Nikolay KUZNIETSOV, Valeriy ZHUIKOV

National Technical University of Ukraine «Kyiv Polytechnic Institute»

Determining of the transformer operating modes by means of vibroacoustic signals

Abstract. *The paper presents the mathematical relations for determining the transformer operation mode using vibroacoustic signals analysis.*

Streszczenie. *W artykule przedstawiono aparat matematyczny do opisu stanów pracy transformatora na podstawie analizy zjawisk wibroakustycznych (**Metody opisu stanu pracy transformatora na podstawie analizy zjawisk wibroakustycznych**)*

Keywords: transformer operation modes, vibroacoustic diagnostic
Słowa kluczowe: diagnostyka wibroakustyczna, stany pracy transformatora

Introduction

Operation of the transformer being a part of the semiconductor power converter directly affects the whole device [1-3]. Identification of the transformer's operating mode will improve the existing methods of converter control, which are based primarily on an analysis of voltages and currents in the converter load [1,2]. Here the required number of sensors must match the number of output transformer windings [4], which complicates the control system of converter with multiwinding transformer.

This paper considers the mathematical relationships for determining the operating mode of the multiwinding transformer by analysis of vibroacoustic signals of two sensors. The determining greatly simplifies the receipt of assessment of transformer state for the tasks of handling a semiconductor converter.

The basic mathematical relations

The main sources of the transformer's vibration are core and windings [5,6]. The core vibration is caused by magnetostriction [6] of the core, and depends on the magnetizing current, geometric and magnetic parameters of the core, the number of coil turns. Function of the core surface motion $x(t)$ [7,8]:

$$x(t) = h \cdot \frac{3 \cdot \lambda_S}{2 \cdot \left(B_S / \mu_0 - H_S \right)^2} \cdot \left(\frac{f\left(i_0(t) \cdot N / l_{av} \right)}{\mu_0} - i_0(t) \cdot N / l_{av} \right)^2 \tag{1}$$

where λ_S is saturation magnetostriction, μ_0 – the magnetic constant, B_S and H_S – the induction and magnetic field under saturation, l_{av} – effective magnetic path length, N – the number of turns in the winding forming the magnetic flux of the core, $i_0(t)$ – core magnetizing current, $f(...)$ – function defined by the magnetic characteristics of the core (basic magnetization curve and hysteresis loop), h – the length of the core in a direction perpendicular to the moving surface.

The coil vibration is caused by the Lorentz force interaction of windings turns [5]. The function of motion of the coil surface $y(t)$ [7]:

$$y(t) = \mu \cdot \mu_0 \sum_{j=1}^{M} \frac{D_j / K_1 + d_j / K_2}{\left(D_j + d_j \right) D_j} \cdot \left(i_j(t) \right)^2 \cdot \left(n_j - 1 \right) \tag{2}$$

where μ is magnetic permeability of the lacquer insulation of coil, M – the number of windings of the transformer, n_j – the number of layers of turns in the j winding, D_j – diameter of the j winding wire, d_j – the thickness of insulation between the wires of j windings, $i_j(t)$ – the current in the wires of j winding, K_1 – elastic modulus of the coil material, K_2 – elastic modulus of insulation material between the windings. Movement of the coil depends on the number of windings, the number of turns in them, the diameters and material of the wire, insulation, flowing currents.

As follows from (1) and (2) the movement of the core and windings are determined by the squares of the currents flowing in them, and the period of vibration is half the period of change in the currents.

Since the vibration of the transformer is formed by two sources, regardless of the number of windings, the vibration and acoustic signals of a multiwinding transformer can be considered with a help of two-winding transformer model.

Modes of the transformer operation

Mode of the transformer operation is defined by core induction (linear (unsaturated) and saturated modes), currents of primary and secondary windings (short-circuit, idle, loaded modes) [3,9,10]. For the numerical evaluation of the transformer operating mode the maximum value of core induction B_{max} during the period of the input voltage, and half the sum of powers at the input and output of the transformer P_{size} are used. In addition, for an adequate assessment of the transformer state, dissipation power P_{lost}, input power P_{in} and output power P_{out} are used.

Maximum induction B_{max} is determined by (1) taking into account the fact that under the greatest value of magnetizing current $i_0(t)=i_{0max}$, the function $f(i_{0max} \cdot N/l_{av})=B_{max}$ degenerates to the basic magnetization curve of the core material. The current $i_0(t)$ is calculated from (1) with known actual cycle of magnetization reversal, which is determined by the core magnetic characteristics, values B_{max} and $i_{0max} \cdot N/l_{av}$. At certain $i_0(t)$ currents in the windings are calculated from (2) and Kirchoff's 1st law for a multiwinding transformer [10]:

$$\begin{cases} i_k(t) = \sum\limits_{l} \dfrac{n_k}{n_l} i_l(t) + i_0(t) \dfrac{i_k(t)}{\sum\limits_{k} i_k(t)} \\ i_l(t) = \sum\limits_{k} \dfrac{n_l}{n_k} i_k(t) - i_0(t) \dfrac{i_l(t)}{\sum\limits_{l} i_l(t)} \end{cases}, \tag{3}$$

where $i_k(t)$ and n_k are the current and the number of turns in the k primary winding, $i_l(t)$ and n_l – the current and the number of turns in the l secondary winding. The system (3) is redundant, so one equation can be excluded from it. Since (1) and (2) contains the squares of the transformer currents, then the solutions will have equal magnitudes and different signs. The energy is supplied to the transformer through single primary winding.

Using the resulting coils currents and induction B_{max} and taking into account the transformer parameters, the powers P_{in}, P_{out}, P_{size}, P_{lost} can be determined:

(4) $$P_{in} = 4 \cdot k_{sk} \cdot f \cdot B_{\max} \cdot S_c \cdot \sum_k N_k I_k ,$$

(5) $$P_{out} = 4 \cdot k_{sl} \cdot f \cdot B_{\max} \cdot S_c \cdot \sum_l N_l I_l ,$$

(6) $$P_{size} = 0.5(P_{in} + P_{out}) = 2 \cdot k_{sj} \cdot f \cdot B_{\max} \cdot S_c \cdot \sum_{j=1}^{M} N_j I_j(t),$$

(7) $$P_{lost} = \sum_{j=1}^{M} I_j{}^2 r_j + P_v \cdot V_c \cdot \frac{f}{f_{norm}} \cdot \left(\frac{B_{\max}}{B_{norm}} \right)^2 ,$$

where I_j, I_k, I_l – effective values of currents of the k primary, l secondary, or j winding, r_j – j winding resistance, k_{sk}, k_{sl}, k_{sj} and N_k, N_l, N_j – the current form factors and the number of turns in the k, l, j windings, f – the voltage frequency, S_c – the area of the core active section, P_v and V_c – specific power losses under frequency f_{norm} and induction B_{norm}, and the transformer core volume. In (4) - (6) the current form factors can be taken the same for all windings, $k_{sk} \approx k_{sl} \approx k_{sj}$. In (7) the first term – losses in the windings, the second one – in the core.

Definition of operation modes

To evaluate the operation of the transformer depending on external factors, the schematic model of the transformer in figure 1 is considered [10].

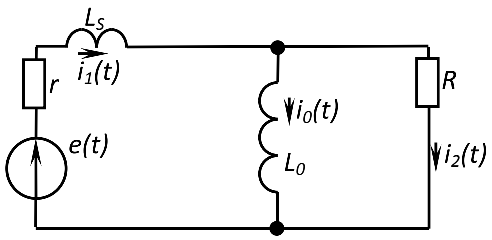

Fig. 1. Schematic model of the 2-winding transformer

In figure 1 $e(t)$ is a voltage source connected to the primary winding, r – the primary winding and the voltage source resistance, L_S – the transformer leakage inductance, L_0 – inductance of the flux linkages, R – resistance of the load and the secondary winding, $i_1(t)$ – the primary winding current, $i_2(t)$ – the secondary winding current, $i_0(t)$ – the core magnetization current.

The main factors affecting the operation mode of the transformer (according model Fig.1) are: 1) the mean value of the primary winding voltage, 2) the value of the transformer's load. As a shape of voltage in semiconductor converters is rarely changed during operation [1, 2], the mean value of the voltage depends on: 1) amplitude, 2) frequency, 3) the duty cycle (for a pulse voltage).

In the schematic model Fig.1 induction of a core is defined by the relationship $B(t)=f(i_0(t))$. Increase in the average value of voltage and load resistance causes an increase of the current $i_0(t)$ so, consequently, the amplitude of the core vibration X^* (according to (1)) and the maximum induction B_{max} increase. When $B_{max} \approx B_S$, the inductance value L_0 changes significantly, which causes the transition between the linear (unsaturated, $B_{max} \le B_S$) and saturated ($B_{max} \ge B_S$) operation modes.

With frequency and voltage induction increasing, according to (1), (4) ... (7) the amplitude of vibration X^*, powers P_{in}, P_{out}, P_{size} and P_{lost} increase due to losses in the core.

Winding currents increase with the mean value of input voltage increasing and load reduction. With current increasing, according to (2), (4) ... (7) the amplitude of the coil vibration Y^* increases, as well as powers P_{in}, P_{out}, P_{size} and P_{lost} due to losses in the windings.

When the inductance L_0 reduces in the saturated mode, the magnetizing current and the magnetic field significantly increases, but the induction, the amplitude of the vibrations of the core and core losses vary slightly. With the increasing of the magnetizing current, the current of the secondary windings is reduced and the current of the primary winding increases, which leads to increase P_{in} and decrease P_{out}. Since the amplitude of the coil vibrations Y^*, powers P_{size} and P_{lost} depends on the currents in the primary and secondary windings both, they can either increase or decrease. In most cases, there is an increase of power and vibration of the transformer as a whole.

Modeling of two-winding transformer operation modes

An influence of the mentioned factors on changes in working modes and vibroacoustic signals is considered with using of the transformer model.

The parameters of the transformer are: 1) the size of core - EI33, material – PC47 (Mn-Zn ferrite), 2) two-winding transformer, wound with copper wire with lacquer insulation, the wire tightly pressed together, 3) seal between the windings was considered inelastic and the diamagnetic, 4) the primary winding has 18 turns, wrap in 2 layers; the diameter of wire 1.12 mm, the outer diameter of the wire 1.247 mm, 5) the secondary winding has 7 turns, wrap in 2 layers; the diameter of wire 2 mm, outer wire diameter 2.172 mm.

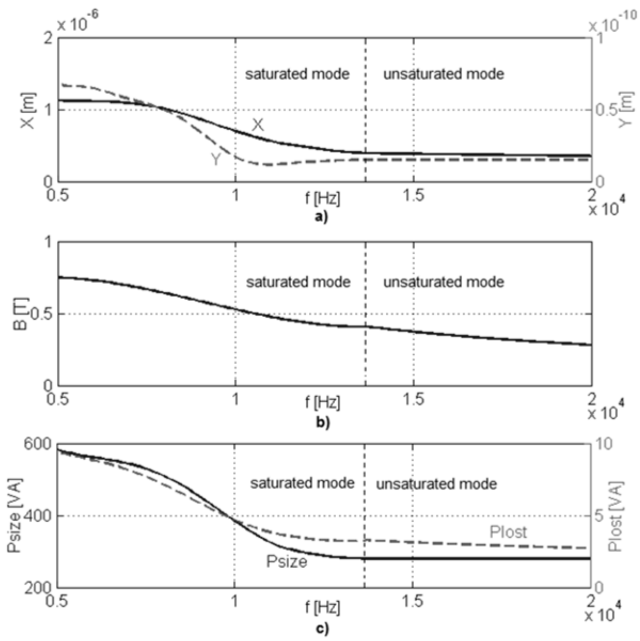

Fig. 2. Changing of the amplitudes of the core X and windings Y movements a), the maximum induction B_{max} b), power P_{size} and P_{lost} c) when the frequency of supply voltage varies.

Parameters of the voltage source $e(t)$ and the load are: 1) the voltage bipolar, symmetric, 2) the duty cycle is 0.8, 3) the duration of the pulse top is 60% of the total pulse duration, front and rear fronts of the pulse has the same duration, 4) the amplitude is 97 V, 5) frequency of voltage is 20 kHz; 6) load resistance – 2.88 Ohms;

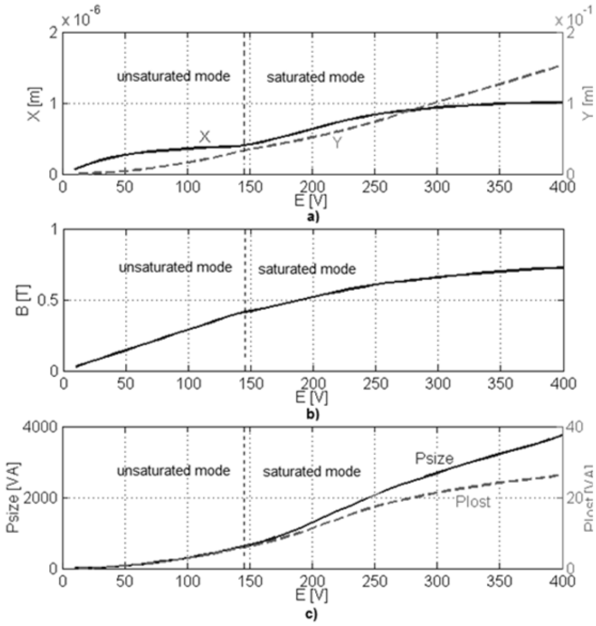

Fig. 3. Changing of the amplitudes of the core X and windings Y movements a), the maximum induction B_{max} b), power P_{size} and P_{lost} c) when the amplitude of supply voltage vary.

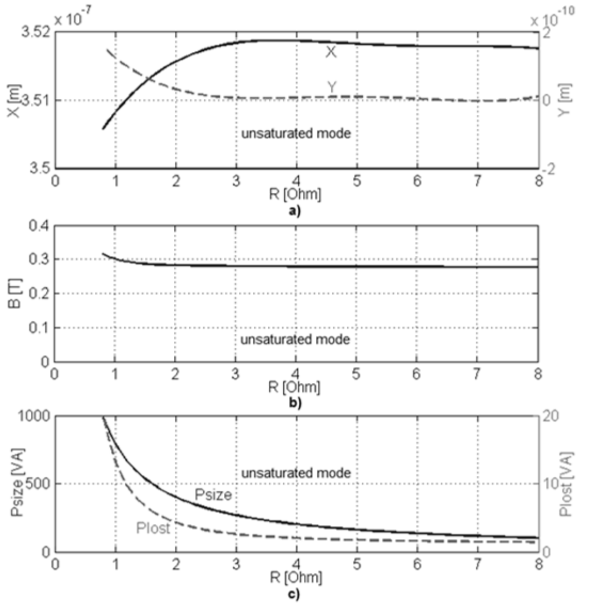

Fig. 4. Changing of the amplitudes of the core X and windings Y movements a), the maximum induction B_{max} b), power P_{size} and P_{lost} c) under the load resistance changing.

The transformer is connected to the half-bridge inverter, made from bipolar transistors with inverse diodes. Valve components are ideal, the transistors come out of saturation if the collector current exceeds value 22 A.

The following parameters have been simulated: 1) the amplitude of the first harmonics X and Y of the motion functions of the core $x(t)$ and coil $y(t)$ surfaces respectively, 2) the magnitude of the maximum induction of the core B_{max} formed by the first harmonic of the magnetizing current, 3) half the sum of powers at the input and output of the transformer P_{size} and dissipation power P_{lost} with changing in frequency (Fig. 2), amplitude (Fig. 3), of the supply voltage and the load resistance in Fig. 4.

In the normal (unsaturated) mode (Fig. 2) changes in vibration, the half-sum of powers at the input and output of the transformer and the dissipation power are negligible, the maximum induction of the core decreases linearly with frequency increasing. In the saturated mode when a frequency decreases, vibration, half the sum of powers at the input and output of the transformer and dissipation power significantly increases. The maximum induction of the core increases too.

The vibration, the maximum induction, both the powers increases with increasing of the voltage in figure 3. The transition from the linear (unsaturated) into the saturated modes does not cause abrupt changes in the values of figure 3.

The vibrations, maximum induction, half the sum of powers at the input and output of the transformer and dissipation power in figure. 4 reduces with increasing of the load resistance. The transformer is in normal mode at all the simulated range of resistances.

Conclusion

The presented relations allow to estimate multiwinding transformer operation mode by the signals of two vibroacoustic sensors, which greatly simplifies such estimation to control semiconductor converters. The efficiency of these relations and methods of their calculation was verified by simulation.

REFERENCES

[1] Мэк Р. Импульсные источники питания. Теоретические основы проектирования и руководство по практическому применению. *Translated from English.* М.:2008 – 272с.
[2] Браун М. Источники питания. Расчет и конструирование *Translated from English*. К.: 2007 - 288.с.
[3] Семенов Б.Ю. Силовая электроника для любителей и профессионалов. М.:2001.
[4] Розанов Ю.К. Основы силовой электроники. М.:1992 – 296с.
[5] Menno van der Veen. Measuring Acoustic Noise Emitted by Power Transformers *109th convention*, Los Angeles. 2000.
[6] Белов К.П. Магнитострикционные явления и их технические приложения. М.:1987-160с.
[7] Кузнецов Н. Моделирование виброакустических сигналов трансформатора полупроводникового преобразователя электроэнергии. *Материалы МНТК СЭЭ'2012,* 2012., *in press*
[8] Szewczyk R. Modelling of the magnetic and magnetostrictive properties of high permeability Mn-Zn ferrites. *Pramana,* Vol. 67, No. 6, pp. 1165-1171, December 2006.
[9] Готлиб Ирвинг М. Источники питания, инверторы, конверторы, линейные и импульсные стабилизаторы, *Translated from English.* М.:2000
[10] Источники электропитания радиоэлектронной аппаратуры, под ред. Найвельта Г.С.М.:1985-576с.

***Authors:** prof. dr. Valeriy Zhuikov, Nikolay Kuznietsov, NTUU "KPI", Faculty of Electronics, Politechnichna st., 16, 03056 Kyiv, Ukraine, E-mail: nikolay_kuznyetsov@i.ua;*