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IMPACT OF OTHER WINDINGS ON FREQUENCY RESPONSE OF POWER TRANSFORMERS

The diagnostics of power transformers is a very fast developing branch. Due to increasing average age of assets and changes in asset management strategies, nowadays companies introduce asset management based on technical condition. One of important methods used for diagnostics of a transformer's active part is Frequency Response Analysis (FRA). It allows determination of mechanical condition of windings, their displacements, deformations and electric faults, as well as some problems with internal leads and connections, core and bushings. In the FRA measurements of many power transformers there can be observed a first resonance, which position on frequency axis and damping factor seems to be similar for primary and secondary windings. The authors are going to explain this strange phenomenon, not depending on inductance of the winding being measured.

KEYWORDS: transformer, Frequency Response Analysis, modelling of windings

1. INTRODUCTION

The modelling of frequency characteristics is useful in the diagnostics of mechanical condition of the transformer windings. Introduction of controlled deformations inside windings is possible only in rare cases of units sent for scrapping. For this reason, only the simulation methods may give an answer to the question of how different types of deformations affect the frequency response of the winding. Earlier works [1] show very good agreement of the simulated response with measured characteristics of the windings separated from the core. In the case of coils located on the core in the frequency range below 10kHz the core parameters determine the response, whereas at high frequencies above 100kHz, the presence of the core is unimportant.

The FRA research results performed on significant number of large and medium transformers show, that there is a first resonance at a frequency of about 1 kHz. This frequency depends on the power of the unit, for small transformers it lays at a few kilohertz. This low resonant frequency would indicate the presence of a large capacity, which cannot exist. Besides, as shown

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in Figures 1, 2 and 3, this resonance exists for all windings of the transformer at the same frequency and has a similar shape. This can be seen especially in Figure 3 for the autotransformer with tertiary winding y1-y2, the response of which contains the same resonance. The paper presents an explanation of the resonance presence and the method of its modelling. Authors of the paper have introduced controlled deformation of windings, which show that for the position and shape of this resonance they have no influence. This means, that this resonance is useless for diagnostic purposes. Modelling algorithms presented in the earlier works did not took into account this resonance, so it is necessary to complete the model and the corresponding algorithm.

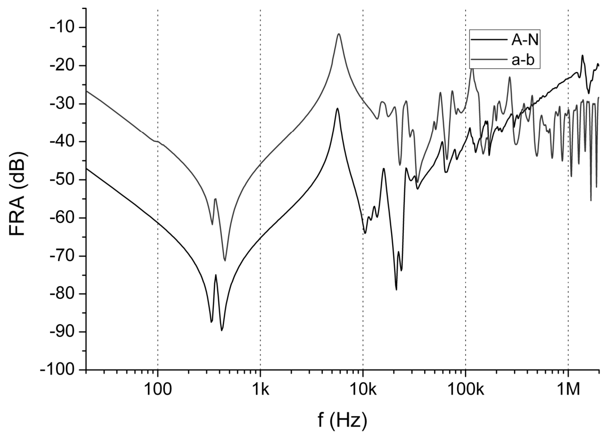

Fig. 1. Frequency response of transformer: TORb 10000/110, 115/22 kV, 10 MVA, YNd11

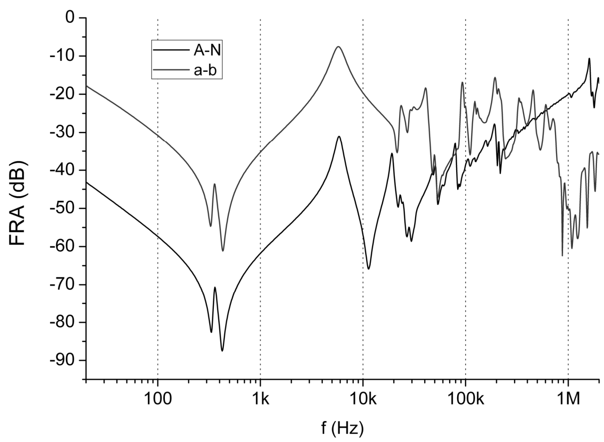

Fig. 2. Frequency response of transformer: TNARBA-25000/110PNPN, 115/16,5 kV, 25 MVA, YNd11

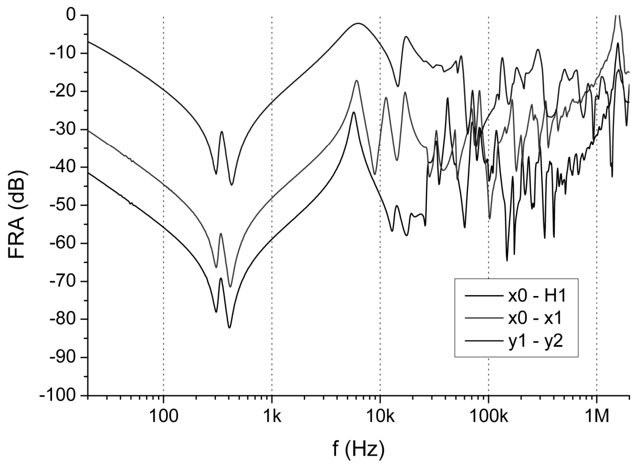

Fig. 3. Frequency response of transformer: RtdXP-125000/200, 230/120/15,75 kV, 160 MVA, YNa

2. THE MODEL CONTAINING LUMPED PARAMETERS

Model of a transformer winding was described in [1]. Each of the turns of the winding has been replaced by a single network element shown in Figure 4.

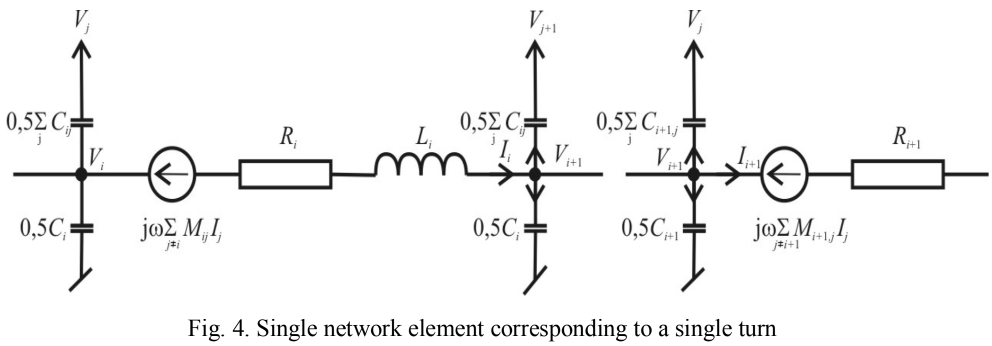

Fig. 4. Single network element corresponding to a single turn

The used element contains resistance, inductance and capacitance of its own, as well as the mutual inductance and capacitance with respect to all other wires. When solving thus resulting network it is not necessary to use circuit simulator, as MicroCap or SPICE, but the network equations are solved directly:

$$
\begin{aligned}
&I_i \cdot (R_i + \mathrm{j}\omega L_i) = V_i - V_{i+1} - j\omega \sum_{j \neq i} M_{ij} I_j , \\
&V_i - V_{i+1} = I_i \cdot R_i + j\omega \sum_{j} M_{ij} I_j .
\end{aligned} \qquad (1)
$$

3. THE REASON FOR THE RESONANCE AT A LOW FREQUENCY

The hypothesis assumed by the authors reads, that the reason for the existence of this resonance is outside the test coil. When testing the frequency response of the low voltage winding, the resonance is formed in the high-voltage winding, that remains open when measuring the FRA. If the transformer is we connected, they were only attached to the bushings, as shown in Figure 5.

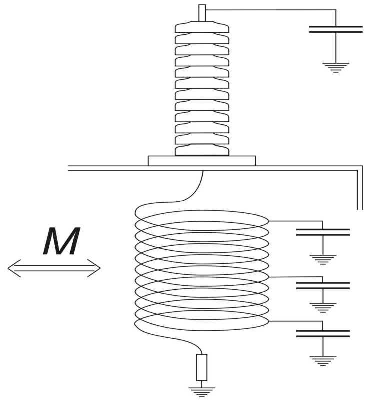

Fig. 5. High-voltage winding inductively coupled to the test coil, self capacitances and capacitances of bushings

Because the analyzed resonance frequency lies about 1kHz, this is the frequency, at which the magnetic coupling coefficient between the windings remains almost equal one. It can be seen that the shape of the resonance depends on whether the winding under the test lies on the central column or on the side column. In the case of the windings at the side columns there can be seen "split" resonance shown in Figures 1, 3.

4. ADDITIONAL LINK IN THE MODEL

From the viewpoint of the measured low voltage winding, high voltage winding can be represented by one element of a concentrated inductance and capacitance. In that case, the model will be completed by an additional element as shown in Figure 6.

Additional element contains a model of the primary winding reduced to a single wire. The parameters R and L of the coil are determined in the same way as the wire parameters of low voltage winding. Bushing capacity C_{bush} with self-capacitance C_d creates a common winding capacitance to earth, in the modeled case assumed to be 200pF. Capacitance was then recalculated to the secondary side and onto one wire delivering for a transformer 15/0,23kV and the secondary winding with 24 turns the capacitance's value:

$$200\text{pF}\cdot(15000/230)^2\cdot 24^2 = 490\mu\text{F}.$$

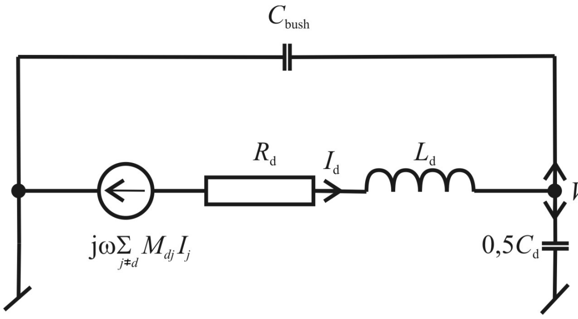

Fig. 6. The element modeling high-voltage winding with mutual inductances and capacitances

Taking into account this additional element (Fig. 6) modelling the primary winding, equations (1) are completed with following:

$$\begin{aligned} -V_d &= I_d \cdot R_d + \text{j}\omega \sum_j M_{dj} I_j \\ I_d &= \text{j}\omega\left(C_{\text{bush}} + 0{,}5 \cdot C_d\right) V_d \,. \end{aligned} \qquad (2)$$

5. FIELD MODEL OF A WINDING

The parameters *R*, *L*, *C* of the windings are determined from the field model. Analysis of the model is performed using the finite element package ANSYS Maxwell. There are determined self parameters of individual coils, as well as all the mutual inductances and mutual capacitances between them. Due to the necessity of modeling individual coils, it is possible to use the 2D model with circular-cylindrical symmetry. Application of three-dimensional model exceeds the capabilities of today's computing equipment. 2D calculations using the described model occupied on the server with processor Xeon 3GHz about 80 hours for a single frequency. Most of the time was spent on matrix calculation of mutual inductance in the winding.

The model consists of a 24 turns with 12 parallel wires (Fig. 7). In the same figure 7 enlargement of the winding segment with winding insulation is shown. At the top there is visible additional coil designed for modeling the impact of the primary winding.

Determination of capacity bases on the energy of the electric field:

$$C_{ij} = \frac{2W_{ij}}{V^2} = \int_\Omega \boldsymbol{D}_i \cdot \boldsymbol{E}_j \,\text{d}\Omega, \text{ where: } W_{ij} = \frac{1}{2}\int_\Omega \boldsymbol{D}_i \cdot \boldsymbol{E}_j \,\text{d}\Omega \qquad (3)$$

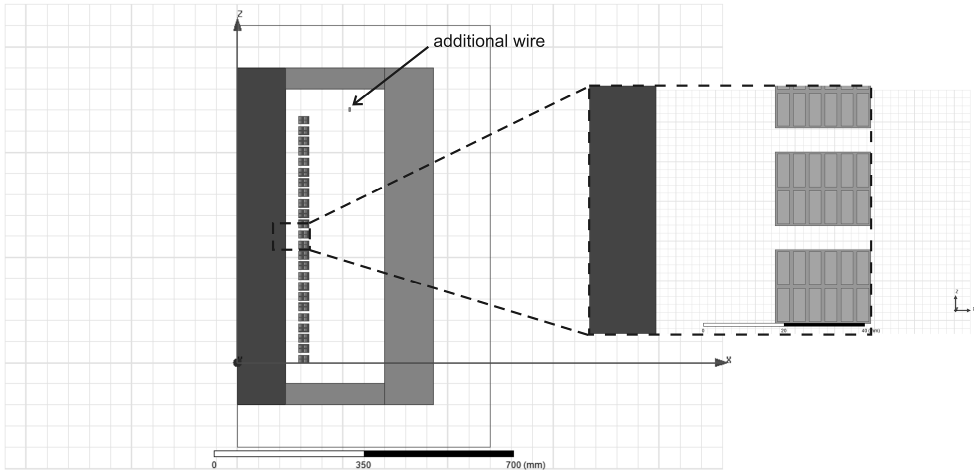

Fig. 7. Field model with coil and core in circular-cylindrical coordinates system

described by the equation

$$\nabla\cdot\left(\varepsilon_{\rm r}\varepsilon_0\nabla\Phi\left(r,z\right)\right)=-\rho\,, \tag{4}$$

where Φ is the potential of a scalar field induced by the charge ρ, ε_0 and $\varepsilon_{\rm r}$ are vacuum and relative permittivity.

To determine the mutual inductance and resistance the model of the electromagnetic field is used, described by the equation

$$\nabla\times\frac{1}{\mu}\left(\nabla\times\boldsymbol{A}\right)+{\rm j}\omega\gamma\boldsymbol{A}=\boldsymbol{J}_{\rm s} \tag{5}$$

wherein $\boldsymbol{A}$ is the magnetic vector potential, in this case having one component, γ conductivity of the conductive area, ω pulsation of the exciting current, and $\boldsymbol{J}_{\rm s}$ current density in the windings. There was taken into account the skin effect and proximity effects of wires.

Inductances are calculated from the energy stored in the electromagnetic field

$$L_{ij}=\frac{4W_{\rm AV}}{I_{\rm Max}^2}=\int\boldsymbol{B}_i\cdot\boldsymbol{H}_j d\Omega,\quad \text{where: } W_{\rm AV}=\frac{1}{4}\int\boldsymbol{B}_i\cdot\boldsymbol{H}_j^* dV\ . \tag{6}$$

In order to determine the resistance of the wires there is calculated power dissipated by the current density $\boldsymbol{J}$:

$$R=\frac{2P}{I_{\rm Max}^2}=\frac{\int\boldsymbol{J}\cdot\boldsymbol{J}^* d\Omega}{\gamma I_{\rm Max}^2}=\frac{\int\boldsymbol{J}\cdot\boldsymbol{J}^* d\Omega}{\gamma},\qquad \text{where: } P=\frac{1}{2\gamma}\int\boldsymbol{J}\cdot\boldsymbol{J}^* d\Omega\,. \tag{7}$$

At the boundary of the finite elements area was used a technique named "balooning", thus eliminating the cutting problem too close to the winding.
Due to the wide frequency range there should be used a large number of finite triangular elements, reaching 200k.

Figure 8 shows the distribution of current density in the winding on the test piece at a frequency of the supply current of f = 1kHz. It shows the skin effect, as well as proximity effect in the wires.

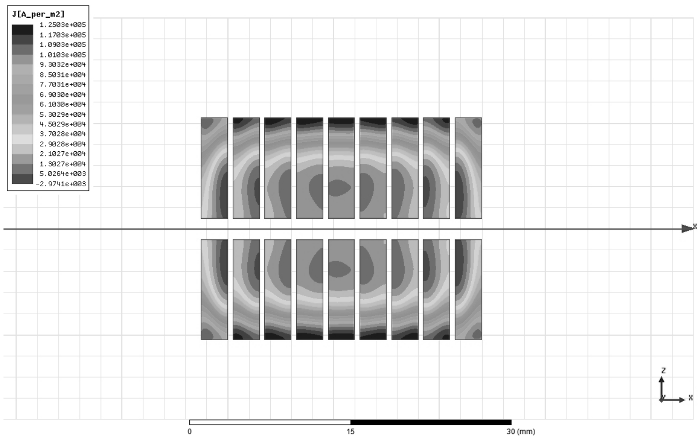

Fig. 8. Current density distribution obtained at the winding

6. RESULTS OF SIMULATION

Field analysis was performed for the frequency range from 100 Hz to 10 MHz. Necessary inductances and resistances values laying between the points of the analysis were obtained by linear interpolation. Frequencies for which simulations were performed were imported from FRA test device. Determination of the capacitance takes place with electrostatic model, which assumes that the capacitances do not depend on frequency.

Result of the comparison of the simulated frequency response versus the measured characteristics for transformer Tr800 15/0,4 is shown in Figure 9. The computer simulation showed that for the frequency range up to 5 kHz the resistance and inductance is determined by the parameters of the core: its magnetic permeability and core losses. At frequencies above 100 kHz core parameters have no meaning. Coils inductances decrease significantly with frequency, and concerning resistance, the losses in the core decide no longer, but only the skin effect and proximity effect of the wires. Images of field show that for high frequency no field penetrates into the core.

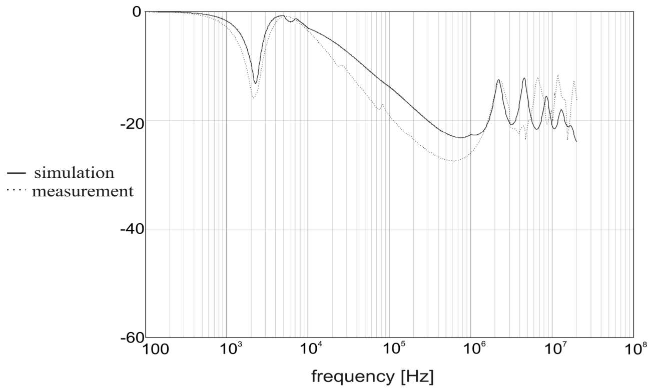

Fig. 9. Comparison of simulated frequency response characteristics of the measured transformer Tr800 15/0,4

7. CONCLUSIONS

The article demonstrates that the first resonance on frequency response characteristic of any winding of the power transformer derives from another high voltage winding. Although this winding is not connected to the measurement circuit, it is grounded by the capacity of bushings, as well as by its own capacity. Modeling this resonance while simulating low-voltage winding response is possible, if the model contains an additional coil magnetically coupled with measured winding.

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