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Difficulties in high frequency transformer modeling

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ABSTRACT

Traditional transformer models available in EMTP-like software packages are not capable of representing transformer behavior during a transient state, which includes high frequencies, since they usually do not adequately take into account the transformer resonant behavior caused by its highly complicated design. Therefore, more complex "Black box" models are developed. Those models can be established without any knowledge of transformer geometry, based on the fitting of the measured admittance matrix of the transformer versus frequency. Unfortunately, the measurement and exploitation of a transformer's admittance matrix are not straightforward. The existing fitting methods include solving a non-convex constrained problem. Hence, it is not always easy to find an optimal solution of the problem. The difficulties, which can arise when building a high frequency "Black box" transformer model, are described in this paper together with a comparison of the performance and fitting accuracy of different numerical packages.

1. Introduction

Over several past decades many transformer models were introduced to represent transformer behavior at high frequencies, which occur during fast transients i.e. lightning strikes or switching of vacuum circuit breakers [1]. Traditional transformer models available in EMTP-like software packages are not capable of representing transformer behavior during a transient state, which includes high frequencies, since they usually do not adequately take into account the transformer resonant behavior caused by its highly complicated design.

In this paper we will concentrate on the "Black box" transformer models. Usage of these models is suggested in IEC 60071-4 standard [2] for insulation coordination studies requiring a higher level of precision. These models can be determined without any knowledge of transformer geometry, based on the fitting of the measured admittance matrix of the transformer versus frequency [3–11]. Therefore, they can only be applicable to evaluate external overvoltages, in order to analyze the interactions between a transformer and the network and to study the insulation coordination of a power system. These models are widely used within power utility companies since they usually do not have access to the transformer design data, which is the property of a transformer manufacturer.

Unfortunately, the measurement and exploitation of a transformer's admittance matrix are not straightforward. Hence, even if numerical packages are available, the fitting methods do not always fit the measured curves accurately enough. Moreover, since a transformer model has to be both stable and passive, it is not always simple to find an optimal solution to the constrained mathematical problem of minimization, which has to be solved in order to fit the curves. Our experience based on several measurements carried out on real transformers is covered in this paper, which also includes a comparison of the performance and fitting accuracy of different numerical packages since the measured curves are not always simple to fit [10,11].

In the second section of the paper a bibliography on high frequency transformer "Black box" modeling is provided, together with a complete procedure for establishing a model. Additionally, results of measurements conducted on a 64 MVA, 24/6.8/6.8 kV, *YNd11d11* transformer are included in this part of the paper. The third section contains an overview of different fitting methods which can be used in order to include a transformer model in an EMTP-like software. A comparison between fitting methods is given in the fourth section. The results are discussed in the fifth.

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2. "Black box" transformer models

In this section an overview on transformer "Black box" modeling is provided as well as a measurements procedure which was used by the authors to establish such a model. Since the model should be used in an EMTP-like program, the procedure for including the measurement results in such a software program is given.

2.1. Different methodologies

Several measurement techniques can be used in order to establish a "Black box" model. These techniques usually differ regarding the choice of the parameter which will be measured. Scattering (S) parameters, impedance (Z) parameters, admittance (Y) parameters and transfer functions can be measured directly from the transformer terminals. To interact with an EMTP-like program, S and Z parameters are usually converted into Y parameters, as is explained in [4,12,13]. Pure transfer function does not interact directly with an EMTP-like program. Nevertheless, in software like MATLAB, the practice for the calculation of transmitted overvoltages is to use transfer functions [6]. In the reference [14], it is explained how to calculate the Y matrix of a cable from the transfer function measurements. The method used to calculate the Y parameters of a transformer from transfer function measurements is proposed in [15].

Depending on which parameter is measured, different measuring equipment has to be used. To measure S parameters, a network analyzer should be used [16–18]. To measure Y and Z, current sensors have to be used. Note that according to Gustavsen [19], insertion impedance is added if a vector network analyzer is used in combination with a current sensor. To measure the transfer function of a transformer, the equipment specified in the standard for frequency response analysis (FRA) [20] has to be used. FRA is a standard test done in order to check the condition of a transformer.

Measurements are usually carried out with low voltage signals due to equipment constraints. It does not have any effect on the accuracy of the HF transformer model since there is no magnetic flux in the core and the transformer is acting as a linear component.

Three different approaches on how to make a model compatible with EMTP-like programs from measurement results can be defined: approximation with rational functions [11,21,22]; direct construction of an equivalent RLC network; indirect usage of a transfer function (i.e. in MATLAB) [6].

The most used approach is to approximate the admittance curves with rational functions. This approach is based on the method proposed by Levy in [23]. The method is used for the FDBFIT transformer model in EMTP-RV [21]. Recently, the method has been improved. The algorithm for the method, called "Vector fitting", was implemented in the MATLAB environment by Gustavsen [24], as an open source code which can be found at [25]. Some explanations on the computer code can be found in [26]. After the rational functions approximating each element of the admittance matrix are obtained, by using a least squared method, passivity has to be enforced since the transformer is a passive component of the network. This can be done simultaneously with the fitting process or at post processing. Explanations of procedures for enforcing passivity can be found in [10,27–33].

As the final representation of the model in EMTP-like programs the following representations are available: lumped parameters [26,34,35]; Norton equivalent (by using recursive convolution) [36,37]; and state space representation [9,38]. Note that the parameters which are obtained by using these methods are not physical and cannot be brought into relation with the transformer geometry.

A "Black box" model cannot be used for a frequency range lower than the frequency of the first maximum of the transformer impedance curve, due to its inability to represent nonlinear transformer behavior. At these frequencies transformer core influence should also be modeled. Therefore, if we want to represent a transformer for a wide frequency range (including the frequencies lower than a few kHz), a traditional transformer model with parallel connected nonlinear inductances should be used for low frequencies, including the power frequency, instead of a "Black box" model. This is done in FDBFIT model, already implemented in EMTP-RV [21,39–42].

"Black box" model can also be used for representations of many other components of electrical networks (i.e. cables [14], overhead transmission lines [37], grounding systems [9], parts of a grid [43], wind turbine [44]) in transient studies which include a wide frequency band.

2.2. "Black box" model: Principle

In this section, a basic approach for deriving a "Black box" model based on state space equations from measurement results, is described. More precisely, a procedure for measuring the admittance (Y) matrix elements of a transformer with FRA equipment and building from these measurements a model compatible with EMTP-RV is presented.

A frequency response analyzer, is only capable of measuring the ratio (H) between the input (V_{in}) and the output (V_{out}) voltages.

$$H(s) = \frac{V_{out}(s)}{V_{in}(s)} \tag{1}$$

Since the FRA measurement equipment is not normally used for measuring a Y matrix, a procedure for measuring it has been established.

The measurement method stems from the following expression:

$$\begin{pmatrix} I_1 \\ I_2 \\ \vdots \\ I_{N-1} \\ I_N \end{pmatrix} = \begin{pmatrix} Y_{11} & \cdots & Y_{1N} \\ \vdots & \ddots & \vdots \\ Y_{N1} & \cdots & Y_{NN} \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \\ \vdots \\ U_{N-1} \\ U_N \end{pmatrix} \tag{2}$$

Expression (2) is valid for a transformer with N terminals. However, the transformer we are considering has 10 terminals: 3 terminals of HV winding, the neutral terminal of HV winding and 6 terminals of two secondary LV windings.

2.2.1. Off-diagonal elements

The electric circuit, which represents the frequency network analyzer, is given in Fig. 1. The coaxial cables are shown in blue and the flat braids are shown in red.

In the equipment we used, the source and the reference leads use the same coaxial cable as it is shown in Fig. 1. The Matching resistance (R) of the frequency network analyzer terminals (source, reference and response) should have the same value as the characteristic resistance of the coaxial cables in order to avoid wave reflections (which can have an effect on the measurement results) at the connection between the network analyzer and the coaxial cables. Therefore, in our calculations we are not taking account the resistance of the coaxial cables. Furthermore, the influence of the connections which are made by straight braids is also ignored.

Note that the measurements of the reference and the response signals are made across the matching resistance of the equipment.

In Fig. 1, the measurement configuration for measuring the $Y_{1,2}$ element of the admittance matrix is shown. Since all the terminals which are not under measurement are grounded, their voltages are equal to 0 V (if the effect of the flat braids is ignored). Therefore, from Eq. (2), for the connection from Fig. 1, the following general