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Implementation of time domain transformer winding models for fast transient analysis using Simulink

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A B S T R A C T

To date, programs available for the simulation of electromagnetic transients in power components and networks do not include transformer winding models able to simulate an impulse test response. This is an important omission, since the standard impulse test defines for most cases the highest dielectric stress that a power transformer will suffer once installed. In this work, two transformer winding models for fast transient analysis are implemented in Simulink: a lumped parameter model based on state-space equations and a distributed parameter model based on multiconductor transmission line theory and Bergeron's method. A test case consisting of a 286 turns winding is provided to demonstrate the performance of the models implemented. Both models are applied to the computation of the transient voltage along the turns of the transformer winding considering lossless case and including series losses.

Introduction

One of the most important standard tests for the design and assessment of power transformers is the impulse test, which defines for most cases the highest dielectric stress that the transformer will suffer once in operation. Therefore, the insulation system is designed in general to withstand this test. Since physical prototypes are expensive and case-specific, simulation tools are preferred in the dielectric design stage of transformers.

In the last decades, several transformer winding models have been proposed in the literature for the digital simulation of electromagnetic transients produced by impulse propagation. These models can be classified in black-box models and internal models. Black-box models are very useful when detailed geometrical information of the windings is missing, and are based on terminal measurements usually performed in the frequency domain [1–3]. However, in the dielectric design stage of new types of transformers or the improvement of existing ones, measurements are not available and one has to rely on internal models. These models can be described either by distributed parameters, using the transmission line theory, or as a ladder connection of lumped parameter segments [4]. Nonetheless, to date commercial programs for the simulation of transient response of electrical components and networks do not include internal models able to predict the response of a transformer winding to an impulse test or any other excitation of high frequency content.

Classical distributed parameter winding models were based on considering the winding as a straight conductor in order to model it as a single-conductor line. With the appropriate modification to the well-known telegrapher equations, this model could consider capacitive coupling between winding turns or segments, but it was not able to consider the corresponding inductive coupling, which can be fundamental to accurately compute transient internal overvoltages along the winding. On the other hand, lumped parameter models can include inductive coupling between turns or segments but they require a large number of segments to approximate the wave propagation phenomena along the winding. However, particular studies, such as the analysis of dielectric stress between turns, require a turn-by-turn representation of the winding. In such case, a lumped parameter model can be sufficient to accurately reproduce the transient response of the winding [5].

A winding representation based on a multiconductor transmission line model has demonstrated accurate results given its ability to consider the inductive and capacitive coupling between turns, as well as the wave propagation along the winding [6–11]. However, this model is usually described in the frequency domain, which precludes its direct implementation in time domain simulation programs. The representation of this model in time domain by means of the method of characteristics has also been reported in the past [12]. Still, the method of characteristics requires the discretization of each winding turn in a number of segments and, since a detailed winding model can consist of hundreds or thousands of turns, the resulting system can be extremely large and, in consequence, the computer times can be excessive.

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In this work, two transformer winding models for fast transient analysis are implemented in Simulink [13]: a lumped parameter model based on state-space equations and a distributed parameter model based on multiconductor transmission line theory and Bergeron's method [14]. Once their features have been established, both models are used to compute the transient voltage at different turns along a transformer winding considering lossless case and including series losses. Implementations were performed using Simulink because of its simple programming language and easiness in developing custom models. In addition, a model described in the frequency domain is used to validate the results from the models implemented in this work.

The main contributions of this paper can be summarized as follows:

- *Creation of two new model blocks in Simulink for the simulation of fast front transients in transformer windings*. Currently, this type of simulations requires implementing specific purpose models, which involves a deep knowledge of winding modeling techniques. The new model blocks will facilitate future fast front transient studies in transformer windings for research and industry applications.
- *Comparison and performance analysis of the models implemented*. This provides important information, in terms of accuracy and computational performance, for future users of the model blocks.

Transformer winding modeling

A typical internal representation for a differential segment Δz of a single transformer winding is shown in Fig. 1 [4]. Parameters per unit length are defined as follows:

L is the series inductance of the winding.
R is the series resistance of the winding (i.e. the loss component of L).
C_s is the series capacitance of the winding (turn-to-turn).
R_s is the loss component of C_s.
C_g is the capacitance to ground of the winding (turn-to-earth).
R_g is the loss component of C_g.

In addition, inductive coupling between segments, corresponding to the turn-to-turn winding inductances, can be included. This coupling is important when studying the interturn voltages caused by a fast front surge.

Lumped and distributed parameter modeling approaches are based on the representation shown in Fig. 1. The models considered in this paper are described below.

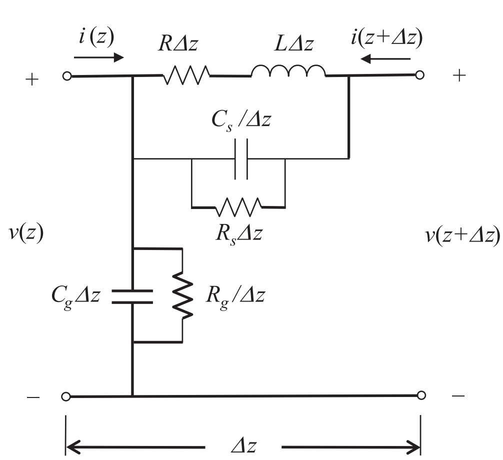

Fig. 1. Equivalent circuit per unit length of a transformer winding [4].

Lumped parameter model

In 1974, Fergestad et al. described a solution approach based on state-space formulation for calculating voltage oscillations in transformer windings [15]. The resulting model included dielectric losses but did not consider series losses, which are in general larger, and therefore more important than dielectric losses to reproduce the damping along the winding. Ragavan and Satish obtained a similar model defining a different set of state variables [16]. In contrast to Fergestad's model, this model includes series losses but does not consider dielectric losses. It also takes into account coupling between windings, which is not analyzed in this paper.

The space variables considered in [16] are the inductive currents and the nodal voltages starting from a lumped parameter representation. The corresponding state-space system of equations is obtained as follows:

$$\frac{d\mathbf{x}(t)}{dt} = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) \tag{1}$$

where

$$\mathbf{x}(t) = \begin{bmatrix} \mathbf{i}(t) \\ \mathbf{v}(t) \end{bmatrix} \tag{2a}$$

$$\mathbf{A} = \begin{bmatrix} -\boldsymbol{\Gamma}\mathbf{R} & \boldsymbol{\Gamma}\mathbf{T}' \\ -\mathbf{C}'^{-1}\mathbf{T}' & \mathbf{0} \end{bmatrix} \tag{2b}$$

$$\mathbf{B} = \begin{bmatrix} \boldsymbol{\Gamma}_k & \mathbf{0} \\ \mathbf{0} & -\mathbf{C}'^{-1}\mathbf{C}'_k \end{bmatrix} \tag{2c}$$

$$\mathbf{u}(t) = \begin{bmatrix} \mathbf{v_k}(t) \\ \frac{d\mathbf{v_k}(t)}{dt} \end{bmatrix} \tag{2d}$$

In (2), $\boldsymbol{\Gamma}$ is the inverse of the inductance matrix, $\mathbf{C}'$ is the capacitance matrix with the k-th row and column removed (where k is the input node), $\mathbf{T}'$ is the incidence matrix with the k-th row removed, $\boldsymbol{\Gamma}_k$ and

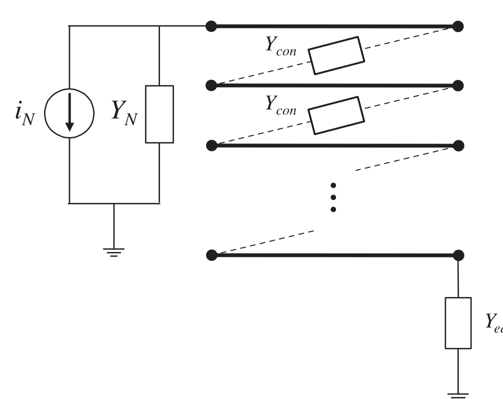

Fig. 2. Winding model based on multiconductor transmission line theory and zigzag connection.

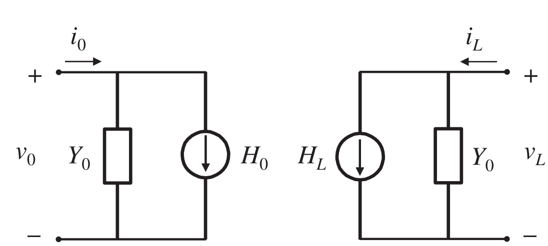

Fig. 3. Dual Norton representation of a single-phase line.