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Research of rnergy processes in circuits containing iron in saturation condition

Abstract. *Problems of application of instantaneous power theory theses to the analysis of electromagnetic and energy processes in nonlinear ferromagnetic circuits at different degrees of its saturation have been considered. Results confirm the necessity to revise the conventional methods and approaches to analyze the nonlinear circuits in saturation conditions.*

Streszczenie. *Rozważono problemy związane z teorią mocy chwilowej zastosowaną do analizy elektromagnetycznych i energetycznych procesów w nieliniowych obwodach ferromagnetycznych w różnym stopniu nasyconych. Wyniki analiz potwierdzają konieczność rewizji metod konwencjonalnych i podejść do analizy obwodów nieliniowych w stanie nasycenia. (**Badania procesów energetycznych w obwodach zawierających żelazo w warunkach nasycenia**)*

Keywords: *magnetic saturation, magnetic material, energy processes, iron losses.*
Słowa kluczowe: nasycenie magnetyczne, materiał magnetyczny, process energetyczny, straty w żelazie

Introduction

Changes of the state of electro-technical and electro-mechanical magnetic systems during their operation cause the problem of diagnostics regarding their electrical and magnetic properties topical. In this case it is often necessary to solve the problems connected with accurate measurements of the magnetic system parameters and characteristics. The influence of devices with changes in their magnetic system on electromagnetic compatibility to the supply system is another important issue.

Problem statement

In the course of long-term operation and repairs of electro-technical and electromechanical devices with magnetic system, made of laminated electro-technical steel, deterioration of its properties occurs. It shows in the change of magnetic characteristics, increase of iron losses and higher degree of magnetic saturation. Change of magnetic system state results in increased level of its saturation. Consequently, the considered devices present a nonlinear load for the supply system. In its turn, it leads to complication of the analysis in their operational conditions, because of the absence of an adequate mathematical description and low information level of the present methods of nonlinear circuit computation. The possibilities of computational methods are significantly extended by application of electromagnetic and energy exchanging processes analysis using instantaneous power contemporary theories [1]. However, in this case new problems arise. They result from the necessity of correction of theoretic notions and calculated relations from the point of understanding the essence of the physical processes that are taking place.

The purpose of the paper consists in investigation of particular features and prospects of application of various methods and approaches to the analysis of electromagnetic and energy processes in nonlinear circuits containing steel in saturation condition.

Theoretical theses

The problem was solved for an ordinary load in the form of inductance with a ferromagnetic core shown in Fig. 1, where R_1, R_μ are winding and magnetizing circuit resistances; X_{s1}, X_μ are inductive reactance of the winding (leakage resistance) and the magnetizing circuit; u_1, i_1 are, correspondingly, circuit output voltage and winding current; e_1 is the winding EMF.

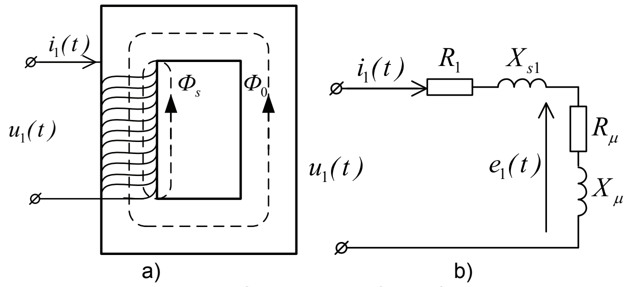


Fig. 1. Equivalent circuit of a load in the form of inductance with a ferromagnetic core (a) and its electrical equivalent circuit (b)

Neglecting the real distribution of magnetic field in the considered magnetic circuit and applying separation of magnetic flux into the main flux Φ_0 and leakage flux Φ_{s1}, magnetic circuit equation for the winding with the number of turns equal to N_1 is presented in the form:

$$(1)\qquad u_1 = R_1 i_1 + L_{s1}\frac{di_1}{dt} + N_1\frac{d\Phi_0}{dt} = R_1 i_1 + L_{s1}\frac{di_1}{dt} + e_1,$$

where L_{s1}– winding inductance determined by leakage flux Φ_{s1}.

Equation (1) is nonlinear due to nonlinear link between flux linkage Ψ_0 and MMF i_1N_1, that is why periodic current, flux and EMF are non-sinusoidal in general case.

In the circuit under consideration, consumed integral active power P_1 is used to cover copper losses P_{cu1} and iron losses P_c. As powers P_1 and P_{cu1} can be determined directly by measurement, power P_c (because it is impossible to measure e_1 directly) is often presented as their difference:

$$(2)\qquad P_c = P_1 - P_{cu1}\,.$$

When classical approach to the analysis of these circuit operational conditions was made the equivalent sinusoidal current and voltage method was applied. The choice of current and voltage equivalent sinusoidal signal was considered in two ways:

– power processes were estimated – from the condition of constant active power in the circuit:

$$(3)\qquad P_1 = I_1U_1\cos\varphi_1 + I_2U_2\cos\varphi_2 + \ldots \\ \ldots + I_nU_n\cos\varphi_n = U_1I_1 = UI_1$$

where U_1, U_2,…, U_n, I_1, I_2,…, I_n are correspondingly, active values of voltage and current harmonics; $\cos\varphi_1, \cos\varphi_2, ..., \cos\varphi_n$ are power coefficient of each of the harmonics (in this case U_2=…=U_n=0, U_1=U and $\cos\varphi_1 = 1$);

– electro-magnetic processes were estimated from the condition of keeping the current active value:

$$I_e = \sqrt{2} I_1 = \sqrt{2}\sqrt{\frac{1}{T}\int_0^T i_1^2 dt} \ . \qquad (4)$$

In the latter case the active power in linear resistance R_1, described by relation $I_1^2 R_1$, remains unchanged.

Energy balance equation for instantaneous values is presented in the form:

$$i_1^2 R_1 + L_{s1} i_1 \frac{di_1}{dt} + e_1 i_1 = u_1 i_1 . \qquad (5)$$

Instantaneous voltage, current and power components were determined using fast Fourier transformation in accordance with recommendations and methods discussed in [2].

Experimental research

The problem of research consisted in experimental estimation of iron losses determination error and adequacy of energy and electromagnetic processes description. They are dependent on the degree of the core magnetic material saturation determined by the known saturation coefficient k_s [3]. Three conditions of the core material: low-saturated ($0.75 < k_s < 1$), medium-saturated ($0.5 < k_s < 0.75$), high-saturated ($k_s < 0.5$), were considered. Experimental model was made according to Fig. 1. However, unlike the initial circuit, two electrically unconnected windings with the numbers of coils N_1 and N_2 were placed on the magnetic core. One of the windings was directly connected to the supply system with sinusoidal voltage u_1, the other one was used to measure the main magnetic flux Φ_0 in the core using the secondary winding EMF e_2 with the aim to independently measure instantaneous iron losses

$$p_c = e_2 i_1 \frac{N_1}{N_2} . \qquad (6)$$

The experimental model parameters: core length $l = 110 mm$; core width $b = 105 mm$; sectional area $S = 3 \cdot 10^{-4} mm^2$; core type – twisted; core material – steel E330 (thickness $d = 0.35 mm$); winding coils numbers – $N_1 = 200$, $N_2 = 1000$; diameter of winding wires with insulation – $d_1 = 0.5 mm$; $d_2 = 0.1 mm$; insulation type – varnish. Core geometric parameters made it possible to place the windings at a sufficient distance from one another to reduce their mutual induction as much as possible. Parameters R_1 and L_{s1} were determined beforehand and were assumed constant during the investigation.

The physical configuration of the used testing system is shown in Fig. 2, and its structure – in Fig. 3. Here TS is a tested sample. Parameters measured directly, current $i_1(t)$ and EMF $e_2(t)$, were taken of the tested sample by means of current CT and voltage VT2 transducers. Output signal $u_1(t)$ passed from off-line source of variable frequency sinusoid alternating voltage, presenting a synchronous generator, to voltage transducer VT1.

Signals went from the transducers through input/output module, presenting a plate of a multi-channel analog-digital converter (12-digit ADC AD7892-AN1 with conversion time 6 microsecond/channel), to computer whose functions were data gathering, storage and processing.

To estimate the influence of eddy currents, measurements were taken at two frequencies – 50 Hz and 265 Hz. During the process of investigation instantaneous values u_1, i_1, e_2 were measured for every level of the magnetic circuit saturation. Further computations of the parameters, that were not measured directly, were performed according to the above stated relations in mathematical package Mathcad 13.

Fig.2. Testing system set-up

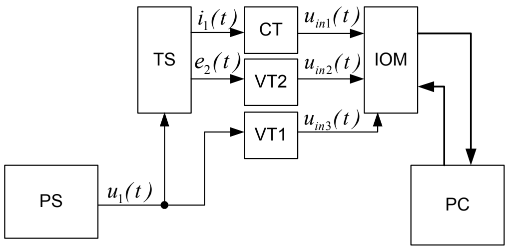


Fig.3. Testing system block diagram

In the course of research it was found out that there is an additional integral losses component which cannot be attributed to measurement error [4]. This component was obtained as a difference of iron losses values determined according to (2) and directly from their instantaneous values computed according to (6). Besides, discrepancy between circuit instantaneous power characteristics and equation (5) was revealed. It is shown in Fig. 4 and also confirms the presence of this additional component. In Fig. 4 numbers from 1 to 5 designate components $u_1 i_1$, $i_1^2 R_1$, $L_{s1} i_1 \frac{di_1}{dt}$, $e_1 i_1$ and unaccounted component p_{unc}, correspondingly.

Dependence of p_{unc} on the magnetic material hysteresis loop form, which does not correspond to a classical form in the saturation condition (Fig. 5), and the tendency to the growth of integral value p_{unc} from 2% to 15% of the total losses, accordingly, at weak and strong saturation of magnetic material, was confirmed.

Computation results also demonstrated considerable, up to 25-30% in the area of allowable saturation (Fig. 6) growth of errors in determination of iron losses when equivalent sinusoids method was used, according to (3).

Here (Fig. 6) P_c – integral iron losses computed using equivalent sinusoid method, and $\sum P_{c\nu}$ – iron losses computed using harmonic components, according to [2] for frequencies of 50 Hz (Fig. 6,a) and 265 Hz (Fig. 6,b).

The reason for this phenomenon lies in a sharp growth of current i_1 and EMF e_2 curves nonlinear distortion coefficients

$$THD_{I1} = \frac{\sqrt{\sum_{\nu=2}^{\infty} I_{1\nu}^2}}{I_{11}}; \tag{7}$$

$$THD_{E2} = \frac{\sqrt{\sum_{\nu=2}^{\infty} E_{2\nu}^2}}{E_{21}} \tag{8}$$

where $I_{1\nu}$, $E_{2\nu}$ and I_{11}, E_{21}, correspondingly, are high and first harmonics of current I_1 and EMF e_2 curves. This is proved by the results given in Fig. 7.

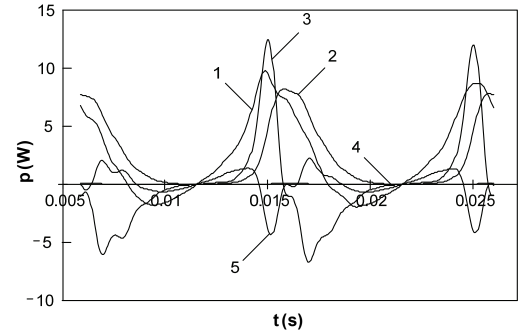


Fig. 4. Circuit elements instantaneous power curves

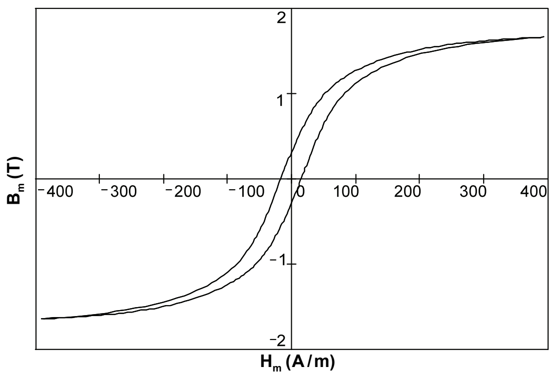


Fig. 5. Hysteresis loop $B_m = f(H_m)$ of high-saturated magnetic material

As a result, the general power balance for integral parameters of the circuit as a whole is upset, being kept only for each separate harmonic. However, in this case, to provide the balance, it is also necessary to recalculate magnetizing circuit resistance R_μ and inductive reactance X_μ calculated as:

$$R_\mu = \mathrm{Re}(\dot{E}_2 / \dot{I}_1)\frac{N_1}{N_2}; \tag{9}$$

$$X_\mu = \mathrm{Im}(\dot{E}_2 / \dot{I}_1)\frac{N_1}{N_2}, \tag{10}$$

where $\dot{E}_2, \dot{I}_2$ are, correspondingly, complex values of EMF e_2 and current i_1 for each separate point of magnetization curve, as their values change with the change of magnetic material saturation degree (Fig. 8).

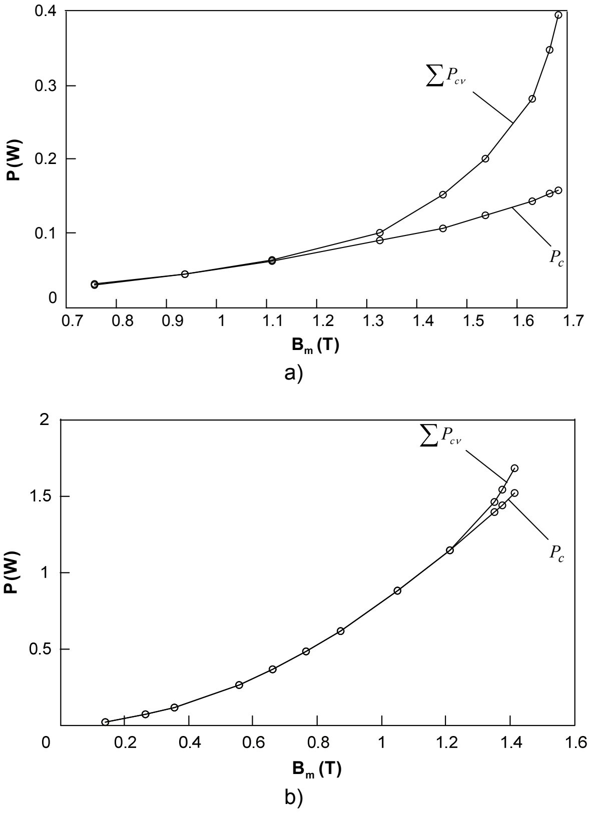


Fig.6. Dependences $P_c = f(B_m)$ for different frequencies of the core material magnetization reversal

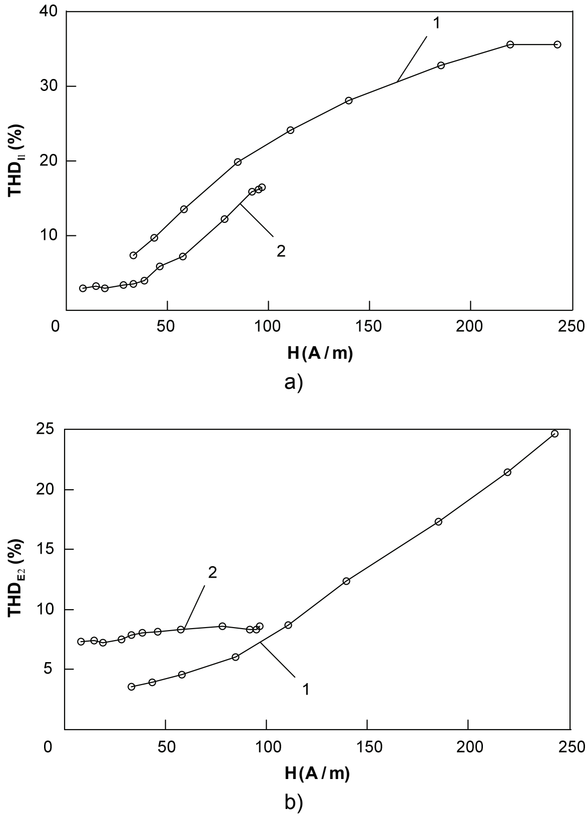
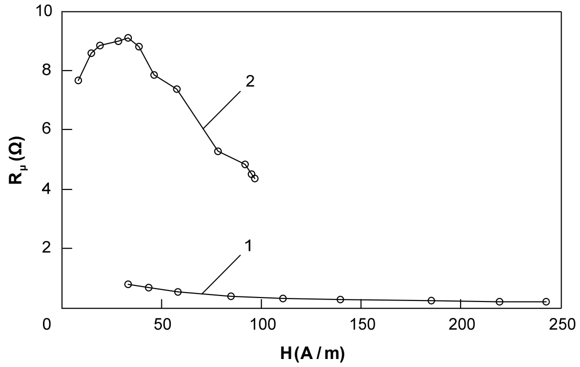
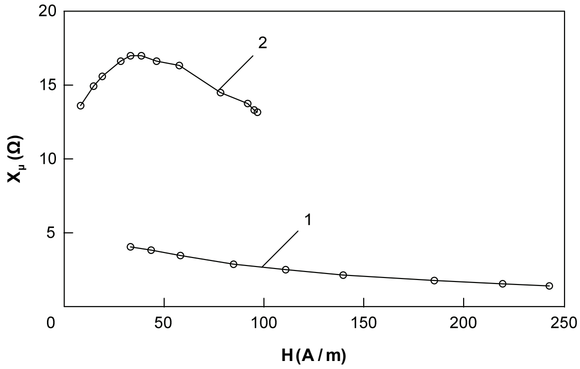


Fig. 7. Dependences $THD_{I1} = f(H)$ and $THD_{E2} = f(H)$ for current $\dot{I}_1$ and EMF e_2 curves: 1 – frequency 50 Hz, 2 – frequency 265 Hz



a)



b)

Fig. 8. Dependences $R_{\mu} = f(H)$ and $X_{\mu} = f(H)$ for magnetizing circuit with iron: 1 – frequency 50 Hz, 2 – frequency 265 Hz

As a result, both values of inductive reactance X_{s1} and, correspondingly, leakage inductance L_{s1}, used in equation (5), change. The cause of these changes consists in general descent of the curve of magnetic permeability μ of the core magnetic material in saturation condition as magnetization reversal frequency grows (Fig. 9).

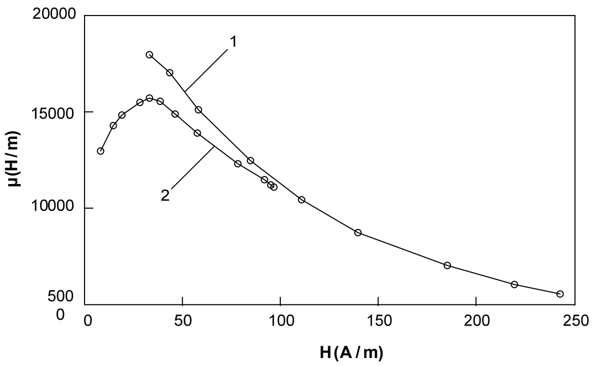


Fig. 9. Dependences $\mu = f(H)$ for the core magnetic material: 1 – frequency 50 Hz, 2 – frequency 265 Hz

Generalizing the obtained results, it is possible, according to (5), to attribute the unaccounted integral losses component in the considered circuit to iron losses P_c, presented by $e_1 i_1$ relation, as copper losses in saturation condition are described by relation $i_1^2 R_1$ with sufficient accuracy.

In the course of the research it was additionally determined that maximum value of magnetic permeability μ of laminated core material in the area of low frequencies is not constant either, but decreases with growth of magnetization reversal frequency. The mentioned effect is known for higher frequencies and is explained by reactive action of eddy currents. It should be noted that at present it is mostly characterized qualitatively and has no adequate mathematical specification providing its quantitative estimation.

The considered effect conditions show a lower position of the measured magnetizing curve (Fig. 10) and resulting in additional errors in determination of iron losses, as well as erroneous interpretation of physical phenomena in the considered circuits.

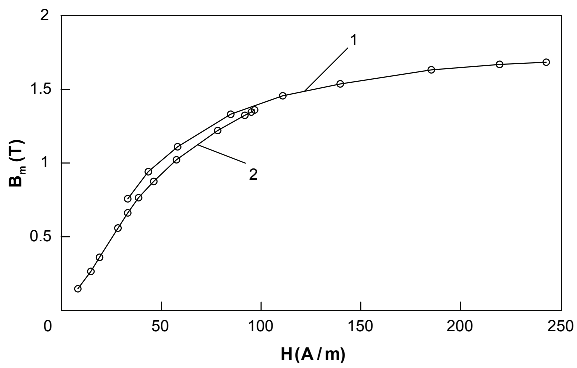


Fig. 10. Magnetization curves $B_m = f(H)$ for the core magnetic material: 1 – frequency 50 Hz, 2 – frequency 265 Hz

Conclusions

1. It has been proved that the existing methods of nonlinear circuits' computation containing iron cannot be applied for its saturated condition, as power processes are not completely taken into consideration in such case.

2. It has been shown that in saturation condition there exists an additional integral component of active losses and that they are interconnected with the level of magnetic material saturation. This makes possible to preliminarily ascribe them to iron losses.

3. Further research results should be directed to the development of the method to describe power processes in circuits with nonlinear inductance in the function of instantaneous parameters. It will allow to express iron losses accurately and to determine the type of parameters nonlinear dependence on the applied excitation. Besides, it is necessary to investigate and to specify in terms of mathematics the effect of eddy currents on laminated core magnetic properties.

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