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Online-Identification of Electromagnetic Parameters of an Induction Motor

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Abstract. Incompliance of the settings of the system to control actual values of the parameters of a variable frequency induction electric drive may sometimes result in complete non-operability of a variable frequency electric drive as well as in the considerable reduction of the dynamic quality parameters. Such parameters as active rotor resistance, rotor inductance, and inductance of the magnetization circuit are available for the immediate measuring. They are not identified in terms of the acceptance tests, and the values presented in catalogues and reference books are calculated ones that may differ considerably from the real values of a certain machine. Despite constant studies by the researchers, a task to identify electromagnetic parameters of the equivalent circuit of an induction motor is still important and topical. The objective of the paper is to develop a method of online-identification of the electromagnetic parameters of an induction motor making it possible to implement accurate regulator adjustment of the frequency control system in terms of operational changes in the driving motor parameters. For the first time, the paper analyzes a steady mode of induction motor operation which does not apply T-network of the equivalent circuit of an induction motor. An approach has been proposed relying on the equation of an induction motor in three-phase fixed coordinate system obtained on the basis of the theory of generalized electromechanical converter.

Keywords: electric drive, identification method, system of equations, equation of electrical equilibrium, mathematical model, equation of flux, phase, angular velocity, steady state, numerical method, identification accuracy, rotor, stator, current, equivalent circuit

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Онлайн-идентификация электромагнитных параметров асинхронного двигателя

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Реферат. Несоответствие настроек системы управления фактическим значениям параметров частотно-регулируемого асинхронного электропривода может иногда приводить к полной

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неработоспособности частотного электропривода, к существенному снижению динамических показателей качества. Такие параметры, как активное сопротивление и индуктивность ротора, индуктивность цепи намагничивания, недоступны для непосредственного измерения. При приемо-сдаточных испытаниях они не определяются, а величины, приводимые в каталогах и справочниках, являются расчетными и могут существенно отличаться от реальных значений конкретной машины. Несмотря на постоянные усилия исследователей, задача идентификации электромагнитных параметров схемы замещения асинхронного двигателя остается важной и актуальной. Авторы статьи разработали метод онлайн-идентификации электромагнитных параметров асинхронного двигателя, что позволит реализовать точную настройку регуляторов системы частотного управления при эксплуатационных изменениях характеристик приводного двигателя. Выполнен анализ установившегося режима работы асинхронного двигателя без использования T-образной схемы его замещения. Предложен подход, опирающийся на уравнения асинхронного двигателя в трехфазной неподвижной системе координат, полученные на основе теории обобщенного электромеханического преобразователя. С учетом аналитических преобразований этих формул получена система нелинейных алгебраических уравнений четвертого порядка, решение которой позволяет определить активное сопротивление ротора, сопротивление рассеивания и главную взаимную индуктивность асинхронного двигателя в предположении, что активное сопротивление статора известно. Произведена верификация предлагаемого метода. На основании данных установившегося режима работы асинхронного двигателя типа 4A250M2У3 выполнена идентификация его электромагнитных параметров, исследовано влияние начального приближения на точность полученных результатов, которые подтверждают работоспособность рассматриваемого метода идентификации.

Ключевые слова: электропривод, метод идентификации, система уравнений, уравнение электрического равновесия, математическая модель, уравнение потокосцепления, фаза, угловая скорость, установившийся режим, численный метод, точность идентификации, ротор, статор, ток, схема замещения

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Introduction

High performance variable-speed machines incorporate a model for the system in either the controller or state estimation stages. The accuracy and general robustness of the machine is dependent on this model. Therefore, it must represent accurately both the electrical and electromagnetic interactions within the machine and associated mechanical systems.

Accurate and reliable parameter estimation techniques for an induction machine are critical for the design and development of high-performance drive systems in which the parameter estimates are used in the field of orientation, motion control, self-sensing, and other advanced algorithms. There are two basic approaches to this problem, viz.:

- online-identification methods – utilize state observer theory (e.g. Kalman filter) and Least Square based techniques;
- offline techniques – rely on statistical curve fitting to the measured data under specific conditions.

To be able to identify the unknown parameters of an induction motor, two main tests will be done on the induction motor according to IEEE test procedure [1]. The standard technique of using the short – circuit, no-load, and

blocked-rotor tests seems to be inaccurate and, consequently, not suitable for the synthesis of high dynamic performance systems.

Reference [2] suggested using an extended Kalman filter for parameter estimation. The machine's response to load perturbations was measured, and the resulting changes in current, voltage, speed, and torque were used to estimate the values of currents, mechanical damping, and magnetizing reactance.

Reference [3] dealt with creating a solution to identify the parameter of an induction motor by using $q, d, 0$ axis for the induction motor modeling. Genetic algorithm was applied to identify the parameters.

Reference [4] demonstrated the use of genetic algorithm to identify an induction motor by adding 4 different levels of noise. Kron's voltage equation was the applied mathematical model.

In reference [5], a parameter identification method was applied to identify all the electric parameters simultaneously. The method assumes that the motor can be described by a time-varying linear model.

Reference [6] presented a new approach to identify the nonlinear model of an induction machine. For simulation purposes, the measured stator voltages and rotor angular speed were treated as input, and the stator currents were simulated as output.

In reference [7], an approach to identify the induction motor parameters in parallel to the normal field-oriented controlled drive operation was represented. Besides an overview of the suitable system identification methods, the parameter estimation approach combined with a FIR-filter to determine the derivatives of measured signals was analyzed in detail as well as the use of the extended Kalman filter or the unscented Kalman filter for combined state and parameter estimation.

Reference [8] discussed an effect of the parameters variation on a variation in the performance characteristics of the motor. In order to identify parameters which have the most impact on motor performance, sensitivity analysis calculations were performed for a particular machine size.

Reference [9] proposed an adaptation mechanism (supervisor) for the PI-gain, allowing improvement of the classical controller, by introducing a certain degree of intelligence in the control strategy of the controller. Estimation of induction motor parameters based on fuzzy rules was represented.

Reference [10] proposed a new method, which derives induction motor (IM) parameters based on the equivalent network of the machine. The approach combined skin effect and saturation of the stator and rotor leakage paths, modelling rotor parameters as a function of the slip.

In reference [11], procedure of the identification was based on the model reference adaptive control (MRAC) system theory. An appropriate choice of the reference model allowed building a Lyapunov function by means of which the updating law of the rotor time constant can be found.

In reference [12], a new method of identification of the induction motor equivalent circuit parameters was introduced and discussed. The proposed method uses single-phase test results as a base test for calculating the equivalent circuit parameters of the induction motor.

Reference [13] described three methods for estimating the lumped model parameters of an induction motor using startup transient data, which was based on Levenberg – Marquardt method.

Reference [14] proposed an off-line parameter identification method that is suitable for self-commissioning of an electric drive in cases when machine and converter comes from different producers. The method was carried out entirely by means of a standard power inverter only by the impressed stator voltages.

Reference [15] proposed an identification method for induction motor parameters at standstill using integral calculations. The rotor time constant and magnetizing inductance were identified. References [16–18] dealt with different identification methods for the induction motor parameters at standstill too.

Reference [19] proposed a novel stator resistance estimation approach for stator winding temperature monitoring based on the wavelet network and parameter identification by the use of wavelet network that accurately localizes the characteristics of a signal in the time frequency domains.

Reference [20] also involved wavelet-transformations to identify the parameters of an induction motor. The approach is based on obtaining a 2D time-frequency plot representing the time-frequency evolution of the main components in an electrical machine transient current. The work used frequency B-spline (FBS) wavelets.

Reference [21] developed and substantiated experimentally new algorithms to identify unknown parameters of induction motors during self-commissioning procedure. To guarantee asymptotic identification, we design adaptive stator current controller based on stator flux observer.

Reference [22] was devoted to the parameter identification of large induction machines from the no-load acceleration-deceleration tests.

References [23, 24] considered solution of the problem of the IM parameters identification on the basis of the analysis of characteristics of external electromagnetic fields generated by an induction motor during the operation.

References [25–27] were mostly the reviews dealing with the analysis of standard procedures of diagnostics and determination of the induction motor parameters, description of the prospects of different methods for IM parameters identification, and comparative analysis of the accuracy of different identification methods and error introduced by the computational methods.

Use of T-network equivalent model for induction machine to analyze the steady mode or for differential IM equations in the system of coordinates $d, q, 0$ are the general features specific to the known papers. The methods proposed in the well-known scientific and technical literature are not suitable for the online-identification of the induction motor parameters being necessary for the development of a system of continuous monitoring of their technical condition.

For the first time, the paper proposed to use the known equations, obtained on the basis of the theory of generalized electromechanical converter, as the theoretical basis of the induction motor description [28]. Advantage of the

method is in the much higher accuracy of a theoretical model of an induction motor compared with the known approaches; that makes it possible to obtain principally new equations to identify the induction motor parameters.

Rearrangement of the equations of induction motor in the three-phase fixed coordinates

While generating the equations, we use following assumptions connected with the idea of an ideal motor:

- motor steel is unsaturated;
- phase windings of a rotor are symmetric and displaced uniformly in space;
- MMF of windings and magnetic fields are propagated sinusoidally along the circumference of an air gap;
- the rotor is symmetric both electrically and magnetically;
- factually arranged windings are replaced with the concentrated ones; MMF is taken as equal to the MMF of the real winding.

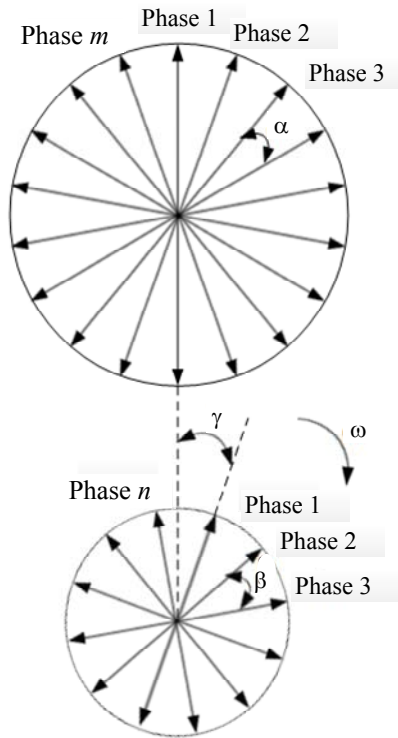


Fig. 1. Scheme of mutual arrangement of the stator and rotor windings of a multiphase induction motor

Multiphase IM is represented as the system of magnetically connected circuits located on the stator and rotor (Fig. 1).

Equation of electric balance for stator windings of a multiphase IM is as follows

$$\begin{cases} U_{S1} = i_{S1}R_S + \frac{d\psi_{S1}}{dt}; \\ U_{S2} = i_{S2}R_S + \frac{d\psi_{S2}}{dt}; \\ \dots \\ U_{SM} = i_{SM}R_S + \frac{d\psi_{SM}}{dt}. \end{cases} \quad (1)$$

Equation of electric balance for rotor windings of a multiphase IM is as follows

$$\begin{cases} U_{R1} = i_{R1}R_R + \frac{d\psi_{R1}}{dt}; \\ U_{R2} = i_{R2}R_R + \frac{d\psi_{R2}}{dt}; \\ \dots \\ U_{RN} = i_{RN}R_R + \frac{d\psi_{RN}}{dt}. \end{cases} \quad (2)$$

In terms of the aforementioned equations, following designations are adopted: U_k , I_k , R_k , $\frac{d\Psi_k}{dt}$ – voltage, current, resistance, and derivative of flux linkage of the corresponding circuit.

Equation of flux linkages for each of the stator phases is

$$\Psi_k = I_k L_k + \sum_{j=1}^{j=N, j \neq k} I_j M_{kj}. \quad (3)$$

Equation of flux linkages for each of the rotor phases is

$$\Psi_k = I_k L_k + \sum_{j=1}^{j=M, j \neq k} I_j M_{kj}, \quad (4)$$

where Ψ_k, I_k, L_k – flux linkage, current, and inductance of the k^{th} circuit; I_j, M_{kj} – current of the j^{th} circuit and mutual inductance of the k^{th} and j^{th} circuits.

While developing a mathematical model, there is the major difficulty due to the fact that mutual spatial arrangement of the rotor and stator windings experiences certain changes resulting in the changing value of the mutual inductance between those windings. As it is known, maximum value of the mutual inductance corresponds to the case when the axes of two phases coincide.

Basing on the geometrical ideas (Fig. 1) formula for mutual inductance between the rotor winding with n number and stator winding with m number may be represented as follows:

$$M_{SmRn} = M_0 \cos \left(\gamma - \frac{2\pi(m-1)}{M} + \frac{2\pi(n-1)}{N} \right). \quad (5)$$

In the general case, equation of flux linkages of the stator winding with m number may be written as follows:

$$\Psi_{Sm} = (L_S - M_S) I_{Sm} + M_0 \sum_{j=1}^N \left(\cos \left(\gamma - \frac{2\pi(m-1)}{M} + \frac{2\pi(j-1)}{N} \right) I_{Rj} \right). \quad (6)$$

Equation of flux linkages of the rotor winding with n number may be written as follows:

$$\Psi_{Rn} = (L_R - M_R) I_{Rn} + M_0 \sum_{j=1}^M \left(\cos \left(\gamma - \frac{2\pi(j-1)}{M} + \frac{2\pi(n-1)}{N} \right) I_{Sj} \right). \quad (7)$$

For a case of standard three-phase induction motor, equations (1)–(7) are rearranged in the known form [15]:

$$\begin{cases} \Psi_A = L_1 I_A + M_{i_a} \cos(\gamma) + M_{i_b} \cos\left(\gamma + \frac{2\pi}{3}\right) + M_{i_c} \cos\left(\gamma - \frac{2\pi}{3}\right); \\ \Psi_B = L_1 I_B + M_{i_a} \cos\left(\gamma - \frac{2\pi}{3}\right) + M_{i_b} \cos(\gamma) + M_{i_c} \cos\left(\gamma + \frac{2\pi}{3}\right); \\ \Psi_C = L_1 I_C + M_{i_a} \cos\left(\gamma + \frac{2\pi}{3}\right) + M_{i_b} \cos\left(\gamma - \frac{2\pi}{3}\right) + M_{i_c} \cos(\gamma). \end{cases} \quad (8)$$

Equation of flux linkages of a rotor:

$$\begin{cases} \Psi_a = L_2 i_a + MI_A \cos(\gamma) + MI_B \cos\left(\gamma - \frac{2\pi}{3}\right) + MI_C \cos\left(\gamma + \frac{2\pi}{3}\right); \\ \Psi_b = L_2 i_b + MI_A \cos\left(\gamma + \frac{2\pi}{3}\right) + MI_B \cos[\gamma] + MI_C \cos\left(\gamma - \frac{2\pi}{3}\right); \\ \Psi_c = L_c i_c + MI_A \cos\left(\gamma - \frac{2\pi}{3}\right) + MI_B \cos\left(\gamma + \frac{2\pi}{3}\right) + MI_C \cos[\gamma]. \end{cases} \quad (9)$$

The represented system of equations is characterized by the clear redundancy for a case of IM operation without a neutral conductor for which a sum of phase currents is equal to zero at any moment of time according to Kirchhoff's first law:

$$I_A + I_B + I_C = 0; \quad i_a + i_b + i_c = 0.$$

The relations are met in three-phase systems without a neutral conductor according to Kirchhoff's first law even in terms of any asymmetry of windings.

Rewrite equations of flux linkages (8) and (9), excluding phase current C of a stator and phase c of a rotor respectively. As a result, we obtain the simplified, reduced equations for IM phase flux linkages in a phase coordinate systems; general order of the IM equation system will reduce by two.

Rewrite the equation of flux linkages of phase A of a stator excluding current phase C from them using Kirchhoff's first law. Thus, we will have the following:

$$\begin{cases} \Psi_A = L_1 I_A + M \left(i_a \cos(\gamma) + i_b \cos\left(\gamma + \frac{2\pi}{3}\right) + (-i_a - i_b) \cos\left(\gamma - \frac{2\pi}{3}\right) \right) \Rightarrow \\ \Psi_A = L_1 I_A + M \left(i_a \left(\cos(\gamma) - \cos\left(\gamma - \frac{2\pi}{3}\right) \right) + i_b \left(\cos\left(\gamma + \frac{2\pi}{3}\right) - \cos\left(\gamma - \frac{2\pi}{3}\right) \right) \right). \end{cases} \quad (10)$$

Finally, simplifying trigonometric expression in brackets in (10), we obtain:

$$\Psi_A = L_1 I_A - M\sqrt{3}i_a \sin\left(\gamma - \frac{\pi}{3}\right) - M\sqrt{3}i_b \sin \gamma.$$

Similarly for phase B of a stator:

$$\begin{cases} \Psi_B = L_1 I_A + M \left(i_a \cos\left(\gamma - \frac{2\pi}{3}\right) + i_b \cos(\gamma) + (-i_a - i_b) \cos\left(\gamma + \frac{2\pi}{3}\right) \right) \Rightarrow \\ \Psi_B = L_1 I_A + M \left(i_a \left(\cos\left(\gamma - \frac{2\pi}{3}\right) - \cos\left(\gamma + \frac{2\pi}{3}\right) \right) + i_b \left(\cos(\gamma) - \cos\left(\gamma + \frac{2\pi}{3}\right) \right) \right) \\ \Psi_B = L_1 I_A - M\sqrt{3}i_a \sin(\gamma) - M\sqrt{3}i_b \sin\left(\gamma + \frac{\pi}{3}\right). \end{cases}$$

Similarly for phase a of a rotor:

$$\begin{cases} \Psi_a = L_2 i_a + M \left(I_A \cos(\gamma) + I_B \cos\left(\gamma - \frac{2\pi}{3}\right) + (-I_A - I_B) \cos\left(\gamma + \frac{2\pi}{3}\right) \right) \Rightarrow \\ \Psi_a = L_2 i_a + M \left(I_A \left(\cos(\gamma) - \cos\left(\gamma + \frac{2\pi}{3}\right) \right) + I_B \left(\cos\left(\gamma - \frac{2\pi}{3}\right) - \cos\left(\gamma + \frac{2\pi}{3}\right) \right) \right) \\ \Psi_a = L_2 i_a + M \sqrt{3} I_A \sin\left(\gamma + \frac{\pi}{3}\right) + M \sqrt{3} I_B \sin(\gamma). \end{cases}$$

Similarly for phase b of a rotor:

$$\begin{cases} \Psi_b = L_2 i_b + M \left(I_A \cos\left(\gamma + \frac{2\pi}{3}\right) + I_B \cos(\gamma) + (-I_A - I_B) \cos\left(\gamma - \frac{2\pi}{3}\right) \right) \Rightarrow \\ \Psi_b = L_2 i_b + M \left(I_A \left(\cos\left(\gamma + \frac{2\pi}{3}\right) - \cos\left(\gamma - \frac{2\pi}{3}\right) \right) + I_B \left(\cos(\gamma) - \cos\left(\gamma - \frac{2\pi}{3}\right) \right) \right) \\ \Psi_b = L_2 i_b + M \sqrt{3} I_A \sin(\gamma) - M \sqrt{3} I_B \sin\left(\gamma - \frac{\pi}{3}\right). \end{cases}$$

For the clarity of presentation, represent the reduced equations of flux linkages of separate IM windings:

$$\begin{cases} \Psi_A = L_1 I_A - M \sqrt{3} i_a \sin\left(\gamma - \frac{\pi}{3}\right) - M \sqrt{3} i_b \sin(\gamma); \\ \Psi_B = L_1 I_B + M \sqrt{3} i_a \sin(\gamma) + M \sqrt{3} i_b \sin\left(\gamma + \frac{\pi}{3}\right); \\ \Psi_a = L_2 i_a + M \sqrt{3} I_A \sin\left(\gamma + \frac{\pi}{3}\right) + M \sqrt{3} I_B \sin(\gamma); \\ \Psi_b = L_2 i_b - M \sqrt{3} I_A \sin(\gamma) - M \sqrt{3} I_B \sin\left(\gamma - \frac{\pi}{3}\right). \end{cases} \quad (11)$$

Assuming that the angular velocity is known and constant and considering that stator and rotor currents are sinusoidal for a steady mode, it is possible to obtain expressions for amplitudes and phases of the stator and rotor currents as well as the values of IM electromagnetic moments.

Write the expressions for phase currents of stator and rotor in terms of a steady mode:

$$\begin{cases} I_A = i_1 \sin(w_1 t - \varphi_1); \\ I_B = i_1 \sin\left(w_1 t - \varphi_1 - \frac{2\pi}{3}\right); \\ i_a = i_2 \sin(w_2 t - \varphi_2); \\ i_b = i_2 \sin\left(w_2 t - \varphi_2 - \frac{2\pi}{3}\right), \end{cases} \quad (12)$$

where i_1, i_2 – amplitudes of the stator and rotor currents respectively; w_1, w_2 – circular frequency of the stator and rotor respectively; φ_1, φ_2 – phase angle of the stator and rotor currents respectively.

Use symbol ω_2 for the angular velocity of a rotor.

It is known from the theory of electric machines that following ratio is completed in terms of steady mode

$$\omega_1 = \omega_2 + \omega_2.$$

Moreover, it is required to take into consideration that the turning angle of a rotor during the uniform motion under the steady mode may be calculated as follows:

$$\gamma = \omega_2 t.$$

Substituting equations (12) in equations (11), it is quite possible to obtain the equations of flux linkages of separate IM windings under the steady mode.

Thus, in terms of phase A , we obtain:

$$\Psi_A = L_1 I_A + \sqrt{3} i_2 M \left(\cos \left(\frac{\pi}{6} + \omega_2 t \right) \sin [w_2 t - \varphi_2] - \sin [\omega_2 t] \sin \left(w_2 t - \varphi_2 - \frac{2\pi}{3} \right) \right).$$

Simplify the products of trigonometric functions using the known trigonometric identities. After simple arrangements and combining similar terms, we will have:

$$\Psi_A = L_1 I_A + \frac{3}{2} M i_2 \sin (w_2 t - \varphi_2).$$

Applying similar method for equations of the rest IM windings, in the end we obtain following equations for flux linkages of separate IM windings under the steady mode:

$$\left\{ \begin{array}{l} \Psi_A = L_1 I_A + \frac{3}{2} M i_2 \sin (w_1 t - \varphi_2); \\ \Psi_B = L_1 I_B + \frac{3}{2} M i_2 \sin \left(w_1 t - \varphi_2 - \frac{2\pi}{3} \right); \\ \Psi_a = L_2 i_a + \frac{3}{2} M i_1 \sin (w_2 t - \varphi_1); \\ \Psi_b = L_2 i_b + \frac{3}{2} M i_1 \sin \left(w_2 t - \varphi_1 - \frac{2\pi}{3} \right). \end{array} \right. \quad (13)$$

As it is clear from the obtained equations, 120-degree shifts are preserved between the flux linkages; that demonstrates the symmetry of flux linkages relative to each other.

Using equations (1), (12), and (13), represent the reduced system of equations of electrical equilibrium in terms of steady mode. Expressions for supply voltages of separate stator windings are as follows:

$$\left\{ \begin{array}{l} U_A = U_0 \sin (w_1 t); \\ U_B = U_0 \sin \left(w_1 t - \frac{2\pi}{3} \right). \end{array} \right.$$

The objective of the further actions is to determine the unknown amplitudes of stator and rotor currents i_1 , i_2 and their phase angles φ_1 , φ_2 in terms of the specified parameters of supply voltage and angular rotor velocity ω_2 .

After differentiation (13) and substitution of the obtained results in (1), reduced system of the equations of electrical equilibrium in the steady mode will be as follows:

$$\begin{cases} U_A = I_A R_S + \frac{3}{2} M \omega_1 i_2 \cos(\omega_1 t - \varphi_2) + L_1 \omega_1 i_1 \cos(\omega_1 t - \varphi_1); \\ U_B = I_B R_S + \frac{3}{2} M \omega_1 i_2 \cos\left(\omega_1 t - \varphi_2 - \frac{2\pi}{3}\right) + L_1 \omega_1 i_1 \cos\left(\omega_1 t - \varphi_1 - \frac{2\pi}{3}\right); \\ 0 = i_a R_r + \frac{3}{2} M \omega_2 i_1 \cos(\omega_2 t - \varphi_1) + L_2 \omega_2 i_2 \cos(\omega_2 t - \varphi_2); \\ 0 = i_b R_r + \frac{3}{2} M \omega_2 i_1 \cos\left(\omega_2 t - \varphi_1 - \frac{2\pi}{3}\right) + L_2 \omega_2 i_2 \cos\left(\omega_2 t - \varphi_2 - \frac{2\pi}{3}\right). \end{cases} \quad (14)$$

The obtained system of equations is of fourth order having four unknowns, i. e. it is a defined system.

Write equation system (14) for the moment of time $t = 2\pi n$, $n = 0 \dots \infty$. For definiteness, set $t = 0$, which is not a critical assumption taking into account the periodicity of sinusoidal currents and voltages. At the moment of time $t = 0$, instant values of the supply voltages and currents of separate windings will be equal to:

$$\begin{cases} U_{A0} = 0; \\ U_{B0} = -U_0 \sin\left(\frac{2\pi}{3}\right); \\ I_{A0} = -i_1 \sin(\varphi_1); \\ I_{B0} = -i_1 \sin\left(\varphi_1 + \frac{2\pi}{3}\right); \\ i_{a0} = -i_2 \sin(\varphi_2); \\ i_{b0} = -i_2 \sin\left(\varphi_2 + \frac{2\pi}{3}\right). \end{cases} \quad (15)$$

Then, system (14), taking into consideration (15) for moment $t = 0$, may be represented as follows:

$$\begin{cases} 0 = -i_1 \sin(\varphi_1) R_S + \frac{3}{2} M \omega_1 i_2 \cos(\varphi_2) + L_1 \omega_1 i_1 \cos(\varphi_1); \\ -U_0 \sin\left(\frac{2\pi}{3}\right) = -i_1 \sin\left(\varphi_1 + \frac{2\pi}{3}\right) R_S + \frac{3}{2} M \omega_1 i_2 \cos\left(\varphi_2 + \frac{2\pi}{3}\right) + L_1 \omega_1 i_1 \cos\left(\varphi_1 + \frac{2\pi}{3}\right); \\ 0 = -i_2 \sin(\varphi_2) R_r + \frac{3}{2} M \omega_2 i_1 \cos(\varphi_1) + L_2 \omega_2 i_2 \cos(\varphi_2); \\ 0 = -i_2 \sin\left(\varphi_2 + \frac{2\pi}{3}\right) R_r + \frac{3}{2} M \omega_2 i_1 \cos\left(\varphi_1 + \frac{2\pi}{3}\right) + L_2 \omega_2 i_2 \cos\left(\varphi_2 + \frac{2\pi}{3}\right). \end{cases}$$

To find the currents and phase angles, it is required to solve the obtained system of nonlinear equations. Introduce following substitution of the variables to simplify the equation system and for its reduction to the system of linear algebraic equations:

$$\begin{cases} i_1 \sin(\varphi_1) = X_1; \\ i_1 \cos(\varphi_1) = X_2; \\ i_2 \sin(\varphi_2) = Y_1; \\ i_2 \cos(\varphi_2) = Y_2. \end{cases} \quad (16)$$

Initial equation for the phase of stator A is:

$$0 = -i_1 \sin(\varphi_1) R_s + \frac{3}{2} M \cos(\varphi_2) w_1 i_2 + \cos(\varphi_1) L_1 w_1 i_1.$$

Applying the aforementioned substitution of variables, reduce the equation to the following form:

$$0 = -X_1 R_s + X_2 L_1 w_1 + \frac{3}{2} M Y_2 w_1.$$

Initial equation for the phase of stator B is:

$$\frac{\sqrt{3}}{2} U_0 = -i_1 R_s \sin\left(\varphi_1 + \frac{2\pi}{3}\right) + \frac{3}{2} M w_1 i_2 \cos\left(\varphi_2 + \frac{2\pi}{3}\right) + L_1 w_1 i_1 \cos\left(\varphi_1 + \frac{2\pi}{3}\right).$$

Taking into consideration following trigonometric identities:

$$\begin{aligned} \sin\left(\varphi_1 + \frac{2\pi}{3}\right) &= \frac{\sqrt{3}}{2} \cos(\varphi_1) - \frac{1}{2} \sin(\varphi_1); \\ \cos\left(\varphi_2 + \frac{2\pi}{3}\right) &= -\frac{\sqrt{3}}{2} \sin(\varphi_2) - \frac{1}{2} \cos(\varphi_2), \end{aligned} \quad (17)$$

we obtain the equation for the phase of stator B in the following form

$$\begin{aligned} \frac{\sqrt{3}}{2} U_0 &= -i_1 R_s \left(\frac{\sqrt{3}}{2} \cos(\varphi_1) - \frac{1}{2} \sin(\varphi_1) \right) - \frac{3}{2} M w_1 i_2 \left(\frac{\sqrt{3}}{2} \sin(\varphi_2) + \frac{1}{2} \cos(\varphi_2) \right) - \\ &\quad - L_1 w_1 i_1 \left(\frac{\sqrt{3}}{2} \sin(\varphi_1) + \frac{1}{2} \cos(\varphi_1) \right) = \\ &= -\frac{\sqrt{3}}{2} R_s X_2 + \frac{1}{2} R_s X_1 - L_1 w_1 \frac{\sqrt{3}}{2} X_1 - \frac{1}{2} L_1 w_1 X_2 - \frac{3\sqrt{3}}{4} M w_1 Y_1 - \frac{3}{4} M w_1 Y_2. \end{aligned}$$

After reduction of the similar terms, we will obtain the following:

$$\frac{\sqrt{3}}{2}U_0 = X_1 \left(\frac{1}{2}R_s - L_1 w_1 \frac{\sqrt{3}}{2} \right) + X_2 \left(-\frac{\sqrt{3}}{2}R_s - \frac{1}{2}L_1 w_1 \right) - \frac{3\sqrt{3}}{4}Mw_1 Y_1 - \frac{3}{4}Mw_1 Y_2.$$

Initial equation for the phase of rotor a is:

$$0 = -i_2 R_r \sin(\varphi_2) + \frac{3}{2}Mw_2 i_1 \cos(\varphi_1) + L_2 w_2 i_2 \cos(\varphi_2).$$

Applying substitution of variables (16), we obtain

$$0 = \frac{3}{2}Mw_2 X_2 - R_a Y_1 + L_2 w_2 Y_2.$$

Initial equation for the phase of rotor b is:

$$0 = -i_2 R_r \sin\left(\varphi_2 + \frac{2\pi}{3}\right) + \frac{3}{2}Mw_2 i_1 \cos\left(\varphi_1 + \frac{2\pi}{3}\right) + L_2 w_2 i_2 \cos\left(\varphi_2 + \frac{2\pi}{3}\right).$$

Taking into consideration trigonometric identities (17), we will obtain:

$$0 = -i_2 R_r \left(\frac{\sqrt{3}}{2} \cos(\varphi_2) - \frac{1}{2} \sin(\varphi_2) \right) - \frac{3}{2}Mw_2 i_1 \left(\frac{\sqrt{3}}{2} \sin(\varphi_1) + \frac{1}{2} \cos(\varphi_1) \right) - L_2 w_2 i_2 \left(\frac{\sqrt{3}}{2} \sin(\varphi_2) + \frac{1}{2} \cos(\varphi_2) \right).$$

Applying substitution of variables (16), we have:

$$0 = -\frac{\sqrt{3}}{2}R_r Y_2 + \frac{1}{2}R_r Y_1 - \frac{3\sqrt{3}}{4}Mw_2 X_1 - \frac{3}{4}Mw_2 X_2 - \frac{\sqrt{3}}{2}L_2 w_2 Y_1 - \frac{1}{2}L_2 w_2 Y_2.$$

After reduction of the similar terms, we will obtain the following:

$$0 = -\frac{3\sqrt{3}}{4}Mw_2 X_1 - \frac{3}{4}Mw_2 X_2 + Y_1 \left(\frac{1}{2}R_r - \frac{\sqrt{3}}{2}L_2 w_2 \right) + Y_2 \left(-\frac{\sqrt{3}}{2}R_r - \frac{1}{2}L_2 w_2 \right).$$

Write the obtained equation in the form of a system:

$$\left\{ \begin{array}{l} 0 = -X_1 R_s + X_2 L_1 w_1 + \frac{3}{2}Mw_1 Y_2; \\ \frac{\sqrt{3}}{2}U_0 = X_1 \left(\frac{1}{2}R_s - \frac{\sqrt{3}}{2}L_1 w_1 \right) + X_2 \left(-\frac{\sqrt{3}}{2}R_s - \frac{1}{2}L_1 w_1 \right) - \\ \quad - \frac{3\sqrt{3}}{4}Mw_1 Y_1 - \frac{3}{4}Mw_1 Y_2; \\ 0 = \frac{3}{2}Mw_2 X_2 - R_a Y_1 + L_2 w_2 Y_2; \\ 0 = -\frac{3\sqrt{3}}{4}Mw_2 X_1 - \frac{3}{4}Mw_2 X_2 + Y_1 \left(\frac{1}{2}R_r - \frac{\sqrt{3}}{2}L_2 w_2 \right) + Y_2 \left(-\frac{\sqrt{3}}{2}R_r - \frac{1}{2}L_2 w_2 \right). \end{array} \right. \quad (18)$$

Identification of the induction motor electromagnetic parameters

Assume that following values are known: supply voltage U_0 ; amplitude and phase of stator current $-i_1$, φ_1 ; active resistance of stator R_S ; angular velocity of rotor ω_2 . Voltage and current of a stator may be defined easily by the immediate measuring in terms of the steady mode with the following processing and determination of the first harmonic parameters. It means that variables X_1 and X_2 , defined with the help of formula (16), are also known.

Online-determination of active resistance of stator R_S is of the highest difficulty. That problem is possible to be solved on the basis of the analysis of starting conditions of an induction motor [29]. The paper [30] proposes a universal method to determine active resistance of the phase of the alternating-current motor stator, according to which the resistance maybe calculated as the ratio of average values of integral functions of the supply voltage and phase current, where averaging is performed from the moment of energizing according to the function:

$$R_S = \frac{\lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T \left(\int_0^t U_A dt \right) dt}{\lim_{T \rightarrow \infty} \frac{1}{T} \int_0^T \left(\int_0^t i_A dt \right) dt} = \frac{i U_{Amean}}{ii_{Amean}}.$$

The proposed solution makes it possible to determine active resistance of the IM stator phases even in terms of the available parametric asymmetry of a stator at each starting, maintaining the importance of the value of active resistance while operating.

Analysis of equation system (18) shows that six parameters remain to be unknown, i. e. active resistance of rotor R_r , complete inductances of stator and rotor phases L_1 and L_2 , main IM mutual inductance M , and rotor current determined by variables Y_1 , Y_2 according to (16).

Since, according to [15], $L_1 = L_{1\delta} - \frac{3}{2}M$; $L_2 = L_{2\delta} - \frac{3}{2}M$, then complete inductances of stator and rotor phases L_1 and L_2 differ by the value of the difference in resistances of stator and rotor dissipation, i. e. the difference is slight.

Additionally, assume that $L_1 = \varepsilon_1 M$, $L_2 = \varepsilon_2 M$, where ε_1 and ε_2 are known numerical coefficients. Thus, we may exclude complete inductances of stator and rotor phases from the unknowns and reduce the number of unknowns down to four: R_r , M , Y_1 , Y_2 .

Rewrite system (18) relative to the adopted unknowns:

$$\left\{ \begin{array}{l} 0 = -X_1 R_s + X_2 \varepsilon_1 M w_1 + \frac{3}{2} M w_1 Y_2; \\ \frac{\sqrt{3}}{2} U_0 = X_1 \left(\frac{1}{2} R_s - \frac{\sqrt{3}}{2} \varepsilon_1 M w_1 \right) + X_2 \left(-\frac{\sqrt{3}}{2} R_s - \frac{1}{2} \varepsilon_1 M w_1 \right) - \frac{3\sqrt{3}}{4} M w_1 Y_1 - \frac{3}{4} M w_1 Y_2; \\ 0 = \frac{3}{2} M w_2 X_2 - R_r Y_1 + \varepsilon_2 M w_2 Y_2; \\ 0 = -\frac{3\sqrt{3}}{4} M w_2 X_1 - \frac{3}{4} M w_2 X_2 + Y_1 \left(\frac{1}{2} R_r - \frac{\sqrt{3}}{2} \varepsilon_2 M w_2 \right) + Y_2 \left(-\frac{\sqrt{3}}{2} R_r - \frac{1}{2} \varepsilon_2 M w_2 \right); \\ \\ X_1 R_s = X_2 \varepsilon_1 M w_1 + \frac{3}{2} M w_1 Y_2; \\ \frac{\sqrt{3}}{2} U_0 - \frac{1}{2} X_1 R_s + \frac{\sqrt{3}}{2} X_2 R_s = -\frac{\sqrt{3}}{2} \varepsilon_1 M X_1 w_1 - \frac{1}{2} X_2 \varepsilon_1 M w_1 - \\ - \frac{3\sqrt{3}}{4} M w_1 Y_1 - \frac{3}{4} M w_1 Y_2; \\ 0 = \frac{3}{2} M w_2 X_2 - R_r Y_1 + \varepsilon_2 M w_2 Y_2; \\ 0 = -\frac{3\sqrt{3}}{4} M w_2 X_1 - \frac{3}{4} M w_2 X_2 + \frac{1}{2} Y_1 R_r - \frac{\sqrt{3}}{2} \varepsilon_2 M w_2 - \frac{\sqrt{3}}{2} R_r Y_2 - \frac{1}{2} \varepsilon_2 M w_2 Y_2. \end{array} \right.$$

$$\text{Designate } K = \frac{\sqrt{3}}{2} U_0 - \frac{1}{2} X_1 R_s + \frac{\sqrt{3}}{2} X_2 R_s.$$

We will obtain the following from the first equation:

$$M Y_2 = \frac{2 X_1 R_s}{3 w_1} - \frac{2 X_2 \varepsilon_1}{3} M = \alpha - \beta M$$

and substitute that expression in the remained equations:

$$\left\{ \begin{array}{l} 0 = X_2 \varepsilon_1 M w_1 + \frac{3}{2} M w_1 Y_2 - X_1 R_s; \\ 0 = -K - \frac{3}{4} w_1 \alpha - \left(\frac{\sqrt{3}}{2} \varepsilon_1 X_1 w_1 + \frac{1}{2} X_2 \varepsilon_1 w_1 - \frac{3}{4} w_1 \beta \right) M - \frac{3\sqrt{3}}{4} M w_1 Y_1; \\ 0 = \varepsilon_2 w_2 \alpha + \left(\frac{3}{2} w_2 X_2 - \varepsilon_2 w_2 \beta \right) M - R_r Y_1; \\ 0 = -\frac{1}{2} \varepsilon_2 w_2 \alpha + \left(-\frac{3\sqrt{3}}{4} w_2 X_1 - \frac{3}{4} w_2 X_2 + \frac{1}{2} \varepsilon_2 w_2 \beta \right) M + \\ + \frac{1}{2} R_r Y_1 - \frac{\sqrt{3}}{2} \varepsilon_2 M w_2 Y_1 - \frac{\sqrt{3}}{2} R_r Y_2. \end{array} \right. \quad (19)$$

The obtained system is the system of nonlinear algebraic equations of fourth order which may be solved numerically.

To verify the proposed approach, the MatLab application was applied; the programme has rather wide range of the implemented numerical methods to solve the systems of nonlinear equations and to offer ample opportunities for their setting. Function *fsolve* was used to find solution for system (19).

Induction motor of 4A250M2Y3 type was used to test experimentally the obtained equations; the motor had following technical characteristics: nominal rated power $P_n = 90$ kW; nominal linear voltage $U_n = 380$ V; nominal rotation frequency $n = 2940$ rot/min; nominal efficiency 0.938; nominal power coefficient $\cos\varphi = 0.88$; starting current ratio $k_i = 7$; and surge capability $k_m = 2.7$.

In terms of that motor, parameters of the equivalent circuit were specified: active resistance of stator and rotor phase $R_s = 0.0312$ Ohm, $R_r = 0.0236$ Ohm; inductance of dissipation of stator and rotor phase $L_{s\delta} = 0.0003394$ H, $L_{r\delta} = 0.0004604$ H; and inductance of magnetization contour $M = 0.0158$ H.

Fig. 2, 3 demonstrate the results of mathematical modeling of the steady mode; the figures indicate the values necessary for further calculations.

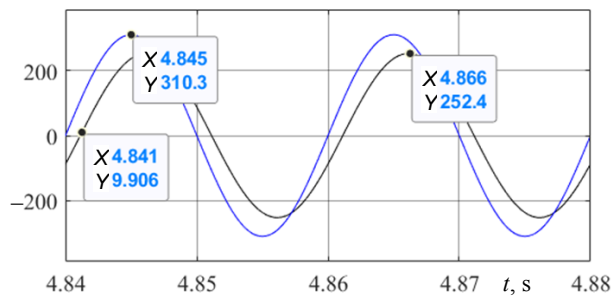


Fig. 2. Diagrams of phase voltage and current in the steady mode of induction motor operation

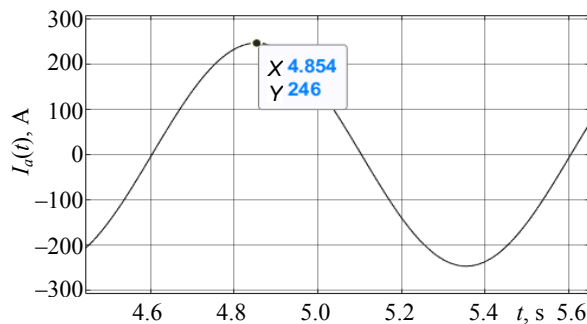


Fig. 3. Diagrams of rotor current in the steady mode of induction motor operation

The graph of the rotor current is given to control the performed identification.

Use the represented diagrams to determine following numerical values necessary to specify the coefficients of equation system (19): $U_0 = 310.3$ V; $I_{10} = 252.4$ A; $f\hat{1} = 0.351858$; $R_s = 0.0312$ Ohm.

The required initial approximation of the solution may be found using the rated values of the machine. While solving equation system (19), missing IM parameters were identified. Tab. 1 represents the data concerning the accuracy of the obtained solutions.

Table 1

Accuracy of the identification of the induction motor parameters

Parameter	Exact value	Value found during the identification	Relative error, %
L_M , H	-0.0158	-0.0145	8.23
R_2 , Ohm	0.0236	0.0238	0.85
I_2 , A	246	245.1816	0.33

The fulfilled study of the parametric sensitivity of equation system (19) has shown that the obtained solutions do not depend practically on the initial approximation of the solution; numerical method provides convergence to the parameter values indicated in Tab. 1.

CONCLUSIONS

1. A reduced system of electrical equilibrium equations of fourth order has been developed on the basis of general system of equations of multiphase induction motor in the coordinate system fixed relative to a stator; the developed system of equations describes the operation of an induction motor in the steady mode.

2. A system of equations has been obtained to identify electromagnetic parameters of an induction motor on the basis of the analysis of the steady mode data; efficiency of the proposed method of identification has been substantiated experimentally. In terms of the induction motor with the power of 90 kW, relative identification error for certain parameters was up to 8 %.

3. High convergence of the solution of the system of nonlinear equations and tolerance of the obtained results to the initial approximation of the parameters being identified has been proved experimentally.

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