

Model of an Induction Motor in a Rotating Coordinate System

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Abstract. The paper is devoted to the creation of a model of an induction drive in a rotating coordinate system during the transition from a three-phase system to a two-phase one. New mathematical replacements are proposed to simplify the solution of equations. From these mathematical replacements a model was created in Matlab Simulink. This model was compared with the model from the Simulink standard library. The comparison was made for the following output parameters: speed, load torque, stator current. The adequacy and correctness of the created model were proved and all the mathematical equations describing it were described.

Keywords: induction motor, mathematical model, modeling, Matlab Simulink.

Introduction

The electromechanical properties of an induction electric motor are most easily and conveniently studied using mathematical modeling, which determines the relevance of the topic accepted for consideration.

At present, the development of mathematical methods for the study of electrical machines is associated with the widespread use of computers, which makes it possible to implement the most complete models of transient processes with a minimum number of assumptions. The essence of the methods consists in the development system of a model and their implementation on a computer in the form of software systems for carrying out computational experiments in any possible conditions for the functioning of electrical machines. Possessing the simplicity of varying the structure and parameters of the design scheme, the mathematical model, with an appropriate level of adequacy, makes it possible to obtain, in the course of computational experiments, the necessary information for the development and design of electrical machines, their control and protection systems. However, as you know, the complexity of the phenomena, occurring in electric machines of alternating current during transient processes, makes their mathematical description and study without several simplifying assumptions practically impossible. The desire to take into account the main factors that determine the properties of the machine, and neglect the secondary factors leads to the consideration of an idealized electrical machine.

Such a machine is usually characterized by the absence of saturation, hysteresis, and eddy currents in the magnetic circuit, the absence of current displacement in the winding conductors, complete symmetry of the stator windings, and several other assumptions. [1] These are the assumptions made when simulating an induction electric motor operation in Matlab Simulink when choosing default blocks from the Simscape/Machines library. This standard model is based on the RL circuit. For more accurate results of electromechanical processes, flowing in an induction electric motor, it is proposed to use a model of an electric motor in a rotating coordinate system. At the same time, there are various ways of calculating this model. Some of them are based on vector control [2-4], others were developed in the 20th century [5-7], and many also have their own unique ways of describing. [8-12] However, these methods use vector multiplication, Euler transformations, and the substitutions made when calculating differential equations lead to many terms in the equation. Therefore, this article proposes the calculation of the induction motor model in a rotating coordinate system during the transition from a three-phase system to a two-phase one.

Mathematical calculation of the induction drive model

Initially, the induction drive is a three-phase electric machine with an implicit-pole rotor, it is proposed to simplify this model to a two-phase one. To simplify the mathematical description of

induction drive, the space vector method turned out to be suitable. The method allows linking the rotor flux linkage equations into a single system with vector state variables. The essence of the method is that the instantaneous values of symmetric three-phase state variables (voltage, currents, flux linkage) can be mathematically transformed so that they are represented by one space vector. We represent a system of equations with vector state variables for the case with an arbitrary orientation of the coordinate system.

$$\vec{U}_S = r_S \vec{i}_S + \frac{d\vec{\Psi}_S}{dt} + j\alpha_k \vec{\Psi}_S, \quad (1.1)$$

$$\vec{U}_R = r_R \vec{i}_R + \frac{d\vec{\Psi}_R}{dt} + j(\alpha_k - p\vartheta_m) \vec{\Psi}_R, \quad (1.2)$$

$$\vec{\Psi}_S = x_S \vec{i}_S + x_m \vec{i}_R, \quad (1.3)$$

$$\vec{\Psi}_R = x_R \vec{i}_R + x_m \vec{i}_S, \quad (1.4)$$

$$m = k \text{Mod}(\vec{\Psi}_i * \vec{i}_k), \quad (1.5)$$

$$\vec{T}_m \frac{d\vartheta_m}{dt} = m - m_c. \quad (1.6)$$

Here \vec{U}_S , \vec{U}_R , \vec{i}_S , \vec{i}_R , $\vec{\Psi}_S$ and $\vec{\Psi}_R$ are two-element vectors of voltages, currents and flux linkages, presented in an arbitrarily oriented orthogonal (two-phase) coordinate system in the form of components along the coordinate axes. The variable ω_k is used to set an arbitrary frequency of rotation of the coordinate system. The auxiliary matrix constant j serves to «flip» the components of vector variables and simplifies the form of writing the system of equations. r_S , r_R – Resistance of stator and rotor, m – torque.

Expanding the content of space vectors, the flux linkage equations 1.3, 1.4 are substituted into the stator and rotor voltage formulas, while equating 1.2 to zero, since the electric motor is short-circuited.

$$\vec{U}_S = r_S \vec{i}_S + \frac{d(x_S \vec{i}_S + x_m \vec{i}_R)}{dt} + j\alpha_k (x_S \vec{i}_S + x_m \vec{i}_R), \quad (2)$$

$$\vec{U}_R = r_R \vec{i}_R + \frac{d(x_R \vec{i}_R + x_m \vec{i}_S)}{dt} + j(\alpha_k - p\vartheta_m)(x_R \vec{i}_R + x_m \vec{i}_S) = 0. \quad (3)$$

The change in the rotor current vector is expressed from equation 3

$$\frac{d\vec{i}_R}{dt} = -\frac{r_R}{x_R} \vec{i}_R - \frac{x_m}{x_R} \frac{d\vec{i}_S}{dt} - j\alpha_k \vec{i}_R - j\alpha_k \frac{x_m}{x_R} \vec{i}_S + jp\vartheta_m \frac{\vec{\Psi}_R}{x_R}. \quad (4)$$

The rotor current vector is expressed from equation 1.4 and then substituted into equation 4

$$\vec{i}_R = \frac{\vec{\Psi}_R - x_m \vec{i}_S}{x_R}, \quad (5)$$

$$\begin{aligned} \frac{d\vec{i}_R}{dt} = & -\frac{r_R x_m \vec{\Psi}_R}{x_R^2} + \frac{r_R x_m^2 \vec{i}_S}{x_R^2} - \frac{x_m^2}{x_R} \frac{d\vec{i}_S}{dt} - \\ & - j\alpha_k \frac{x_m \vec{\Psi}_R}{x_R} + jp\vartheta_m \frac{x_m \vec{\Psi}_R}{x_R}. \end{aligned} \quad (6)$$

Equations 5 and 6 are inserted into equation 2 to calculate the stator voltage vector

$$\begin{aligned} \vec{U}_S = & r_S \vec{i}_S + \frac{x_S d\vec{i}_S}{dt} - \frac{r_R x_m \vec{\Psi}_R}{x_R^2} + \frac{r_R x_m^2 \vec{i}_S}{x_R^2} - \\ & - \frac{x_m^2}{x_R} \frac{d\vec{i}_S}{dt} + jp\vartheta_m \frac{x_m \vec{\Psi}_R}{x_R} + j\alpha_k x_S \vec{i}_S - \frac{j\alpha_k x_m^2 \vec{i}_S}{x_R}. \end{aligned} \quad (7)$$

The following replacements are introduced

$$r = r_S + k_R^2 r_R, \quad (8.1)$$

$$k_R = \frac{x_m}{x_R}, \quad (8.2)$$

$$x'_S = x_S - \frac{x_m^2}{x_R}, \quad (8.3)$$

$$T_R = \frac{X_R}{r_R}. \quad (8.4)$$

Let's describe the vectors of stator and rotor voltages with introduced substitutions

$$\vec{U}_S = r_S \vec{i}_S + \frac{x'_S d\vec{i}_S}{dt} + j\alpha_k x'_S \vec{i}_S - \frac{k_R \vec{\Psi}_R}{T_R} + jp\vartheta_m k_R \vec{\Psi}_R, \quad (9)$$

$$\vec{U}_R = -k_R r_R \vec{i}_S + \frac{\vec{\Psi}_R}{T_R} + \frac{d\vec{\Psi}_R}{dt} + j(\alpha_k - p\vartheta_m) \vec{\Psi}_R = 0. \quad (10)$$

In the case of coordinates orientation along the stator flux linkage, the moment can be expressed from equation 1.5 as

$$m = \vec{\Psi}_{Sa} \vec{i}_{S\beta} - \vec{\Psi}_{S\beta} \vec{i}_{Sa}. \quad (11)$$

In this case, the stator flux linkage vector from equation 1.3 is transformed by replacing the rotor current vector from equation 5

$$\vec{\Psi}_S = x_S \vec{i}_S + x_m \left(\frac{\vec{\Psi}_R - x_m \vec{i}_S}{x_R} \right). \quad (12)$$

And this equation 12 of the stator flux linkage vector can now be written along the axes, taking into account the replacements 8.1-8.4

$$\vec{\Psi}_{Sa} = x'_S \vec{i}_{Sa} + k_R \vec{\Psi}_{Ra}, \quad (13)$$

$$\vec{\Psi}_{S\beta} = x'_S \vec{i}_{S\beta} + k_R \vec{\Psi}_{R\beta}. \quad (14)$$

Accordingly, in the equation of moment 11, it is possible to replace the vectors of the stator flux linkage along the axes

$$m = k_R (\vec{\Psi}_{Ra} \vec{i}_{S\beta} - \vec{\Psi}_{R\beta} \vec{i}_{Sa}). \quad (15)$$

Space vectors of stator voltage, stator current, rotor flux linkage can be described by these equations

$$\vec{U}_S = U_{Sx} + jU_{Sy}, \quad (16.1)$$

$$\vec{i}_S = i_{Sx} + ji_{Sy}, \quad (16.2)$$

$$\vec{\Psi}_R = \Psi_{Rx} + j\Psi_{Ry}. \quad (16.3)$$

As a result of changes, substitutions and transformations, the system of equations 1.1-1.6, which mathematically describes the work of the induction drive in a rotating coordinate system, will take the following new form

$$\begin{aligned} \vec{U}_{Sx} = & r \vec{i}_{Sx} + \frac{x'_S d\vec{i}_{Sx}}{dt} - \alpha_k x'_S \vec{i}_{Sy} - \\ & - \frac{k_R}{T_R} \vec{\Psi}_{Rx} - p\vartheta_m k_R \vec{\Psi}_{Ry}, \end{aligned} \quad (17.1)$$

$$\begin{aligned} \vec{U}_{Sy} &= r\vec{i}_{Sy} + \frac{x'_s d\vec{i}_{Sy}}{dt} - \alpha_k x'_s \vec{i}_{Sx} - \\ &- \frac{k_R}{T_R} \vec{\Psi}_{Ry} + p\vartheta_m k_R \vec{\Psi}_{Rx}, \end{aligned} \quad (17.2)$$

$$\begin{aligned} \vec{U}_{Rx} &= 0 = \frac{1}{T_R} \vec{\Psi}_{Rx} + \frac{d\vec{\Psi}_{Rx}}{dt} - \\ &- k_R r \vec{i}_{Sx} - (\alpha_k - p\vartheta_m) \vec{\Psi}_{Ry}, \end{aligned} \quad (17.3)$$

$$\begin{aligned} \vec{U}_{Ry} &= 0 = \frac{1}{T_R} \vec{\Psi}_{Ry} + \frac{d\vec{\Psi}_{Ry}}{dt} - \\ &- k_R r \vec{i}_{Sy} + (\alpha_k - p\vartheta_m) \vec{\Psi}_{Rx}, \end{aligned} \quad (17.4)$$

$$m = k_R (\vec{\Psi}_{Rx} \vec{i}_{Sy} - \vec{\Psi}_{Ry} \vec{i}_{Sx}), \quad (17.5)$$

$$\vec{T}_m \frac{d\vartheta_m}{dt} = m - m_c. \quad (17.6)$$

Accepting $T'_s = \frac{x'_s}{r}$ the system of equations 17.1-17.6 transforms into operator form

$$\begin{aligned} \vec{U}_{Sx} &= r(1 + T'_s p) \vec{i}_{Sx} - \alpha_k x'_s \vec{i}_{Sy} - \\ &- \frac{k_R}{T_R} \vec{\Psi}_{Rx} - p\vartheta_m k_R \vec{\Psi}_{Ry}, \end{aligned} \quad (18.1)$$

$$\begin{aligned} \vec{U}_{Sy} &= r(1 + T'_s p) \vec{i}_{Sy} - \alpha_k x'_s \vec{i}_{Sx} - \\ &- \frac{k_R}{T_R} \vec{\Psi}_{Ry} + p\vartheta_m k_R \vec{\Psi}_{Rx}, \end{aligned} \quad (18.2)$$

$$\begin{aligned} \vec{U}_{Rx} &= 0 = \frac{1}{T_R} (1 + T_R p) \vec{\Psi}_{Rx} - \\ &- k_R r \vec{i}_{Sx} - (\alpha_k - p\vartheta_m) \vec{\Psi}_{Ry}, \end{aligned} \quad (18.3)$$

$$\begin{aligned} \vec{U}_{Ry} &= 0 = \frac{1}{T_R} (1 + T_R p) \vec{\Psi}_{Ry} - \\ &- k_R r \vec{i}_{Sy} + (\alpha_k - p\vartheta_m) \vec{\Psi}_{Rx}, \end{aligned} \quad (18.4)$$

$$m = k_R (\vec{\Psi}_{Rx} \vec{i}_{Sy} - \vec{\Psi}_{Ry} \vec{i}_{Sx}), \quad (18.5)$$

$$\vec{T}_m p \vartheta_m = m - m_c. \quad (18.6)$$

From equations 18.1, 18.2 the stator current is expressed

$$\begin{aligned} i_{Sx} &= \left(U_{Sx} + \alpha_k x'_s i_{Sy} + \frac{k_R}{T_R} \Psi_{Rx} - \right. \\ &- \left. p\vartheta_m k_R \Psi_{Ry} \right) \frac{1}{r(1 + T'_s p)}, \end{aligned} \quad (19)$$

$$\begin{aligned} i_{Sy} &= \left(U_{Sy} - \alpha_k x'_s i_{Sx} + \frac{k_R}{T_R} \Psi_{Ry} - \right. \\ &- \left. p\vartheta_m k_R \Psi_{Rx} \right) \frac{1}{r(1 + T'_s p)}, \end{aligned} \quad (20)$$

And from equations 18.3, 18.4 the rotor flux linkage is expressed

$$\Psi_{Rx} = k_R r i_{Sx} + (\alpha_k - p\vartheta_m) \Psi_{Ry} \frac{T_R}{1 + T_R p}, \quad (21)$$

$$\Psi_{Ry} = k_R r i_{Sy} - (\alpha_k - p\vartheta_m) \Psi_{Rx} \frac{T_R}{1 + T_R p}. \quad (22)$$

The speed from equation 18.6 will be

$$\vartheta_m = \frac{1}{\vec{T}_m p} (m - m_c). \quad (23)$$

Thus, from the obtained final equations 19-23, a mathematical model of induction drive in a rotating coordinate system was created. At the same time, this model was transformed from a three-phase into a two-phase one – figure 1.

Imitation modeling

In this paper, a model of an AIR160S4 induction electric motor is considered with the following parameters presented in Table.

To assess the adequacy and correctness of the assembled model, it was proposed to compare it with the induction motor model from the standard Simulink/Simscape library – figure 2.

The rotor speed and the torque developed by the motors are shown in the figure 3 for the model in a rotating coordinate system – blue, and for the

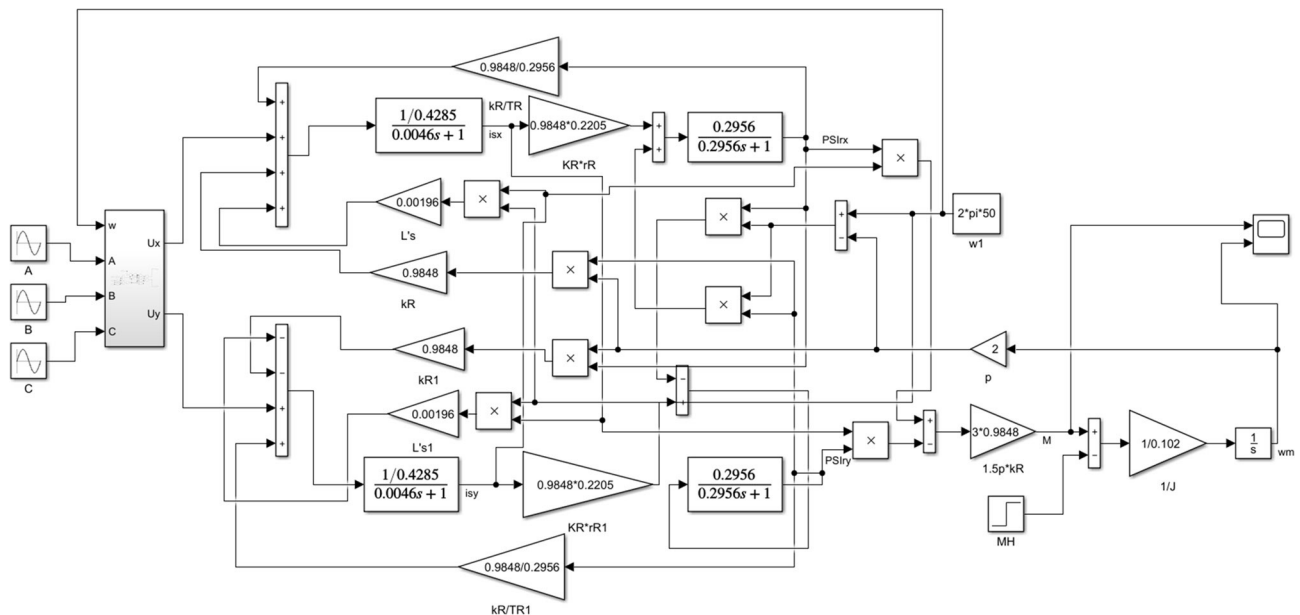


Figure 1 – Model assembled in Simulink

AIR160S4 parameters									
Motor	Power, kW	Speed, rpm	Voltage, V	Efficiency, %	Power factor	Is/In	Ms/Mn	Mmax/Mn	Moment of inertia, kg·m ²
AIR160S4	15	1450	400	89.5	0.86	7.7	2.2	2.6	0.075

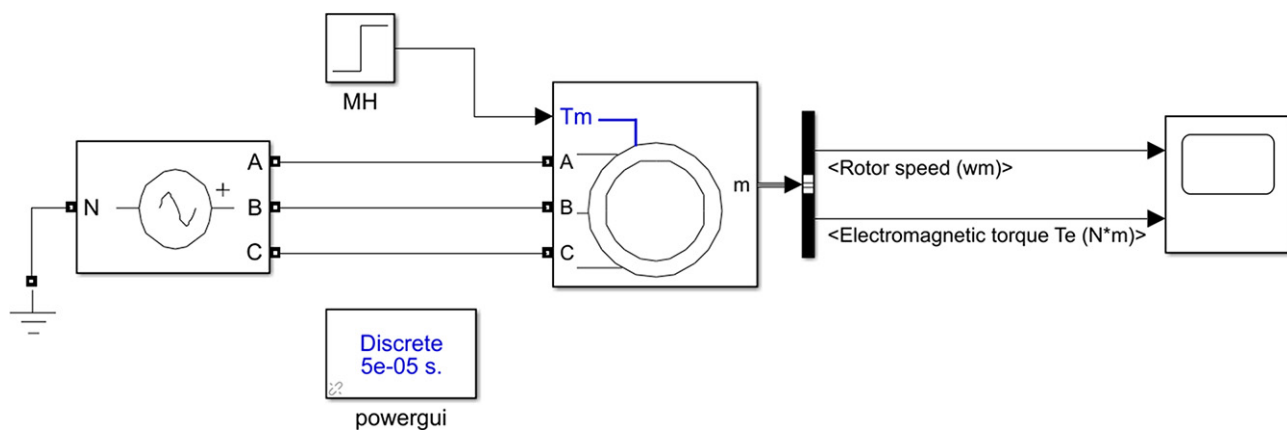


Figure 2 – Standard model of an induction motor in Simulink

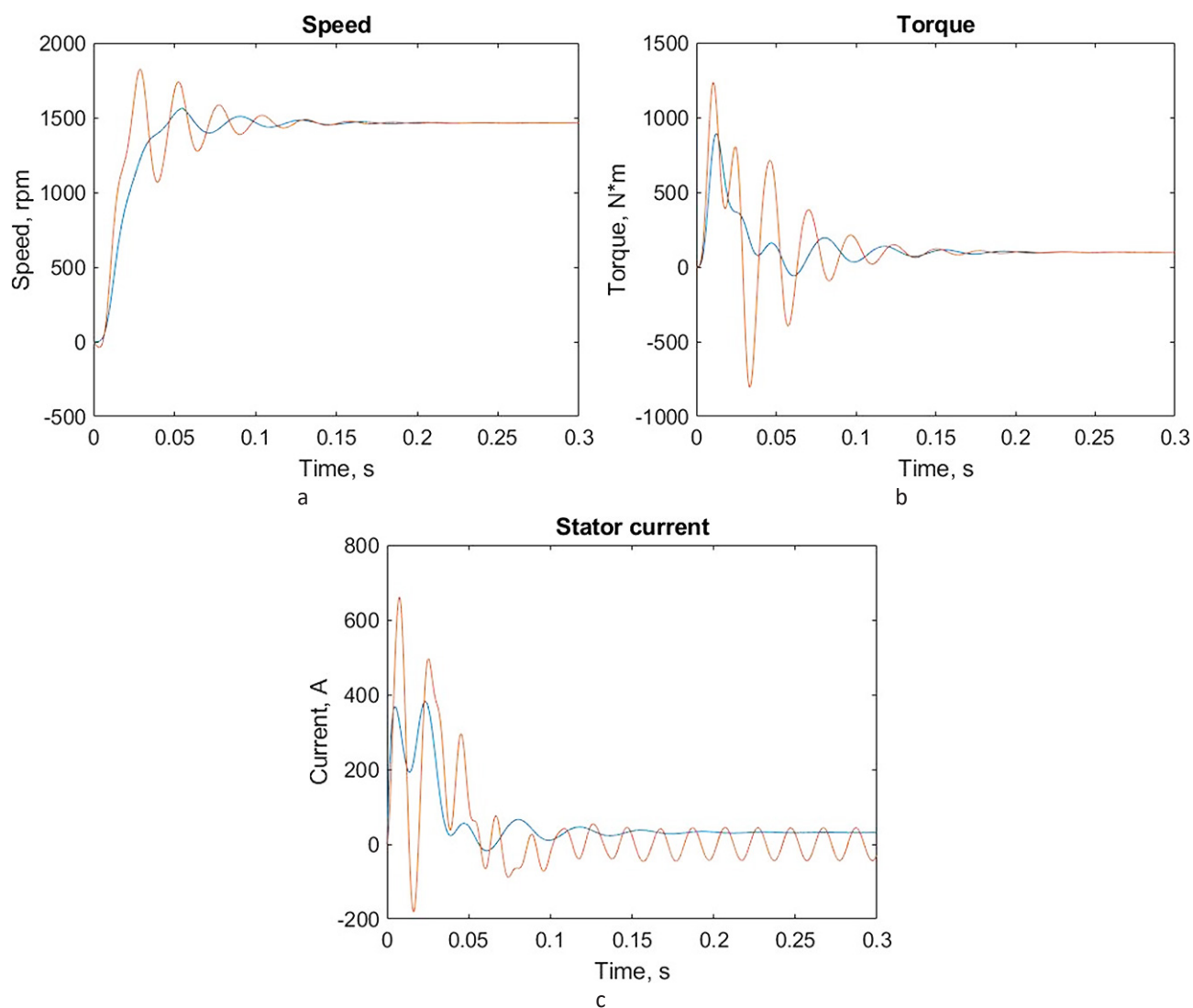


Figure 3 – Output characteristics of electric drives: a – speed, b – torque, c – stator current

standard model – orange.

From the obtained characteristics, it can be seen that the output values coincide, and the processes take place at the same time. However, the system from the standard library is more oscillatory, so the model in the rotating coordinate system has a better transient process. It is planned to compare these models with a real electric drive to obtain the most accurate results in further researches.

Conclusion

Mathematical substitutions in the equations

and the used methods have shown the adequacy and correctness of their use. Analysis of the data, obtained from simulation modeling of the developed model, showed small discrepancies with the standard block from the Simulink library. The use of the obtained mathematical equations, as well as the model assembled in Matlab Simulink, will make it possible to qualitatively evaluate the operation of an induction drive in statics and dynamics. This model will be used in future research, including the creation of a buffer power source based on a supercapacitor for an induction electric drive.

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Айналмалы координат жүйесіндегі асинхронды қозғалтқыштың моделі

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Аңдатпа. Мақала үш фазалы жүйеден екі фазалы жүйеге өту кезінде айналмалы координаттар жүйесінде асинхронды жетектің моделін құруға арналған. Теңдеулерді шешуді жеңілдету үшін жаңа математикалық алмастырулар ұсынылады. Осы математикалық алмастырулар негізінде Matlab Simulink-те модель құрылды. Бұл модель Simulink стандартты кітапханасының үлгісімен салыстырылды. Салыстыру келесі шығыс параметрлерімен жүргізілді: айналу жиілігі, жүктеме моменті, статор тогы. Жасалған модельдің сәйкестігі мен дұрыстығы дәлелденді және оны сипаттайтын барлық математикалық теңдеулер сипатталды.

Кілт сөздер: асинхронды қозғалтқыш, математикалық модель, модельдеу, Matlab Simulink.

Модель асинхронного двигателя во вращающейся координатной системе

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Аннотация. Статья посвящена созданию модели асинхронного привода во вращающейся системе координат при переходе от трехфазной системы к двухфазной. Предлагаются новые математические замены для упрощения решения уравнений. На основе этих математических замен в Matlab Simulink была создана модель. Эта модель сравнивалась с моделью из стандартной библиотеки Simulink. Сравнение производилось по следующим выходным параметрам: частота вращения, момент нагрузки, ток статора. Доказана адекватность и корректность созданной модели и описаны все математические уравнения, ее описывающие.

Ключевые слова: асинхронный двигатель, математическая модель, моделирование, Matlab Simulink.

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