UDC 621.313.333
DOI: 10.15587/1729-4061.2017.104146

REFINED CALCULATION OF INDUCTION MOTOR EQUIVALENT CIRCUIT NONLINEAR PARAMETERS BY AN ENERGY METHOD

Розглянуто використання методу повних рівнянь складових миттєвої потужності для задач визначення електромагнітних параметрів асинхронного двигуна. Отримано залежності, що описують складові миттєвої потужності на нелінійному активному опорі та нелінійній індуктивності ротора в залежності від струму ротора. Показана ефективність використання методу повних рівнянь складових миттєвої потужності при ідентифікації нелінійних параметрів асинхронного двигуна

Ключові слова: асинхронний двигун, енергетичний метод, схема заміщення, нелінійні електромагнітні параметри

Рассмотрено использование метода полных уравнений составляющих мгновенной мощности для задач определения электромагнитных параметров асинхронного двигателя. Получены зависимости, описывающие составляющие мгновенной мощности на нелинейном активном сопротивлении и нелинейной индуктивности ротора в зависимости от тока ротора. Показана эффективность использования метода полных уравнений составляющих мгновенной мощности при идентификации нелинейных параметров асинхронного двигателя

Ключевые слова: асинхронный двигатель, энергетический метод, схема замещения, нелинейные электромагнитные параметры

M. Zagirnyak
Doctor of Technical Sciences, Professor, Rector
Department of Electric Machines and Devices*
E-mail: mzagirn@kdu.edu.ua

D. Rod'kin
Doctor of Technical Sciences, Professor, Head of Department
Department of Systems of Automatic Control and Electric Drive*
E-mail: sau@kdu.edu.ua

Iu. Romashykhin
PhD, Associate Professor
Department of Systems of Automatic Control and Electric Drive*
E-mail: romashykhin.iurii@gmail.com

Zh. Romashykhina
PhD
Department of Electric Machines and Devices*
E-mail: romashykhina.zhanna@gmail.com

A. Nikolenko
PhD, Associate Professor, Head of Department**
Gagarina ave., 4, Dnipro, Ukraine, 49600

V. Kuznetsov
PhD, Associate Professor**

*Kremenchuk Mykhailo Ostrohradskyi National University
Pershotravneva str., 20, Kremenchuk, Ukraine, 39600
**Department of the electrical engineering and electromechanic
National metallurgical academy of Ukraine
Gagarina ave., 4, Dnipro, Ukraine, 49600

1. Introduction

At the stage of improvement of mathematical description of electric machines, the importance of accurate determination of their characteristics with the use of various methods and means of implementation grows. At present, the processes of energy conversion taking into account the induction motor (IM) particular nonlinear parameters are the object of the research. There is also a necessity for the research of electrical energy processes regulation and its conversion into mechanical one when IM operates at constant values of voltage and frequency [1, 2]. As a rule, IM nonlinear parameters represent physical properties of structural materials and phenomena in them. These phenomena occur under the impact of electromagnetic actions that can be observed in the process of transformation of the electrical energy into the mechanical one [3, 4].

In a certain way, availability of electric machines nonlinear parameters influences operating characteristics – the values of the starting and critical torques, admissible mechanical load, etc. In this connection, there appears a necessity for determination of real characteristics taking into consideration the peculiar features of the electric machine.

Knowledge of the parameters of induction machine nonlinearities is required in two typical cases.

1. In design of new-generation machines meant for variable-frequency electric drive systems. It is necessary for creation of systems providing maximum starting torque, maximum overload capacity, minimum operating temperature at the assigned load, etc.

2. In determination of IM complete electromagnetic parameters (EMP) in the process of production test after repair or during the current monitoring of parameters of the electrical equipment in service. It is necessary for determination of the real values of the starting torque, overloading and loading capacity of the electric motors.

Thus, development of the method for identification of IM parameters, taking into account their nonlinearity, is a topical task.

2. Literature review and problem statement

The interest in the problem of determination of induction motors electromagnetic parameters essentially grew in connection with the development of static frequency converters for the purposes of alternating current controlled electric drive [5]. At that time, there appeared a great number of papers dealing with determination of resistive impedance and inductance concerning simplified and detailed equivalent circuits [6]. The simplest solutions were obtained due to the use of L-shaped equivalent circuits with the magnetizing circuit taken to the terminals. More accurate results were obtained when the T-shaped equivalent circuit was used.

The analysis of the equivalent circuit with linear (constant) values of its components and resistances with taking into account the effect of current displacement in the rotor is common for the papers related to the considered problem [7]. The problem of taking into account the current displacement effect in the rotor is further developed by division of the rotor into several layers [8]. However, the drawback of this approach consists in impossibility to know the IM real geometric parameters and low accuracy of the obtained results. Elimination of the drawbacks concerning the knowledge of the geometric parameters is described in the paper [9], where the parameters of rotor resistance and leakage inductance are changed in order to take into account the effect of current displacement. The method of IM parameters identification [10] based on the integral calculation in the quiescent state for the admitted assumptions concerning IM parameters constancy is rather accurate. However, constancy of parameters in [9] and [10] can only be taken with possible big errors.

In [11], it is shown that creation of IM mathematical model is one of the ways of obtaining information about it. However, the information of the real state of the motor and current displacement effect influence on the rotor parameters is not taken into consideration in [11]. The use of genetic algorithms is rather topical but quite a lot of experiments are required to create a genetic model [12]. The paper [13] contains description of a method developed for the online assessment of the stator and rotor resistance with the use of artificial neural networks. In the mentioned approach, the assessment of the rotor resistance is insensitive to the change of the stator resistance, which is inadmissible.

Thus, there are a great number of the IM parameter determination methods based on the use of mathematical models or neural networks. However, they do not enable the assessment of the nonlinear characteristics and properties of the electric machines of this class.

The energy method is one of the modern methods for IM EMP determination [14]. The paper [14] contains the structure of creation of identification equations and special features of their use for IM EMP determination. Improvement of the energy method is shown in [15] in the form of introduction of the rotor nonlinear resistive impedance into the equivalent circuit; it takes into account the effect of current displacement in the rotor.

The analysis reveals that there are some factors due to which the interest in the considered problem shifts towards the IM characteristics detailing. Here the accent is based on the known propositions concerning IM nonlinear properties. This means that the possibilities of the energy method can be extended due to refinement of the expressions for the nonlinear parameters of the equivalent circuit.

3. The aim and objectives of the study

The aim of the research consists in the development of the methods for taking into account IM equivalent circuit nonlinear parameters when the energy method is used.

To achieve this aim, the following tasks of the research were solved:

– refinement of the expressions describing nonlinear inductance in the function of the rotor current;

– determination of the instantaneous power components for nonlinear inductance;

– assessment of the efficiency of the induction motor equivalent circuit parameter identification taking into account the refined expressions for the calculation of nonlinear resistive impedance and inductance with the use of the energy method.

4. The materials and methods of the research

Taking into account IM nonlinear properties refers to the sphere of their parameters identification during post-repair tests and current monitoring of the electric machines condition in the process of their operation.

Literature [1, 15] review revealed that the rotor resistive impedance is characterized by nonlinear variation due to the influence of current displacement effect and can be approximated by an even-power polynomial. In this case, the polynomial for the description of the rotor nonlinear resistive impedance can be limited to the second power with sufficient accuracy [15, 16]:

$$R_2(I_2) = R_{20} + k_R (i_2(t))^2, \tag{1}$$

where R_{20} – the rotor resistive impedance without taking into consideration its variation due to the displacement effect; k_R – the coefficient of approximation of nonlinear resistive impedance; $i_2(t)$ – rotor current flowing through the nonlinear resistive impedance.

In the general form, the rotor current can be presented by the dependence:

$$i_2(t) = \sum_{m=0}^{M} I_{2m} \cos(m\Omega t - \psi_m) = \\ = \sum_{m=0}^{M} I_{2am} \cos(m\Omega t) + \sum_{m=0}^{M} I_{2bm} \cos(m\Omega t), \tag{2}$$

where m – the number of the current harmonic; M – the quantity of the analyzed current harmonics; I_{2m} –

the value of the rotor current of the m-th harmonic; Ω – the circular frequency of the network; ψ_m – the angle of current harmonics phases shift; $I_{2am}=I_{2m}\cos\psi_m$ – the cosine component of the rotor current of the m-th harmonic; $I_{2bm}=$ $=I_{2m}\sin\psi_m$ – the sine component of the rotor current of the m-th harmonic.

The effect of current displacement in the rotor at the start also influences the value of inductive reactance that can also be expressed by a nonlinear dependence on current [14]:

$$L_2(I_2)=L_{20}-k_L\left(i_2(t)\right)^2, \qquad (3)$$

where L_{20} – rotor inductance without taking into account its variation caused by the displacement effect; k_L – the coefficient of nonlinear inductance approximation.

IM EMP determination taking into consideration dependences (2) and (3) is possible with the use of the energy method. This method is based on the use of complete equations of balance of instantaneous power harmonics components of the power supply and all the consumers [15, 17].

When the energy method is used, the system of equations is based on equality of the components of instantaneous power p(t) of the power supply and the sums of powers of all the consumers [14, 15]:

$$p_s(t)=\sum_{j=1}^{G}p_j(t), \qquad (4)$$

where j – the index of the corresponding consumer; G – the number of the consumers.

In relation to IM, each element of the equivalent circuit is considered to be a consumer (Fig. 1), i.e. consumers include stator resistive impedance R_1 and inductance L_1, rotor resistive impedance $R_2(I_2)$ and inductance $L_2(I_2)$ and magnetization circuit inductance L_μ [6].

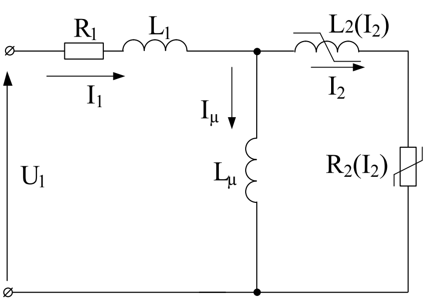

Fig. 1. T-shaped induction motor equivalent circuit with nonlinear resistive impedance and nonlinear inductance of the rotor

The method for calculation of instantaneous power components for linear elements of the equivalent circuit is described in [14, 17]. Determination of instantaneous power components for nonlinear resistive impedance is given in [15]. That is why it is necessary to additionally obtain instantaneous power components for the rotor nonlinear inductance.

Instantaneous powers for nonlinear elements of the equivalent circuit are determined as follows:

$$p_{R2}(t)=i_2^2(t)R_2(I_2)=i_2^2(t)\left(R_{20}+k_R\left(i_2(t)\right)^2\right);$$

$$p_{L2}(t)=i_2(t)\frac{d\left(L_2(I_2)i_2(t)\right)}{dt}=$$
$$=L_2(I_2)i_2(t)\frac{di_2(t)}{dt}+i_2^2(t)\frac{dL_2(I_2)}{dt}=$$
$$=\left(L_{20}-k_L\left(i_2(t)\right)^2\right)i_2(t)\frac{di_2(t)}{dt}+$$
$$+i_2^2(t)\frac{d\left(L_{20}-k_L\left(i_2(t)\right)^2\right)}{dt}. \qquad (5)$$

Instantaneous power components for the rotor nonlinear inductance:

$$P_{0L2}=L_{20}A_0;$$
$$P_{kaL2}=L_{20}k_LA_k+$$
$$+\frac{1}{2}k_L\Omega b(-2kA_0B_k-\sum_{n1=1}^{N}\sum_{n2=1}^{N}(n_2-n_1)A_{n1}B_{n2}+$$
$$+\sum_{n1=1}^{N}\sum_{n2=1}^{N}(n_1-n_2)A_{n1}B_{n2}-$$
$$-\sum_{n1=1}^{N}\sum_{n2=1}^{N}(n_1+n_2)A_{n1}B_{n2}-2\sum_{n1=1}^{N}\sum_{n2=1}^{N}n_1A_{n1}B_{n2}); \qquad (6)$$
$$P_{kbL2}=L_{20}k_LB_k+$$
$$+\frac{1}{2}k_L\Omega b(-2kA_0A_k+\sum_{n1=1}^{N}\sum_{n2=1}^{N}(n_1\pm n_2)A_{n1}A_{n2}+$$
$$+\sum_{n1=1}^{N}\sum_{n2=1}^{N}(n_1-n_2)B_{n1}B_{n2}-\sum_{n1=1}^{N}\sum_{n2=1}^{N}(n_1+n_2)B_{n1}B_{n2}-$$
$$-2\sum_{n1=1}^{N}\sum_{n2=1}^{N}n_1(A_{n1}^2-B_{n2}^2)),$$

where k – the number of the instantaneous power harmonic; P_{0L2}, P_{kaL2}, P_{kbL2} – constant, cosine and sine components of instantaneous power for nonlinear inductance;

– in the calculation of P_{kaL2}, the following is taken into consideration:

– for the third summand $k=n_2-n_1$ at $n_1<n_2$;
– for the fourth summand $k=n_1-n_2$ at $n_1>n_2$;
– for the fifth summand $k=n_1+n_2$;
– for the sixth summand $k=2n_1$ at $n_1=n_2$;

– in the calculation of P_{kbL2}, the following is taken into consideration:

– for the third summand $k=|n_1\pm n_2|$;
– for the fourth summand $k=n_1-n_2$ at $n_1>n_2$;
– for the fifth summand $k=n_1+n_2$;
– for the sixth summand $k=2n_1$ at $n_1=n_2$;

$$A_0=\frac{1}{2}\sum_{m1=1}^{M}\sum_{m2=1}^{M}\left(I_{2am1}^2-I_{2bm1}^2+2I_{2am1}I_{2bm2}\right);$$

$$A_n=\frac{1}{2}\left(\sum_{m1=1}^{M}\sum_{m2=1}^{M}2I_{2am1}I_{2am2}-\sum_{m1=1}^{M}\sum_{m2=1}^{M}2I_{2bm1}I_{2bm2}+\right.$$
$$\left.+\sum_{m1=1}^{M}\sum_{m2=1}^{M}2I_{2bm1}I_{2bm2}+\sum_{m1=1}^{M}\left(I_{2am1}^2-I_{2bm1}^2\right)\right); \qquad (7)$$

$$B_n=\frac{1}{2}\left(\sum_{m1=1}^{M}\sum_{m2=1}^{M}2I_{2am1}I_{2bm2}+\sum_{m1=1}^{M}\sum_{m2=1}^{M}2I_{2bm1}I_{2am2}-\right.$$
$$\left.-\sum_{m1=1}^{M}\sum_{m2=1}^{M}2I_{2bm1}I_{2am2}+\sum_{m1=1}^{M}I_{2am1}I_{2bm1}\right),$$

where n – the number of the cosine or sine harmonic component of the square of the rotor current $i_2^2(t)$; I_{2am1}, I_{2am2} – cosine components of the rotor current for harmonics m_1, m_2; I_{2bm1}, I_{2bm2} – sine components of the rotor current for harmonics m_1, m_2; in the calculation of A_0, $m_1=m_2$ is taken into account; in the calculation of A_n, B_n, the following is taken into account:

– for the first summand $n=m_2 \pm m_1$ at $m_1<m_2$;
– for the second summand $n=m_1+m_2$;
– for the third summand $n=m_2-m_1$ at $m_1<m_2$;
– for the fourth summand $n=m_1$.

For a T-shaped equivalent circuit (Fig. 1), the resistive impedances and inductances of the stator, rotor and magnetization circuit are the unknown parameters. The rotor and magnetization circuit current harmonics are not known either. The total number of the unknown parameters is 17.

To get the required number of identification equations, it is necessary to analyze three voltage and current harmonics at a time. Additional equations are obtained due to the use of equations created according to the first Kirchhoff's law. The specific features of the choice of voltage and current harmonics and generation of instantaneous power harmonic components are given in [14].

Thus, with the use of three harmonics of voltage and current (the first, the third and the fifth harmonics), the equations of the balance of instantaneous power harmonic components will be of the form:

$$\begin{cases} P_{0s}=P_{0R1}+P_{0R2}; \\ P_{2as}=P_{2aR1}+P_{2aR2}+P_{2aL1}+P_{2aL\mu}+P_{2aL2}; \\ P_{2bs}=P_{2bR1}+P_{2bR2}+P_{2bL1}+P_{2bL\mu}+P_{2bL2}; \\ P_{4as}=P_{4aR1}+P_{4aR2}+P_{4aL1}+P_{4aL\mu}+P_{4aL2}; \\ P_{4bs}=P_{4bR1}+P_{4bR2}+P_{4bL1}+P_{4bL\mu}+P_{4bL2}; \\ P_{6as}=P_{6aR1}+P_{6aR2}+P_{6aL1}+P_{6aL\mu}+P_{6aL2}; \\ P_{6bs}=P_{6bR1}+P_{6bR2}+P_{6bL1}+P_{6bL\mu}+P_{6bL2}; \\ P_{8as}=P_{8aR1}+P_{8aR2}+P_{8aL1}+P_{8aL\mu}+P_{8aL2}; \\ P_{8bs}=P_{8bR1}+P_{8bR2}+P_{8bL1}+P_{8bL\mu}+P_{8bL2}; \\ P_{10as}=P_{10aR1}+P_{10aR2}+P_{10aL1}+P_{10aL\mu}+P_{10aL2}; \\ P_{10bs}=P_{10bR1}+P_{10bR2}+P_{10bL1}+P_{10bL\mu}+P_{10bL2}; \end{cases} \quad (8)$$

the equations created according to the first Kirchhoff's law for the IM T-shaped equivalent circuit (Fig. 1):

$$\begin{cases} I_{1a1}=I_{\mu a1}+I_{2a1}; \quad I_{1b1}=I_{\mu b1}+I_{2b1}; \\ I_{1a3}=I_{\mu a3}+I_{2a3}; \quad I_{1b3}=I_{\mu b3}+I_{2b3}; \\ I_{1a5}=I_{\mu a5}+I_{2a5}; \quad I_{1b5}=I_{\mu b5}+I_{2b5}, \end{cases} \quad (9)$$

where P_{0s}, P_{0R1}, P_{0R2} – constant components of instantaneous power of the voltage source, stator and rotor resistive impedances;

P_{kas}, P_{kaR1}, P_{kaR2}, P_{kaL1}, $P_{kaL\mu}$, P_{kaL2} – cosine components of instantaneous power of the voltage source, stator and rotor resistive impedances, inductances of the stator, magnetization circuit and rotor;

P_{kbs}, P_{kbR1}, P_{kbR2}, P_{kbL1}, $P_{kbL\mu}$, P_{kbL2} – sine components of instantaneous power of the voltage source, stator and rotor resistive impedances, inductances of the stator, magnetization circuit and rotor;

I_{1a1}, I_{1a3}, I_{1a5}, I_{1b1}, I_{1b3}, I_{1b5} – cosine and sine components of the first, third and fifth harmonics of the stator current;

$I_{\mu a1}$, $I_{\mu a3}$, $I_{\mu a5}$, $I_{\mu b1}$, $I_{\mu b3}$, $I_{\mu b5}$ – cosine and sine components of the first, third and fifth harmonics of the magnetization current;

I_{2a1}, I_{2a3}, I_{2a5}, I_{2b1}, I_{2b3}, I_{2b5} – cosine and sine components of the first, third and fifth harmonics of the rotor current.

To confirm the obtained theoretical provisions, an experimental research was carried out.

5. The results of the experimental research of the induction motor parameter identification taking into account the nonlinear elements

The experimental research was carried out for IM switched to a transformer via a block of voltage and current sensors. The experiments were performed for the following voltage levels: 220 V, 180 V, 120 V, 40 V, recorded by the voltage and current sensors. Then the required levels of voltage and current harmonics were singled out.

During the experiments, 4AP100L4U3 IM was used:

– rated power of 4 kW;
– rated voltage of 220 V;
– rated current of 8.7 A;
– stator resistive impedance of R_1=1.35 Ohm;
– stator inductance of L_1=0.00676 Hn;
– magnetization circuit inductance of L_μ=0.246 Hn;
– rotor resistive impedance of R_2=1.38 Ohm;
– rotor inductance of L_2=0.00678 Hn.

The equivalent circuit parameters were calculated with the use of the system of identification equations (8), (9) the measured values of voltage and current, as well as instantaneous power harmonic components for the elements. Tables 1, 2 contain the measured values of the stator current harmonics for the following voltage levels 220 V, 180 V, 120 V, 40 V, and also the calculated components of the rotor current harmonics and the magnetization circuit. Table 2 contains the calculated electromagnetic parameters of IM equivalent circuit taking into consideration their nonlinearity. Table 2 also contains the coefficients of approximation of the rotor nonlinear resistive impedance and nonlinear inductance. Besides, these Tables contain the rotor current cosine and sine components I_{2a1}, I_{2a3}, I_{2a5}, I_{2b1}, I_{2b3}, I_{2b5}, resistive impedance R_{20}, inductance L_{20} and coefficients k_R and k_L describing the rotor nonlinear resistive impedance and nonlinear inductance.

As a result of the analysis of the obtained data (Tables 1, 2), errors of determination of IM equivalent circuit EMP are calculated; they are shown in Table 3. Maximum error of determination of the parameters of the analyzed motor is 4.07 %. Verification based on comparison of the stator current experimental and calculated curves (Fig. 2) revealed the adequacy of the obtained results as the determination coefficient R^2 equals 0.995.

Table 1

Measured and calculated values of induction motor currents

Measured values of currents (A)						
Parameter	Harmonic number					
	cosine components			sine components		
	1	3	5	1	3	5
Stator current harmonics I_1 at the stator voltage 220 V	27.514	–0.687	0.052	25.96	–1.11	0.072
Stator current harmonics I_1 at the stator voltage 180 V	24.48	–0.569	0.034	21.133	–0.603	0.021
Stator current harmonics I_1 at the stator voltage 120 V	18.28	–0.259	$7.01\cdot10^{-3}$	13.60	–0.146	$-1.98\cdot10^{-3}$
Stator current harmonics I_1 at the stator voltage 40 V	6.70	–0.013	$-2.29\cdot10^{-4}$	4.33	$-4.2\cdot10^{-3}$	$-9.14\cdot10^{-4}$
Calculated values of induction motor currents (A)						
Magnetization current harmonics I_μ at the stator voltage 220 V	1.807	–0.312	0.014	1.24	0.029	–0.01
Magnetization current harmonics I_μ at the stator voltage 180 V	0.994	–0.179	$-2.23\cdot10^{-3}$	0.107	–0.162	$-3.08\cdot10^{-3}$
Magnetization current harmonics I_μ at the stator voltage 120 V	–0.597	0.083	$7.753\cdot10^{-4}$	3.359	–0.057	$8.71\cdot10^{-4}$
Magnetization current harmonics I_μ at the stator voltage 40 V	–0.284	$-4\cdot10^{-3}$	$-4.25\cdot10^{-4}$	0.551	$-1.1\cdot10^{-4}$	$1.65\cdot10^{-4}$
Rotor current harmonics I_2 at the stator voltage 220 V	25.707	–0.375	0.038	24.718	–1.139	0.082
Rotor current harmonics I_2 at the stator voltage 180 V	23.489	–0.39	0.036	21.026	–0.441	0.024
Rotor current harmonics I_2 at the stator voltage 120 V	18.878	–0.342	$6.236\cdot10^{-3}$	10.336	–0.089	$-2.85\cdot10^{-3}$
Rotor current harmonics I_2 at the stator voltage 40 V	6.98	$-8.9\cdot10^{-3}$	$-1.87\cdot10^{-4}$	3.778	$-4.1\cdot10^{-3}$	$-1.08\cdot10^{-3}$

Table 2

Results of determination of induction motor parameters taking into account the equivalent circuit nonlinear elements

Parameter	Identified parameters			
Stator voltage value, V	220	180	120	40
Magnetization circuit inductance L_μ, Hn	0.248	0.248	0.248	0.246
Stator inductance L_1, Hn	$6.8\cdot10^{-3}$	$6.7\cdot10^{-3}$	$6.8\cdot10^{-3}$	$6.75\cdot10^{-3}$
Rotor inductance L_{20}, Hn	$5.435\cdot10^{-3}$	$5.795\cdot10^{-3}$	$6.286\cdot10^{-3}$	$6.707\cdot10^{-3}$
Rotor resistive impedance R_{20}, Ohm	3.235	2.74	2.06	1.463
Coefficient k_R, Ohm/A^2	$1.359\cdot10^{-3}$	$1.315\cdot10^{-3}$	$1.42\cdot10^{-3}$	$1.314\cdot10^{-3}$
Coefficient k_L, Hn/A^2	$0.9853\cdot10^{-6}$	$0.9525\cdot10^{-6}$	$1.03\cdot10^{-6}$	$1.162\cdot10^{-6}$

Table 3

Errors of induction motor parameter determination taking into account the nonlinear elements of the equivalent circuit

Parameter	Errors of the identified parameters			
Stator voltage value, V	220	180	120	40
Error of determination of magnetization circuit inductance ΔL_μ, %	0.813	0.813	0.813	0
Error of determination of the stator inductance ΔL_1, %	0.591	0.887	0.592	0.148
Error of determination of the rotor inductance ΔL_2, %	3.087	3.232	3.741	4.070
Error of determination of the rotor resistive impedance ΔR_2, %	2.467	2.847	3.448	3.911

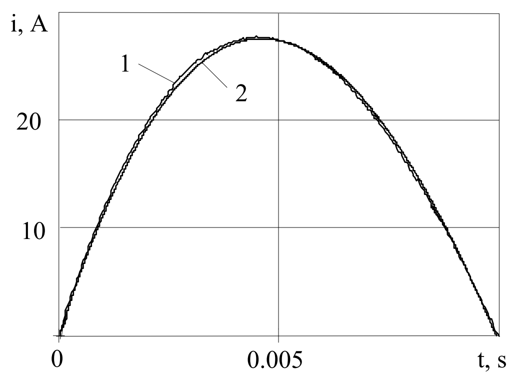

Fig. 2. The stator current curves:
1 – experimental; 2 – calculated

For practical purposes, it is convenient to use resistive impedance and inductance dependences on supply voltage for refinement of the start and energy characteristics, creation of models, etc. Dependences on the supply voltage of the efficient value of the rotor current first harmonic, rotor resistive impedance and rotor inductance are shown in Fig. 3–5. It can be seen from the analysis of the mentioned dependences that when the supply voltage changes, the rotor current values change (Fig. 3), the values of nonlinear resistive impedance (Fig. 4) and the rotor nonlinear inductance (Fig. 5) change accordingly.

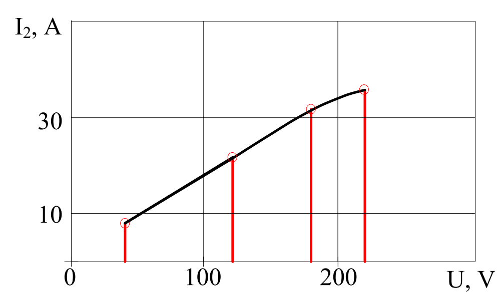

Fig. 3. The rotor current first harmonic effective value dependence on supply voltage

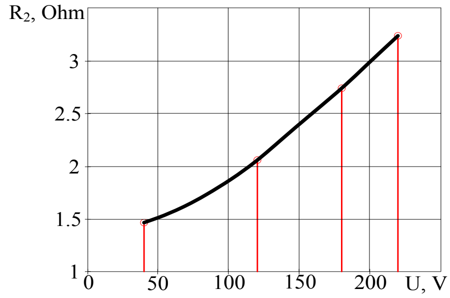

Fig. 4. The rotor resistive impedance dependence on supply voltage

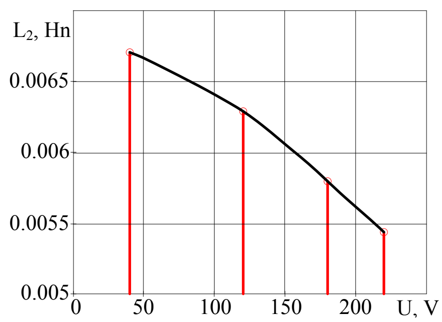

Fig. 5. The rotor inductance dependence on supply voltage

Thus, the analysis of the obtained results revealed that the energy method allows determination of IM parameters taking into account their nonlinearity in equivalent circuits. Results shown in Tables 1, 2 make it possible to come to the conclusion as to the expediency of the use of the energy method for identification of nonlinearities parameters.

The performed research made it possible to specify the calculation of IM parameters due to the use of the energy method. The essential advantage consists in additional introduction of nonlinear resistive impedance and inductance of the rotor into the equivalent circuit; they take into account the effect of current displacement in the rotor.

The performed research and the analysis of the obtained results revealed the efficiency and expediency of the use of the proposed method for the calculation of the nonlinear character of resistive impedance and inductance by the energy method.

The proposed method of induction motor nonlinear parameter determination with the use of the energy method is recommended for application at electrical-repair enterprises for identification of the parameters of motors with defects or breakages. The described method can be practically realized in creation of the software for determination of induction motor parameters in the problems of outgoing inspection at electrical-repair enterprises and enterprises-manufacturers.

In the future, the proposed method can be used for the analysis of the processes in IM as a nonlinear electromechanical converter. In this case, the number of the identified parameters in the equivalent circuit can be extended.

6. Discussion of the results of identification of induction motor electromagnetic parameters taking into account their nonlinearities

The expressions for taking into account the nonlinear character of the resistive impedance and inductance of the rotor made it possible to improve the energy method for identification of the induction motor electromagnetic parameters. The performed experimental research and the analysis of the obtained data revealed the efficiency and expediency of the use of the proposed method for identification of the induction motor electromagnetic parameters.

The improvement of the energy method consists in introduction of additional components into the system of identification equations. These components take into account the nonlinear character of the resistive impedance and inductance of the rotor. This allowed enhancement of the accuracy of identification of the induction motor electromagnetic parameters when the energy method is used.

In the future, the proposed method can be used to improve the accuracy of calculation of the induction motor electromagnetic parameters and published data in the problems of outgoing inspection at electrical-repair enterprises and enterprises-manufacturers.

7. Conclusions

1. Expressions enabling improvement of the method for the calculation of the induction motor electromagnetic parameters due to the introduction of nonlinear elements into the equivalent circuit to take into account the effect of current displacement in the rotor have been obtained.

2. Expressions for the instantaneous power components at the nonlinear resistive impedance and inductance, making it possible to take into consideration the effect of current displacement in the rotor during identification of the electromagnetic parameters by the energy method, have been obtained.

3. The use of the proposed method enabled improvement of the efficiency of the energy method application taking into account the effect of current displacement in the rotor, in particular, it allowed the decrease of the error of the induction motor electromagnetic parameters identification to 4.07 %. The adequacy of the obtained results has been assessed by the determination coefficient that makes 0.995.

References

1. Voldek, A. I. Electrical Machines. Machines of alternating current [Text] / A. I. Voldek, V. V. Popov. – Sankt-Peterburg, 2010. – 356 p.
2. Voliansky, R. Synthesis of active compensation system of spring oscillation in two–mass electromechanical object [Text] / R. Voliansky, A. Sadovoy // Eastern-European Journal of Enterprise Technologies. – 2015. – Vol. 4, Issue 7 (76). – P. 21–26. doi: 10.15587/1729-4061.2015.47178
3. Maga, D. Additional losses in permanent magnet brushless machines [Text] / D. Maga, M. Zagirnyak, D. Miljavec // Proceedings of 14th International Power Electronics and Motion Control Conference EPE-PEMC 2010. – 2010. doi: 10.1109/epepemc.2010.5606520

4. Zagirnyak, M. Diagnostic signs of induction motor broken rotor bars in electromotive force signal [Text] / M. Zagirnyak, Z. Romashykhina, A. Kalinov // 2016 17th International Conference Computational Problems of Electrical Engineering (CPEE). – 2016. doi: 10.1109/cpee.2016.7738722
5. Hasegawa, M. Parameter Identification Scheme for Induction Motors Using Output Inter-Sampling Approach [Text] / M. Hasegawa, D. Ogawa, K. Matsui // Asian Power Electronics Journal. – 2008. – Vol. 2, Issue 1. – P. 15–22.
6. Rodkin, D. I. Rationale for settlement circuit for induction motors [Text] / D. I. Rodkin, Y. V. Romashihin // Technical Electrodynamics. – 2012. – Issue 2. – P. 89–90.
7. Park, J. Evaluation of the detectability of broken rotor bars for double squirrel cage rotor induction motors [Text] / J. Park, B. Kim, J. Yang, S. B. Lee, E. J. Wiedenbrug, M. Teska, S. Han // 2010 IEEE Energy Conversion Congress and Exposition. – 2010. doi: 10.1109/ecce.2010.5617950
8. Benecke, M. Skin effect in squirrel cage rotor bars and its consideration in simulation of non-steady-state operation of induction machines [Text] / M. Benecke, R. Doebbelin, G. Griepentrog, A. Lindemann // Piers online. – 2011. – Vol. 7, Issue 5. – P. 421–425.
9. Popenda, A. Model-simulation investigations of induction motor with the consideration of skin effect in rotor bars [Text] / A. Popenda // Przeglad elektrotechniczny. – 2012. – Vol. 88, Issue 12. – P. 29–31.
10. Lee, S.-H. Identification of Induction Motor Parameters at Standstill Based on Integral Calculation [Text] / S.-H. Lee, A. Yoo, H.-J. Lee, Y.-D. Yoon, B.-M. Han // IEEE Transactions on Industry Applications. – 2017. – Vol. 53, Issue 3. – P. 2130–2139. doi: 10.1109/tia.2017.2650141
11. Zagirnyak, M. Decomposition of electromotive force signal of stator winding in induction motor at diagnostics of the rotor broken bars [Text] / M. Zagirnyak, A. Kalinov, Zh. Romashykhina // Scientific Bulletin of National Mining University. – 2016. – Issue 4 (154). – P. 54–61.
12. Emara, H. M. Parameter identification of induction motor using modified Particle Swarm Optimization algorithm [Text] / H. M. Emara, W. Elshamy, A. Bahgat // 2008 IEEE International Symposium on Industrial Electronics. – 2008. doi: 10.1109/isie.2008.4677254
13. Karanayil, B. Identification of Induction Motor Parameters in Industrial Drives with Artificial Neural Networks [Text] / B. Karanayil, M. F. Rahman, C. Grantham // Advances in Fuzzy Systems. – 2009. – Vol. 2009. – P. 1–10. doi: 10.1155/2009/241809
14. Mosyundz, D. Energy method of nonlinear inductance parameters identification [Text] / D. Mosyundz // XIV International PhD Workshop, OWD. – 2012. – P. 456–460.
15. Zagirnyak, M. Identification of nonlinearities of induction motor equivalent circuits with the use of the instantaneous power method [Text] / M. Zagirnyak, D. Rodkin, I. Romashykhin, N. Rudenko, V. Chenchevoi // 2016 17th International Conference Computational Problems of Electrical Engineering (CPEE). – 2016. doi: 10.1109/cpee.2016.7738721
16. Shimoni, K. Theoretical electrical engineering [Text] / K. Shimoni. – Moscow: Ripol Klassik, 2013. – 778 p.
17. Akagi, H. Instantaneous Power Theory and Applications to Power Conditioning [Text] / H. Akagi, M. Watanabe. – New York: Wiley, 2007. – 379 p.