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doi:10.15199/48.2018.10.11

Verification of transformers windings models for FRA

***Abstract**. The aim of the article is to present the research carried out for verification of simulated transformer windings inductances. In the first stage of the research, the coil was wound on the distribution transformer core and the frequency response of this coil was measured. In the second stage, the computer model based on 3D Finite Elements Method (FEM) was prepared. Surveys indicate the need to assume equivalent core material properties in order to carry out the correct simulation. Presented research can be used for modelling the inductance of the winding in wide frequency range.*

***Streszczenie.** Celem artykułu jest przedstawienie badań przeprowadzonych w celu weryfikacji symulowanych indukcyjności uzwojeń transformatorów. W pierwszym etapie badań cewka została nawinięta na rdzeń transformatora rozdzielczego oraz zmierzono jej odpowiedź częstotliwościową. W drugim etapie opracowano model komputerowy 3D oparty na metodzie elementów skończonych (MES). Przeprowadzone badania wskazują na konieczność stosowania zastępczych wartości parametrów materiału rdzenia w celu wykonania poprawnej symulacji. Prowadzone badania mogą być wykorzystane do modelowania indukcyjności uzwojenia w szerokim zakresie częstotliwości. (**Weryfikacja modeli uzwojeń transformatora dla metody FRA**).*

Keywords: complex permeability, frequency-dependent parameters, Frequency Response Analysis (FRA), modelling of transformer windings
Słowa kluczowe: przenikalność magnetyczna zespolona, parametry zależne od częstotliwości, analiza odpowiedzi częstotliwościowej, modelowanie uzwojeń transformatora

Introduction

In recent years, the frequency response analysis (FRA) became a common method in a diagnostics of the deformation and displacement in the transformer windings. The IEC 60076-18 standard [1], which describes the techniques of performing FRA measurements was developed. There are several commercial FRA analysers on the market, while the measurement itself is one of the standard post-production measurements of the power transformers.

Currently, research problems around FRA are focused on the proper interpretation methods of the obtained frequency responses, because there are still problems with the interpretations of the results [2]. The second research problem is a correct simulation of the active part of the transformer, especially the core, which can be used for simulation and calculation the frequency response of the power transformer windings in a wide frequency range.

Proper representation of core parameters is required for a correct and accurate power transformer modelling. For many years it was assumed that the influence of the core may be neglected above 10 kHz due to the total displacement of the magnetic flux from the core at high frequencies. However, recent work of Bjerkan [3] and research carried out over the last several years by Wilcox et al. [4] indicate that the correct representation of frequency-dependent core permeability and losses are highly relevant. Analysis of the complex permeability as a function of frequency (Fig.6) shows that the core cannot be replaced by a shield or even air at any frequencies in normal high-frequency transformer model [3]. Furthermore, in order to perform a correct simulation of the core behaviour in wide frequency range, it is necessary not only to consider the equivalent frequency-dependent magnetic permeability, but also the equivalent conductivity.

The aim of this paper is to present the equivalent parameters of core material for accurate computer frequency response analysis of the transformer windings. The identification of core properties is based on reference FRA measurement and finite elements method (FEM) computer models. In order to confront the results of the winding frequency response with the response of computer model the actual coil inductances were compared to the inductances computed in FEM software.

Physical coil model

Physical model of the coil is wound on a pressboard tube mounted on stepped shape, laminated transformer core. The coil has 8-turns and is placed on the outer column of the core. As it is shown on in Fig.1, the factory windings, both LV and HV, are mounted on the other two columns.

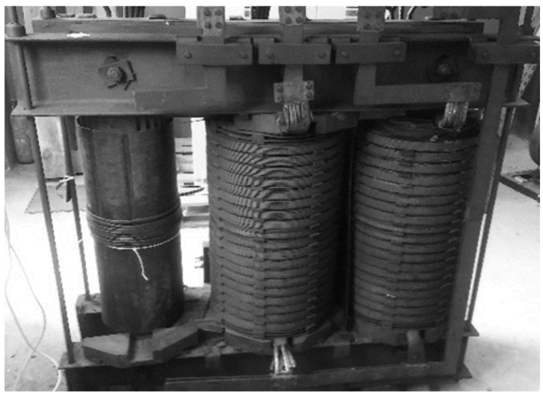

Fig.1. The coil wound on the first column of laminated, distribution transformer core and the factory windings (both LV and HV) mounted on the other two columns.

The rectangular cross-section wire from LV winding was used for wound the 8-turns coil (Fig.2). The core is originally from 800 kVA distribution transformer and its dimensions are 961,2x1000 mm. The active part of the transformer was pulled out of the tank and the windings were unplugged from the bushings.

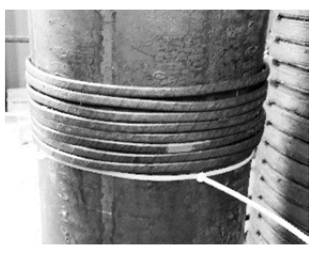

Fig.2. 8-turns coil wound with rectangular cross-section wire mounted on the pressboard tube

For the purpose of the comparison the results of the inductance values of the 8-turns coil and the results obtained from the computer analysis, an additional 8-turns air coil was made (Fig.3).

Fig.3. 8-turns air coil model

The air coil had the same dimensions as the coil on the magnetic core. This approach was made to check the compliance of both coils inductance values. Conformity of the results can be checked at high frequencies, where the magnetic field is completely displaced from the core and hence each coil can be treated as an air coil.

3D computer model of the coil in FEM software

In second stage of the research the computer models of coils were prepared while maintaining the original dimensions. Models are based on Finite Elements Method (FEM). The software used for the simulations was ANSYS Maxwell v. 19.0, especially 3D eddy current solver, which computes steady-state, time-varying (AC) magnetic fields at a given frequency. The eddy current field solver calculates the eddy currents by solving the magnetic potential vector and the electric scalar potential in the field equation:

$$\nabla \times \frac{(\nabla \times \mathbf{A})}{\mu} = (\gamma + j\omega\varepsilon)(-j\omega\mathbf{A} - \nabla\phi), \tag{1}$$

where: $\mathbf{A}$ – magnetic vector potential, ϕ – electric scalar potential, μ – magnetic permeability, ω – angular frequency at which all quantities are oscillating, γ – conductivity, ε – permittivity.

Computation domain was reduced to half of the model due to symmetry of the object. The boundary conditions for the problem are set as Dirichlet boundary (magnetic field is tangential to the boundary and flux cannot cross it) and outer boundary conditions of the problem is set as Neumann boundary.

Geometry of the 8-turns coil model is shown in Fig.4a.

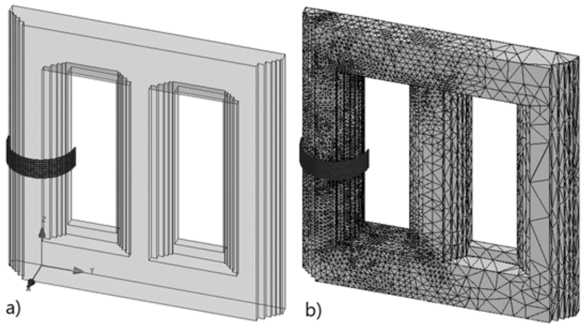

Fig.4. 8-turns coil model in FEM software, a) computation domain (1/2 of the model due to symmetry of the object), b) finite element mesh

The LV winding, which was also used in the analysis has 288 turns in 12 parallel 24-turns coils. One of the parallel coils (24 turns) was simulated. Turns of the coil were evenly distributed over the entire available column height (Fig.5a). The boundary conditions corresponds with boundary conditions adopted for 8-turns coil.

Fig.4b and Fig.5b presents the finite elements meshes of the models.

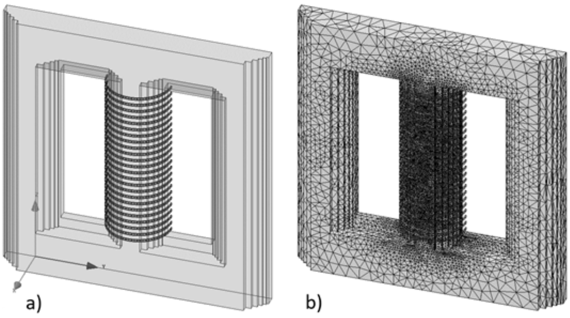

Fig.5. 24-turns coil model in FEM software, a) computation domain (1/2 of the model due to symmetry of the object), b) finite element mesh

The inductance of the coils has been computed using the energy of the electromagnetic field delivered by FEM:

$$W_{AV} = \frac{1}{8}\int \mathbf{BH}^* d\Omega, \tag{2}$$

$$L = \frac{8W_{AV}}{I^2_{\max}} = \int \mathbf{BH}^* d\Omega, \tag{3}$$

where: W_{AV} – average energy of magnetic field, L – inductance,
$\mathbf{B}$ – magnetic flux density, $\mathbf{H}^*$ – magnetic field intensity conjugate, $I_{\max}$ – peak current.

Parameters of the core

Conducted research took into account equivalent complex permeability and equivalent conductivity of core ferromagnetic material.

Assuming one-dimensional propagation of the electromagnetic wave into the laminated ferromagnetic core with sheet thickness is $2D$, wave equation can be written as [5]:

$$H_y(z) = H_{y0}\frac{\cosh kz}{\cosh kD}, \tag{4}$$

where k is:

$$k = \sqrt{j\omega\mu\gamma} = (1+j)\sqrt{\frac{\omega\mu\gamma}{2}} = \frac{(1+j)}{\delta} \tag{5}$$

and δ is the skin-depth:

$$\delta = \sqrt{\frac{2}{\omega\mu\gamma}}. \tag{6}$$

Complex permeability in laminated core is given by the equation:

$$\underline{\mu} = \frac{1}{H_{y0}} \cdot \overline{B} = \frac{1}{H_{y0} \cdot 2D}\int_{-D}^{D}(\mu H_y)dz, \tag{7}$$

where: $\underline{\mu}$ – complex permeability, H_{y0} – magnetic field intensity on the surface, $\overline{B}$ – average magnetic flux density.

Substituting (6) in (7) there is:

$$\underline{\mu} = \mu_0 \mu_r \cdot \frac{\sinh kD}{kD \cdot \cosh kD} = \mu_0 \left(\mu' + j\mu'' \right), \qquad (8)$$

where: μ_0 – vacuum permeability, μ_r – relative permeability.

Splitting (8) to real and imaginary parts:

$$\mu' = \frac{\mathrm{Re}\left(\underline{\mu}\right)}{\mu_0} = \frac{\mu_r \delta}{2D} \left(\frac{\sinh\left(\frac{2D}{\delta}\right) + \sin\left(\frac{2D}{\delta}\right)}{\cosh\left(\frac{2D}{\delta}\right) + \cos\left(\frac{2D}{\delta}\right)} \right), \qquad (9)$$

$$\mu'' = \frac{-\mathrm{Im}\left(\underline{\mu}\right)}{\mu_0} = \frac{\mu_r \delta}{2D} \left(\frac{\sinh\left(\frac{2D}{\delta}\right) - \sin\left(\frac{2D}{\delta}\right)}{\cosh\left(\frac{2D}{\delta}\right) + \cos\left(\frac{2D}{\delta}\right)} \right). \qquad (10)$$

Real part of complex permeability represents the ability of core material to conduct the magnetic flux, while imaginary part represents the core losses coming from eddy currents circulating inside the laminations. Fig.6 shows complex permeability as a function of frequency.

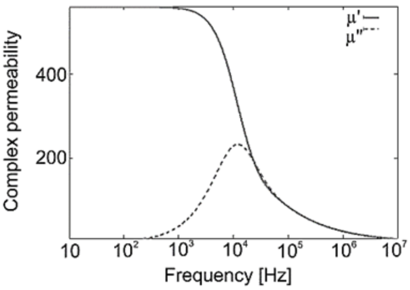

Fig.6. Complex permeability of ferromagnetic laminated material (μ_r = 560, γ = 10^6 S/m, $2D$ = 0,22 mm) as a function of frequency

The complex permeability is calculated taking into account maximum equivalent permeability of the ferromagnetic material, equivalent anisotropic conductivity and the thickness of the steel sheet. In the conducted research, the conductivity of the core material was adopted at the level of one million S/m, which corresponds to the conductivity values of laminated cores made of Fe-Si sheets.

In the computer simulation, it is assumed that the permeability of the material varies with the frequency as the real part of the complex permeability. For every particular frequency, the permeability value is entered as a material property in FEM software.

Results

The frequency response of 8-turns coil and LV winding form second column were measured with Omicron FRAnalyzer in the frequency range of 20 Hz – 2 MHz. Based on the frequency response of the coils, their inductances were determined as a function of frequency.

The computer analysis was conducted in frequency range of 50 Hz – 1 MHz. As it has already been mentioned, the permeability of the core material changes according to the real part of complex permeability curve (Fig.6).

Inductance of the 8-turns coil calculated for computer model and measured on actual coil is shown in Fig.7.

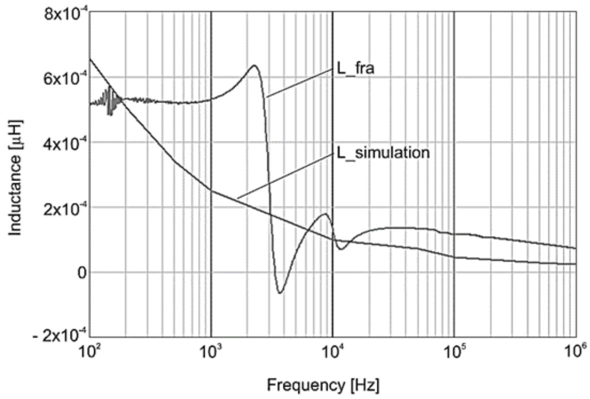

Fig.7. Inductance of the 8-turns coil calculated for computer model and measured on actual coil as a function of frequency

The first curve (L_simulation) represents the inductances calculated in the frequency domain simulation. In line with the expectations, the inductance of the coil decreases with the increase of the frequency. The second curve (L_fra) shows the inductance values obtained from FRA measurements. Sufficiently accurate comparisons of simulation and measurement is difficult due to resonance, which occurs at several kHz. The occurrence of resonance is caused by windings placed on the other columns of the core. Despite the fact that the other windings are open and disconnected from bushings, a small inter-turn capacitance and ground capacitance to core are sufficient to create this resonance. This phenomenon is described in more details later in the article.

Despite the resonance, which makes it difficult to accurately compare the inductance value, it can be seen that the character of inductance changes obtained from measurements and simulations is consistent across the entire frequency domain.

It should be noted that the inductance of 8–turns air coil (Fig.3) is 20 μH, which corresponds with the inductance of core coil at frequency around 1 MHz. This fact allows to assume that the simulation was performed correctly.

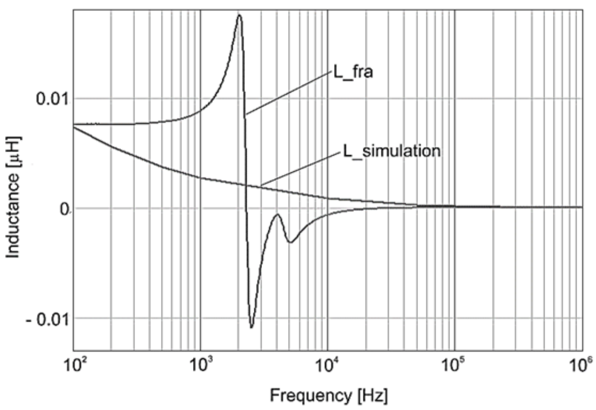

Fig.8. Inductance of the 24-turns coil calculated for computer model and measured on actual coil as a function of frequency

In the second part of analysis the simulation of the 24-turns coil was carried out. Fig.8 presents calculated and measured inductance of this coil. Similarly to the 8-turns coil, the first curve (L_simulation) represents the inductance calculated in the course of computer analysis in the frequency domain, while the L_fra curve of inductance values obtained from FRA measurements.

In this case the resonance also occurs at the frequency of about 2 kHz, but it is clearly visible that the nature of changes in inductance along with the frequency in both stages of the test is the same. In addition, the inductances accomplished from the analysis at low and high frequencies coincides with the coil inductance values obtained from FRA. Taking this into considerations, it can be assumed, that if there was no resonance resulting from the presence of the other windings on the core, the simulation would coincide with the measurements in the entire frequency domain.

Noteworthy is the reason of resonance occurring at several kHz in FRA measurements. It makes the comparison of results in some part of the frequency range difficult. This phenomenon is known and has previously been described in the literature, among others in [6]. It has been proven that the results of FRA measurements are affected by any capacitance versus core, not necessarily directly related to the measured windings. The formation of resonance in the tested coil is mainly caused by HV winding mounted on the column, although this winding is open.

In order to confirm this thesis, the capacitances of 3 nF and 5 nF were connected in parallel to the HV winding. The results of this experiment are shown in Fig.9.

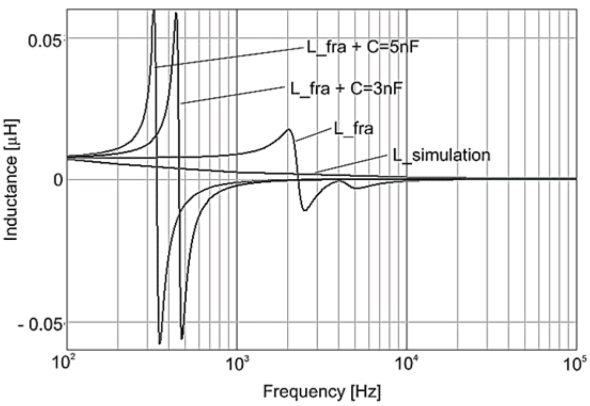

Fig.9. The influence of additional capacitances on occurrence of resonance in FRA measurements

Including the additional capacitance to the HV winding caused shifting of the resonance towards the lower frequencies. The larger the capacitance, the resonance is shifting more to the left on the *x* axis. The conducted experiment clearly indicates that the frequency response of the tested winding is affected not only by its own capacitance, but also by all the capacitances of other windings in the tested object. Combined with high inductance, of 32 H in this case, the high voltage windings affect the behaviour of low-voltage winding.

Conclusions

As a result of the research, a comparison of the results of the winding frequency response with the response of computer model.

Surveys indicate the need to assume equivalent core material properties for each frequency. Adopting the magnetic permeability and conductivity values of a ferromagnetic material at the catalogue values level, without taking into account core lamination, leads to erroneous results.

Parameters of the laminated core at medium and high frequencies can be approximated using the complex magnetic permeability.

In future work it is necessary to refine the method of the equivalent core material parameters representation. While magnetic permeability is well-mapped by complex permeability, attempts to systematize the representation of equivalent conductivity values have not been successful yet and are based mainly on simulation experience.

Windings placed on the other two columns of the core cause resonances, which are hindering proper verification of inductance values of coils in wide frequency range.

The next stage of research should be preparation of the physical transformer model containing only one winding (e.g. 40-turns coil), then FRA measurement and numerical simulation of this winding.

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