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High frequency transformer model derived from limited information about the transformer geometry

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ABSTRACT

To represent transformer behaviour during a transient state which includes high frequencies, it is necessary to consider the resonances which occur inside the transformer. One strategy is to deduce the transformer model from the measurements of the transformer's frequency response, another one is to construct the model based on a careful representation of the inside of the apparatus.

In the paper a model is presented which is compatible with EMTP-type software programs based on a finite element method (FEM) calculations and the complex permeability approximation. The model can be classified as a Grey Box transformer model, according to the terminology of the CIGRE. The model's frequency dependent parameters are derived from limited information about the transformer geometry. State space equations are used to input the model into an electromagnetic transient calculation software program. This approach requires specific mathematical treatments to avoid stability issues during simulations. The model is validated for lightning impulse studies using the field test measurements of overvoltages that had occurred at the external transformer's terminals.

1. Introduction

Numerous transformer models have been developed during the past decades, some of which are capable of representing the electromagnetic behaviour of a transformer at high frequencies. Fast front transients related to lightning strikes or switching of vacuum circuit breakers are sources of the high frequency electromagnetic waves, which are studied in the paper. High frequency transformer models should consider resonances which may occur inside the transformer when stimulated by a high frequency overvoltage wave. Unfortunately, these models are often too complex to be of practical use or they require confidential information on a transformer geometry.

High frequency transformer models can be classified into three different groups, depending on the data needed for their construction: Black Box, White Box and Grey Box [1–6]. Due to the limitations of the Black Box models [5,6] (they require measurement data which is not always available) and the White Box models [1] (they require a detailed knowledge of the transformer's design), the Grey Box models have been introduced [2–4]. Grey Box is the common name for the models which range between the Black Box and the White Box models' approaches. The aim of the Grey Box models is to obtain a physical and accurate model of transformers from the data which is usually provided by transformer manufacturers such as nameplate data, basic geometry of the transformer window and measurement results. These models can be used both for the calculation of the voltage distribution along the windings of a transformer and for the calculation of the transferred overvoltages between its sides.

There are two different approaches to construct all these models. The first one (Grey Box or White Box) is to construct a network with lumped or distributed parameters values of which are calculated from the geometry of the transformer window and adjusted based on measurement results if necessary [2–4]. The complexity of these models depends on the level of precision with which the transformer's inner geometry is taken into account. The second approach (for Black Box) is to construct a model from the frequency response analyser (FRA) measurements, made on the transformer terminals. The model response can be fitted with rational functions [7] or with a generic circuit model the parameters of which represent electromagnetic relations inside the transformer [8–12]. [13] proposes to use artificial neural network methods to

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determine the Grey Box model parameters from the FRA measurements.

Recently, in addition to the classical Grey Box modelling approach, some studies were carried out in the area of practical determination of the Black Box transformer model derived from the White Box model [14,15]. It is possible to directly transform the complex White Box models to the state space equations which describe the transformer at the terminals of interest. By using this approach, the White Box models can easily be used in an EMTP-type software program. Another advantage of this approach is that the transformer manufacturer is able to provide utilities with accurate transformer models without divulging any confidential information related to the transformer's inner design.

The second section of the paper describes a detailed procedure for the calculation of the frequency dependent nodal admittance matrix of a Grey Box transformer model which is based on finite element method (FEM) calculations and derived from limited information about the transformer geometry. It also presents some approximations based on the concepts of complex permeability and homogenization, which have been made in order to reduce the model size. The inclusion of the model in EMTP-like software using rational approximation, passivity enforcement and state space equations is explained in the third section. Some elements of validation based on lightning impulse test measurements conducted on a 64 MVA, 24/6,8/6,8 kV, *YNd11d11* power transformer are given in the fourth. Section five is the conclusions.

2. Grey Box transformer model principle

In this section a model which can be classified as a Grey Box transformer model is described. It is based on finite element method (FEM) calculations and its parameters are derived from limited information about the transformer geometry.

First the concept of the Grey Box models implemented as segmented lumped *RLCG* networks is presented. In what follows, the method for deriving the *RLCG* parameters from the geometry of the transformer window and its windings is described in detail. Both constant and frequency dependent model's parameters are determined by using a finite element calculation method (FEMM software) [16]. Then the model's frequency dependent admittance matrix calculation is presented. Finally, the model's limitations are stressed.

The high frequency model presented in this section is linear and cannot be used to study the low frequency transients such as temporary overvoltages, inrush current, ferroresonance, etc. To study such transients, the non-linear transformer behaviour should be included in the model.

2.1. Segmented lumped RLCG network model

In this paragraph the principle of a model based on the division of transformer windings into segments which are represented as lumped *RLCG* equivalent networks is presented [17–19].

In the model the values of the parameters are calculated from the transformer geometry and other data known by the transformer purchaser such as the capacitances inside the transformer, the measurements of which can be made during the transformer production process. Each *RLCG* element represents a physical part (segment) of the transformer's winding. An example of a *RLCG* network which represents one phase of a two windings transformer modelled with only one segment per winding is given in Fig. 1.

From Fig. 1, it can be seen that the transformer is represented with the inductances, resistances and capacitances of each winding, the mutual inductance and resistance (related to the proximity effect), the capacitance and conductance between the windings and the capacitances and conductance to the ground of each winding.

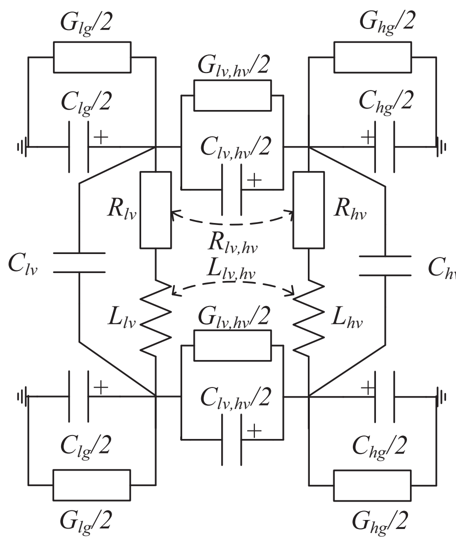

Fig. 1. *RLCG* network for one phase of a two winding transformer.

At this stage, it is necessary to introduce the segmentation used in the model. The idea is to divide the transformer geometry into segments (some authors refer to the "electrical element" [20]), as it is shown in Fig. 2.

It is well known that when simulating the electromagnetic behaviour of an electric component the length of the segment, l should preferably be at least 10 times smaller than the wavelength of the highest applied signal frequency, f_{max} for which the model is built:

$$l = \frac{v}{10 * f_{max}} \tag{1}$$

In (1) v stands for the speed of electromagnetic waves in the transformer's dielectrics, which can be calculated as:

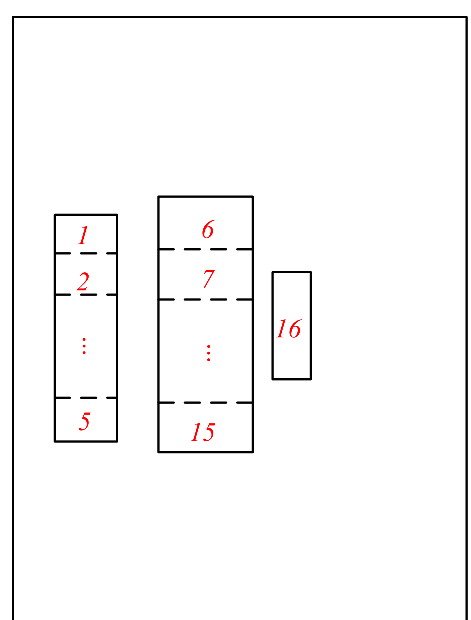

Fig. 2. Transformer segmentation (3 windings with different numbers of segments).