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Modeling of Frequency Dependent Parameters in Time Domain High Frequency Transformer Simulations

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Abstract

Modeling details of frequency dependent parameters and a method for taking those into account in time domain high frequency (HF) transformer simulations are presented. Frequency dependent turn resistance and core losses are considered. The suggested method is general and thus not limited only to the considered frequency dependent parameters. Frequency dependent turn resistance and core losses are obtained by performing frequency domain (FD) finite element method (FEM) simulations. The obtained frequency dependences are approximated by a set of functions with existing Inverse Fourier Transform (IFT) and used in convolution integrals of the time domain model of a transformer winding system. The obtained simulation results are verified by comparison against measurements.

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Keywords: Frequency dependent parameter; time domain simulation; power tranformers; finuite element methos; trapezoidal rule.

1. Introduction

Oil-immersed transformers were and still are a dominant solution for power transmission and distribution systems. Due to their negative environmental impact and the risk of fire and explosion, oil-immersed transformers are presently, however, being replaced by newly developed dry-type transformers whenever possible, i.e. in the range of lower power (<30MVA) and voltage (<100kV) [1].

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Removing oil poses a considerable design challenge in terms of cooling and insulation of the winding system. A considerable aspect of the modern transformer design is to ensure a capability of the winding system to withstand atmospheric over-voltages and switching transients. As an illustration, it is worth mentioning that the testing level of the lightning impulse (LI) voltage is precisely defined by the IEC standard [2]. The standard LI has a rise time of 1.2μs and a time-to-half-value of 50μs [2], thus covering a wide frequency range starting from 0 up to 1MHz.

An accurate transformer modeling and simulation in the LI frequency range can be performed in time domain only by considering all the electric and magnetic couplings between winding turns as separate modeling entities [3]-[5]. The coupling coefficients can be accurately determined only by performing FEM, BEM or MoM field simulations [3], [4].

The accuracy of the previously published approach [3] and [4] for LI-modeling and simulation of transformers was confirmed by numerous measurements and thereafter used for daily design. The simulation approach was developed to achieve a high level of accuracy for predicting the results of the LI-test [2] prior to the manufacturing of the unit.

The LI-test according to the IEC norm [2] should be performed with the LV-coil in short-circuit while connecting the LI-generator to the HV-side. The effect of the magnetic core in this arrangement is then reduced to a negligible level. This is, however, not so if very fast electromagnetic transients in normal operation of the transformer are analyzed, or if the coupling between different transformer's phases under switching transients are considered. In those cases the influence of the core must be taken into account. The very recent publication [6] demonstrates the theory for modelling the frequency dependent core parameters by introducing complex inductances of the winding system in which the imaginary part of the inductance takes into account the core losses over the wind frequency range of interest.

The main purpose of this paper is manifold: (a) to demonstrate a 2-D vector FEM approach for obtaining the complex inductive coupling of the winding system, (b) to show the representation of the frequency dependent core parameters in the subsequent time domain high frequency transformer simulations, and (c) to present validation of the results by comparison against measurements.

2. Frequency Dependent Parameters

Frequency dependent parameters considered in this paper are the turn resistance and the core losses. The turn resistance at different frequencies can be obtained by performing an axisymmetric 2-D FEM eddy current simulation. Thus, the skin effect and proximity effect are accurately taken into account. This is a well-known simulation approach and can be performed by using any of available commercial electromagnetic field solvers. The frequency dependent turn resistance of the testing transformer considered in this paper is presented in Fig. 1.

The red curve shown in Fig. 1 (left) is obtained by performing the FEM eddy current simulation over the frequency range covered by the LI-voltage. This curve can be approximated by a set of functions with existing IFT, as follows [7], [8]

$$R(\omega) = \alpha_0 + \sum_{j=1}^{N_a} \frac{\alpha_j \omega^2}{\omega^2 + \beta_j^2} \tag{1}$$

where α_j and β_j are the unknown coefficients to be determined by a curve fitting procedure and N_a is the number of approximation terms. The blue approximated curve from Fig. 1 (left) is obtained by using N_a=5, which means that the approximation has 11 coefficients. They are determined by using the well-known least-square approach (LSA). The approximation (1) is also presented in Fig. 1 (left, blue line). The approximation overlaps with the original FEM curve.

The IFT of the approximation (1) has the following form

$$r(t) = \alpha_0 \delta(t) + \sum_{j=1}^{N} \alpha_j \left[\delta(t) - \frac{\beta_j}{2} e^{-\beta_j |t|} \right] \tag{2}$$