Запропоновано для моделювання асинхронного двигуна транспортних засобів скористатися системою диференційних рівнянь, записаною в «загальмованих координатах». З метою підвищення стійкості алгоритму скорочено кількість рівнянь системи шляхом вираження фазних струмів через фазні потокозчеплення. Розраховано параметри двигуна-прототипу за класичною методикою. Розроблено алгоритм врахування механічних втрат та втрат потужності в сталі двигуна. Реалізовано в програмному середовищі MATLab імітаційне моделювання асинхронного двигуна з симетричними обмотками. Визначено основні технічні параметри двигуна за допомогою імітаційної моделі. Виконано порівняння результатів моделювання з результатами класичних розрахунків. Похибка при визначенні параметрів на моделі і виконаних розрахунковим шляхом не перевищила 7 %. Це свідчить про високу збіжність результатів моделювання з результатами розрахунків. Запропоновано для дослідження асинхронного двигуна з несиметричними обмотками статора алгоритм, який полягає у врахуванні зміни взаємної індуктивності при зміні комплексного опору однієї, або декількох фаз обмоток двигуна. Запропонований алгоритм організації несиметричного режиму обмоток статора дозволить без зміни структури моделі дослідити динамічні процеси в асинхронному двигуні при несиметрії фаз обмоток статора при їх пошкодженні. Врахування втрат потужності в сталі та механічних втрат підвищить достовірність отриманих результатів. Похибка визначення параметрів асинхронного двигуна при несиметричних обмотках статора, отриманих при моделюванні, і знятих експериментально не перевищила 3 %, що свідчить про адекватність моделі.

Це дозволить застосувати запропоновану імітаційну модель асинхронного двигуна при дослідженні динамічних процесів в двигунах транспортної інфраструктури при виникненні такого дефекту, як міжвиткове замикання в обмотках статору

Ключові слова: оптимальне управління перевезеннями, параметри інфраструктури залізниці, математичне моделювання, асинхронний двигун, несиметрія обмоток

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MATHEMATICAL MODELING OF AN INDUCTION MOTOR FOR VEHICLES

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1. Introduction

The process of optimal railroad transportation management requires information on the technical condition of transport infrastructure facilities. The technical condition of infrastructure facilities depends on the technical state of the elements that a facility is composed of. One such element is an induction motor. Induction motor is used as a tractive engine and as an auxiliary machine for some series of electric rolling stock, in the drives of rail turnouts, as well as in other electric drives of railroad infrastructure. The effective operation of electric rolling stock, traffic safety, etc. depends on its working state.

The increased requirements for the level of quality and reliability of AC electric motors during transportation, as well as the enhanced impact of the wide range of operational factors, necessitate constant development of diagnostic methods. The main condition that contributes to reducing the failure of electric motors during operation is the timely diagnosing and forecasting of their current state with a high degree of reliability of the results.

The growing level of needs at diagnosing and choosing the appropriate methodology necessitates thorough research into the processes of manifestation of various defects of the stator, which account for a significant proportion of all failures in the induction electric motors. These tasks require using a mathematical model of an induction motor with a high degree of reliability that could make it possible to investigate the asymmetrical modes, arising in the process of operation at different types of the stator damage.

2. Literature review and problem statement

While considering the methodological approaches for constructing a mathematical model for an induction electric motor, it is necessary to take into account that the choice of a methodology should allow for the possibility of considering a series of assumptions [1–3]. First of all, some authors recommend that the power voltage system of an induction motor should be considered symmetrical and sinusoidal while the stator and rotor windings – symmetrical. It is also necessary to assume that the stator and rotor of an induction machine are smooth.

This approach to the modeling of induction machines has been employed in a large number of studies; each of the proposed models, however, is aimed at resolving a single practical task. Thus, work [4] solves the problem of building a model, in order to accurately determine a shaft rotation frequency of the engine operated under a load, based on the loss of electrical power in the engine steel. Paper [5] addresses the development of an induction motor with a short-circuited rotor operating under an alternating load. Study [6] proposed a model to solve the task of multi-criteria control over a drive with an induction motor. The model for precise measurement of the mechanical coordinate of an induction motor is given in paper [7]; the method for the identification of mechanical parameters – in study [8]. The optimization of the tractive induction motor regimes was considered in detail in work [9].

The mathematical models constructed on the basis of these methods make it possible to explore the dynamic processes in electric drives with induction motors; but only on a condition for the symmetry of stator and rotor windings and at a proper system that powers an electric machine.

However, despite the assumption that the power voltage system is symmetrical and sinusoidal, an analysis of the operation of induction motors with defects should consider the fact that most of the defects lead to the asymmetrical regimes in an induction motor [10, 11].

Research into electromagnetic processes employs a large number of approaches to the simulation of induction motors. Their differences are mainly related to the choice of a coordinate system hosting the differential equations that describe the operation of an induction motor. When modeling induction motors with asymmetrical windings, one should apply a system of differential equations within the «inhibited coordinates», as it was noted in work [2]. When solving the set task, the use of other coordinate systems is incorrect. This is confirmed by the results reported in works [12, 13].

When constructing induction motor models in the «inhibited coordinates», the issue that has remained unresolved is accounting for the mechanical losses and losses in steel. Disregarding these types of losses leads to the acquisition of inaccurate data on the engine shaft rotation frequency, the values of phase currents of the stator and rotor, etc.

The techniques to account for the mechanical losses are suggested in paper [14]. Underlying these methods is the assumption that the losses of mechanical power should be taken into consideration by introducing an additional static momentum to the model, which depends on both the loss of power and the engine shaft rotation frequency. The issue related to the losses in the motor's steel has remained open. This problem was tackled in studies [4, 15]. They also offered to consider the power losses in the engine's steel by introducing an additional static momentum to the model.

The above models did not imply the combination of losses in the motor's steel and mechanical losses. In addition, none of the above studies considered the impact of asymmetry of the motor stator windings on a change in the mutual inductance of the windings. The solution can be found in works [16, 17]. In [16], it was suggested that a single-phase engine, in order to convert parameters, could be represented as an ideal transformer, and the factor of voltage deviation from the symmetric regime was replaced with a voltage ratio; however, the mathematical apparatus and the algorithm of its application were given only conceptually in the cited work.

Determining the parameters of induction motors under steady modes, powered by a single-phase network, makes it possible, with great accuracy, to construct a mathematical model for establishing the energy, mechanical, and operating characteristics of a given engine under a steady regime [17]. Given the asymmetry, not only the transient processes, but also the established modes, are dynamic, which is why they are described by differential equations in any coordinate system. To obtain the static parameters as a function of some variable, a given system is differentiated analytically, and then it is integrated, based on the numerical method, for this variable. When performing differentiation, there may be a question of method convergence.

In the case of asymmetry of the stator phases, the integrated phase resistances change, which, in turn, leads to a change in the inductance of the phases. Changing the inductance of phases leads to a change in the inductance of the engine magnetic circuit. The change in the inductance of the magnetic circuit of the engine in the implementation of a mathematical model was considered in study [18]; the authors proposed determining the inductance of an induction motor based on a magnetization curve. The implementation of this technique is associated with certain difficulties, specifically, it is necessary to have the magnetization curve itself.

Further research into different modes of engine operation implies devising an approach to mathematical modeling of an induction motor with asymmetrical windings in the «inhibited coordinates» taking into consideration the losses in steel, as well as mechanical losses. It is also necessary to suggest the principle of model construction, which implies the calculation of an additional static momentum as a function of the power losses in steel, mechanical losses, as well as motor shaft rotation frequency. In addition, to implement the proposed modeling principle, it is necessary to calculate the mutual inductance of windings at a change in the integrated resistance of one or several windings and to take into consideration the calculated mutual inductance of windings in the model.

The proposed model could be adapted for studying the induction motor operation in case it demonstrates such a defect as interturn short circuit in the stator windings. In addition, the proposed model could be used to determine the starting and working characteristics of the engine, to calculate energy indicators during the operation of the induction motor with the specified defect.

3. The aim and objectives of the study

The aim of this study is to improve a mathematical model for the simulation of an induction motor with asymmetrical stator windings. This would make it possible to better account for the influence of defects in the induction motor operation in order to determine the method to diagnose them and estimate the degree of damage.

To accomplish the aim, the following tasks have been set:

– to calculate the parameters for a prototype engine in line with the classical procedure;

– to simplify the system of differential equations in the «inhibited coordinates» describing the induction motor operation;

– to simulate an induction motor in the MATLAB programming environment considering the losses in steel and mechanical losses;

– to construct an algorithm to account for a change in the mutual inductance of windings due to the change in the integrated resistance of one or several windings;

– to calculate the parameters for a motor according to the data obtained during modeling and to compare the results of simulation and calculation.

4. Materials and research methods

4. 1. The object of study

The prototype engine chosen for our research is the induction motor with a short-circuited rotor of the AIP132M4 series, with a capacity of 11 kW, a synchronous frequency of the stator field rotation of 1,500 rev/min, a power voltage of 220/380 V, with an efficiency of 88 %, $\cos\varphi_1=0.845$. The following parameters were calculated for the rated mode of this motor in line with the procedure from [19]:

– torque on the motor shaft; the motor shaft rotation frequency; usable power;

– the active, reactive, and full power supplied from the grid; losses in steel and in copper of the stator and losses in the rotor; mechanical losses;

– the phase current of the stator winding; the efficiency and power factor $\cos\varphi_1$.

In addition, we calculated resistance: the active resistance of the stator winding and active resistance of the rotor winding, brought to the stator winding; the reactive resistance of the stator winding and the rotor winding resistance brought to the stator winding and in a magnetizing circuit. The calculation results are given in Table 1.

Table 1

Results of calculating the motor AIP132M4 parameters

Parameter	Parameter value
Torque on motor shaft M, Nm	72.671
Motor shaft rotation frequency n, rpm	1,450
Usable power P_{a2}, kW	11.005
Active power consumed from the grid P_{a2}, kW	12.491
Reactive power consumed from the grid Q_{a1}, kW·Ar	7.84
Full power consumed from the grid S, kW·A	14.748
Acting value of the stator phase current I_1, A	22.343
Losses in steel ΔP_s, W	215.16
Losses in the stator copper ΔP_{e1}, W	748.8
Losses in the rotor copper ΔP_{e2}, W	390.4
Mechanical losses ΔP_{mech}, W	59.743
Efficiency, η, %	88.1
Power factor $\cos\varphi_1$	0.847
Active resistance of the stator winding r_1, Ohm	0.5
Active resistance of the rotor winding brought to the stator winding r_2', Ohm	0.36
Reactive resistance of the stator winding x_1, Ohm	0.56
Reactive resistance of the rotor winding brought to the stator winding x_2', Ohm	0.938
Reactive resistance in a magnetizing circuit x_μ, Ohm	22.828

Some of the parameters for the prototype engine, calculated according to the classical technique, differ from the specifications. Thus, the error of calculating the usable power was 0.045 %, the error of calculating the efficiency was 0.114 %, the $\cos\varphi_1$ calculation error was 0.237. This is due to the error in the calculation procedure.

4. 2. Improving a system of differential equations in the «inhibited coordinates» describing the induction motor operation

In [28], the systems of equations describing the dynamic processes in an induction motor are represented in the «inhibited coordinates».

The equation of electromagnetic processes in an induction motor [19]:

$$\begin{cases} u_{s\alpha} = r_{s\alpha}\cdot i_{s\alpha} + \dfrac{\mathrm{d}\psi_{s\alpha}}{\mathrm{d}t}; \\ u_{s\beta} = r_{s\beta}\cdot i_{s\beta} + \dfrac{\mathrm{d}\psi_{s\beta}}{\mathrm{d}t}; \\ u_{s\gamma} = r_{s\gamma}\cdot i_{s\gamma} + \dfrac{\mathrm{d}\psi_{s\gamma}}{\mathrm{d}t}; \\ -u_{r\alpha} = r_{r\alpha}\cdot i_{r\alpha} + \dfrac{\mathrm{d}\psi_{r\alpha}}{\mathrm{d}t} + \dfrac{\left(\psi_{r\beta}-\psi_{r\gamma}\right)\cdot p\cdot\omega_r}{\sqrt{3}}; \\ -u_{r\beta} = r_{r\beta}\cdot i_{r\beta} + \dfrac{\mathrm{d}\psi_{r\beta}}{\mathrm{d}t} + \dfrac{\left(\psi_{r\gamma}-\psi_{r\alpha}\right)\cdot p\cdot\omega_r}{\sqrt{3}}; \\ -u_{r\gamma} = r_{r\gamma}\cdot i_{r\gamma} + \dfrac{\mathrm{d}\psi_{r\gamma}}{\mathrm{d}t} + \dfrac{\left(\psi_{r\alpha}-\psi_{r\beta}\right)\cdot p\cdot\omega_r}{\sqrt{3}}, \end{cases} \quad (1)$$

where u is the voltage, V; i is the current, A; t is the time, s; r is the active resistance, Ohm; ψ is the flux linkage, A·Gn; p is the number of poles pairs; the lower indices α, β, γ denote the belonging to the corresponding phase; the lower index s is the belonging to the stator; the lower index r is the belonging to the rotor; ω_r is the mechanical rotor rotation frequency, rad/s.

Flux linkage is described by the following system of differential equations [27]:

$$\begin{cases} \psi_{s\alpha} = L_{s\alpha}\cdot i_{s\alpha} - 0.5\cdot M\cdot i_{s\beta} - 0.5\cdot M\cdot i_{s\gamma} + \\ + M\cdot\left(i_{r\alpha} - 0.5\cdot i_{r\beta} - 0.5\cdot i_{r\gamma}\right); \\ \psi_{s\beta} = L_{s\beta}\cdot i_{s\beta} - 0.5\cdot M\cdot i_{s\alpha} - 0.5\cdot M\cdot i_{s\gamma} + \\ + M\cdot\left(i_{r\beta} - 0.5\cdot i_{r\beta} - 0.5\cdot i_{r\gamma}\right); \\ \psi_{s\gamma} = L_{s\gamma}\cdot i_{s\gamma} - 0.5\cdot M\cdot i_{s\alpha} - 0.5\cdot M\cdot i_{s\beta} + \\ + M\cdot\left(i_{r\gamma} - 0.5\cdot i_{r\alpha} - 0.5\cdot i_{r\beta}\right); \\ \psi_{r\alpha} = L_{r\alpha}\cdot i_{r\alpha} - 0.5\cdot M\cdot i_{r\beta} - 0.5\cdot M\cdot i_{r\gamma} + \\ + M\cdot\left(i_{s\alpha} - 0.5\cdot i_{s\beta} - 0.5\cdot i_{s\gamma}\right); \\ \psi_{r\beta} = L_{r\beta}\cdot i_{r\beta} - 0.5\cdot M\cdot i_{r\alpha} - 0.5\cdot M\cdot i_{r\gamma} + \\ + M\cdot\left(i_{s\beta} - 0.5\cdot i_{s\beta} - 0.5\cdot i_{s\gamma}\right); \\ \psi_{r\gamma} = L_{r\gamma}\cdot i_{r\gamma} - 0.5\cdot M\cdot i_{r\alpha} - 0.5\cdot M\cdot i_{r\beta} + \\ + M\cdot\left(i_{s\gamma} - 0.5\cdot i_{s\alpha} - 0.5\cdot i_{s\beta}\right), \end{cases} \quad (2)$$

where L is the full inductance of the phase, Gn; M is the mutual inductance of the stator and rotor phases, Gn.

The electromagnetic torque equation of an induction motor [16]:

$$M_{EM} = \frac{\sqrt{3}}{2}\cdot M\cdot p\begin{bmatrix}\left(i_{s\alpha}\cdot i_{r\gamma}+i_{s\beta}\cdot i_{r\alpha}+i_{s\gamma}\cdot i_{r\beta}\right)- \\ -\left(i_{s\alpha}\cdot i_{r\beta}+i_{s\beta}\cdot i_{r\gamma}+i_{s\gamma}\cdot i_{r\alpha}\right)\end{bmatrix}. \quad (3)$$

The motion equation for the motor shaft at a single-mass mechanical part:

$$\frac{\mathrm{d}\omega_r}{\mathrm{d}t} = J\cdot\left(M_{EM}-M_C\right), \quad (4)$$

where J is the moment of inertia of the masses rotating on the rotor shaft, k·gm^2; M_C is the static momentum on the rotor shaft, N·m.

When modeling an induction motor using equations (1) to (4), there may be some difficulties associated with the robustness of the algorithm of the model implementation. This is due to the presence of a large number of integration operations in the algorithm. To reduce the number of integration operations, it is advisable to reduce the number of differential equations. To this end, we shall express the derivatives from phase flux linkages through the flux linkage. To this end, the derivatives from the flux linkages are expressed through the flux linkage. We shall substitute the system of equations (1) with the equations from system (2). We obtain after the transformations:

$$\begin{cases}\frac{\mathrm{d}\psi_{s\alpha}}{\mathrm{d}t} = z_{11}\cdot\psi_{s\alpha}+z_{12}\cdot\psi_{s\beta}+z_{13}\cdot\psi_{s\gamma}+ \\ +\,z_{14}\cdot\psi_{r\alpha}+z_{15}\cdot\psi_{r\beta}+z_{16}\cdot\psi_{r\gamma}; \\ \frac{\mathrm{d}\psi_{s\beta}}{\mathrm{d}t} = z_{21}\cdot\psi_{s\alpha}+z_{22}\cdot\psi_{s\beta}+z_{23}\cdot\psi_{s\gamma}+ \\ +\,z_{24}\cdot\psi_{r\alpha}+z_{25}\cdot\psi_{r\beta}+z_{26}\cdot\psi_{r\gamma}; \\ \frac{\mathrm{d}\psi_{s\gamma}}{\mathrm{d}t} = z_{31}\cdot\psi_{s\alpha}+z_{32}\cdot\psi_{s\beta}+z_{33}\cdot\psi_{s\gamma}+ \\ +\,z_{34}\cdot\psi_{r\alpha}+z_{35}\cdot\psi_{r\beta}+z_{36}\cdot\psi_{r\gamma}; \\ \frac{\mathrm{d}\psi_{r\alpha}}{\mathrm{d}t} = z_{41}\cdot\psi_{s\alpha}+z_{42}\cdot\psi_{s\beta}+z_{43}\cdot\psi_{s\gamma}+ \\ +\,z_{44}\cdot\psi_{r\alpha}+z_{45}\cdot\psi_{r\beta}+z_{46}\cdot\psi_{r\gamma}; \\ \frac{\mathrm{d}\psi_{r\beta}}{\mathrm{d}t} = z_{51}\cdot\psi_{s\alpha}+z_{52}\cdot\psi_{s\beta}+z_{53}\cdot\psi_{s\gamma}+ \\ +\,z_{54}\cdot\psi_{r\alpha}+z_{55}\cdot\psi_{r\beta}+z_{56}\cdot\psi_{r\gamma}; \\ \frac{\mathrm{d}\psi_{r\gamma}}{\mathrm{d}t} = z_{61}\cdot\psi_{s\alpha}+z_{62}\cdot\psi_{s\beta}+z_{63}\cdot\psi_{s\gamma}+ \\ +\,z_{64}\cdot\psi_{r\alpha}+z_{65}\cdot\psi_{r\beta}+z_{66}\cdot\psi_{r\gamma},\end{cases} \quad (5)$$

where z_{ij} are the coefficients derived following the transformation, which are the functions of full inductances of phases and mutual inductances of the stator and rotor phases. That is:

$$z = f\left(L, M\right), \quad (6)$$

where L is the full inductance of the corresponding phase of the stator or rotor, which is determined from formula [19]:

$$L = L_\sigma + M, \quad (7)$$

where L_{ij} is the inductance of the corresponding phase of the stator or rotor, Gn.

The mutual inductance is determined from the following formula:

$$M = \frac{2}{3}\cdot L_\mu, \quad (8)$$

where L_μ is the inductance of the magnetizing chain, Gn.

The equations for determining the phase currents then take the form:

$$\begin{cases} i_{s\alpha} = u_{sa} - r_{sa}\cdot\begin{pmatrix}a_{11}\cdot\psi_{s\alpha}+a_{12}\cdot\psi_{s\beta}+a_{13}\cdot\psi_{s\gamma}+ \\ +a_{14}\cdot\psi_{r\alpha}+a_{15}\cdot\psi_{r\beta}+a_{16}\cdot\psi_{r\gamma}\end{pmatrix}; \\ i_{s\beta} = u_{s\beta} - r_{s\beta}\cdot\begin{pmatrix}a_{21}\cdot\psi_{s\alpha}+a_{22}\cdot\psi_{s\beta}+a_{23}\cdot\psi_{s\gamma}+ \\ +a_{24}\cdot\psi_{r\alpha}+a_{25}\cdot\psi_{r\beta}+a_{26}\cdot\psi_{r\gamma}\end{pmatrix}; \\ i_{s\gamma} = u_{s\gamma} - r_{s\gamma}\cdot\begin{pmatrix}a_{31}\cdot\psi_{s\alpha}+a_{32}\cdot\psi_{s\beta}+a_{33}\cdot\psi_{s\gamma}+ \\ +a_{34}\cdot\psi_{r\alpha}+a_{35}\cdot\psi_{r\beta}+a_{36}\cdot\psi_{r\gamma}\end{pmatrix}; \\ i_{r\alpha} = -r_{ra}\cdot\begin{pmatrix}a_{41}\cdot\psi_{s\alpha}+a_{42}\cdot\psi_{s\beta}+a_{43}\cdot\psi_{s\gamma}+ \\ +a_{44}\cdot\psi_{r\alpha}+a_{45}\cdot\psi_{r\beta}+a_{46}\cdot\psi_{r\gamma}\end{pmatrix}+ \\ +\frac{\left(\psi_{r\beta}-\psi_{r\gamma}\right)\cdot p\cdot\omega_r}{\sqrt{3}}; \\ i_{r\beta} = -r_{r\beta}\cdot\begin{pmatrix}a_{51}\cdot\psi_{s\alpha}+a_{52}\cdot\psi_{s\beta}+a_{53}\cdot\psi_{s\gamma}+ \\ +a_{54}\cdot\psi_{r\alpha}+a_{55}\cdot\psi_{r\beta}+a_{56}\cdot\psi_{r\gamma}\end{pmatrix}+ \\ +\frac{\left(\psi_{r\gamma}-\psi_{r\alpha}\right)\cdot p\cdot\omega_r}{\sqrt{3}}; \\ i_{r\gamma} = -r_{s\gamma}\cdot\begin{pmatrix}a_{61}\cdot\psi_{s\alpha}+a_{62}\cdot\psi_{s\beta}+a_{63}\cdot\psi_{s\gamma}+ \\ +a_{64}\cdot\psi_{r\alpha}+a_{65}\cdot\psi_{r\beta}+a_{66}\cdot\psi_{r\gamma}\end{pmatrix}+ \\ +\frac{\left(\psi_{r\alpha}-\psi_{r\beta}\right)\cdot p\cdot\omega_r}{\sqrt{3}}. \end{cases} \quad (9)$$

We build a single system of differential equations of the first order from the systems of equations (3) to (5) and (8). By solving this system in the Mathcad programming environment, we derive values for the motor shaft rotation frequency, electromagnetic momentum, and phase currents, which will be needed for further calculations.

4. 3. The implementation of an induction motor model in the MATLAB programming environment considering the losses in steel, as well as the mechanical losses

The dependence between the power, torque, and the angular frequency of motor shaft rotation is determined from expression [20]:

$$M = \frac{P}{\omega}, \quad (10)$$

where P is the power, W; M is the torque, N·m; ω is the angular frequency of the motor shaft rotation frequency, N·m.

The static momentum that accounts for the mechanical losses are calculated:

$$M_{c.mech} = \frac{\Delta P_{mech}}{\omega_n}. \quad (11)$$

The angular velocity of motor shaft rotation under a rated mode is calculated from expression [20]:

$$\omega_n = \frac{\pi \cdot n_n}{30}, \tag{12}$$

where n_n=1,450, rpm – the rated speed of motor shaft rotation (Table 1); ΔP_{mech}=59.743, W – mechanical losses (Table 1).

Then ω_n=151.7671450, rad/s; $M_{c.mech}$=0.39365, N·m.

The momentum that takes into consideration the losses in steel is calculated from the following formula:

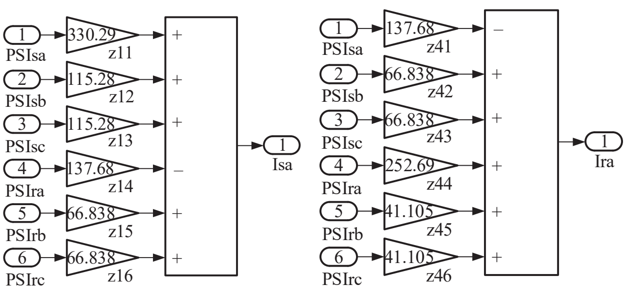
$$M_{c.s} = \frac{\Delta P_s}{\omega_n}, \tag{13}$$

where ΔP_s=215.16, W – losses in steel (Table 1).

Thus, $M_{c.s}$=1.418, N·m.

When switching to another mode (for example, idling), one should calculate the motor shaft angular velocity, which corresponds to a given mode.

The improvement of the simulation model of an induction motor in the MATLAB programming environment started with the implementation of a system of differential equations (9). The implementation of the equation for calculating the stator current is shown on the example of calculating the static current of phase A (Fig. 1, *a*), the equations for calculating the rotor current – on the example of calculating the rotor current of phase A (Fig. 1, *b*).



a *b*

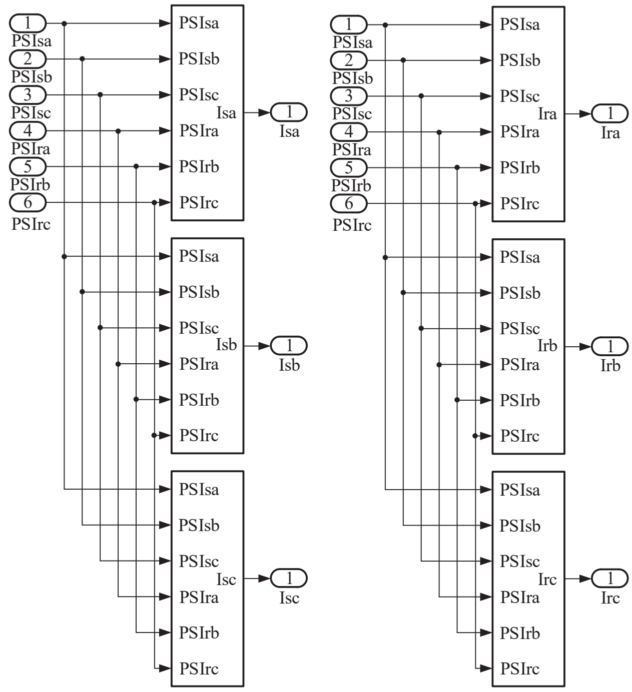
Fig. 1. Implementation based on the calculation model: *a* — stator current of phase A; *b* — rotor current of phase A

Next, the implementation of the calculation of each equation was combined in a separate block and then the blocks were combined to each other, as shown in Fig. 2, *a* for the stator currents and in Fig. 2, *b* – for the rotor currents.

Next, the blocks (Fig. 2, *a*, *b*) were combined into separate units for the calculation of stator currents (Stator Current Calculation Unit) and rotor currents (Rotor Current Calculation Unit).

The implementation of the system of equations for calculating the phase flux linkages is shown in Fig. 3, 4. Fig. 3 shows the implementation of equations for calculating the stator flux linkages; Fig. 4 – rotor flux linkages. This is followed by the combination into a linkage calculating unit.

The implementation of equations for calculating the momentum is shown in Fig. 5. The elements used to calculate the momentum are merged into a Moment Calculation unit. It is necessary to pay attention to the three elements of the unit: mutual induction is the element that assigns the value of mutual inductance; taking into consideration mechanical losses is the element the accounts for mechanical losses; taking into consideration losses in steel is the element that considers losses in steel.



a *b*

Fig. 2. Implementation based on the model of calculation equations: *a* — stator currents; *b* — rotor currents

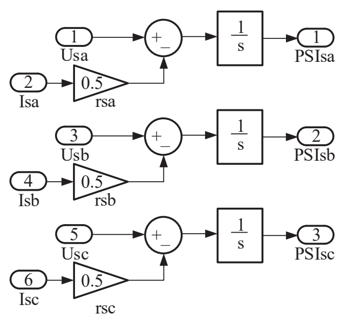


Fig. 3. Implementation of equations for the calculation of stator flux linkages

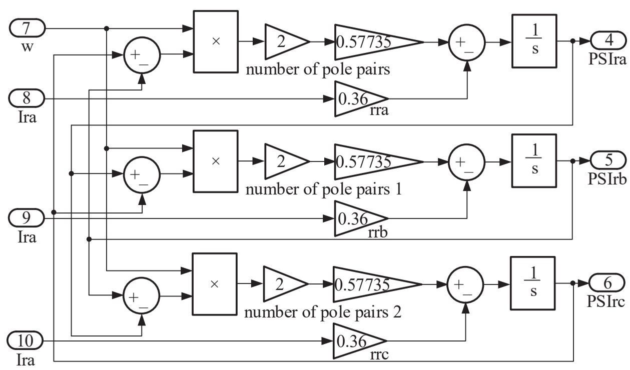


Fig. 4. Implementation of equations to compute the rotor flux linkages

Next, the blocks were merged by connecting the respective block ports. Phase voltage is fed by means of Sine Wave blocks, where the corresponding amplitude and frequency are set. It should be noted that the amplitude should be assigned using instantaneous values. In addition, one should add those elements that implement equation (4) in order to compute the motor shaft rotation frequency. The following parameters are displayed: the stator phase voltage, the stator phase currents, the rotor phase currents, the motor shaft rotation frequency, and the usable momentum on a motor shaft. For this purpose, an oscilloscope was used, which is implemented based on the Scope element. A given oscilloscope has four sections: Us, Is, Ir, n, M. The first section demonstrates the stator phase voltage, the second – the stator phase currents, the third – the rotor phase currents, the fourth – the motor shaft rotation frequency and the torque on a motor shaft (Fig. 6). The signals that correspond to the torque on the motor shaft and the motor shaft rotation frequency are displayed by the Display measuring unit. This is necessary to determine the exact value of the specified quantities. If necessary, measuring the amplitude and phase angles of the stator voltage, the rotor currents, employs a Complex to Magnitude-Angle unit, whose input is fed a corresponding signal; at the output, we acquire signals that correspond to the amplitude and phase of this signal. Next, the resulting signals are displayed using the Display units.

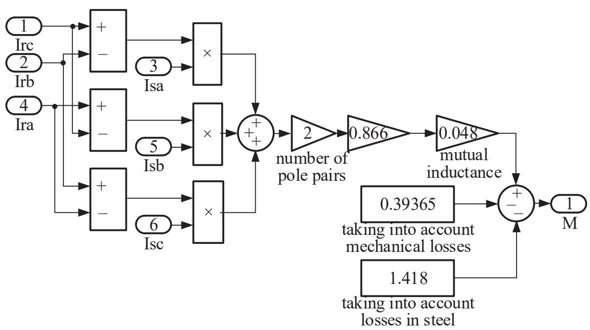


Fig. 5. Implementation of equations for calculating the momentum

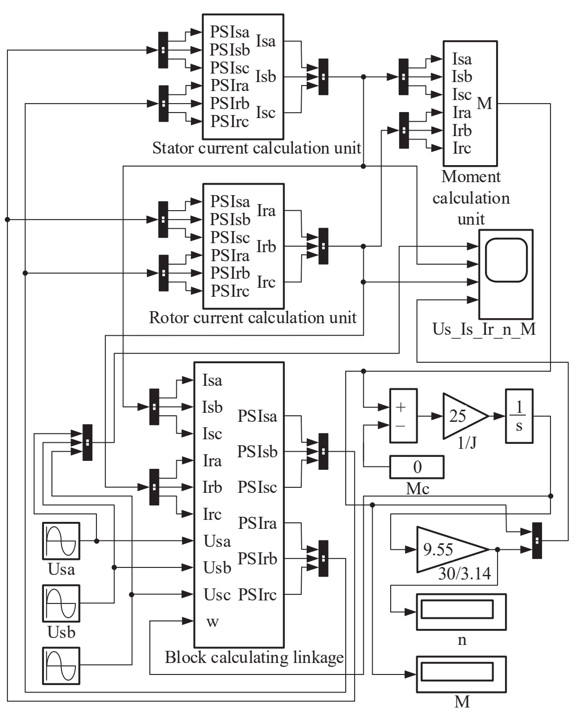


Fig. 6. An induction motor model

Following the series of the specified improvements and modifications, we obtained a model, which, after confirmation of its adequacy, could be used for further research into the operation of an induction motor with the symmetric and asymmetrical stator windings.

5. Simulation results

5. 1. Calculation of the motor parameters based on the data acquired during simulation; comparison of the simulation and calculation results

After the model was assigned the stator symmetrical phase voltages, whose time diagrams are shown in Fig. 7, we derived values for the phase currents of the stator (Fig. 8), the phase currents of the rotor (Fig. 9), the rotation frequency of a motor shaft, and the torque on a motor shaft (Fig. 10) for the rated mode. The values for the phase voltage of the stator and the phase currents of the stator and rotor are set by the instantaneous values of these parameters. To account for the mechanical losses and losses in steel at idling whose motor shaft rotation frequency is n=1,500, rpm, it is necessary to recalculate the momenta based on formulae (11) and (12). When setting the static torque value on the motor shaft to zero, we have acquired the diagrams of the motor shaft rotation frequency and the torque on a motor shaft shown in Fig. 11.

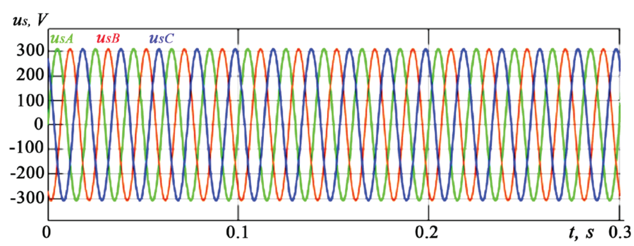


Fig. 7. Time diagrams of the stator phase voltages for the rated mode

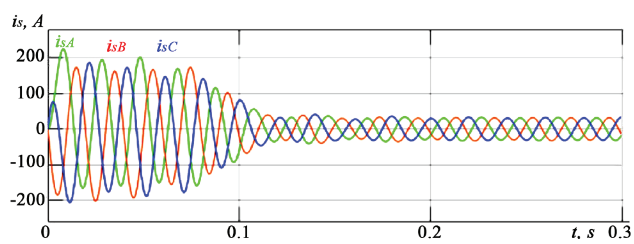


Fig. 8. Time diagrams of the stator phase currents for the rated mode

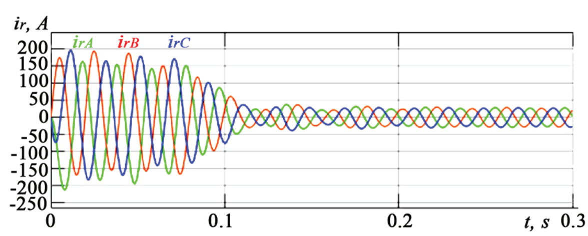


Fig. 9. Time diagrams of the rotor phase currents for the rated mode

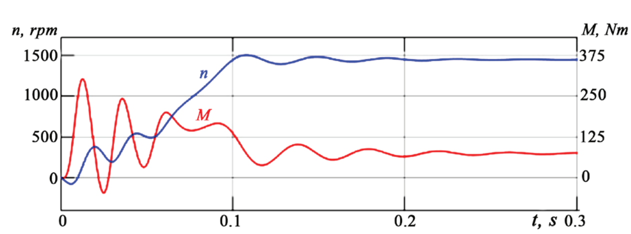


Fig. 10. Time diagrams of the motor shaft rotation frequency (n) and the torque on a motor shaft (M) for the rated mode

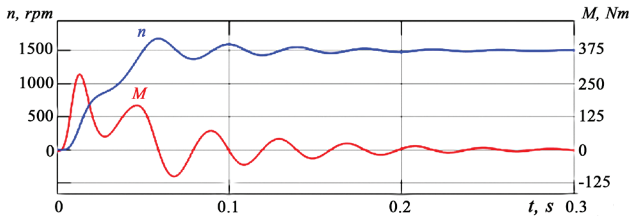


Fig. 11. Time diagrams of the motor shaft rotation frequency (n) and the torque on a motor shaft (M) for the mode of idling

The motor shaft rotation frequency n=1,450 rpm and the torque M=72.443 N·m, derived in the course of the simulation, for the rated mode, and the motor shaft rotation frequency n=1,500 rpm and the torque M=0 N·m for the mode of idling, correspond to the specifications for a prototype motor. The comparison of the simulation results and those derived from the earlier calculations in line with the classical procedure is given in Table 2.

Table 2

Results of simulating and calculating the motor parameters

Parameter	Calculation	Model	Relative error, %
Torque on motor shaft M, Nm	72.671	72.443	0.314
Motor shaft rotation frequency n, rpm	1,450	1,450	0
Usable power P_{a2}, kW	11.005	11.0	0.045
Active power consumed from the grid P_{a2}, kW	12.491	12.29	1.609
Reactive power consumed from the grid Q_{a1}, kW·Ar	7.84	7.479	4.604
Full power consumed from the grid S, kW·A	14.748	14.39	2.427
Acting value of the stator phase current I_1, A	22.343	72.443	0.314
Losses in steel ΔP_s, W	215.16	211.798	1.563
Losses in the stator copper ΔP_{e1}, W	748.8	701.137	6.365
Losses in the rotor copper ΔP_{e2}, W	390.4	378.14	–3.14
Mechanical losses ΔP_{mech}, W	59.743	59.743	0
Efficiency, η, %	88.1	89.5	–1.593
Power factor cosφ_1	0.847	0.854	–0.834

Table 2 shows that the simulation error is quite low and is within 0.045–6.365 %. It demonstrates the high accuracy of modeling and simulating the processes occurring in an induction motor with symmetrical windings. In other words, the simulation model of the induction motor can be considered adequate with a high degree of reliability.

5. 2. Construction of an algorithm for considering a change in the mutual inductance of windings due to a change in the integrated resistance of one or several windings

To simulate the operation mode of an induction motor with asymmetrical windings, arising in the case of damage to one or several windings of the stator, one should consider a change in the inductance of scattering and active resistance of the corresponding winding (windings). That is, one needs to find the difference between the valid values of the specified parameters and the rated values. Next, consider the change in the mutual inductance of windings.

To determine a change in the mutual inductance of windings, one should establish the effect exerted by a change in the integrated resistance of one winding (several windings) on the inductance of the magnetic circuit. Studies [21, 22] derived a dependence between the inductances of the windings and the geometric dimensions of the windings. Considering that the air gap is uniform, and by analyzing the values for the expressions of the inductances of scattering and the phase mutual inductances, it was concluded that the inductance of each phase scattering and the mutual phase inductances can be written in a general form:

$$L_{ij}^{XY} = (L')_{ij}^{XY} \cdot F(\alpha_{ij}, \varphi_{ij}), \tag{14}$$

where $(L')_{ij}^{XY}$ is the component that depends on the geometric dimensions of a winding; $F(\alpha_{ij}, \varphi_{ij})$ is the component that takes into consideration angular offsets between phase voltages α_{ij} and the difference between the angular shifts of the phase currents of the stator and rotor φ_{ij} of the corresponding windings under a symmetrical mode.

Since the component $F(\alpha_{ij}, \varphi_{ij})$ refers to a symmetric mode, it is advisable to restrict the consideration only to the component $(L')_{ij}^{XY}$. The component of inductance, depending on the geometric dimensions of a winding, equals [22]:

$$(L')_{ij}^{XY} = l_\beta \cdot Z_i^X \cdot Z_j^Y \cdot \frac{\pi}{n^2} \cdot \frac{r_r^3}{g} \cdot \mu, \tag{15}$$

where μ is the magnetic permeability; n is the number of periods in the spatial distribution of a current layer, which, for a nonpolar machine, corresponds to the number of poles p pairs; $g=r_s-r_r$ is the radial magnitude of an air gap; r_s is the stator surface radius; r_r is the rotor surface radius; $Z_j=w/l$ is the linear density of the conductor of a current layer of the corresponding winding; w_j^X is the number of turns of the corresponding winding; l_j^X is the length of the corresponding winding; l_β is the axial length of an air gap.

The inductance of the motor magnetic circuit is determined from expression [30]:

$$L_\mu = \sum_i \sum_j L_{ij}^{XY}, \quad X \neq Y. \tag{16}$$

Since the equality $(L')_{ij}^{XY} = (L')_{ji}^{XY}$ holds, we substituted, in equation (16), the value of one of these inductances [22]. Thus, equation (16) was substituted with the value of the inductances calculated by using expression (15) taking into consideration a change in the number of turns, which corresponds to the change in the integrated resistance of a stator winding:

$$L'_\mu = \sum_i \sum_j (L')_{ij}^{XY}, \quad X \neq Y. \tag{17}$$

After substituting the value of the magnetic chain inductance for an asymmetric mode from expression (16) in expression (8), we derived the value of the mutual inductance for the assigned mode.

By applying expression (7), we determined the full phase inductances, and the results are substituted in expressions for coefficients z (6). The resulting changes to the parameters are adjusted on the simulation model. After that, the simulation model is ready to be used to investigate the electromagnetic processes in an induction motor with the stator asymmetric windings at different damage.

While establishing the values for the active resistance and inductance of the stator phase A, smaller by 20 % than the corresponding parameters of the basic motor, when maintaining other parameters unchanged, a series of new parameters for the motor were obtained. We recalculated the coefficients z (6), mutual inductance, the losses expressed via momenta and the static momentum of resistance based on the above algorithm. By changing the model parameters, we acquired time diagrams of the phase currents of the stator (Fig. 12) and rotor (Fig. 13), the motor shaft rotation frequencies, and the torque on a motor shaft (Fig. 14).

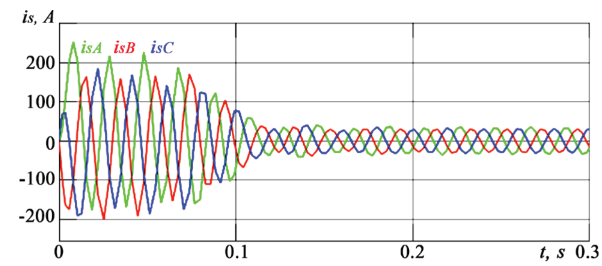


Fig. 12. Time diagrams of the stator phase currents at the asymmetry of the stator windings

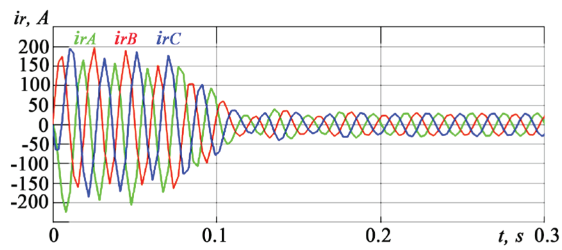


Fig. 13. Time diagrams of the rotor phase currents at the asymmetry of the stator windings

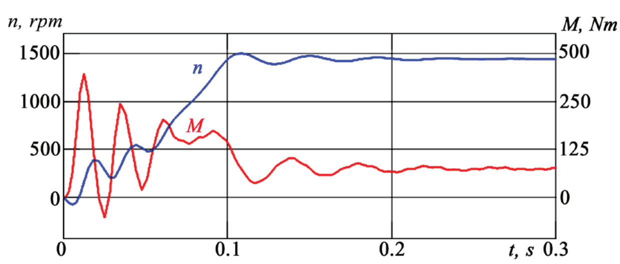


Fig. 14. Time diagrams of the motor shaft rotation frequency (n) and the torque on a motor shaft (m) at the asymmetry of the stator windings

We compared the simulation results with the data acquired experimentally [23, 24] according to the following parameters: the torque pulse rate on a motor shaft f_p, the pulse coefficient of the torque on a motor shaft k_{pM}, the factor of imbalance of phase currents k_{imbI}. The value for the pulse coefficient of torque on a motor shaft k_{pM} was calculated from formula [2]:

$$k_{pM}=\frac{M_{\max}-M_{\min}}{M_{mean}}\cdot 100\,\%, \tag{18}$$

where $M_{\max}$ is the maximum value of the torque, N·m; $M_{\min}$ is the minimum value of the torque, N·m; M_{mean} is the mean value of the torque, N·m.

The value of the imbalance factor of phase currents k_{imbI} was calculated based on expression [2]:

$$k_{imbI}=\frac{I_{S\max}-I_{S\min}}{I_{Ssym.mode}}\cdot 100\%, \tag{19}$$

where $I_{S\max}$ is the maximum value of the stator phase current, A; $I_{S\max}$ is the minimum value of the stator phase current, A; $I_{Ssym.mode}$ is the value of the stator phase current at the symmetrical stator windings, A.

Calculations were performed for the rated mode and are summarized in Table 3.

Table 3

Comparison of simulation results and experimental data

Parameter	Model	Experiment	Error, %
Pulsation frequency f_p, Hz	100	100	0
Torque pulsation coefficient on motor shaft k_{pM}, %	4.002	4.112	2.675
Imbalance factor of the stator phase currents k_{imbI}, %	16.22	16.58	2.171

It follows from the comparison of simulation results and those acquired experimentally (Table 3) that the parameter determination error does not exceed 3 %. This indicates the adequacy of the reported improved induction motor model with a short-circuited rotor, which makes it possible to analyze the dynamic modes at the asymmetrical stator windings.

6. Discussion of the results of an induction motor simulation

Our calculation of the parameters for an induction prototype motor, based on the procedure proposed in work [19] (Table 1), and the comparison of results with the specifications, have shown that the error of the calculation did not exceed 1 %, which indicates the properly selected procedure and the performed calculation.

The characteristics of an induction motor (Fig. 8–11), defined in the course of our simulation, testify to the high stability of the algorithm for implementing a mathematical model of the motor in the MATLAB programming environment (Fig. 6). The high implementation stability was achieved by simplifying the basic mathematical model of an induction motor recorded in the «inhibited coordinates» (1) to (4). The simplification implied expressing the corresponding derivatives from the phase flux linkages through the phase flux linkages (5).

The parameters for an induction motor, calculated on the basis of simulation results, as well as comparing them with the parameters for an induction prototype motor, calculated according to the procedure proposed in [19], have shown that the maximum error in determining the parameters did not exceed 7 %. This confirms the adequacy of the proposed model. Such a result is achieved by considering the power losses in the motor's steel, as well as the mechanical losses. In the model, these losses are expressed through additional static momenta: $M_{c.mech}$ is the momentum that takes into consideration mechanical losses (11) and $M_{c.s}$ is the momentum that takes into consideration the losses in steel.

In the organization of an asymmetric mode of the stator windings in an induction motor, the characteristics for the induction motor, defined in the course of the simulation, and those acquired experimentally differ by not more than 3 %. This convergence of results is explained by the following.

The mathematical model of an induction motor in the «inhibited coordinates» employs a parameter such as the mutual inductance (1) to (4), depending on the inductance of the motor magnetic circuit (8). The inductance of a magnetic circuit is the sum of the partial mutual inductances of each phase of the stator and rotor windings (16). The partial mutual inductances, as well as the inductances of phase scattering, primarily depend on the geometric dimensions of the windings, in particular the number of turns (15). A change in the number of turns of one of the stator windings leads to a change in the inductance of scattering of this phase of a stator winding and to a change in the partial mutual inductances associated with this phase. The consideration of the change in the full mutual inductance of the motor windings did provide for a high level of convergence between the simulation results and experimental data.

The advantages of a given simulation model include the possibility to investigate the dynamic processes in an induction motor with a short-circuited rotor, which includes the asymmetrical windings of the stator with high reliability of the results.

The high reliability in determining the motor parameters is achieved due to the following:

– the introduction of an additional static momentum, taking into consideration the mechanical losses and losses in the motor's steel;

– the consideration of a change in the magnitude of mutual inductance at a change in the integrated resistance of the motor windings.

The disadvantage of the model is that the model could be used only for studying the motor operation provided the quality of power, that is, at the symmetrical system of stator voltages and at the sinusoidal shape of these voltages.

A given model is a continuation of such research works as «Methods for improving the energy efficiency, reliability, and diagnosing of modern and hybrid vehicles» (No. of the State registration 0114U007085); «Construction of methods for reducing the energy intensity and improving the systems for diagnosing the railroad transportation equipment» (No. of State registration 0116U006406), which were carried out at the State University of Infrastructure and Technologies, the Department of Traction Rolling Stock (Ukraine).

This work could be advanced by the following:

– to investigate the processes occurring in an induction motor at interturn short circuiting in one or several phases, when diagnosing the degree of interturn short-circuiting in the stator winding, etc.;

– to study the operation of an induction motor with asymmetrical windings, which is powered by a poor power supply system;

– to examine the mutual influence of the operation of drives with alternating and direct current motors.

6. Conclusions

1. We have advanced and improved a mathematical model in which the differential equations are recorded in the «inhibited coordinates». In order to reduce the number of integration operations, when determining the dynamic variables that describe the motor operation, the system of differential equations has been simplified by representing the phase currents through the flux linkage.

2. In order to conduct a thorough analysis aimed at comparing and estimating the results obtained in the course of the simulation, we have performed the manual calculation of the parameters and characteristics for an induction prototype motor with a short-circuited rotor of specific power, thus establishing the parameters for a replacement scheme for different modes of operation according to the classical procedure.

3. We have improved the simulation mathematical model of the motor with symmetrical windings taking into consideration the losses of power in steel and the mechanical losses by employing the MATLAB programming environment in the «inhibited coordinates». The derived mathematical model has the high robustness of the implementation algorithm due to the simplification of the basic mathematical model.

4. To establish the degree of adequacy of the constructed model, we have compared the simulation results and the results of calculations. The maximum error in determining the parameters is within 0.045–6.365 %, confirming the adequacy and a high level of the accuracy of the simulation model. The power, the motor shaft rotation frequency under the rated and idling modes almost completely coincide with the specifications for a material prototype motor.

The maximum error in determining the parameters is within 0.045–6.365 %, confirming the adequacy and a high level of the accuracy of the simulation model. The power, the motor shaft rotation frequency under the rated and idling modes almost completely coincide with the specifications for a material prototype motor.

5. For the mathematical model of an induction motor, an algorithm has been proposed to consider a change in the mutual inductance of windings due to a change in the integrated resistance of one or several windings. That could significantly improve the understanding of those dynamic processes that actually occur in a motor with asymmetrical windings, and would enable the further development of diagnostic measures in order to identify the degree of damage to a stator winding.

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