MULTI-HARMONIC APPROACH TO DETERMINE LOAD DEPENDENT LOCAL FLUX VARIATIONS IN POWER TRANSFORMER CORES

Björn Riemer and Kay Hameyer

RWTH Aachen University, Institute of Electrical Machines
Schinkelstraße 4, 52056 Aachen, Germany, e-mail: bjoern.riemer@iem.rwth-aachen.de

***Abstract* – This paper presents a weak coupled multi-harmonic approach to determine the local flux distribution in power transformer cores. The method is based on lumped parameters extracted from 2D and 3D Finite Element models determined in the time domain, while the transformers working point is calculated in the frequency domain. The proposed method allows for a fast determination of the working point. When compared to a time-stepping approach savings in the computational effort are >90% at comparable accuracy.**

I. INTRODUCTION

Power transformers are counted among the most important components in the energy transmission grid. Due to its continuous operation a high efficiency is indispensible. Amongst others, the losses of transformers depend on stray fluxes and its local distribution. According to the load, the superposition of exciting and stray flux can lead to significant local flux variations in the core, especially for transformers with large short circuit impedances, e.g. phase-shifting transformers.

Since saturation of the core definitely has to be avoided possible load-dependent local flux variations have to be considered already in the design stage.

Several approaches to model the magnetic load of transformer cores are given in the literature. Magnetic equivalent circuits offer a computationally efficient way to calculate the main behaviour of a transformer. However, the local resolution of stray flux paths is rather low.

The accuracy of the calculated flux distribution can be increased by means of the finite element method. In general power transformers have distinctive three dimensional geometries and stray flux paths. By means of 3D FEM, the transformer geometry and the flux paths can be represented accurately. However, a 3D nonlinear FEM requires a high computational effort. In general the transformers working point is defined by the voltage. Thus a voltage driven simulation is necessary. Considering a time-stepping simulation the transient phenomenon has to decay, before the steady state can be analysed. This can be a challenge due to quite large time constants of power transformers.

A well known alternative approach is a nonlinear time-harmonic simulation. This approach considers only the fundamental component of the electrical and magnetic quantities. The core material is represented by an effective B-H characteristic, which can be adapted based on the magnetic energy [1]. The harmonic balance finite element method accounts for a defined set of higher harmonics in a single computational step [2]. A strong coupled multi-harmonic approach is presented in [3]. The finite element formulation is transferred to the frequency domain and a technical relevant set of harmonics is incorporated to the system matrix. The method has a lower computational effort when compared to a time-stepping approach. Nevertheless there are some disadvantages of this method. A drawback of this method is the complexity of the strong coupled spatial discretisation and the considered frequency domains. The system matrix increases with the number of selected harmonics. This can be a limitation especially for 3D models of large power transformers.

In this paper a weak coupled multi-harmonic approach is presented. The method is based on lumped parameters extracted from Finite Element simulations. The method is applied to a 2D FE model of a three-phase five limb power transformer and a 3D FE model of a single phase power transformer.

II. THEORETICAL FRAMEWORK

The transformer is represented by its lumped parameters and therefore by the differential equations

$$\mathbf{u}(t) = \mathbf{R} \cdot \mathbf{i}(t) + \partial_t \mathbf{\Psi}(\mathbf{i}(t)), \tag{1}$$

with the phase voltages $\mathbf{u}$, the winding resistance matrix $\mathbf{R}$, the phase currents $\mathbf{i}$, and the flux linkage matrix $\mathbf{\Psi}=\mathbf{L}(\mathbf{i}(t))\cdot\mathbf{i}(t)$. Transformation of differential equation (1) into the frequency domain yields:

$$\underline{\mathbf{U}}(n) = \mathbf{R} \cdot \underline{\mathbf{I}}(n) + j\omega(n)\underline{\mathbf{\Psi}}(n), \tag{2}$$

with

$$\underline{\mathbf{\Psi}}(n) = \mathbf{L}(n) \otimes \underline{\mathbf{I}}(n). \tag{3}$$

$\otimes$ denotes convolution. The winding resistances are considered to be constant and will be calculated analytically by the winding geometry. The inductance matrix is extracted systematically from a Finite Element model of the transformer by means of static simulations in the time domain. The method to extract the inductance matrix is described in detail in [4].

The working point of the transformer, considering nonlinear core material, is determined as follows:

1.) Determine initial inductance matrix for linear material properties (core reluctivity at rated flux density).
2.) Calculate fundamental component of the transformer currents $\underline{\mathbf{I}}$ for a given excitation $\underline{\mathbf{U}}$ by equation (2).
3.) Transform $\underline{\mathbf{I}}$ into time domain.
4.) Extract secant inductance matrix $\underline{\mathbf{L}}$ at N time steps of one period, considering nonlinear material properties.

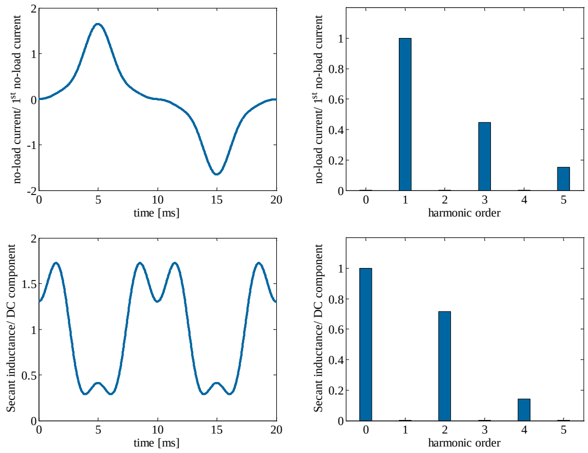

Fig.1. Top: No load current 1 Ph. transformer and harmonic contents.
Bottom: Secant inductance 1 Ph. transformer and harmonic contents.

5.) Transform secant inductance matrix **L** into frequency domain.
6.) Calculate harmonic contents of the transformer currents by equation (2).
7.) Repeat steps 3.)-6.) until the deviation of the currents harmonic content between two iteration steps is less than a defined error limit **ε.**

This weak coupled multi-harmonic approach offers some advantages compared to a strong coupled multi-harmonic approach. The size of the system matrix of the Finite Element system is constant and does not depend on the number of harmonics to be considered. The number N of extraction points is variable, and the secant inductance matrices are determined by a static FE computation based on the magnetic vector potential with the current shape functions as excitation. This yields a symmetric Finite Element system matrix and a good convergence for the nonlinear Newton Raphson iterations. Each extraction point N is independent. Therefore the calculations offer a good opportunity for parallelization, leading to a further decrease of the overall simulation time.

III. APPLICATION

The proposed method is applied to a 3D Finite Element model of a single phase transformer and a 2D Finite Element model of a five limb three phase transformer. The single phase transformer, depicted in Figure 2 (left), is rated at S=100MVA with a rated voltage at U=220kV. The three-phase transformer, depicted in Figure 2 (right), is rated at S=120MVA with a phase-to-phase voltage of U=220kV. The no-load operation is calculated for both transformer types. The no-load currents are plotted in Figure 1 for the single phase transformer, respectively in Figure 3 for the three-phase transformer. Figure 1 additionally depicts the harmonic contents of the secant inductance matrix for the no-load operation. Due to incipient saturation even harmonics occur in the spectrum of the inductance resulting in odd harmonics of the current. Figure 4 depicts the convergence behaviour of the proposed method. It shows the relative deviation of the harmonic contents between

Fig.2. left: Single phase transformer,
right: Three-phase five limb transformer.

the iteration steps. At iteration step 15 the deviation of the fundamental component of the stator current is less than 1%. When compared to a time-stepping approach [4], the computational effort is less than 10% at comparable accuracy.

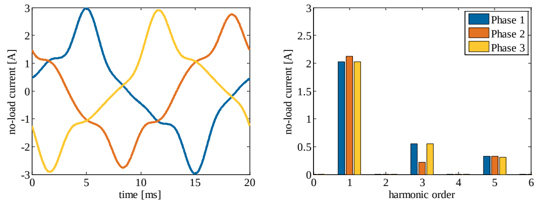

Fig.3. No load current 3Phase 5Limb Transformer,
left: time characteristic; right: harmonic contents.

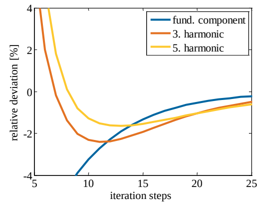

Fig.4. Convergence behaviour of spectral current components.

IV. CONCLUSIONS

This paper presents an approach for the efficient calculation of the flux distribution of power transformers considering nonlinear material. The calculation is based on a weak coupled multi-harmonic method. It can be applied to 2D and 3D Finite Element models. The savings of the proposed approach compared to a time-stepping method is >90% at comparable accuracy. In the full paper further results will be presented regarding the load dependent local flux variations inside the transformer core based on 3D FE models. Furthermore a direct comparison of the method to a time-stepping approach will be given.

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