc power systems [4–6]. The combined effect of fast rising and falling times of voltage pulses, high switching frequencies, and cable length may result in serious disturbances [7] that can overstress insulation systems at the load and inverter sides. Therefore, common-mode currents of high frequency are induced as well as dv/dt overvoltage transients at the load terminal, which are boosted by the impedance mismatch between cable and load, which can damage insulation systems and reduce cable-load performance. This effect has been studied by several authors, especially in induction motor drive systems fed by long cables [8–10]. The sudden overvoltage effects in PWM-modulated drive systems comprise a wide range of frequencies since they include the switching harmonics [11] and the resonance frequency of the cable [7]. Depending on cable length they can range from dc up to the MHz range [10,11]. Therefore high-frequency models of lengthy cables are appealing to accurately analyze these electromagnetic effects in systems fed by electronic power converters, since they allow reducing design time, costs [1] and failure occurrence. Such models must take into account both the distributed nature of the cable and the frequency dependence of the effects derived [11].

Different cable models have been proposed to reproduce both the frequency and temporal behavior. The telegrapher's equations, which are a set of partial differential equations that allow describ-

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ing the current and voltage on a transmission line with respect to time and line distance, can be transformed into a set of difference equations [6,8,9,12] or into a set of ordinary differential equations (macromodel) through some kind of discretization process [1,7,10,11,13–15]. The model dealt with in this work is based on the last transformation despite the inconvenience in computational burden, although this drawback is minimized thanks to the use of existing computers.

Cable models may be roughly classified into different categories, that is, lumped parameter or distributed parameter models [1,5–7,12,14,15] and constant parameter or by frequency-dependent parameter models. Cable models with distributed parameters can be more accurate than lumped parameter models depending on cable length and signal frequency, although the later ones allow a better physical interpretation of the problem while simplifying the mathematical complexity, so they can be easily integrated in any electromagnetic transients program [12]. Constant-parameter cable models [5] are less accurate than cable models taking into account frequency-dependent features [1,6–15] to simulate transient effects, however they are computationally faster, although CPU requirements of the last models are not excessive for current computers. Frequency-dependent cable models are usually developed in the frequency-domain, so time-domain results are obtained by applying numerical transformations. Cable models based on lumped parameters are developed in the time domain, but the frequency-dependent features can be included in the model by using cascade of cells with lumped parameters [8–11,13,15], the accuracy of the equivalent circuit depending on the number of elements (R, L and C) in each cell, the number of cells, the length of the cable and the analyzed frequency range [13]. Lumped parameter cable models can be developed directly in the time-domain for transient simulations. This is an advantage of such cable models since most power components are modeled in the time domain, so a cable model based on the electric circuit approach, using cascade of cells with lumped parameters is applied in this work.

Parametric cable models can be based on measurements [1,5,7–9,13–15,23,32] or can be calculated as a function of the cable structure and the physical characteristics of the cables by finite-element analysis [2,14] or by applying specific equations [10,11,13]. The last approach results in certain inaccuracies because of the applied approximations whereas parametric models adjusted by means of finite-element analysis require large preparation and simulation times, so measurement-based parametric models outperform the other options. However, cable parameters estimation from measurements is not a simple task, but the models can be accurate for a wide frequency range even under the presence of resonance phenomena, so this option is applied in this work. Models with a limited number of elements facilitate their fitting [8,9,15], but in this work a methodology is established for any number of elements in each cell and for a wide frequency range and under resonance effects. Parameters estimation usually requires the use of complex algorithms [1,10,13], so from a practical standpoint this paper proposes to use a GA-based approach to simplify the parameter estimation and fitting process [7].

To accurately reproduce transient overvoltage effects, a high-frequency model of both, the cable and the load is required. The high-frequency cable model must include effects such as the eddy currents (skin and proximity effects) and dielectric losses. To this end, lumped parameter models are appealing since they allow replicating the temporal and frequency response of spatially distributed physical systems such as cables by constructing a topology composed of different discrete entities or cells connected in series [11]. It is a recognized fact that such models can accurately predict the overvoltage transients when selecting an appropriate number of cells [14]. These models can include R-L ladder networks to simulate high-frequency eddy currents effects [7] and G-C ladder networks to model capacitive effects to ground [5]. High-frequency lumped parameter models have also been successfully applied to other electrical systems such as to simulate the high-frequency behavior of power transformers [15,16], ac electrical motors [14,17] or servo drives [18], sometimes in combination with finite element models to determine the values of the constitutive parameters [19]. A possible approach to solve the whole electrical network composed of the discrete cells, is the transmission-line modelling (TLM) technique [8] which uses discrete models of the components involved and allows accurately reproduce the overvoltage transients. The TLM approach provides an accurate alternative to the state equation formulation while avoiding to solve the associated differential equations [20,21].

This paper focuses on the optimal fitting of the parameters included in wide-band low-voltage cable models fed by switching power converters, which are of very interest in industry, automobile or aeronautics applications among others. Therefore the high frequency effects due to the switching power converter are dominant and greatly influence cable behavior and response.

This paper is focused to accurately adjust the parameters involved in an improved lumped cable model for multi-conductor cables of arbitrary length. This model is intended to estimate overvoltage transients by taking into account frequency effects when the cable system is fed by a PWM-modulated switching power converter. The cable model applied in this paper is similar to that proposed in [22] but using only one cell per meter of cable length instead of 32, thus greatly reducing the computational requirements and the simulation time without any significant effect on model accuracy, as proved in Section 4. Each single cell includes a longitudinal and a transversal impedance in a ladder circuit configuration. The ladder equivalent circuit of the longitudinal impedance allows taking into account both the skin and proximity effects, whereas the ladder equivalent circuit of the transversal impedance allows considering the dielectric losses.

Genetic algorithms (GA) have been widely applied in optimization problems in many disciplines [23,24] including the optimal estimation of transmission line parameters [25], transformers parameters [16,26] or impulse generators [27] among others. In [28] nonlinear transfer functions were approximated by applying a GA approach, by which the optimal values of the expansion coefficients were found, thus providing more accurate results than the classical Chebyshev polynomial approximation. Sales et al. [29] developed a multi-objective GA-based method for line topology identification, using either one-port or two-port experimental data. In [7] a frequency-domain cable model was adjusted by applying a GA optimization procedure to determine the parameters of the impulse propagation function in the Laplace domain.

This paper proposes a new fitting procedure to determine the optimal values of the parameters constituting each single cell of the ladder network used to model the cable. This is a nonlinear optimization problem with a large search space [30] that requires the use of efficient search algorithms to reach an accurate solution while maintaining the computational burden as low as possible. The proposed fitting method is based on a genetic algorithm (GA) approach to select the optimal values of such parameters to accurately reproduce both the frequency-domain and time-domain response of the whole cable. In this paper an interactive GA algorithm to determine the optimal values of the parameters of a single cell is presented. The suggested method is straightforward and does not require additional simulation or learning software tools such as FEM (finite element method) or APLAC, as required by other approaches [22].

It must be pointed out that although the IGA-based approach proposed in this paper has been applied to adjust the values of the parameters of the cable model, it can be applied to many other