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IMPLEMENTATION OF MAGNETIC CORE FREQUENCY CHARACTERISTICS IN MODELLING OF POWER TRANSFORMERS

ABSTRACT *This article is dedicated to the modelling of power transformers based on their frequency characteristics of impedance. The possible approaches to the modelling of transformers still do not take into account (audited and confirmed by the authors of the range up to 300 kHz) the influence of the magnetic core. Authors presented a measuring system to study the frequency characteristics of a reference coil with and without the magnetic core and to demonstrate the impact of this core on the measurement. The equivalent circuit model of studied system was also proposed.*

Keywords: *modelling, frequency characteristics, approximation, magnetic core*
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1. INTRODUCTION

Modelling of electrical devices like transformers is based on replacing them by some electrical circuit composed of different active or passive element. Such a representation (i.e. by two-terminal R, L, C circuit or other linear or nonlinear elements) has to reproduce the specific behavior of device subjected to a certain specific excitation or stresses. Electrical devices can consist of many small parts, which can be modelled as whole or separately, creating a complex system. The structure and form of presentation of the model is naturally dependent on the complexity of the modeled device, or the phenomenon as well as the user's needs and scope of study. Basically, there can be distinguished two forms of presentation of the model: mathematical and physical (geometric). The mathematic form can be expressed as electrical circuit, analytical or computer model as well [1].

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The geometric model of an electrical device allows for very accurate and clear understanding of the principles and characteristics of phenomena. The disadvantage is the cost and time of the model building. In general, modelling of electrical devices was shown on Figure 1.

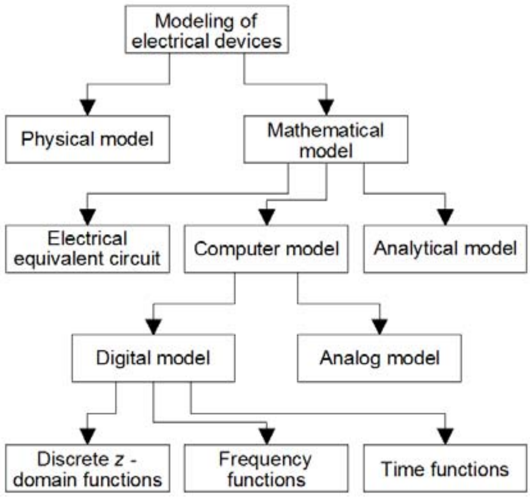

Fig. 1. Modelling of electrical devices [1]

The most frequent use type of modelling of dynamic systems is the mathematical modelling defined as representation of an object or phenomenon as a set of coefficients included mathematical relationships [2]. The applicability of mathematical models is possible in the case of repetition or similar phenomena which must be quantitative.

The equivalent electrical circuit is build based on mathematical model and as physical system have to fulfill the laws of mathematics.

There are 3 possible and still considered ways for the modelling of power transformers [6]:

- modelling as transmission line,
- equivalent circuit with distributed parameters,
- equivalent circuit with lumped parameters.

In the frequency modelling of the power transformers the influence of magnetic core have to be taken into account. The first problem is to find how far that influence exists. It was shown in [3-5] that up to 300 kHz the magnetic core affects frequency response of the power transformers. The second problem is to know how to create model of a device including that influence and find physical explanation of it. Authors in this paper tried to analyze all mentioned problems.

2. TRANSFORMER MODEL

The equivalent circuit of a transformer winding can be modeled as a lader structure formed by inductances L, resistances R and capacitances C (Fig. 2). This model is used to present voltage distribution in different sections [7]. This circuit does not take into account the mutual impedances and the accuracy of the model that depends on the correct representation of the frequency dependence of these elements.

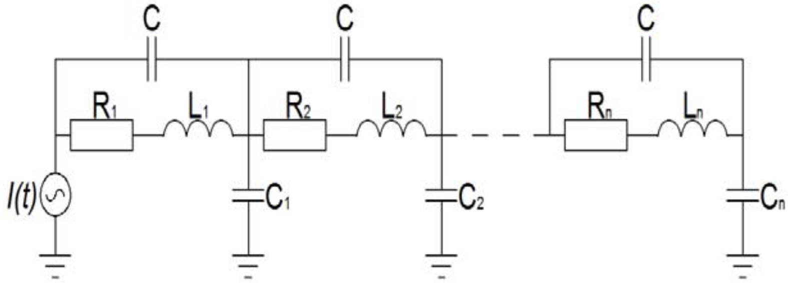

Fig. 2. Equivalent circuit for a transformer winding [7]

Each R and L in Figure 2 represents the resistance and inductance of each coil in transformer winding; C represents the capacitance of one coil and $C_1 - C_n$ – its coil-to-ground capacitance.

Equivalent circuit of a single coil is shown on Figure 3. Circuit is built by: R1, L1 – resistance and inductance of wires; C – capacitance of a coil; C_{IN} – input capacitance, R_{Cin} – complete resistance of a input capacitance. The C_{IN} represents the electric field for a small frequencies. By removing the input capacitance, which was shown in next section, the frequency information about the coil is expanded.

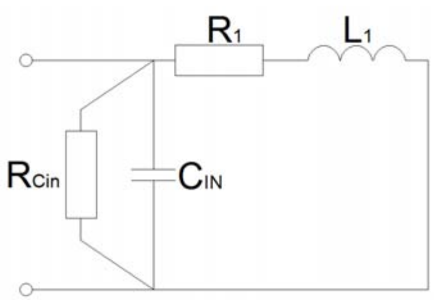

Fig. 3. Equivalent circuit of a single coil

3. MEASUREMENT TECHNIQUE

The frequency characteristics of the reference coil were measured by impedance analyzer HP4192A in a setup from Figure 4.

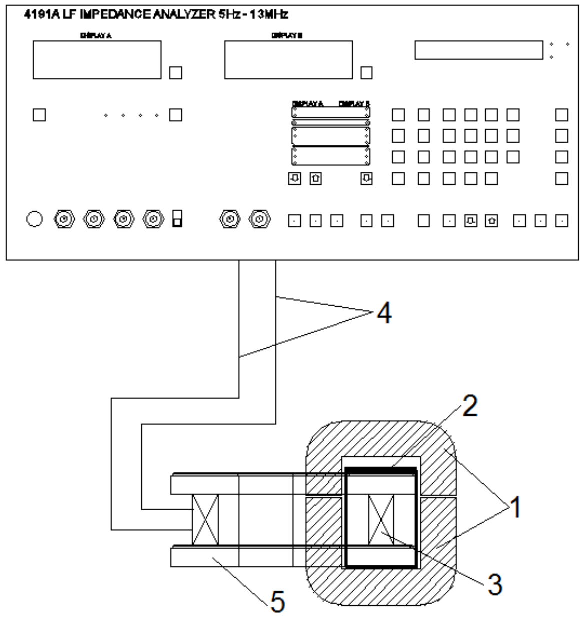

Fig. 4. Measurement setup for measuring of frequency characteristics of reference coil:
1 – removable magnetic core, 2 – isolated copper tape, 3 – winding of reference coil, 4 – copper measurement leads, 5 – porcelain construction of reference coil

The setup was built from:
- reference coils – 2 coils with inductance 5 mH and 10 mH
- magnetic core taken from small 25 VA transformer, built from 2 parts
- copper tape with isolated connection to get the same capacity with and without removable core
- impedance analyzer HP4192A

Impedance analyzer HP4192A measured characteristics as a function of frequency in range 10 Hz – 5 MHz:

$$A = 20\log_{10}\left(\frac{Z}{R}\right) \tag{1}$$

where:

Z – impedance of inductor,

R – resistance of current shunt additional in HP4192A.

The voltage test signal was in peak 1 V. The current was not measured directly.

4. RESULTS

The measurement was taken first on an alone magnetic core with 4 different length of air gaps between 2 parts, as shown in Figure 5. The air gap was controlled with using dielectric (paper) spacers with thickness of 1 mm.

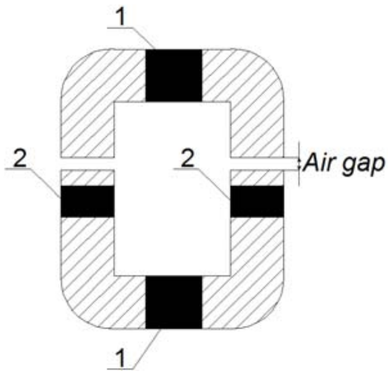

Fig. 5. Magnetic core with measurements leads and air gap between both parts:
1 – exciting coils, 2 – coils sensing the flux in core

The result of this measurement was shown in Figure 6. Air gap with no. 1 responds to lack of air gap, no. 2 with 1 spacer, no. 3 with 2 spacers and no. 4 with 3 spacers.

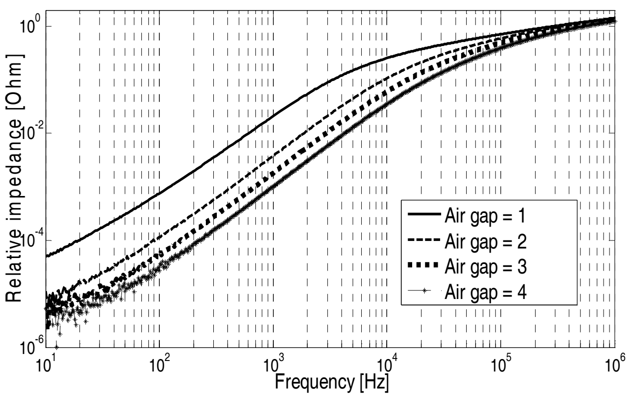

Fig. 6. Relative impedance of magnetic core with different air gaps between both parts in frequency range 10-10^6 Hz

Next measurements were taken directly in setup shown in Figure 2. The results of those measurements were shown in Figure 7. As it was proved in [3] and [4] the influence of magnetic core on frequency characteristics of reference coil is observed till 300 kHz.

In order to get larger frequency range to combine characteristic of coreless coil and characteristic of the core, the characteristic of the coil with core was deprived of the capacitive component as shown in Figure 8.

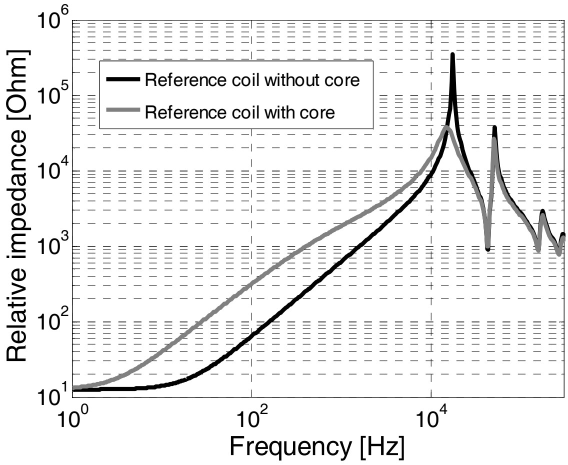

Fig. 7. Relative impedance of reference coil with and without magnetic core

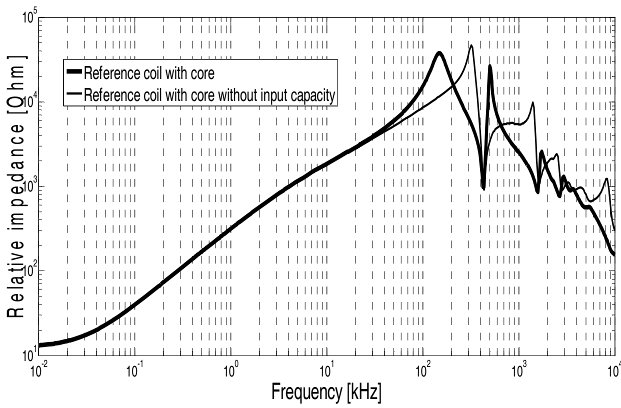

Fig. 8. Relative impedance of reference coil with magnetic core and without input capacity

By measuring the impedance of the reference coil without the magnetic core and by measuring the impedance of the magnetic core it should be possible by adding those two impedances to get result as in measuring the impedance of the reference coil with the magnetic core. The results are shown below in Figures 9 and 10.

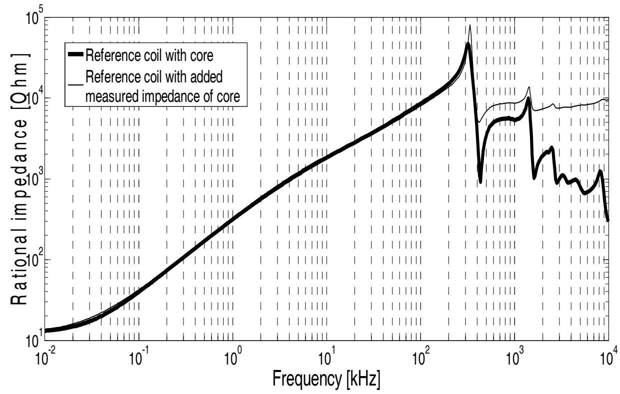

Fig. 9. Relative impedance of reference coil without input capacity for measured impedance of reference coil with core and for measured separately impedance of reference coil and magnetic core

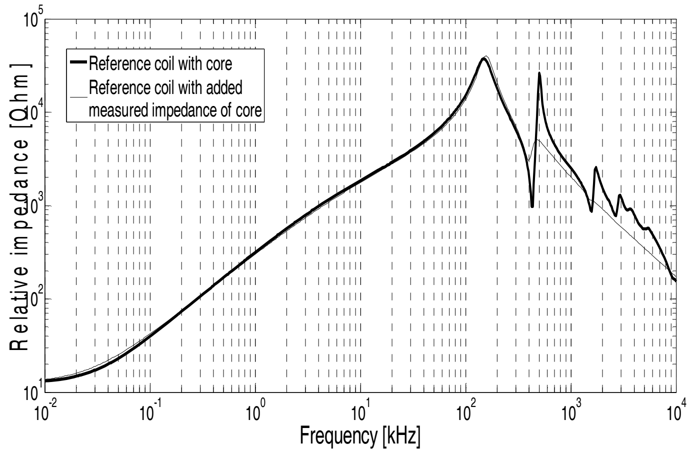

Fig. 10. Relative impedance of reference coil with input capacity for measured impedance of reference coil with core and for measured separately impedance of reference coil and magnetic core

As it is shown above the influence of magnetic core on frequency characteristics of reference coil is obvious. It results in different magnitude of impedance and the maximum of impedance function is slightly shifted. It is caused by eddy-currents in magnetic core. For higher frequencies, the eddy-currents are pushed from the center of magnetic sheet, which results in higher impedance of core (Fig. 6). The magnetic flux is also pushed from the sheet. It can be assumed, that for frequencies above 300 kHz the magnetic core does not support magnetic effect in transformers.

5. MODELLING OF REFERENCE COIL WITH MAGNETIC CORE

After measurements the question of implementing ferromagnetic material (core) rises. The core introduces permeance to a measured setup. The model of a reference coil shown in Figure 3 was modified by removing the input capacitance C_{in} (Fig. 11). Now the information about inductance vs frequency is expanded. By measuring the reference coil without the core, the inductance in air L_1 can be obtained.

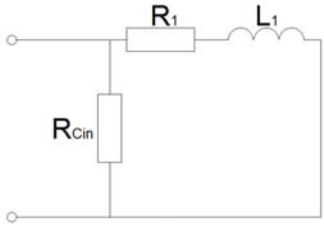

Fig. 11. Circuit model of reference coil without magnetic core and input capacitance

Applying to the measurement setup the ferromagnetic core, the structure of the equivalent circuit should be changed. The model of the reference coil with the magnetic core and without the input capacitance is shown in Figure 12.

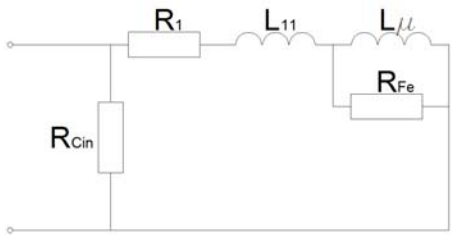

Fig. 12. Circuit model of reference coil with magnetic core and without input capacitance

For only a purpose of explaining appearance of additional elements in equivalent circuit, the equivalent circuit from Figure 10 is constructed. The magnetic core is built from inductance L_μ and resistance R_{Fe} – it is a simplification. The inductance L_{11} can be found as inductance L_1 reduced since the area of magnetic field is smaller because of adding magnetic core (Fig. 13). Now measured inductance of a coil can found as $L_{11} + L_{Fe}$.

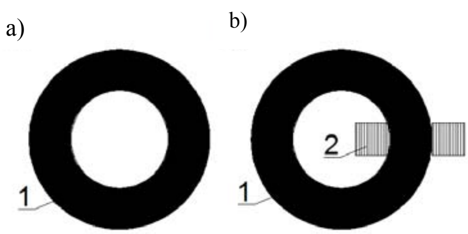

Fig. 13. Cross-section of reference coil without core a) and with magnetic core b): 1 – reference coil, 2 – magnetic core

Since the core introduces permeance, which can be represented by resistance and inductance, to a measured setup and is built from transformer sheets, the real equivalent circuit for a core should be created as on Figure 14.

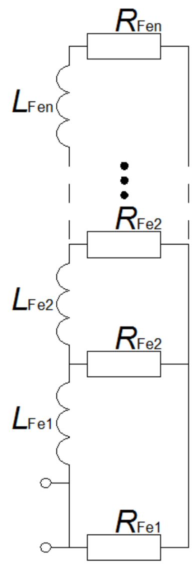

Fig. 14. The representation of magnetic core built from inductances L_{Fe1}÷L_{Fen} resistances R_{Fe1}÷R_{Fen} of each transformer sheet

6. CONCLUSIONS

Authors presented the basic directions in the modelling of transformers. The necessity of creating the model in wide frequency range, that includes all magnetic and electric phenomena, do not have to be explained. The measurement setup with results were shown and explained. Authors introduced the equivalent circuit model for the coil with the magnetic core, that can be used in the modelling of transformers.

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UWZGLĘDNIENIE CHARAKTERYSTYK CZĘSTOTLIWOŚCIOWYCH RDZENIA MAGNETYCZNEGO W MODELOWANIU TRANSFORMATORÓW ELEKTROENERGETYCZNYCH

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STRESZCZENIE *Niniejszy artykuł poświęcony jest modelowaniu transformatorów elektroenergetycznych na podstawie ich charakterystyk częstotliwościowych impedancji. Przedstawione możliwe podejścia do modelowania transformatorów nadal nie uwzględniają, w zbadanym i potwierdzonym przez autorów zakresie do 300 kHz, wpływu rdzenia magnetycznego. Autorzy przedstawili układ pomiarowy do badania charakterystyk częstotliwościowych cewki wzorcowej z rdzeniem i bez rdzenia magnetycznego oraz udowodnili wpływ tego rdzenia na pomiar. Został także zaproponowany model obwodowy badanego układu z uwzględnieniem rdzenia magnetycznego.*

Słowa kluczowe: *modelowanie, charakterystyka częstotliwościowa, aproksymacja, rdzeń magnetyczny*

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