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IMPROVED METHOD FOR CALCULATION OF PARAMETERS OF ELECTROMAGNETIC AND POWER PROCESSES IN ELECTRIC CIRCUITS WITH STEEL IN SATURATION MODE

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The reasons for increased degree of saturation of magnetic system of electric machines with a long error-free running time are substantiated. It is proved that application of the conventional methods of calculation of electromagnetic and power processes parameters at practical degrees of saturation results in inadmissible errors. During the process of the problem solution an improved parameter calculation method applicable under the considered conditions is grounded. A sufficient degree of coincidence of the calculation results with the experimental data as to integral parameters and instantaneous power and electromagnetic characteristics is obtained. References 8, table 1, figures 6.

Key words: circuit with steel, electromagnetic processes, power processes, degree of saturation.

Introduction. During operation of electromechanical and electrotechnical devices their magnetic systems are characterized by different degrees of saturation. It is accordingly taken into consideration during their calculations. So, most electric machines are designed in such a way that maximum unsaturated condition of magnetic system correspond to their typical operation – the point of transfer from a linear section of magnetization curve to the zone of saturation. Due to this fact the stability of their characteristics is provided at insignificant excitation oscillations. In this case general degree of saturation is an averaged value changing from a low one in yokes and poles to a high one in teeth. The same principles of magnetic system design remain for different types of transformers. The magnetic system operating point calculated for a typical operation, as a rule, is characterized by a lower degree of saturation. The proper change of saturation degree across the magnetic circuit is not very significant.

In some cases the degree of magnetic system saturation exceeds the admissible value. It can be caused by both low quality of used magnetic materials or production technology and various errors in the process of devices design. Deterioration of the condition of electric machines and transformers in the course of their operation and repairs additionally contributes to the degree of magnetic system saturation. It can be explained by aging of both magnetic materials and structural components of magnetic systems – stators and rotors of electric machines, yokes and rods of transformers. In this case aging of structural components is more significant. It is expressed in violation of inter-lamina insulation and, correspondingly, in the growth of eddy flows. As a result, electromagnetic parameters of the devices change and their power and thermal characteristics sharply deteriorate.

The above said makes the problem of account of magnetic system saturation degree topical. It implies the solution of problems connected with accurate determination of parameters and characteristics of this system under the given conditions and substantiation of the adequate analytical description of electromagnetic and power processes in the considered devices [8].

Problem statement. The purpose of the research carried out in the paper consists in development of a calculation procedure for parameters of nonlinearity of alternating current electric circuits using a power method, verification of its availability by example of calculation of parameters of nonlinear inductance.

Devices with highly saturated magnetic systems are known to be a nonlinear load for mains supply. It results in the fact that, when supplied by alternating sinusoidal voltage, the consumed current becomes nonsinusoidal. It causes occurrence of additional power flows between the mains and the load, which violate electromagnetic compatibility of consumers. When the degree of saturation is high (saturation coefficient $k_S < 0.5$ [1]), losses components sharply increase, efficiency falls and device heat exchange deteriorates. All this complicates the analysis of their operation conditions due to the absence of adequate mathematical description and insufficient accuracy and information value of the existing methods of nonlinear circuit calculation.

In theoretical electrical engineering such circuits are mainly calculated by the method of equivalent sinusoids. It implies substitution of a nonsinusoidal current by a corresponding sinusoidal current with the same value of active power. It provides the possibility of the use of vector diagrams and conventional systems of differential equations. However, the solution obtained in this case is true only for the calculated point. The circuit parameters change for another current value. So, use of this method at $k_s < 0.5$ does not provide the possibility to describe the processes in the considered devices adequately. The error of determination of losses components in static condition also grows, and dynamic conditions characteristics practically do not correspond to the experimental results [5].

The possibilities of calculation are significantly broadened with the use of spectral analysis methods. In this case real time dependence for current is substituted by a harmonic series obtained as a result of spectral decomposition. However, new problems arise in this case. They can be explained by the necessity of correction of theoretical notions and calculation relations from the point of view physical essence of the occurring processes [6].

The purpose of the paper consisted in development of a simple and practically applicable method for determination of parameters and description of electromagnetic and power processes in nonlinear circuits containing saturated steel as well as estimation of its applicability and validity at different degrees of magnetic system saturation.

Research materials and results.

Theoretical theses. Calculation of parameters of electric machines and transformers is usually based on differential equations and equivalent circuits. Taking into account the specific features of the analyzed problem, there is no sense in using complex objects as the main problem is connected with adequate description of processes in magnetizing circuit. This circuit enables taking into consideration magnetic processes in devices by introduction of a corresponding branch in the electric equivalent circuit. Thus, to substantiate the offered method of problem solution it is sufficient to use a simple nonlinear circuit with load in the form of inductance with a ferromagnetic core and a winding, containing W_1 turns, shown in Fig. 1 (equivalent circuit of load in the form of inductance with a ferromagnetic core (*a*) and its electric equivalent circuit (*b*)) Here R_1, R_μ – resistances of, respectively, the winding and magnetizing circuit; L_{s1}, L_μ – inductances of, respectively, the winding and magnetizing circuit; $u_1(t), i_1(t)$ – respectively, circuit output voltage and winding current; $e_1(t)$ – winding EMF.

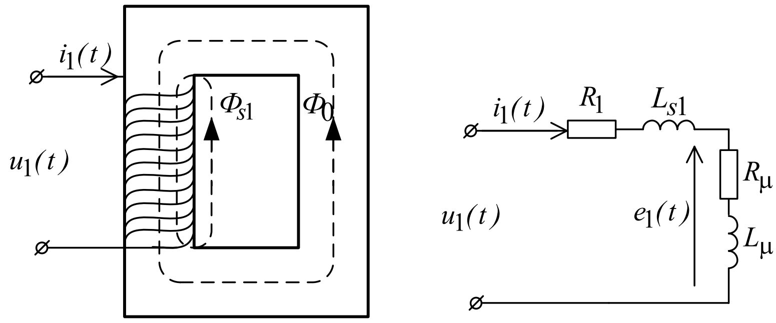

Fig. 1, *a, b*

When magnetic flux is divided into the main flux Φ_0 and leakage flux Φ_{s1}, the equation of the electric circuit can be presented by a classical relation

$$u_1 = R_1 i_1 + L_{s1}\frac{di_1}{dt} + W_1\frac{d\Phi_0}{dt} = R_1 i_1 + L_{s1}\frac{di_1}{dt} + e_1, \tag{1}$$

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

When magnetic circuit is saturated, this equation is nonlinear due to nonlinear connection between flux linkage $\Psi_0 = \Phi_0 W_1$ and MMF $i_1 W_1$. It results in nonsinusoidality of periodical currents, fluxes and voltages and limits the application of equivalent quantity method and vector diagrams as well as particular principles of complex quantity method. In this case equation (1) can be used under the condition of taking into account the polyharmonic composition of current $i_1(t)$ and EMF $e_1(t)$ included into it.

Power balance equation for instantaneous values, created on the basis of (1), will be of the form:

$$i_1{}^2 R_1 + L_{s1} i_1 \frac{di_1}{dt} + e_1 i_1 = u_1 i_1 . \tag{2}$$

Having compared (2) with the circuit in Fig. 1, it is possible to come to the conclusion that product $e_1 i_1$ is to completely describe power processes in magnetizing circuit (parameters R_μ, L_μ).

According to this, for factual determination of R_μ, L_μ it is necessary to have dependence $e_1(t)$ that can be obtained indirectly being expressed from (2) when all the other parameters are known.

In this case it should be taken into account that, when saturation degree and frequency grow, the value of magnetic permeability μ considerably decreases due to reactive action of eddy currents as can be seen in Fig. 2 (dependences $\mu = f(H)$ for magnetic material of the core: 1 – frequency 50 Hz, 2 – frequency 250 Hz) [5]. The considered effect causes additional errors in determination of steel losses as well as erroneous interpretation of physical phenomena in the analyzed circuits.

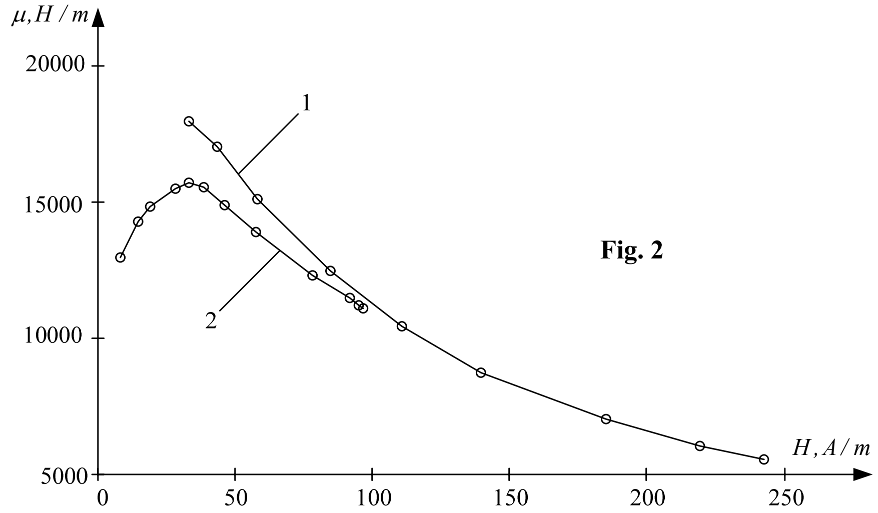

Fig. 2

Parameters R_1, L_{s1} necessary for the calculation can be obtained by direct measurement and later assumed constant. Expression for $i_1(t)$, taking into account its nonsinusoidality, is to be determined according to the results of spectral decomposition based on Fourier transform in accordance with recommendations [6].

Another problem in determination of parameters R_μ, L_μ is their presentation in the circuit (Fig. 1, *b*) as connected in series. This approach is artificial and caused by the necessity to simplify the calculation of magnetizing circuit for electric machines equivalent circuits.

When steel losses in electric machines and transformers are determined, the following proportionality is used [3]

$$\Phi_m \sim B_m \sim E_1/k_f \sim U_1/k_f \ , \qquad (3)$$

where Φ_m – magnetic flux maximum value; E_1 – stator winding EMF; k_f – form coefficient.

It allows evaluation of steel losses according to generally accepted relations of the form:

$$P_\mu = c_h f^* U_1{}^2 + c_{ec} f^{*2} U_1{}^2 \ , \qquad (4)$$

where c_h, c_{ec} – coefficients taking into account division of steel losses, respectively, into hysteresis losses and eddy current losses; U_1 – supply voltage; f^* – relative frequency reduced to the frequency of supply voltage (usually 50 Hz).

Proportionality (3) is upset when the degree of saturation grows as electric and magnetic values contained in it lose linear interconnection and are of different forms.

This prevents the use of expression (4) at high degrees of saturation. Besides, the use of (4) implies neglect of active resistance of magnetizing circuit, which is admissible for transformers and, concerning electric machines, is absolutely contrary to fact.

The above said substantiates the use of value E_1 instead of value U_1 in (4). In general case value E_1 is of a polyharmonic character. It implies the substitution of series connection of elements by parallel one in representation of magnetizing circuit.

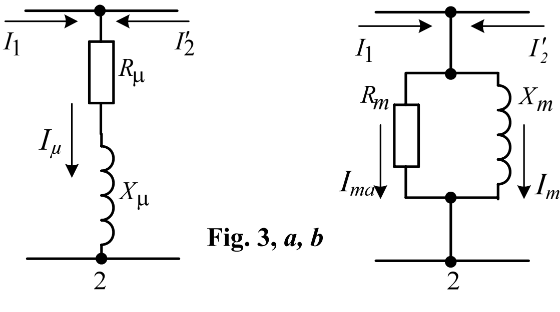

Fig. 3, *a, b*

Let us consider the special features of such transformation by the example of a typical magnetizing circuit used in calculations of electric machines and transformers and taking steel losses into account (Fig.3) (Series (*a*) and parallel (*b*) representation of magnetizing circuit in the equivalent circuit) [2].

In Fig. 3 $I_1, I_2', I_\mu, I_{ma}, I_{mr}$ – correspondingly, current of the initial winding, reduced current of the second winding, magnetization current for the circuit Fig. 3, *a*, active and reactive components of magnetization current for the circuit Fig. 3, *b*; R_μ, X_μ, R_m, X_m – resistance and inductive reactance of magnetization circuit for the circuits in Fig. 3, *a* and Fig. 3, *b*, respectively.

Let us estimate the correspondence of the magnetizing circuit in Fig. 3, *b* to real physical phenomena when the saturation degree changes. Taking into consideration (3), steel losses P_μ are proportional to squared voltage U_{12} at the output of the magnetizing circuit (Fig. 3, *b*).

If resistance R_m is connected to terminals in parallel to X_m, as it is shown in Fig. 3, *b*, losses in this resistance will also be proportional to U_{12}^2. The value of resistance R_m is determined in such a way that its losses equal the steel losses:

$$P_\mu = \left(m_1 U_{12}^2\right)/R_m = \left(m_1 E_1^2\right)/R_m \,, \tag{5}$$

where m_1 – the number of the phases of the device.

Hence
$$R_m = \left(m_1 E_1^2\right)/P_\mu \,. \tag{6}$$

Value P_μ, at the assigned EMF E_1 is refined according to experimental data. Then R_m can also be considered known.

In this instance magnetization current I_μ divides along two branches of magnetizing circuit into an active I_{ma} component and a reactive I_{mr} one. The former component is determined by steel losses power and the latter one creates a flux in the core.

As the degree of the core saturation increases, at $f = \text{const}$ resistance X_m decreases proportionally to μ. In this case for the circuit in Fig 3, *b* $R_m = \text{const}$, and value R_μ for the circuit in Fig 3, *a* reduces, which results in an additional error in determination of steel losses when this circuit is used. Thus, circuit in Fig. 3, *b* to a greater extent corresponds to real physical processes in circuits with steel under saturation condition.

Special attention should be paid to the problem of determination of power parameters of the considered circuit. As curves of EMF $e_1(t)$ and current $i_1(t)$ are of a polyharmonic character, it is better to determine losses in steel and copper as average in the period of values of their instantaneous values. It will enable elimination of the calculation errors occurring in multiplication of polyharmonic series $e_1(t)$ and $i_1(t)$ due to ambiguity of decomposition and nonlinearity contained in spectral transformations.

As a result, a calculation equations system reflecting the algorithm of determining magnetizing circuit parameters and describing electromagnetic and power processes in the considered circuit in the saturation condition was obtained. It is of the following form:

$$\dot{E}_1 = \dot{U}_1 - \dot{I}_1(R_1 + j\omega L_{s1})\,; \qquad \underline{Z}_\mu = \dot{E}_1 / \dot{I}_1\,; \tag{7,8}$$

$$R_\mu = \operatorname{Re}(\underline{Z}_\mu) = X_m^2 R_m / \left(R_m^2 + X_m^2\right); \qquad L_\mu = \operatorname{Im}(\underline{Z}_\mu)/\omega = R_m^2 X_m / \left(\left(R_m^2 + X_m^2\right)\omega\right); \tag{9,10}$$

$$L_m = X_m/(j\omega)\,; \qquad e_1 = u_1 - R_1 i_1 - L_{s1}\, di_1/dt\,; \qquad L_m(t) = e_1/((i_1 - e_1/R_m)\omega)\,; \tag{11–13}$$

$$p_\mu = e_1^2/R_m\,; \qquad P_\mu = \frac{1}{T}\int_0^T p_\mu dt\,; \qquad p_{cu} = i_1^2 R_1\,; \qquad P_{cu} = \frac{1}{T}\int_0^T p_{cu} dt\,. \tag{14–17}$$

Here ω is the angular frequency; T is the fundamental frequency period; $\underline{Z}_\mu$ is the complex impedance of the magnetization circuit; $\dot{E}_1, \dot{U}_1, \dot{I}_1$ are complex circuit EMF, voltage and current, respectively; $p_\mu, p_{cu}, P_\mu, P_{cu}$ are instantaneous and integral values of iron and copper losses, respectively; $L_m(t), L_m$ are instantaneous and integral values of magnetizing inductance, respectively.

Equations (7)–(11) are used to determine R_m, L_m when there is no saturation. When $\dot{U}_1, \dot{I}_1$ are known, $\dot{E}_1$, that is used to determine $\underline{Z}_\mu$ according to (8), is found from (7). Resistance R_m is calculated as a result of solution of equation system (9)–(10). Then maximum value L_m is found on the basis of (11). Equations (12)–(17) describe the electromagnetic and power processes in the considered circuit at different degrees of magnetic material saturation. They allow one to directly take into account possible polyharmonic character of electrical values variations. In this case parameters R_1, L_{s1}, R_m are assumed constant, current $i_1(t)$ is presented by a polyharmonic series obtained as a result of spectral decomposition, and circular frequency ω is corrected for every considered harmonic in accordance with its number. The calculation results in the possibility to estimate time variation of values characterizing the magnetizing circuit, such as p_μ and $L_m(t)$ and also to determine their integral values.

Experimental research. The problem of this research consisted in verification of the adequacy of the developed method and its accuracy as compared with the basic one grounded on the equivalent sinusoid method [3] at different degrees of magnetic circuit steel saturation (for low-saturated ($0.75 < k_s < 1$), medium-saturated ($0.5 < k_s < 0.75$) and high-saturated ($k_s < 0.5$) conditions).

To estimate the adequacy of parameter determination a secondary winding with number W_2 of turns was applied on the magnetic core. It was used to determine the main magnetic flux Φ_0 in the core by value EMF e_2 of the secondary winding with the aim of independent measuring instantaneous values of steel losses

$$p_\mu = e_2 i_1 \frac{W_1}{W_2} \qquad (18)$$

and alternative determination of values R_m, L_m using relations

$$R_m = \frac{E_2^2 W_1^2}{P_\mu W_2^2}, \qquad R_\mu = \mathrm{Re}\left(\frac{\dot{E}_2 W_1}{\dot{I}_1 W_2}\right), \qquad (19,20)$$

relation (9), transformed relative to X_m, and relation (11) for determination of L_m.

Parameters of experimental specimen: core length $l = 110\,mm$; core width $b = 105\,mm$; sectional area $S = 3 \cdot 10^{-4}\,mm^2$; core type – helical; core material – steel E330 (thickness $d = 0.35mm$); numbers of winding turns $W_1 = 200$, $W_2 = 1000$; diameters of winding wires with insulation $d_1 = 0{,}5mm$; $d_2 = 0{,}1mm$; insulation type – varnish. Geometric parameters of the core allowed location of the windings at a sufficient distance from one another to make their mutual induction as low as possible. Value R_1 was directly determined by a measuring bridge and L_{s1} was calculated using the results of the experience of short circuit. Later during research they were considered constant.

In the process of research instantaneous values u_1, i_1, e_2 were measured for every level of saturation of the magnetic circuit. The measurements were made by means of a measuring and diagnostic complex with the use of a module of a multichannel analog digital converter (16-bit analog digital converter with conversion frequency 400 kHz). Further processing of the data and relevant calculation were made with the use of mathematical methods realized in [4].

The results of calculation and measurements are given in Table. Fig. 4 contains time dependence for $L_m(t)$ (*1* – calculated, *2* – experimental) and Fig. 5 – time dependences for $p_\mu(t), p_{cu}(t)$ with indication of average values of P_μ, P_{cu}. Fig. 6 shows a comparative analysis of dependences $p_\mu(t)$ (*1*– calculated, *2* – experimental), obtained in accordance with (14) and (18).

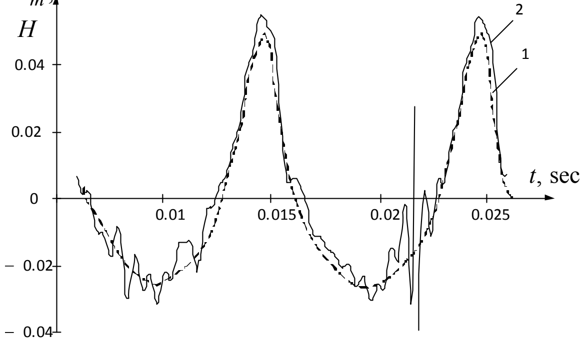

Fig. 4

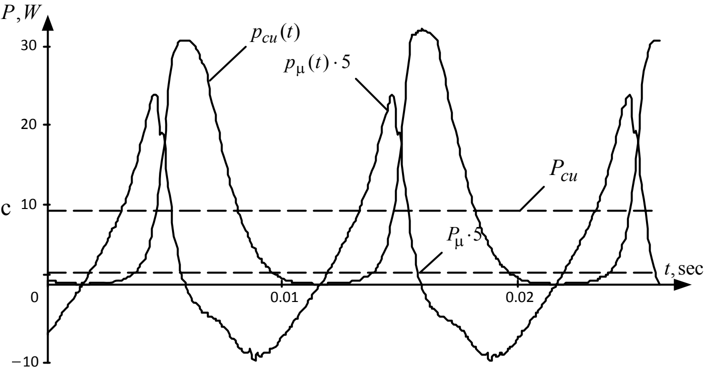

Fig. 5

The demonstrated results confirm the adequacy of determination of steel losses and sufficiently accurate presentation of instantaneous power and electromagnetic characteristics of the considered circuit at different degrees of saturation.

The data of calculations, measurements and corresponding errors are summarized in Table.

Parameter		Saturation degree		
		$0,75 < k_s < 1$	$0,5 < k_s < 0,75$	$k_s < 0,5$
P_μ, W	experiment	0,075	0,092	0,137
	basic method	0,069	0,085	0,121
	error, %	-8,00	-7,61	-11,68
	new method	0,073	0,091	0,134
	error, %	– 2,67	– 1,09	– 2,19
R_μ, Ω	experiment	3,51	2,54	1,73
	basic method	3,55	2,61	1,82
	error, %	1,14	2,76	5,20
	new method	3,54	2,58	1,78
	error, %	+0,85	+1,57	+2,89
L_μ, H	experiment	0,00202	0,00161	0,00117
	basic method	0,00192	0,00142	0,00084
	error, %	-4,95	-11,80	-28,21
	new method	0,00198	0,00155	0,00107
	error, %	– 1,98	– 3,73	– 9,40
R_m, Ω	experiment	734	699	655
	basic method	772	734	706
	error, %	5,18	5,01	7,79
	new method	760	714	673
	error, %	+2,18	+2,15	+2,75
L_m, H	experiment	0,0353	0,0281	0,0172
	basic method	0,0325	0,0214	0,0112
	error, %	-7,93	-23,84	-34,88
	new method	0,0331	0,0254	0,0165
	error, %	– 6,23	– 9,60	– 4,24

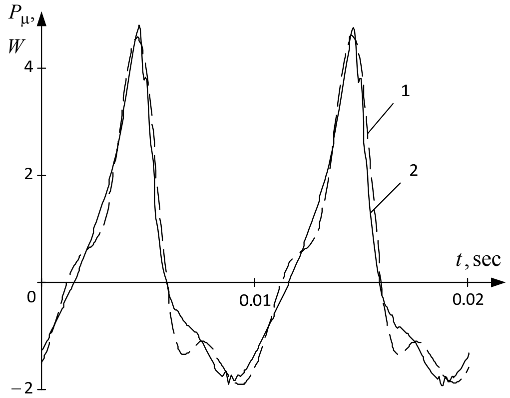

Fig. 6

It is obvious in Table and Figs. 4 and 6 that results of calculation coincide to a sufficient degree with the data of the experiments as to integral parameters and instantaneous power and electromagnetic characteristics.

Besides, calculation of the power balance confirmed the efficiency of the use of the offered circuit transformations, which makes it possible to take into account the properties of magnetic material more completely.

Conclusion.

1. A method for determination of the parameters of alternating current nonlinear circuits with steel, applicable at increased saturation of magnetic material, has been developed. This method is characterized by the error of parameter determination under the condition of average saturation of about 3−5% and under the condition of high saturation – by the error of about 7−9%, which is by 3−8 times less than in the case of the use of the basic calculation method.

2. The offered calculation relations provide obtaining an adequate mathematical description in time function of basic electromagnetic and power processes in nonlinear circuits with steel under saturated condition.

3. Further research results should be directed to expansion of the possibilities to use the developed method for more complicated types of electrotechnical and electromechanical devices. It enables one to improve the calculation of losses and efficiency, as well as heat processes in the considered devices, at different degrees of magnetic material saturation.

1. *Cathey, Jimmie J.* Electric machines: analysis and design applying Matlab. – Boston: McGraw-Hill, 2001. – 530 p.

2. *Ivanov-Smolenskii A.V.* Electric machines: Textbook for higher educational institutions. – Moskva: Energiia, 1980. – 928 p. (Rus)

3. *Kostenko M.P., Piotrovskii L.N.* Electric machines, part 1. – Leningrad: Energiia, 1964. – 548 p.; part 2. – Leningrad: Energiia, 1965. – 704 p. (Rus)

4. *Mathcad.* Users Guide. Mathcad 2000 Professional. **–** MathSoft, Inc.: 101 Main Street, Cambridge, Massachusetts 02142, USA. **–** 335 p.

5. *Prus V., Nikitina A., Zagirnyak M., Miljavec D.* Research of energy processes in circuits containing iron in saturation condition // Przeglad Elektrotechniczny (Electrical Revue). – 2011. – No 3. – Pp. 149–152.

6. *Prus V.V., Zagirnyak M.V., Kolotylo I.A., Miljavec D.* Estimate and taking into account change of steel losses in induction motors in process of their aging // Proceedings of International IEEE Conference EUROCON 2009. – Saint Petersburg, Russia, 2009. – Pp. 790–795.

7. *Prus V.V., Zagirnyak M.V., Nikitina A.V. //* Grounds for efficiency and prospect of the use of instantaneous power components in electric systems diagnostics // Przeglad Elektrotechniczny (Electrical Revue). – 2006. – No 12. – Pp. 123–125.

8. *Zidaric B., Zagirnyak M., Lenasi K., Miljavec D.* Hysteresis losses in soft magnetic composite materials // COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering. – 2006. – Vol. 25. – No 1. – Pp. 157–168.

УТОЧНЕНИЙ МЕТОД РОЗРАХУНКІВ ПАРАМЕТРІВ ЕЛЕКТРОМАГНІТНИХ І ЕНЕРГЕТИЧНИХ ПРОЦЕСІВ В ЕЛЕКТРИЧНИХ КОЛАХ ЗІ СТАЛЛЮ В РЕЖИМІ НАСИЧЕННЯ

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Обґрунтовано причини підвищення ступеню насичення магнітної системи електричних машин із тривалим напрацюванням на відмову. Доведено, що застосування існуючих методів розрахунків параметрів електромагнітних та енергетичних процесів при ступенях насичення, що зустрічаються на практиці, приводить до неприпустимих похибок. У процесі розв'язку задачі обґрунтовано уточнений метод розрахунку параметрів, застосовний у розглянутих умовах. Отриманий достатній ступінь збігу результатів розрахунків з даними експериментів за інтегральними параметрами та миттєвими енергетичними й електромагнітними характеристиками. Бібл. 8, табл. 1, рис. 6.

Ключові слова: коло зі сталлю, електромагнітні процеси, енергетичні процеси, ступінь насичення.

УТОЧНЕННЫЙ МЕТОД РАСЧЕТА ПАРАМЕТРОВ ЭЛЕКТРОМАГНИТНЫХ И ЭНЕРГЕТИЧЕСКИХ ПРОЦЕССОВ В ЭЛЕКТРИЧЕСКИХ ЦЕПЯХ СО СТАЛЬЮ В РЕЖИМЕ НАСЫЩЕНИЯ

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Обоснованы причины повышения степени насыщения магнитной системы электрических машин с продолжительной наработкой на отказ. Доказано, что применение существующих методов расчета параметров электромагнитных и энергетических процессов при встречающихся на практике степенях насыщения приводит к недопустимым погрешностям. В процессе решения задачи обоснован уточненный метод расчета параметров, применимый в рассматриваемых условиях. Получена достаточная степень совпадения результатов расчетов с данными экспериментов по интегральным параметрам и мгновенным энергетическим и электромагнитным характеристикам. Библ. 8, табл. 1, рис. 6.

Ключевые слова: цепь со сталью, электромагнитные процессы, энергетические процессы, степень насыщения.

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