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Analysis of Magnetization Currents

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Abstract – An analytical method for harmonic estimation of magnetization currents has been developed. The method is based on the results of the waveforms qualitative analysis. The calculation and the experimental results are compared. A good matching is observed.

Keywords: Harmonics, Magnetization current, Hysteresis

1. Introduction

Transformers and coils with ferromagnetic cores are widely used in power systems and in power electronic converters. Magnetization currents of such elements are non-sinusoidal because of the hysteresis [1-4]. The hysteresis leads to the appearance of the harmonics in the transformer current. This phenomenon is widely discussed in current publications [5-7], emphasizing the importance of the problem.

The shape of the transformer magnetization current may be evaluated by numerical calculations as presented in [5, 6]. In addition, the influence of the flux density on the harmonic current contents is discussed in [6]. The improved model of the transformer protection system is developed by changing the magnetization current spectrum [7]. All the research outlined above shows that the calculation of magnetization current harmonics is significant for engineering practice.

The present article proposes and applies an analytical approach based on experimental measurements. For this purpose, a qualitative analysis of experimentally obtained magnetization current shapes is carried out. The measured values of the magnetization current harmonics are compared with the calculated results.

2. Description of the Measuring Procedure

The magnetization currents of two transformers with ferromagnetic cores, 230/9V and 230/24V, 50Hz, are examined. The measurement set up is shown in Fig. 1. The voltage and current across the winding of no-load transformers have been measured by oscilloscope. The experimental results of the measurements appear in Fig. 2 and Fig. 3, where current and voltage waveforms are shown. The waveforms observed are quite similar. Such curves are typical for circuits with magnetic hysteresis [1, 2, 5, 6].

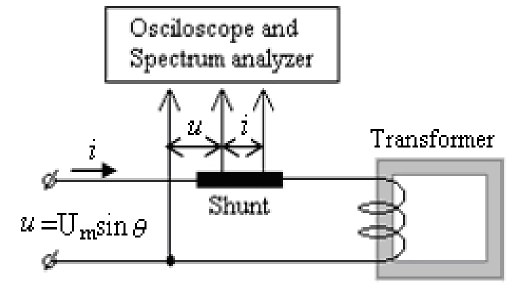

Fig. 1. Diagram of the measurement process

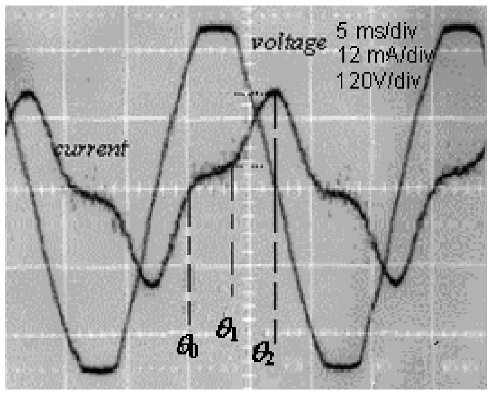

Fig. 2. Voltage and current waveform of 230/9V transformer

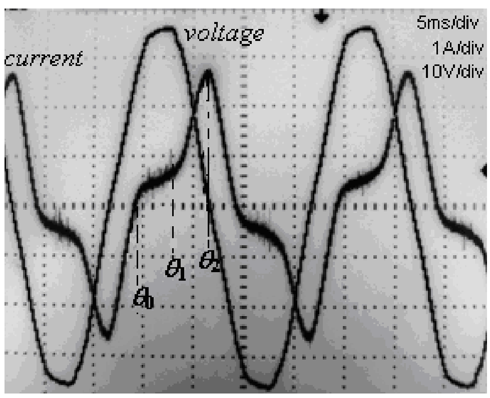

Fig. 3. Voltage and current waveform of 230/24V transformer

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3. Qualitative Analysis of the Magnetization Currents

The harmonic contents of the currents have been measured by a spectrum analyzer. The results of the measurements are shown in Figs. 4 and 5, where the basic and third harmonics are the most essential. All the other harmonics (the fifth and higher) are very small and they will be neglected. Using these assumptions, the instantaneous magnetization current i_μ may be expressed as:

$$i_\mu = i_{\mu 1} + i_{\mu 3} \tag{1}$$

where $i_{\mu 1}$ and $i_{\mu 3}$ are the instantaneous currents of the basic and third harmonics, respectively.

There are three turning-points (θ_0, θ_1 and θ_2) of the current waveforms (Figs. 2 and 3). The currents equal zero at θ_0, while they reach their maxima at the point θ_2. The instant θ_1 is the middle point of the interval $\theta_0 \div \theta_2$. This is a turning point where the velocity of the currents' growth has changed.

The duration of the $\theta_0 \div \theta_2$ interval is 120^o of the basic harmonic or a full period of the third harmonic. The intervals $\theta_0 \div \theta_1$ and $\theta_1 \div \theta_2$ are equal, i.e. $\theta_1 - \theta_0$ = $\theta_2 - \theta_1 = 60^o$ of the basic 50Hz frequency or 180^o of its third harmonic.

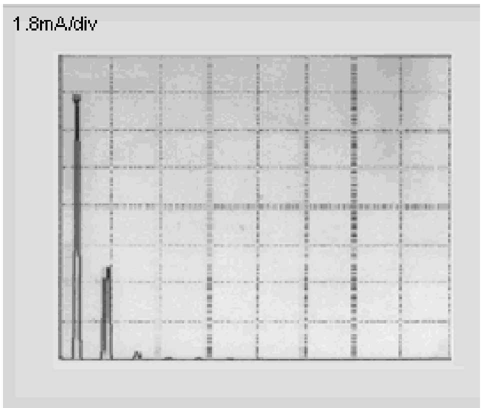

Fig. 4. Current harmonic contents of 230/9V transformer

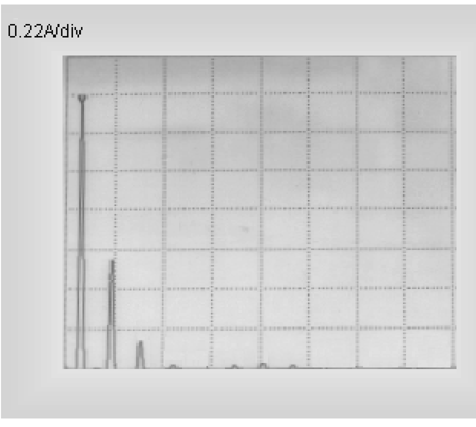

Fig. 5. Current harmonic contents of 230/24V transformer

According to (1) the magnetization current may be decomposed as shown in Fig. 6, where the current itself is on the axis "a"; its basic harmonic is on the axis "b"; the third harmonic is on the axis "c". Using this decomposition, the following may be concluded. The current i_μ is zero at the moment θ_0, i.e., at this moment, the basic and third harmonics are equal in their absolute values, but their signs are opposite (Fig. 6, b and c). During interval $\theta_0 \div \theta_1$ the current i_μ grows slowly, while during interval $\theta_1 \div \theta_2$ it grows rapidly. Such a behavior of the current i_μ may be explained assuming that during $\theta_0 \div \theta_2$ interval the basic current harmonic grows, achieving a maximum around θ_2. The third harmonic decreases from its maximum at θ_0 to a minimum at θ_1 and then it grows in the opposite direction during interval $\theta_1 \div \theta_2$, achieving its maximum at the instant θ_2.

Based on this analysis, the basic and third harmonics may be described as follows:

$$i_{\mu 1}(\theta) = \mathrm{I}_{m\mu 1} \sin(\theta - \theta_0 - \psi_1)\ , \tag{2}$$

$$i_{\mu 3}(\theta) = \mathrm{I}_{m\mu 3} \cos 3(\theta - \theta_0) \tag{3}$$

where $\mathrm{I}_{m\mu 1}$ and $\mathrm{I}_{m\mu 3}$ are the amplitudes of the basic and third harmonics, respectively, and ψ_1 is the initial angle of the basic harmonics. Assuming that $\theta_0 = 0$ and substituting the Eqs. (2) and (3) in (1) the following current analytical expression is obtained:

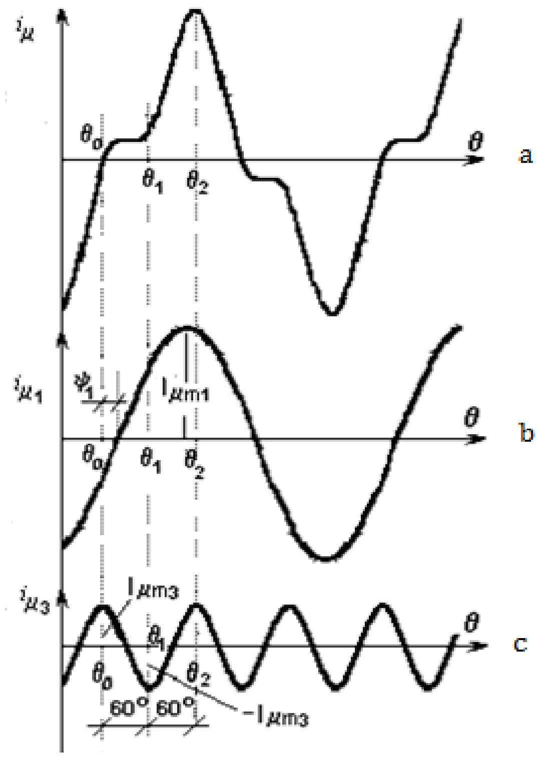

Fig. 6. Decomposition of the magnetization current

Table 1. Measured and calculated current harmonics

		$I_{m\mu1}$	$I_{m\mu3}$	ψ_1
Fig. 2	MR (mA)	11.9	4.26	
	CR (mA)	12	4.17	20.3°
	ε(%)	0.84	2.11	
Fig. 3	MR (A)	1.59	0.64	
	CR (A)	1.66	0.61	21.6°
	ε(%)	4.4	4.67	

$$i_\mu(\theta) = I_{m\mu1}\sin(\theta - \psi_1) + I_{m\mu3}\cos 3\theta \qquad (4)$$

The Eq. (4) contains three unknowns: $I_{m\mu1}$, $I_{m\mu3}$ and ψ_1. Their values may be calculated if a set of three algebraic equations containing these unknowns will be obtained. Measuring i_μ at $\theta = \theta_0 = 0$, $\theta = \theta_1 = 60°$ and $\theta = \theta_2 = 120°$ in Figs. 2 and 3, a set of three algebraic equations will be obtained for the current of each transformer.

The first set of equations, corresponding to the current of the first transformer, is as follows:

$$\begin{aligned} i_\mu(0) &= I_{m\mu1}\sin(-\psi_1) + I_{m\mu3} = 0 \\ i_\mu(60) &= I_{m\mu1}\sin(60 - \psi_1) - I_{m\mu3} = 3.5 \\ i_\mu(120) &= I_{m\mu1}\sin(120 - \psi_1) + I_{m\mu3} = 16 \end{aligned} \qquad (5)$$

where all numerical values are measured in milli-amperes from Fig. 2.

Analogically, the second set of equations, corresponding to the second transformer, is as follows:

$$\begin{aligned} i_\mu(0) &= I_{m\mu1}\sin(-\psi_1) + I_{m\mu3} = 0 \\ i_\mu(60) &= I_{m\mu1}\sin(60 - \psi_1) - I_{m\mu3} = 0.42 \\ i_\mu(120) &= I_{m\mu1}\sin(120 - \psi_1) + I_{m\mu3} = 2.25 \end{aligned} \qquad (6)$$

where all numerical values are measured in amperes from Fig. 3.

Solving the sets (5) and (6), the $I_{m\mu1}$, $I_{m\mu3}$ and ψ_1 values are calculated for each current. The calculated results (CR), the measured results (MR) and the calculated error ε are shown in Table 1.

The error ε is found as follows:

$$\varepsilon = \frac{|\mathrm{MR} - \mathrm{CR}|}{\mathrm{MR}} * 100,\ \% \qquad (7)$$

The observed errors are less than 5% which proves that the proposed method is sound. The error of the phase angle ψ_1 is not calculated because the spectrum analyzer used did not allow its measurement.

4. Conclusion

An analytical method for harmonic calculation of magnetization currents is proposed. This method is based on qualitative analysis of the current waveforms, obtained experimentally. The magnetization currents of two unloaded transformers are analyzed. The currents' waveforms are similar and typical for the curves with hysteresis. Three characteristic points of the magnetization current are determined. These points are typical for the waveforms of the currents with hysteresis.

The qualitative analysis of the magnetization current waveforms allows developing the analytical method for calculation of the current basic and third harmonics. The results of the calculations are compared with the experimental results. A good matching is observed. The errors obtained are less than 5%.

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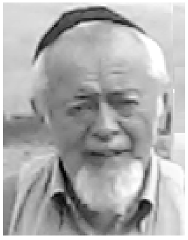

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