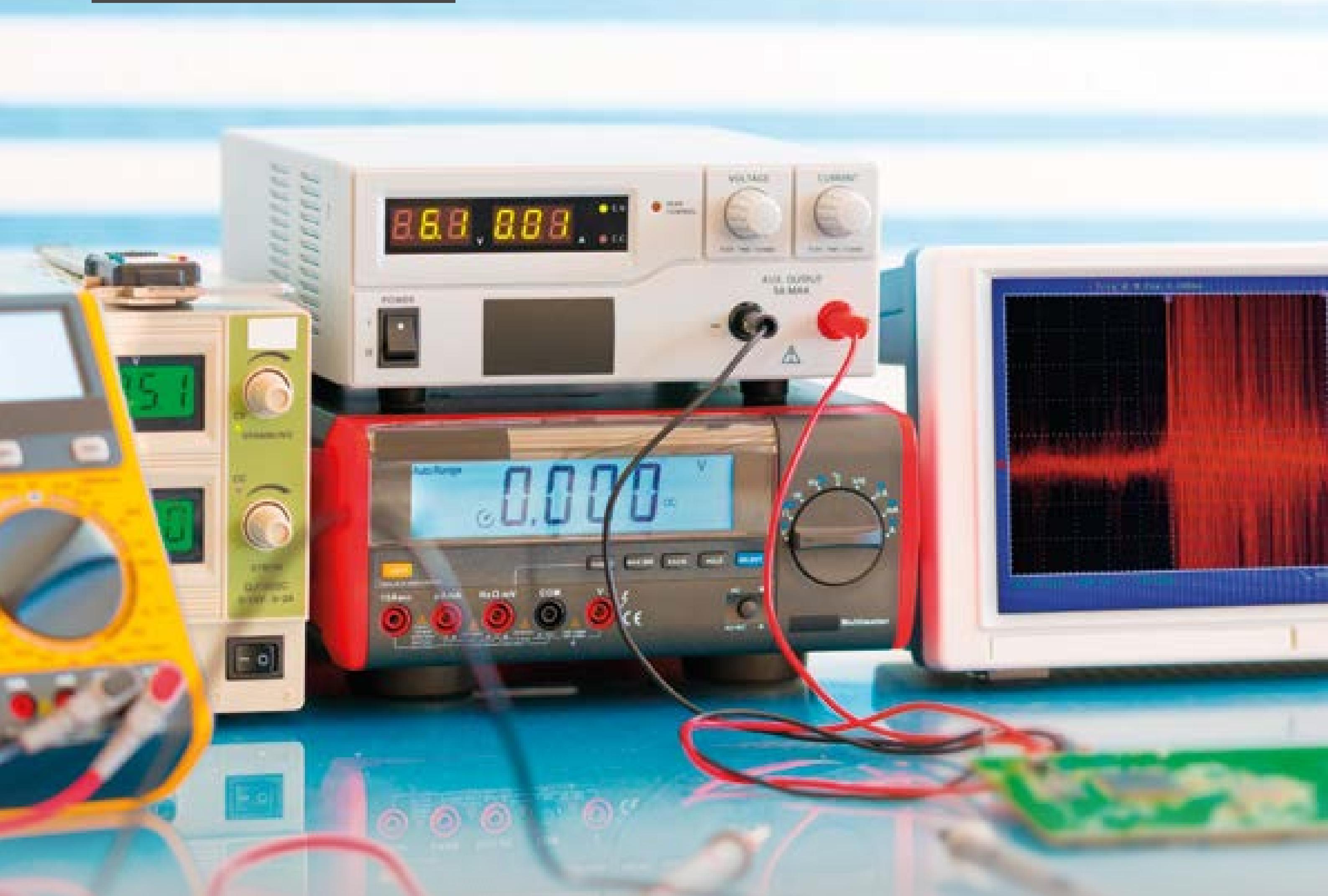

Transformers and power quality – Part II

Modelling and researching generation of higher harmonics in small three-phase transformers

ABSTRACT

This article investigates the generation of high harmonics in the magnetizing current of small three-phase transformers using the magnetic field analysis, the Finite Element Method (FEM). Through the analysis of the magnetic field in low power three-phase transformers, the magnetizing current waveform in the three phases of the transformer was obtained. The Fourier transform was then applied to obtain the harmonic analysis of the phase currents and determine their harmonic spectrum. Using the magnetic field analysis approach, the study aims to show that the generation of high harmonics in three-phase transformers – either low power ones or the power transformers in the electricity network – significantly influences the quality of electricity and its deterioration.

KEYWORDS

FEM, three-phase transformers, high harmonics, power quality, electrical power system

1. Introduction

The magnetization phenomenon in a three-phase transformer is more complicated than in a single-phase transformer. In a no-load mode of the three-phase transformer, the influence of the third harmonic of the current and magnetic flux is considerable. Depending on the wiring diagram of the primary and secondary windings and the magnetic system design, the waveform of the magnetizing current and the magnetic flux is different. Therefore, Part II of the article on transformers and power quality investigates three-phase transformers separately from the single-phase units, which were discussed in Part I.

From the classical theory of electrical machines [1] it is known that in the magnetization of steel cores of various transformers currents with an increased frequency (3f, 5f, 7f, etc.) pass through the primary winding, with the third and fifth harmonics being most pronounced. They are generated as a result of non-linearity of the transformer magnetic characteristics and saturation of the core material. If, due to the delta connection diagram of windings, the third harmonic of the magnetizing current reactive component cannot exist, it emerges (including the multiples of 3) in the magnetic flux and in MMF (magnetomotive force).

The spectrum of the generated harmonics depends on the vector group of the transformer. Magnetization currents of the three-phase three-limb core transformers not only contain higher harmonics, but are also unbalanced due to the asymmetry of the magnetic circuit [1].

The transformer becomes a generator of high frequency currents which have adverse effect on the equipment connected to the power network and the communication lines. This is also directly related to deterioration of the electricity quality [2, 3, 4].

The aim of this article is to study the mechanism of generation of higher harmonics from the field point of view, and the influence of small three-phase transformers used in households and industry, which are external loads, on the quality of the power system. Specific studies have been done on the three-phase transformer shown in Figure 1. Its specifications are provided in Table 1.

2. Modelling of the electromagnetic field of the transformer based on Maxwell's equations in differential form

The quasi-stationary magnetic field of the transformer was modelled based on the system of differential equations of the electromagnetic field, recorded on the magnetic vector potential $\vec{A}$ and the potential of the electric field V as in Part I of this article.

The magnetic vector potential $\vec{A}$ is calculated according to (1) [5]:

The generation of high harmonics in low power three-phase transformers was studied using the magnetic field analysis approach

Figure 1. Investigated transformer

Table1. Technical data of the investigated three-phase 50 Hz transformer

Quantity	Value
Rated power [VA]	1,500
Primary voltage [V]	380/220
Rated frequency [Hz]	50
Connection type	Yy0
Secondary no-load voltage ±5 % [V] U_{21} / U_{22}	8.5 / 15
Rated secondary current [A] I_{21} / I_{22} / I_{23} / I_{24}	15/30
Number of turns of the primary winding	590
Number of turns of the secondary windings w_{21} / w_{22}	22/40
Diameter of the wire [mm] • primary winding • secondary winding	0.6 2.24/3.00
Material of the transformer core	Ст 2212
Class of insulation	F

An FEM simulation of the transformer and an analysis of the magnetic field were used to obtain the forms of the phase currents in the primary side of the transformer

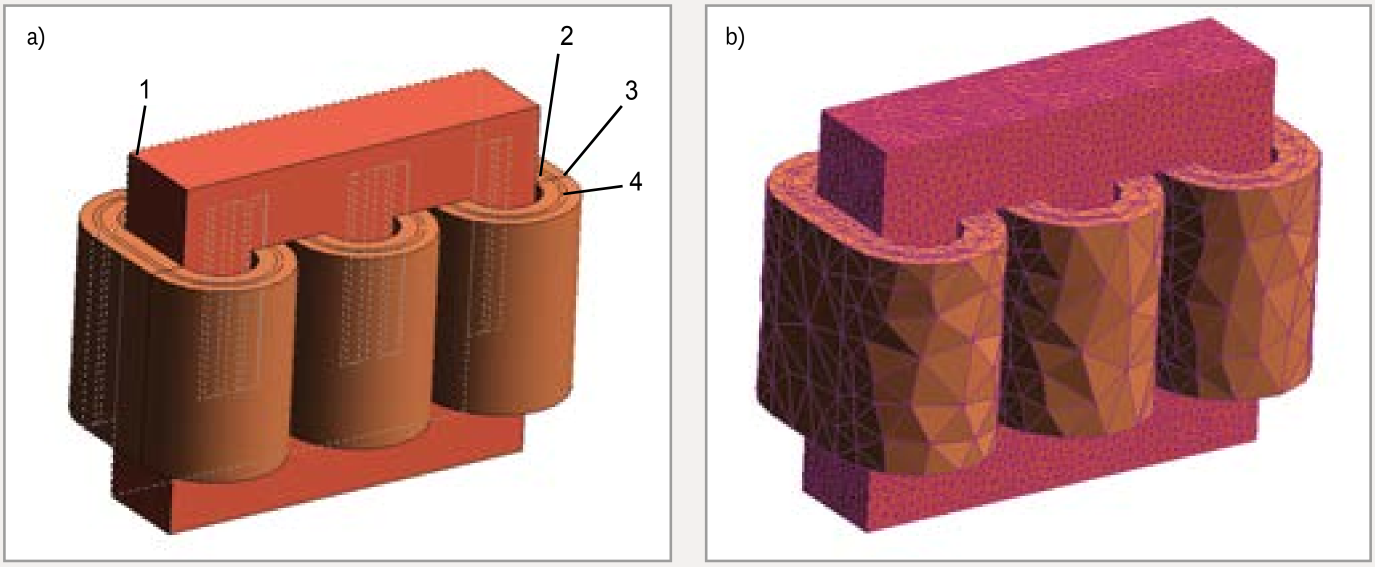

Figure 2. FEM model: a) region in which equations of the magnetic field are solved: 1 - magnetic core of the transformer; 2 - primary coil; 3, 4 - secondary coils; b) discretized area

Figure 3. Basic magnetization curve of the magnetic steel 2212

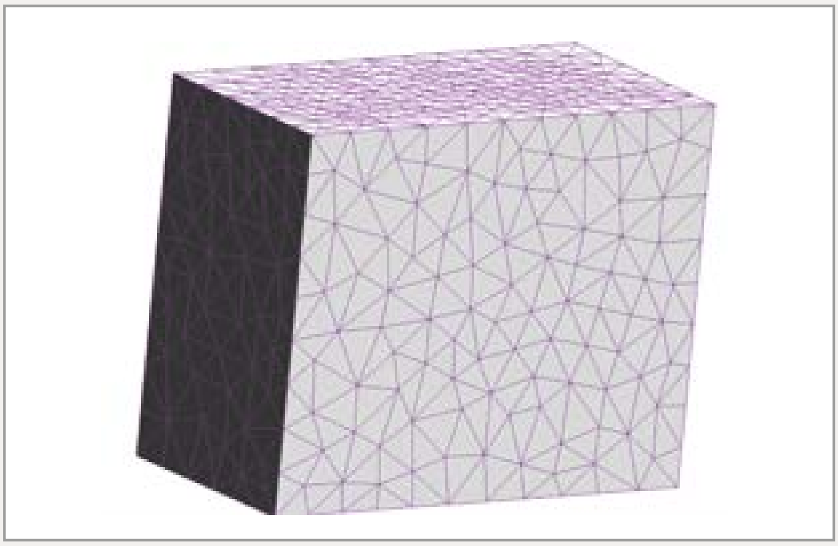

Figure 4. "Air box" surrounding the model for applying boundary conditions

$$\vec{\nabla}\times\left(\frac{\vec{\nabla}\times\vec{A}}{\mu}\right)+\gamma\left(\frac{\partial\vec{A}}{\partial t}-v\times\vec{\nabla}\times\vec{A}\right)=-\gamma\,\vec{\nabla}V. \quad (1)$$

Then, the magnetic flux density $\vec{B}$ and the intensity of the magnetic field $\vec{H}$ are obtained.

The analysis of the transformer's magnetic field was conducted in three dimensions in the region shown in Fig. 2a, divided into a network of 7,960 finite elements in the shape of a tetrahedron (Fig. 2b).

2.1. Numerical modelling of the three-phase transformer

After the non-linear modelling was performed, the basic magnetization curve was used for the modelling of the material core (Fig. 3).

2.2. Boundary conditions

Setting the boundary conditions in the three-dimensional case was performed by surrounding the model with an "air box"

The harmonic analysis results obtained via FFT were confirmed by the experimental study of a small three-phase three-limb core transformer, which was simulated by FEM

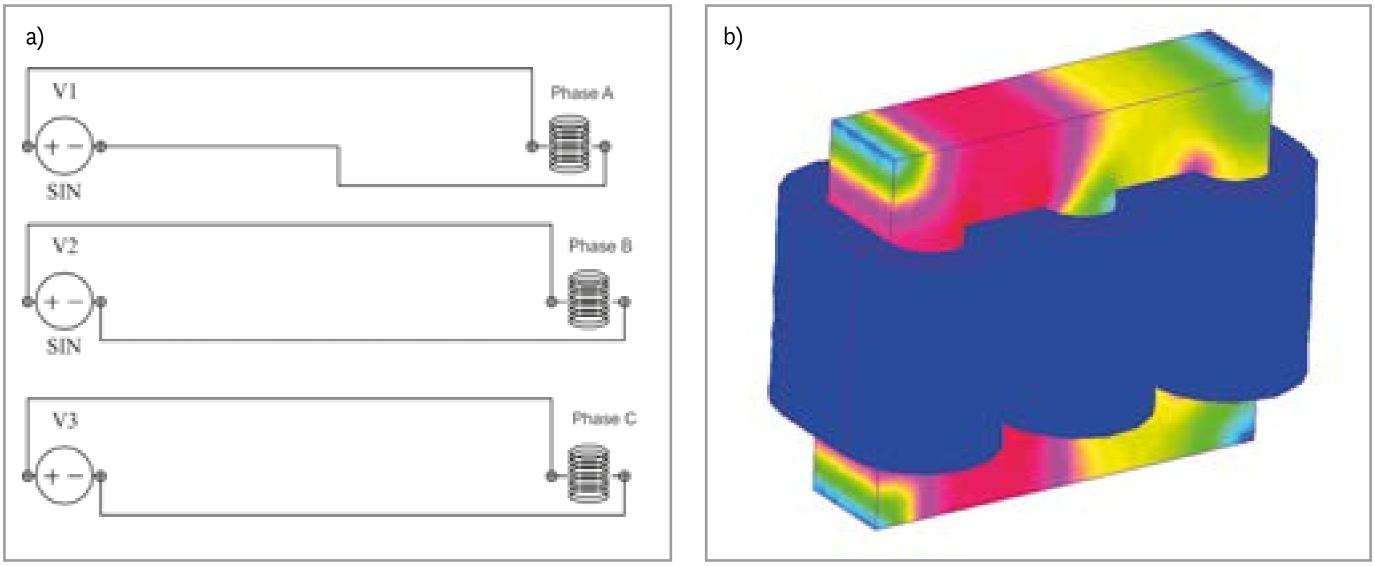

Figure 5. Modelling of the transformer: a) electric circuit of the model; b) distribution of the magnetic flux density

(Fig. 4). Flux tangential boundary conditions were set by default on the walls of this box [5]. As in the two-dimensional models, here too the normal component of the magnetic flux density was set to zero, which a Neumann boundary condition.

2.3. Modelling of the transformer windings and power source

The three-phase electrical circuit of the transformer is shown in Fig. 5a. The primary winding of the transformer is star-connected. It is energized by a three-phase source, consisting of three sinusoidal voltage sources - E_1, E_2, E_3, which is also star-connected (Figure 5b), and modelled as the "voltage driven" source. For each of the three phases of the source supplying the primary winding with sinusoidal voltage, the voltage amplitude, frequency, and its initial phase were set, so the network was modelled supplying the transformer with three-phase sinusoidal voltage.

3. Fourier's analysis of the transformer current

The purpose of the modelling is to prove that the transformer generates high harmonics of the current due to the saturation of the core material. The FEM program allows visualizing of the waveform for each phase current of the transformer (Fig. 7).

In order to obtain a harmonic composition of the currents along the primary winding, the Fast Fourier Transform analysis was used. As a result, the harmonic spectrum of

The main reason for the generation of the magnetizing current harmonics is the non-linearity of the magnetic characteristics of the studied transformer

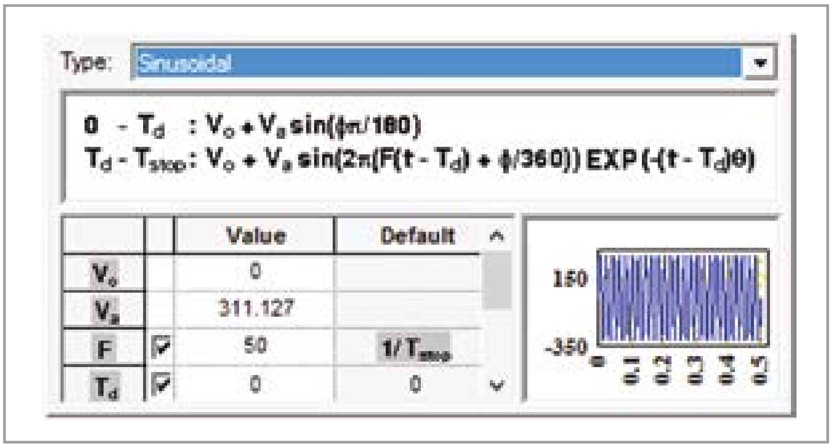

Figure. 6. The waveform and parameters of the three-phase supply voltage for the transformer

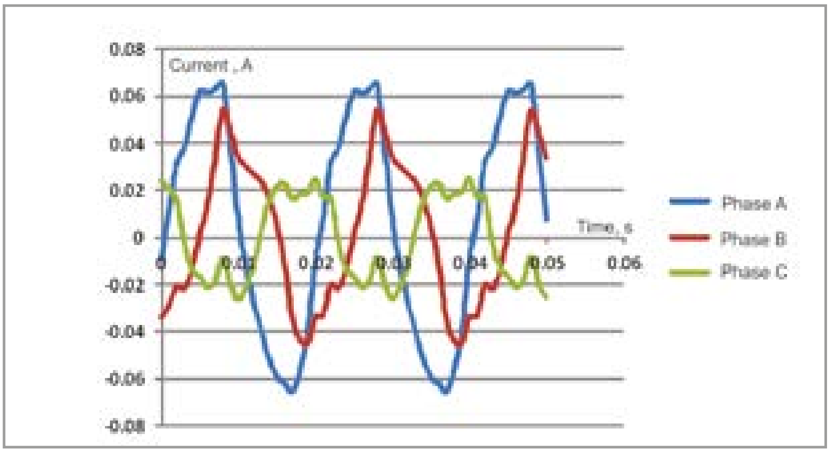

Figure 7. The waveform of the phase currents along the transformer primary winding

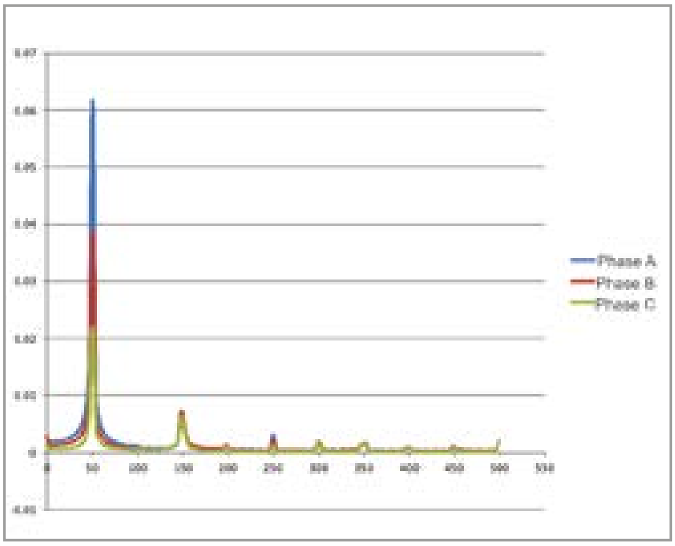

Figure 8. Harmonic spectrum of the phase currents for the primary winding of the transformer

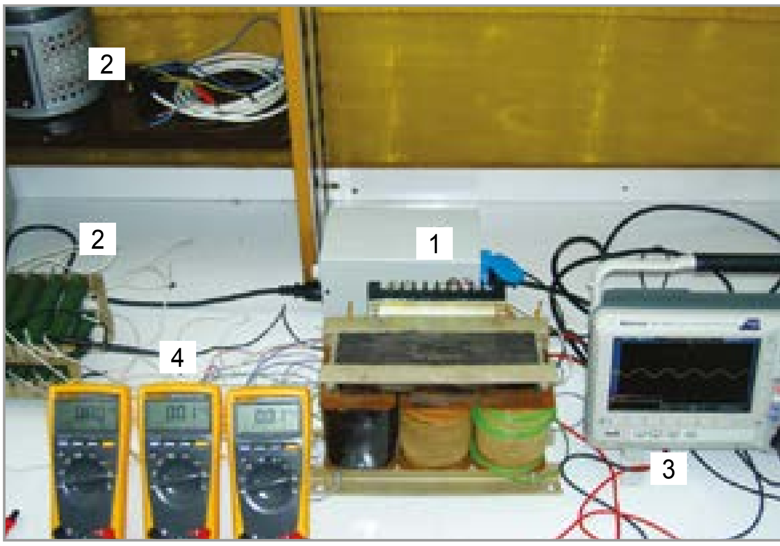

Figure 9. Experimental set-up: 1 – investigated transformer; 2 – phase resistors; 3 - digital oscilloscope; 4 - digital meters

the phase currents was obtained, as shown in Fig. 8.

Table 2 presents the RMS values, together with the amplitudes of the harmonics. The analysis showed that they differ slightly, within the limits of the FEM calculation error, which indicates the correctness of the constructed FEM model of the transformer, especially the approach to modelling and the calculation of the harmonics generated by the transformer due to strong non-linearity in the magnetic properties of the core steel.

4. Experimental study of the harmonic composition of the magnetizing current of the transformer

In order to verify the accuracy of the results of the current harmonic analysis obtained by post processing with the FEM analysis, an experiment was conducted in which the waveform of the no-load magnetizing current of the modelled transformer was measured using a digital oscilloscope. The experimental set-up is shown in Fig. 10.

The current waveform of the transformer was taken from the voltage drop on the resistors 2 (R_1, R_2, R_3) as shown in the electrical scheme (Fig. 10).

The current waveform is displayed on the digital oscilloscope (Fig. 11).

Figure 11 clearly shows that the phase current contains high harmonics generated due to non-linearity in the magnetic characteristics of the steel core and its saturation. With the digital meters (see Fig. 9, label 4) the RMS value of the current was measured. These "true RMS" digital meters measured the real RMS value of the current, although it is non-sinusoidal. The measurement results are displayed in Table 3.

The analysis revealed that in practice, apart from the fundamental harmonic, the current contains pronounced third and fifth harmonics

The digital oscilloscope has a built-in feature to help realize FFT. Table 3 presents a comparison of the measured RMS values of the phase currents along with the amplitudes of the higher harmonics with the results obtained via FEM. It was found that in practice, apart from the fundamental harmonic with the RMS value I_1, the current contains pronounced third and fifth harmonics, with the RMS values I_3 and I_5 respectively.

Table 2. Results from the FFT analysis of the phase currents

Magnitude	Harmonic amplitudes				RMS value
	I_0 (=0 Hz)	I_1 (=50 Hz)	I_3 (=150 Hz)	I_5 (=250 Hz)	I
Unit	mA	mA	mA	mA	mA
Phase A					
FEM	1	61.5	5.43	3	43.73
Phase B					
FEM	2.8	38.8	6.9	2.1	28.04
Phase C					
FEM	1.2	22	6.2	2.1	16.27

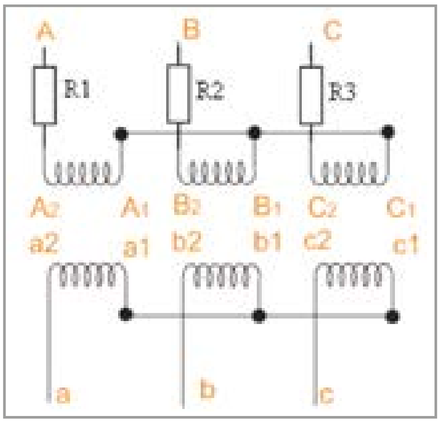

Figure 10. The electrical scheme of the experimental set-up

Table 3. Comparison of the harmonic analysis results for the transformer current using FEM and experiments

Magnitude	Harmonic amplitudes				RMS value
	I_0	I_1	I_3	I_5	I
Unit	mA	mA	mA	mA	mA
			Phase A		
Experience	2.9	59.2	4.2	2.4	42.1
FEM	1	61.5	5.43	3	43.73
			Phase B		
Experience	1.9	37.5	5.4	1.5	26.88
FEM	2.8	38.8	6.9	2.1	28.04
			Phase C		
Experience	0.8	20.5	5.3	1.8	15.05
FEM	1.2	22	6.2	2.1	16.27

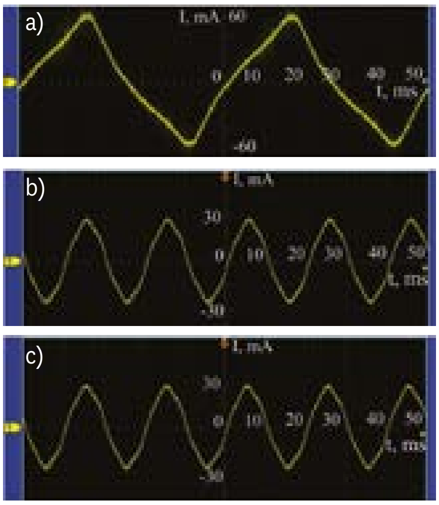

Figure 11. The waveform of the phase currents of the investigated transformer a) for phase A; b) for phase B; c) for phase C

Conclusion

This article explores the generation of high harmonics in low power three-phase transformers based on the magnetic field analysis. An FEM simulation of the transformer and an FEM analysis of the magnetic field were used to obtain the forms of the phase currents in the primary side of the transformer. The harmonic analysis results obtained via FFT were confirmed by the experimental study of a small three-phase three-limb core transformer, which was simulated by FEM.

The main reason for the generation of the magnetizing current harmonics is the non-linearity of the magnetic characteristics of the studied transformer. Besides being non-sinusoidal, the phase currents are non-symmetrical due to the asymmetry in the transformer magnetic circuit.

Magnetizing current harmonics penetrate directly into the power supply grid and decrease the quality of energy. The most pronounced higher harmonics are those with the number 3, 5 and 7.

Magnetizing current harmonics, the 3rd, 5th and 7th being the most pronounced, penetrate directly into the power supply grid and decrease the quality of energy

Conclusions made here in relation to low power three-phase transformers can be equally applied to power transformers in the grid, considering that they have exactly the same basic principle of work and uniform configuration of the magnetic circuit.

To eliminate the adverse effects of the harmonics with number 3 and multiples of 3 in power transformers, it is necessarily for one of the three-phase transformer windings to be delta connected.

A modern method to eliminate the harmonics generated by three-phase transformers is the use of active filters included in suitable places in the network. Filters for harmonics with zero sequence can also be used.

The FEM model of a three-phase three-limb core transformer presented in the article and the proposed approach can be successfully used by transformer manufacturers in the design stage to calculate the type and level of the generated higher harmonics.

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