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Impact of a passive nonlinear load on saturation in the magnetic core of a multi-winding transformer

Abstract.*This paper deals with the saturation in magnetic core of a multi-winding transformer which supplies nonlinear passive load. Such systems are often a part of DC-DC converters. In order to investigate the saturation phenomenon in multi-winding transformers, a laboratory transformer was build. Analysis of time responses measured during different experiments performed on the transformer was used to explain the phenomenon in the terms of physics. It represents theoretical background for prevention of magnetic core saturation in systems with multi-winding transformers.*

Streszczenie. *W artykule rozważono nasycenie rdzenia magnetycznego transformatora wielouzwojeniowego z nieliniowym pasywnym obciążeniem. Taki układ występuje często w przekształtnikach stałoprądowych. W celu przebadania zjawiska nasycenia zbudowano transformator laboratoryjny. Analizy przebiegów czasowych mierzonych podczas różnych eksperymentów pozwalały na wyjaśnienie fizycznej natury zjawiska, co, z kolei, jest podstawą do ochrony rdzenia wielouzwojeniowego transformatora przed nasyceniem. (**Wpływ pasywnego nieliniowego obciążenia na nasycenie rdzenia magnetycznego wielo-uzwojeniowego transformatora**)*

Keywords: magnetic cores, multi-winding transformer, saturation, passive load.
Słowa kluczowe: rdzenie magnetyczne, wielouzwojeniowy transformator, nasycenie, obciażenie pasywne.

Introduction

Multi-winding transformers with magnetic cores are indispensable components of dc-dc converters. The magnetic cores are normally composed of ferromagnetic material with magnetically nonlinear behavior. Thus, the behavior of the entire multi-winding transformer is magnetically nonlinear as well.

A special type of multi-winding transformers are those installed in the middle-frequency resistance spot welding systems [1]-[4] with rated power over 100 kVA. Such systems are normally used for material joining in the automotive industry. The multi-winding transformer, in this case called also welding transformer, is mounted on the robot arm and moves with it. In order to minimize the moving mass, the mass of the transformer is minimized. In this way the best possible utilization of material, copper in the windings and electric steel in the magnetic core, is achieved. Unfortunately, the magnetic cores of such optimized multi-winding transformers can become saturated.

The authors in [3] to [7] deal with the saturation in the magnetic cores of 100 kVA to 160 kVA industrial multi-winding transformers operating in the DC-DC converters. They are applied as voltage sources in the middle-frequency resistance spot welding systems. Discussed are problems related with the magnetic core saturation that appears during the switch-on of the system and during normal operation, as well as problems related with the resistance spot welding system control and control system topology. Similarly, the authors in [8] and [9] focus on saturation in the magnetic cores of general purpose DC-DC converters. However, none of these papers gives a deeper insight into the saturation phenomenon which appears in the magnetic cores of multi-winding transformers.

The aim of this paper is to get a deeper insight into the saturation phenomenon in the magnetic cores of multi-winding transformers. In order to do this, a laboratory multi-winding transformer was build. On the contrary to [3] to [9], where the pulse-with-modulated voltages are applied, in this paper, the sinusoidal supply voltages are used. The test laboratory transformer was supplied with different amplitudes of sinusoidal supply voltage while it was loaded with different balanced and unbalanced passive loads. The currents and voltages, measured during the tests performed under different operating conditions, were analyzed in order understand and explain the phenomenon of magnetic core saturation in multi-winding transformers in terms of physics.

Laboratory multi-winding transformer and experimental system

The experimental system is schematically presented in Fig. 1a). It consists of the voltage source, laboratory multi-winding transformer, output rectifier and load. The voltage source supplies the multi-winding transformer with sinusoidal supply voltage u. The multi-winding transformer consists of the primary winding, denoted with the index 1, and two secondary windings, denoted with indices 2 and 3. The output rectifier, consisting of the diodes D_1 and D_2, is connected to the two secondary windings. It supplies the passive load, in the form of the load resistance R_L, with the DC voltage. Fig. 1b) shows the laboratory multi-winding transformer with magnetic core.

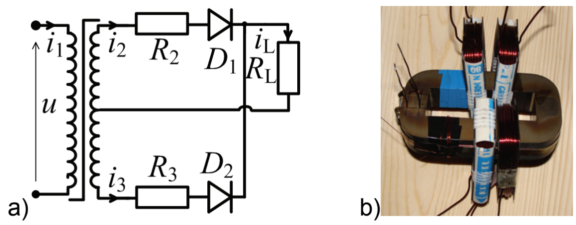

Fig.1. Experimental system a) and laboratory multi-winding transformer with magnetic core b)

In general, the voltage balances in individual windings of the multi-winding transformer, shown in Fig. 1, can be described by (1), (2) and (3). Equation (1) describes the voltage balance in the primary winding while equations (2) and (3) describe the voltage balances in the two secondary windings:

$$u = R_1 i_1 + L_{\sigma 1}\frac{di_1}{dt} + N_1\frac{d\phi}{dt} \tag{1}$$

$$N_2\frac{d\phi}{dt} = -R_2 i_2 - L_{\sigma 2}\frac{di_2}{dt} - f_{D1}(i_2) - R_2\left(i_2 + i_3\right) \tag{2}$$

$$N_3\frac{d\phi}{dt} = R_3 i_3 + L_{\sigma 3}\frac{di_3}{dt} + f_{D2}(i_3) + R_3\left(i_2 + i_3\right) \tag{3}$$

where i_1, R_1, $L_{\sigma 1}$ and N_1 are the current, resistance, leakage inductance and number of turns of the primary winding, i_2, R_2, $L_{\sigma 2}$ and N_2 are the current, resistance, leakage inductance and number of turns of the first secondary winding, whereas i_3, R_3, $L_{\sigma 3}$ and N_3 are the current, resistance, leakage inductance and number of turns of the second secondary winding. The nonlinear characteristics of the output rectifier diodes D_1 and D_2 are marked with f_{D1} and f_{D2} respectively, while ϕ is the magnetic flux due to the magneto-motive-force Θ (4).

(4) $$\Theta = N_1 i_1 + N_2 i_2 - N_3 i_3$$

In order to simplify the analysis and measurements, the primary winding, as well as both secondary windings, have the same number of turns N=N_1=N_2=N_3. Thus, the magnetizing current i_m can be defined by (5).

(5) $$i_m = \frac{\Theta}{N} = i_1 + i_2 - i_3$$

In the next section, the currents measured during the tests, performed with different amplitudes of applied sinusoidal voltages, are compared considering (1) to (5) and the magnetically nonlinear characteristics of the magnetic core $\phi(i_m)$, in the cases of balanced and unbalanced load. Based on these results, the explanation for magnetic core saturation in the multi-winding transformers is given.

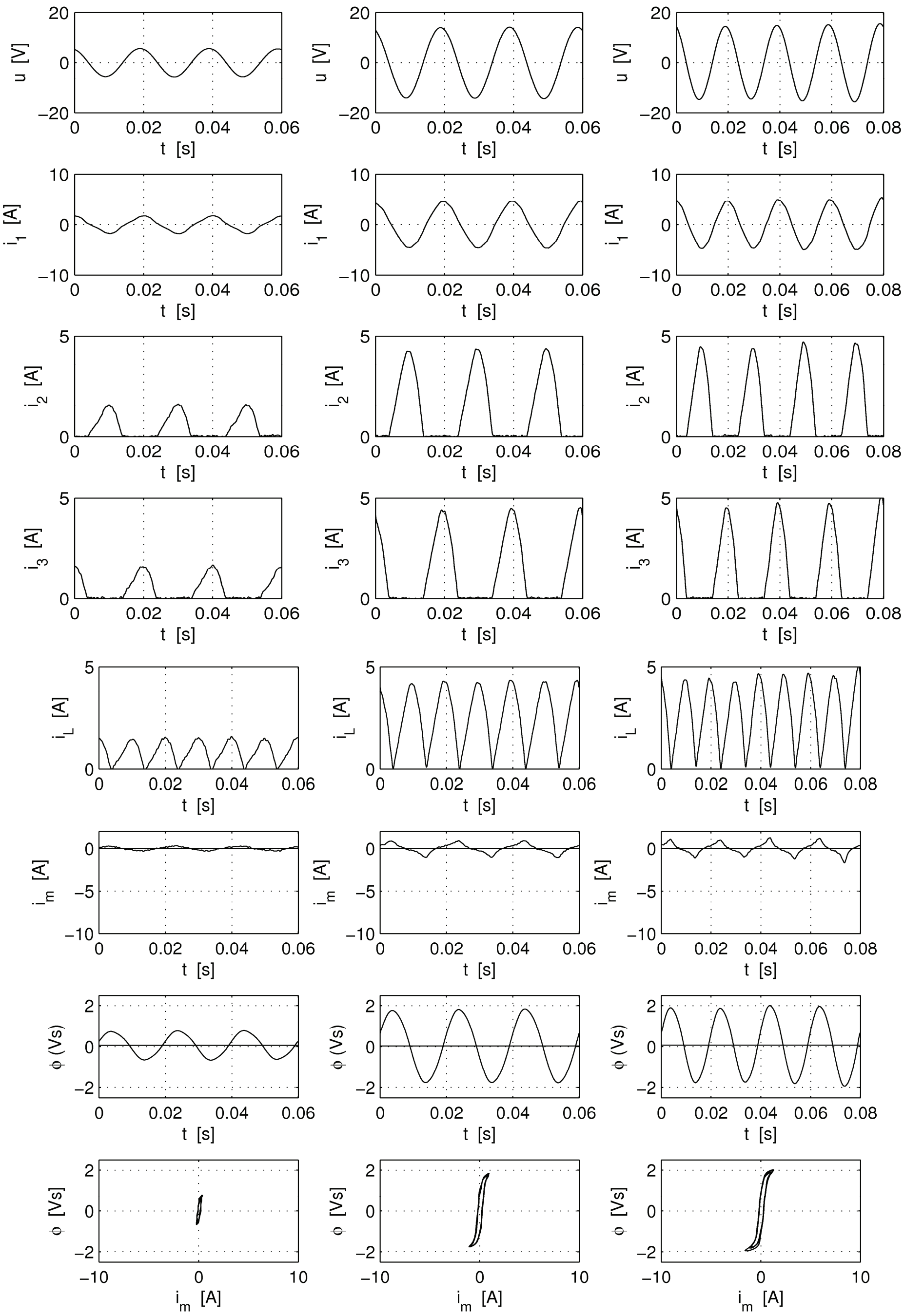

Fig.2. Applied voltage u, currents i_1, i_2 and i_3, load current i_L, magnetizing current i_m, magnetic flux ϕ and characteristic $\phi(i_m)$ given for balanced nonlinear load, where R_2=R_3

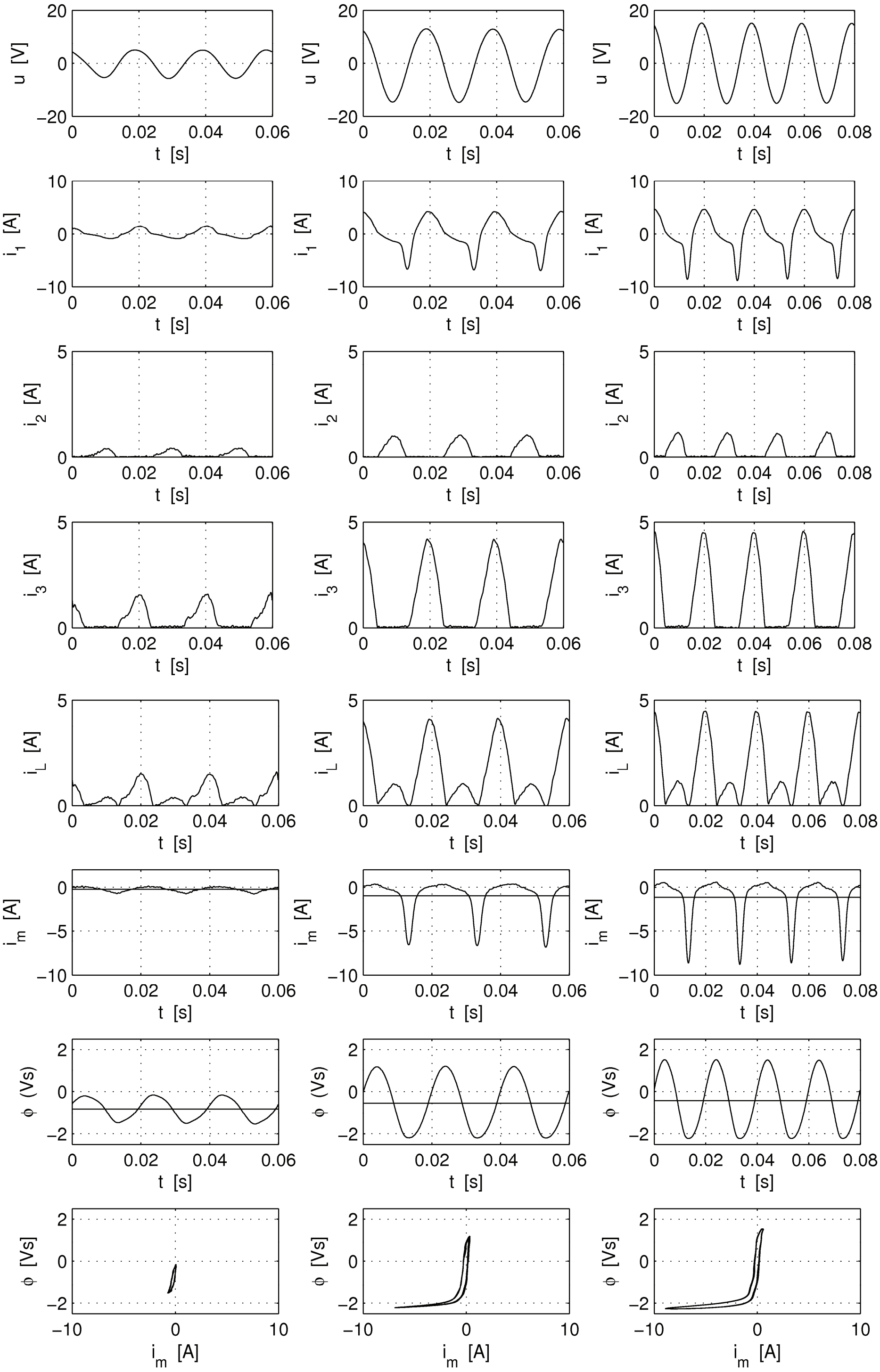

Fig.3. Applied voltage u, currents i_1, i_2 and i_3, load current i_L, magnetizing current i_m, magnetic flux ϕ and characteristic $\phi(i_m)$ given for unbalanced nonlinear load, where $R_2>R_3$

Analysis of measured results

The authors in [3]-[7] have shown that the unbalanced characteristics of the output rectifier diodes can cause magnetic core saturation in the welding transformers supplied with pulse-with-modulated voltages. In this paper, the magnetic core saturation in the multi-winding transformers is explained through the relation between the magnetic flux and the magnetizing current, or more generally through the relation between the magnetic flux and the magneto-motive-force. Since, the saturation phenomenon is related to the magnetically nonlinear behavior of the magnetic core, which can be described by the characteristic $\phi(i_m)$, the experiments performed with any form of supply voltages should lead to the same results. In the given case, the primary winding of the multi-winding transformer, shown in Fig. 1, is supplied with the sinusoidal voltages. The applied voltages have different amplitudes. Fig. 2 shows the results for the balanced nonlinear load, where R_2=R_3, while Fig. 3 shows the results for unbalanced nonlinear load, where $R_2>R_3$. The results are organized in the form of two matrices, where graphs in individual columns are given for the same amplitude of sinusoidal supply voltage. Figs. 2 and 3 show the three sinusoidal supply voltages u, the primary winding current i_1, as well as currents i_2 and i_3 flowing in both secondary windings, the load current i_L, the magnetizing current i_m, the magnetic flux ϕ and the characteristic $\phi(i_m)$.

The three sinusoidal supply voltages shown in the first rows of Figs 2 and 3 are almost identical. Their amplitudes are increasing in individual columns from the left to the right. However, there exists substantial difference between the primary winding currents i_1 shown in Figs. 2 and 3. While the waveforms of the currents i_1 shown in Fig. 2 are almost sinusoidal, the waveforms of the currants i_1 shown in Fig. 3 are distorted. The secondary windings' currents i_2 and i_3, shown in Fig. 2, are balanced, while the ones shown in Fig. 3 are not. The unbalance of the secondary currents is caused by the unbalanced resistances of the secondary windings $R_2 > R_3$ in combination with the nonlinear characteristics of the output rectifier diodes. The unbalance of the secondary currents itself is insufficient to cause saturation of the magnetic core. However, the reasons for the magnetic core saturation become evident after the analysis of the magnetizing currents i_m, corresponding magnetic fluxes ϕ and characteristics $\phi(i_m)$, is performed. In all results presented in Fig. 2, the magnetizing currents i_m contain only negligible share of the DC component. The analysis performed for the magnetic fluxes ϕ gives similar results. All this lead to the symmetrical hysteresis loops, which are given in the form of three $\phi(i_m)$ characteristics, shown in Fig. 2.

Let us focus our observation on the results shown in Fig. 3, where the currents i_2 and i_3 are unbalanced. The applied voltages u, shown in Figs. 2 and 3 are almost identical. Since, the term $d\phi/dt$ contributes the major share to the voltage balance on the right hand side of (1), the changes of ϕ shown in Figs. 2 and 3 are almost identical as well. However, there exists a substantial difference between results shown in Figs. 2 and 3. The unbalanced currents i_2 and i_3, shown in Fig. 3, cause also unbalance in the corresponding magnetizing currents i_m, which contain a substantial share of DC component. The DC component in the magnetizing current i_m causes the DC component in the magnetic flux ϕ, which consequently lead to the asymmetrical hysteresis loops in the form of three $\phi(i_m)$ characteristics, shown in Fig. 3.

According to (1), not the magnetic flux ϕ, but its time derivative $d\phi/dt$ is substantial for the voltage balance. Thus, for the same applied voltage u, the same time derivative $d\phi/dt$ is needed, regardless on the presence of DC component in the magnetic flux ϕ. Since, the magnetic flux ϕ, shown in Fig. 3, contains a substantial share of negative DC component, the corresponding $\phi(i_m)$ is not symmetrical as the one shown in Fig. 2. It is displaced for the DC components. The required peak to peak change of the magnetic flux is under 3.8 T, which is enough to stay outside the highly saturated region, as shown in Fig. 2. However, the presence of negative DC component in the magnetic flux ϕ, shown in Fig. 3, causes operation at negative values under -2.1 T, which means operation in the highly saturated region for the most negative values of changing magnetic flux ϕ. The voltage balance (1) is fulfilled at each time instant t, which means that also for the most negative values of the magnetic flux ϕ, the required $d\phi/dt$ is reached. However, to achieve the required $d\phi/dt$ in the highly saturated region, the changes of the magnetizing current i_m must be increased substantially, as shown in Fig. 3. The only active source of energy in the discussed system is the supply voltage. Thus, the required changes of the magnetizing current can be achieved only through the corresponding changes in the primary winding current i_1, as shown in Fig. 3.

Conclusion

In the case study, this paper explains the magnetic core saturation in the multi-winding transformers. It is shown that the unbalance of the secondary winding itself is insufficient to cause saturation of the magnetic core. It must be supported by the nonlinear characteristics of the load. If the unbalance of the secondary currents combined with the nonlinear load characteristics is sufficient to cause a substantial share of the DC component in the magnetizing current, the DC component appears in the magnetic flux too. The DC components in the magnetizing current and in the magnetic flux lead to the operation along asymmetrical hysteresis loop, which leads to the saturation of the magnetic core. To prevent the magnetic cores of multi-winding transformers form being saturated, the DC component of the magnetic flux must be controlled through the DC component of the magnetizing current.

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