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. 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]:

\[ R_\tau(I_\tau) = R_{20} + k_R(I_\tau(t))^2, \]  

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; \( I_\tau(t) \) – rotor current flowing through the nonlinear resistive impedance.

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

\[ I_\tau(t) = \sum_{m=0}^{M} I_{2m} \cos(m\Omega t - \psi_n) = \sum_{m=0}^{M} I_{2m} \cos(m\Omega t) + \sum_{m=0}^{M} I_{2m} \cos(m\Omega t), \]  

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; \( \Omega \) – the circular frequency of the network; \( \psi_{\text{im}} \) – the angle of current harmonics phases shift; \( I_{2m\text{an}}=I_{2m}\cos\psi_{\text{im}} \) – the cosine component of the rotor current of the m-th harmonic; \( I_{2m\text{sin}}=I_{2m}\sin\psi_{\text{im}} \) – 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]:

\[
L_2(i_2) = L_20 - k_i(i_2(t))^2,
\]

(3)

where \( L_20 \) – rotor inductance without taking into account its variation caused by the displacement effect; \( k_i \) – the coefficient of nonlinear inductance approximation.

IM EMP determination taking into consideration dependencies (2) and (3) is possible with the use of the energy method. This method is based on the 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]:

\[
p_j(t) = \sum_{i=1}^{G} p_{ij}(t),
\]

(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 \( L_\mu \) [6].

![Fig. 1. T-shaped induction motor equivalent circuit with nonlinear resistive impedance and nonlinear inductance of the rotor](image)

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:

\[
P_{ij}(t) = i_{ij}(t)\frac{d(L_2(i_2(t))i_2(t))}{dt} =
\]

\[
= L_2(i_2(t))\frac{di_2(t)}{dt} + i_2^2(t)\frac{dL_2(i_2(t))}{dt} =
\]

\[
= L_{2n} - k_i(i_2(t))^2 \frac{di_2(t)}{dt} +
\]

\[
i_2^2(t)\frac{d(L_{2n} - k_i(i_2(t))^2)}{dt}.
\]

(5)

Instantaneous power components for the rotor nonlinear inductance:

\[
P_{nli} = L_{2n}A_\nu A_\nu +
\]

\[
+ \frac{j}{2}k_i|\Omega|\frac{d}{dt}(-2kA_\nu B_\nu - \sum_{n=1}^{N} (n - n_i)A_{n1}B_{n2} +
\]

\[
+ \sum_{n=1}^{N} (n_1 - n)A_{n1}B_{n2} - \sum_{n=1}^{N} (n_1 + n)A_{n1}B_{n2} - 2\sum_{n=1}^{N} n_iA_{n1}B_{n2});
\]

(6)

\[
P_{nli} = L_{2n}k_iB_\nu +
\]

\[
+ \frac{j}{2}k_i|\Omega|\frac{d}{dt}(-2kA_\nu A_\nu + \sum_{i=1}^{M} (n_1 \pm n)A_{n1}A_{n2} +
\]

\[
+ \sum_{n=1}^{N} (n_1 - n)B_{n1}B_{n2} - \sum_{n=1}^{N} (n_1 + n)B_{n1}B_{n2} - 2\sum_{n=1}^{N} n^2A_{n1}B_{n2});
\]

(7)

where \( k \) – the number of the instantaneous power harmonic; \( P_{0il}, P_{0li}, P_{0li} \) – constant, cosine and sine components of instantaneous power for nonlinear inductance;

- in the calculation of \( P_{nli} \), the following is taken into consideration:
  - for the third summand \( k=n_2\leq n_1 \) at \( n_1\leq n_2 \);
  - for the fourth summand \( k=n_1\leq n_2 \) 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 \( P_{nli} \), the following is taken into consideration:

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

\[
A_\nu = \frac{1}{2}\sum_{n=1}^{M} \sum_{n=1}^{M} (I_{2n1}^2 - I_{2n2}^2 + 2I_{2n1}I_{2n2}I_{2n1}I_{2n2});
\]

\[
A_\nu = \frac{1}{2}\left( \sum_{n=1}^{M} \sum_{n=1}^{M} 2I_{2n1}I_{2n2} - \sum_{n=1}^{M} \sum_{n=1}^{M} 2I_{2n1}I_{2n2} +
\]

\[
+ \sum_{n=1}^{M} \sum_{n=1}^{M} 2I_{2n1}I_{2n2} + \sum_{n=1}^{M} I_{2n1}^2 - I_{2n1}^2 \right);
\]

(8)

\[
B_\nu = \frac{1}{2}\left( \sum_{n=1}^{M} \sum_{n=1}^{M} 2I_{2n1}I_{2n2} + \sum_{n=1}^{M} \sum_{n=1}^{M} 2I_{2n1}I_{2n2} -
\]

\[
- \sum_{n=1}^{M} \sum_{n=1}^{M} 2I_{2n1}I_{2n2} + \sum_{n=1}^{M} I_{2n1}^2 + I_{2n1}^2 \right),
\]

(9)
where \( n \) – the number of the cosine or sine harmonic component of the square of the rotor current \( i_2(t) \); \( I_{2a1}, I_{2a2} \) – cosine components of the rotor current for harmonics \( m_1, m_2; I_{2b1}, I_{2b2} \) – 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 \( A_m, B_m \), the following is taken into account:

- for the first summand \( n=m_2\pm m_1 \) at \( m_2<m_1 \);
- for the second summand \( n=m_1+m_2 \);
- for the third summand \( n=m_2\pm m_0 \) at \( m_0<m_2 \);
- for the fourth summand \( n=m_3 \).

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:

\[
P_{n1} = P_{a1R} + P_{a1L} + P_{b1R} + P_{b1L};
\]
\[
P_{n2} = P_{a2R} + P_{a2L} + P_{b2R} + P_{b2L};
\]
\[
P_{n3} = P_{a3R} + P_{a3L} + P_{b3R} + P_{b3L};
\]
\[
P_{ns} = P_{a4R} + P_{a4L} + P_{b4R} + P_{b4L};
\]
\[
P_{n6} = P_{a6R} + P_{a6L} + P_{b6R} + P_{b6L};
\]
\[
P_{ns} = P_{a8R} + P_{a8L} + P_{b8R} + P_{b8L};
\]
\[
P_{n10} = P_{a10R} + P_{a10L} + P_{b10R} + P_{b10L};
\]
\[
P_{n12} = P_{a12R} + P_{a12L} + P_{b12R} + P_{b12L};
\]
\[
P_{n14} = P_{a14R} + P_{a14L} + P_{b14R} + P_{b14L};
\]

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

\[
I_{1a1} = I_{a1}, I_{1a2} = I_{b1}, I_{1a3} = I_{a3}, I_{1a5} = I_{b3};
\]
\[
I_{1b1} = I_{a5}, I_{1b3} = I_{a3}, I_{1b5} = I_{b3};
\]
\[
I_{1b7} = I_{a5}, I_{1b9} = I_{a3}, I_{1b11} = I_{b3};
\]

where \( P_{01}, P_{02}, P_{03} \) – constant components of instantaneous power of the voltage source, stator and rotor resistive impedances;

\( P_{a1R}, P_{a1L}, P_{b1R}, P_{b1L}, P_{a3R}, P_{a3L}, P_{b3R}, P_{b3L}, P_{a5R}, P_{a5L}, P_{b5R}, P_{b5L}, P_{a7R}, P_{a7L}, P_{b7R}, P_{b7L} \) – sine components of instantaneous power of the voltage source, stator and rotor resistive impedances, inductances of the stator, magnetization circuit and rotor;

\( P_{a9R}, P_{a9L}, P_{b9R}, P_{b9L}, P_{a11R}, P_{a11L}, P_{b11R}, P_{b11L}, P_{a13R}, P_{a13L}, P_{b13R}, P_{b13L}, P_{a15R}, P_{a15L}, P_{b15R}, P_{b15L} \) – cosines components of instantaneous power of the voltage source, stator and rotor resistive impedances, inductances of the stator, magnetization circuit and rotor.

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 \( L_1=0.00678 \) Hn;
- magnetization circuit inductance of \( L_2=0.246 \) 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 \( I_{2a1}, I_{2a3}, I_{2a5}, I_{2b1}, I_{2b3}, I_{2b5}, I_{2a7}, I_{2a9}, I_{2a11}, I_{2b7}, I_{2b9}, I_{2b11} \), resistive impedance \( R_2 \), inductance \( L_2 \) 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.
Errors of induction motor parameter determination taking into account the nonlinear elements of the equivalent circuit

| Parameter          | Errors of the identified parameters |
|--------------------|-------------------------------------|
| Stator voltage V   | 220 180 120 40                      |
| Error of determin-  | 0.813 0.813 0.813 0 0               |
| ation of magne-     | tization circuit inductance ΔLm%    |
| tation of the stator | 0.591 0.887 0.592 0.148             |
| inductance ΔLs%     | 3.087 3.232 3.741 4.070             |
| Error of determin-  | 2.467 2.847 3.448 3.911             |
| ation of the rotor  | tative impedance ΔRr%               |
| resistive impedance |                                    |
| ΔR2%               |                                    |
| Measured and calculated values of induction motor currents

| Parameter          | Measured values of currents (A) | Harmonic number |
|--------------------|---------------------------------|-----------------|
| Stator current harmonics I1 at the stator voltage 220 V | 22.514 -0.687 0.052 25.96 -1.11 0.072 |
| Stator current harmonics I1 at the stator voltage 180 V | 24.48 -0.569 0.034 21.133 -0.663 0.021 |
| Stator current harmonics I1 at the stator voltage 120 V | 18.28 -0.259 7.01·10^-3 13.60 -0.146 -1.98·10^-3 |
| Stator current harmonics I1 at the stator voltage 40 V | 6.70 -0.013 -2.29·10^-4 4.33 -4.21·10^-3 -9.14·10^-4 |

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 | 0.248 0.248 0.248 0.248 |
| Stator inductance | 6.8·10^-3 6.7·10^-3 6.8·10^-3 6.75·10^-3 |
| Rotor inductance | 5.435·10^-3 5.795·10^-3 6.286·10^-3 6.707·10^-3 |
| Rotor resistive impedance | 3.235 2.74 2.06 1.463 |
| Coefficient kR | 1.359·10^-3 1.315·10^-3 1.42·10^-3 1.314·10^-3 |
| Coefficient kL | 0.9853·10^-4 0.9525·10^-4 1.03·10^-6 1.162·10^-6 |

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.
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 nonlinearity

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.

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