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Calculation of the permissible load of an induction motor with parametric winding asymmetry

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The purpose of the research presented in this article is to develop an engineering methodology for determining the permissible load torque of a three-phase asynchronous motor with parametric electromagnetic asymmetry of the stator windings, which ensures that the insulation service life is maintained at an acceptable level.

Based on the full phase (ABC–abc) mathematical model of an induction motor, in which the asymmetrical active resistances and inductances of one of the stator phases are explicitly specified, a numerical simulation was carried out in the MATLAB Simulink environment. Using the temperature-exponential model of insulation ageing, the dependence of the relative service life on the current multiplicity was determined. Using the least squares method, an analytical approximation of the multiplicity of insulation resource reduction as a function of the asymmetry coefficient and load moment was obtained.

It is shown that even moderate asymmetry of the active resistance of the stator phase (±20–30%) leads to a significant increase in currents and copper losses, as well as to a multiple reduction in the insulation resource at nominal load. It is established that a targeted reduction in the load moment by 5–10% of the nominal value allows compensation for the negative impact of asymmetry and returns the insulation resource to unity.

A generalised analytical model of insulation resource reduction is proposed that simultaneously accounts for the parametric asymmetry coefficient and the level of mechanical load, and, based on it, an engineering methodology for calculating the permissible load for partially damaged induction motors is developed.

The results obtained allow operators to make informed decisions about continuing to operate engines with detected parametric asymmetry, and to adjust the load to prevent accelerated thermal ageing of the insulation and unplanned failures.

Keywords: induction motor, parametric asymmetry, permissible load, insulation life, copper losses

INTRODUCTION

Induction motors (IM) remain the main type of electric machines in industrial electric drives due to their simplicity of design, high reliability, and reasonable cost. At the same time, increasing requirements for energy efficiency, reliability, and the predictability of electric drive resources require a deeper consideration of real operational factors, among which the electromagnetic and electrical asymmetry of the stator and rotor windings is a key factor. The asymmetry of the winding parameters leads to the redistribution of currents between the phases, increased copper losses, additional pulsations in electromagnetic torque, and local overheating, which ultimately significantly reduce the service life of the insulation and the motor's overall reliability.

Traditionally, in calculations and modelling, the assumption of complete symmetry of three-phase windings and uniformity of the air gap is made, which allows for moving to generalised two-channel models (d–q coordinate system), simplifying inductive couplings, and using compact equivalent circuits. However, in real operating conditions of induction motors, this assumption is often violated. Electromagnetic asymmetry can occur due to (1) interturn short circuits in one of the stator phases; due to uneven resistance of contact connections and repair inserts, (2) manufacturing deviations (variation of conductor parameters, geometric inaccuracies in the installation of slot windings), (3) damage or deformation of the rotor (change in the parameters of the short-circuited rotor rods).

In such cases, simplified symmetrical models prevent accurate estimation of the actual level of currents in the 'weakened' phase, additional copper losses, uneven heating, and, most importantly, the impact of asymmetry on insulation life.

In practice, electric drives with partially damaged or 'ageing' induction motors often continue to operate due to the technological impossibility of quick replacement of units. In these conditions, the task is not only to detect the presence of asymmetry but also to calculate the permissible motor load given the existing parametric deviations to prevent accelerated insulation ageing. Known approaches to diagnosing asymmetries usually focus on analysing the harmonic composition of currents and voltages, assessing electricity quality indicators (voltage asymmetry, the presence of reverse-sequence components), and diagnosing characteristic defects (broken rotor bars, interturn short circuits, etc.).

However, the issue of quantifying the permissible load moment given an already detected asymmetry in the winding parameters is considered in most works only in passing or is completely ignored.

The influence of electromagnetic asymmetry on the service life of insulation is especially critical. Exceeding currents, even within the limits close to the nominal but with large local overloads of individual phases, leads to a significant increase in the temperature of individual sections of the windings. As a result, the relative insulation resource can decrease by dozens of times, directly affecting the reliability of the electric drive and leading to unplanned downtime of technological equipment. That is why it is important for operators to have an engineering methodology that, based on the estimated asymmetry coefficient, allows them to determine the range of permissible loads on the motor shaft, at which the insulation resource will not be less than unity (i.e., its additional 'accelerated' depletion will not occur).

In this context, models of an induction motor are particularly valuable, as they explicitly account for the winding parameters' electromagnetic asymmetry. The use of a full IM model in phase coordinates (ABC–abc), where the resistances and inductances of individual phases can be specified independently, allows for obtaining a detailed picture of the redistribution of currents, copper losses and electromagnetic torque at different values of the asymmetry coefficient. Based on such models, it is possible to form generalised dependencies: 'asymmetry coefficient – relative currents – relative losses – relative insulation service life', and then to build analytical or empirical relations for calculating the permissible load torque.

ANALYSIS OF THE STATE-OF-THE-ART

A modern approach to the mathematical modelling of induction motors that explicitly accounts for parametric and structural asymmetries is demonstrated in [1]. The proposed model

analyses the influence of parameter deviations on the dynamic modes IM. In two consecutive works [7, 8], various mathematical representations of the induction machine (models in αβ- and dq-coordinates, simplified and full models) are systematised and validated experimentally, including voltage sag and re-acceleration modes. These studies confirm that full dynamic models are necessary for accurate assessment of transients and overloads. In [15], an extended analytical model of a motor with stator interturn circuits is developed, specifically accounting for the influence of rotor slot harmonics. Complex electromagnetic effects associated with asymmetry are derived to the level of explicit model parameters (equivalent resistances, mutual inductances), which are then used to analyse dynamics. A separate group of studies concerns the refinement of motor parameters based on experimental transients. In [9], a methodology for refining IM parameters is proposed.

A significant part of modern publications is devoted to the relationship between electromagnetic modes, losses, and insulation service life. In [2], additional losses in steel are analytically estimated, a thermal model is developed, and the insulation service life is predicted under harmonics and supply-voltage asymmetry. This shows that even a relatively small asymmetry or distortion of the network significantly reduces the motor resource. In [3], the heating of a low-power IM motor is simulated under the combined effects of voltage asymmetry and interturn short-circuit, demonstrating significant local overheating and a reduction in residual resource. In [4], emphasis is placed on predicting insulation ageing based on the 'resource loss – time' trend and additional diagnostic indicators (crest factor). In [5] and [17], load regulation and total losses in IM motors are investigated. They show that targeted torque/power limitation, taking into account the thermal state, significantly reduces the rate of insulation ageing and the frequency of failures. The development of the ideas of derating curves is illustrated in [6]: here, using the ANFIS model, the maximum permissible torque of the IM is estimated for various factors of voltage asymmetry, overvoltage, harmonics, temperature, and a map 'factor – permissible deformation/moment' is constructed.

Several studies [11–16] focus on the detection of interturn damage and asymmetry using current or voltage signals. In [11], a functional method for diagnosing interturn faults in the presence of supply-voltage asymmetry is proposed, and the conditions for distinguishing between 'network' and 'machine' asymmetry are analysed. Classical works [12, 14, 15] develop analytical models of an engine with interturn damage, or optimisation/heuristic algorithms for estimating damage parameters, for example, using simulated annealing [14]. Modern works [13] and [16] demonstrate the transition to machine learning and neural networks for diagnosing interturn faults. In [13], the current vector in the αβ plane is analysed, and interturn defects are detected based on the shape of the elliptical trajectory; in [16], a small ResNet network is used to detect defects early using the current derivative.

In [10], modern methods for increasing the energy efficiency of IM – optimisation of voltage regimes, frequency and flux control, use of frequency converters, and improvement of diagnostic and monitoring systems – are summarised. Many recommendations emphasise the need to limit the load under adverse power supply conditions; however, specific algorithms for calculating the permissible load often rely on reference derating curves or empirical coefficients.

The purpose of the work. The purpose of the work is to develop and verify an engineering approach to determining the permissible load torque of an induction motor with parametric electromagnetic asymmetry of the stator windings.

Research material. We form a mathematical model of an induction motor in phase coordinates, taking into account the three-phase structure of the stator and rotor windings, the connection of the stator windings in a star with an isolated neutral, and the parametric electromagnetic asymmetry of one of the stator phases.

Let us consider a three-phase IM motor with a stator winding in a fixed coordinate system: *A*, *B*, *C* and a rotor short-circuited winding in a rotating coordinate system *a*, *b*, *c*. Rotor parameters are given to the stator side.

The instantaneous electrical equilibrium equations for the stator phases have the form:

$$u_A = R_A i_A + \frac{d\psi_A}{dt},$$
$$u_B = R_B i_B + \frac{d\psi_B}{dt}, \quad (1)$$
$$u_C = R_C i_C + \frac{d\psi_C}{dt},$$

where $u_{A,\,B,\,C}$ – instantaneous phase voltages (between the corresponding phase terminal and neutral N); $i_{A,\,B,\,C}$ – instantaneous currents in the stator phases; $\psi_{A,\,B,\,C}$ – flux linkage of the corresponding phases; $R_{A,\,B,\,C}$ – active resistances of the stator phases.

Similarly, for the rotor (driven to the stator):

$$u_a = R_a i_a + \frac{d\psi_a}{dt},$$
$$u_b = R_b i_b + \frac{d\psi_b}{dt}, \quad (2)$$
$$u_c = R_c i_c + \frac{d\psi_c}{dt},$$

where $u_{a,\,b,\,c}$, $i_{a,\,b,\,c}$, $\psi_{a,\,b,\,s}$, $R_{a,\,b,\,c}$ – voltages, currents, flux linkage, and active resistances of the rotor phases.

In vector-matrix form (for further calculations) (1), (2) are written as:

$$\mathbf{U}_s = \mathbf{R}_s \mathbf{I}_s + \frac{d\boldsymbol{\psi}_s}{dt},$$
$$\mathbf{U}_r = \mathbf{R}_r \mathbf{I}_r + \frac{d\boldsymbol{\psi}_r}{dt}, \quad (3)$$

where

$$\mathbf{U}_s = \begin{bmatrix} U_A \\ U_B \\ U_C \end{bmatrix}, \mathbf{I}_s = \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}, \boldsymbol{\Psi}_s = \begin{bmatrix} \psi_A \\ \psi_B \\ \psi_C \end{bmatrix},$$
$$\mathbf{U}_r = \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix}, \mathbf{I}_r = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}, \boldsymbol{\Psi}_r = \begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix}, \quad (3)$$

– vectors of voltages, currents and flux linkages of phases *A*, *B*, *C* stator and phases *a*, *b*, *c* rotor, respectively.

The matrices of active resistances of the stator and rotor are diagonal:

$$\mathbf{R}_s = \begin{bmatrix} R_A & 0 & 0 \\ 0 & R_B & 0 \\ 0 & 0 & R_C \end{bmatrix}, \mathbf{R}_r = \begin{bmatrix} R_a & 0 & 0 \\ 0 & R_b & 0 \\ 0 & 0 & R_c \end{bmatrix}. \quad (4)$$

The phase flux linkages are given by the complete matrix of machine inductances:

$$\begin{bmatrix} \boldsymbol{\psi}_s \\ \boldsymbol{\psi}_r \end{bmatrix} = \mathbf{L}(\theta) \begin{bmatrix} \mathbf{i}_s \\ \mathbf{i}_r \end{bmatrix} = \begin{bmatrix} \mathbf{L}_{ss} & \mathbf{L}_{sr} \\ \mathbf{L}_{rs} & \mathbf{L}_{rr} \end{bmatrix} \begin{bmatrix} \mathbf{i}_s \\ \mathbf{i}_r \end{bmatrix}, \quad (5)$$

where $\mathbf{L}_{ss}$, $\mathbf{L}_{rr}$ – matrices of intrinsic and mutual inductances of the stator and rotor phases; $\mathbf{L}_{sr}$, $\mathbf{L}_{rs}$ – matrices of mutual inductances between the stator and the rotor; θ – angular position of the rotor.

Substituting (5) into (3), we obtain a system of vector equations in which the phase currents are interconnected through inductive couplings. The model at this stage describes a three-phase electromagnetic subsystem without accounting for the specific method of connecting the stator windings.

For symmetrical IM, the active resistances and inductances of the stator phases are considered the same:

$$R_A = R_B = R_C = R_{s0},\ L_A = L_B = L_C = L_{s0}, \quad (6)$$

and the matrix $\mathbf{L}_{ss}$ has a circulant structure, which corresponds to a uniform magnetic field and identical magnetic phase parameters.

Parametric electromagnetic asymmetry models situations in which one of the phases has changed electrical and magnetic parameters (interturn short circuits, degraded connections, repair inserts, etc.). Without loss of generality, we will assume that phase *B* is damaged. Let us introduce:

– unbalance coefficient of active resistance:

$$k_R = \frac{R_B}{R_{s0}}, \quad (7)$$

– inductance asymmetry coefficient:

$$k_L = \frac{L_B}{L_{s0}}. \quad (8)$$

Physically, when an inter-turn short circuit occurs, the number of effectively working turns of a phase decreases. Taking into account the fact that the resistance of the winding is proportional to the number of turns, and the inductance is proportional to the square of the number of turns, in a first approximation, the following relation is valid:

$$k_L \approx k_R^2 \quad (9)$$

Then the matrix of active stator resistances takes the form:

$$R_s = \begin{bmatrix} R_{s0} & 0 & 0 \\ 0 & k_R R_{s0} & 0 \\ 0 & 0 & R_{s0} \end{bmatrix}, \quad (10)$$

i.e., the resistance of phase *B* is scaled to k_R, while phases *A* and *C* retain their nominal values.

In the stator, inductance matrix $\mathbf{L}_{ss}$ are changing:

– diagonal element corresponding to phase *B*:

$$L_{BB} = k_L L_{s0}, \quad (11)$$

– mutual inductances between phase *B* and phases *A*, *C*. For a smooth-pole IM, they can be written as:

$$L_{AB} = L_{BA} = k_L L_m, L_{BC} = L_{CB} = k_L L_m, \quad (12)$$

where L_m – nominal mutual inductance between the phases of a symmetrical machine. Phases *A* and *C* retain their nominal parameters:

$$L_{AA} = L_{CC} = L_{s0}, L_{AC} = L_{CA} = L_m. \quad (13)$$

As a result, matrix $\mathbf{L}_{ss}$ loses the perfect symmetry characteristic of a fully functional machine, and the full matrix $\mathbf{L}(\theta)$ becomes asymmetric with respect to the phase reversal. This leads to: different instantaneous and effective values of the currents in the phases i_A, i_B, i_C even with a symmetrical power supply, changed shape and level of electromagnetic moment pulsations, and a more complex structure of magnetic connections between the stator and rotor.

The parametric electromagnetic asymmetry of one phase is thus described by a set of parameters ($k_R k_L$), which are explicitly included in matrices $\mathbf{R}_s$ and $\mathbf{L}_{ss}$.

The energy of the electromagnetic field of the IM can be written as:

$$W_{em} = \frac{1}{2}[\mathbf{i}_s^T \ \mathbf{i}_r^T]\Lambda(\theta)\begin{bmatrix} \mathbf{i}_s \\ \mathbf{i}_r \end{bmatrix}. \quad (14)$$

The electromagnetic torque is determined from the derivative of the energy with respect to the rotor rotation angle:

$$W_e = \frac{\partial W_{em}}{\partial \theta}. \quad (15)$$

The mechanical motion of the rotor is described by the equation:

$$J\frac{d\omega}{dt} = M_e - M_L - M_{mech}, \quad (16)$$

where *J* – the reduced moment of inertia; ω – angular frequency of rotation of the rotor; M_L – static load moment on the shaft; M_{mech} – moment of mechanical losses.

The angular position of the rotor is related to the speed by the ratio:

$$\frac{d\theta}{dt} = \omega. \quad (17)$$

Thus, the electromechanical subsystem is described by equations (14)–(17), which relate electromagnetic variables to mechanical coordinates.

The model described above is implemented as a MATLAB Simulink model (Fig. 1).

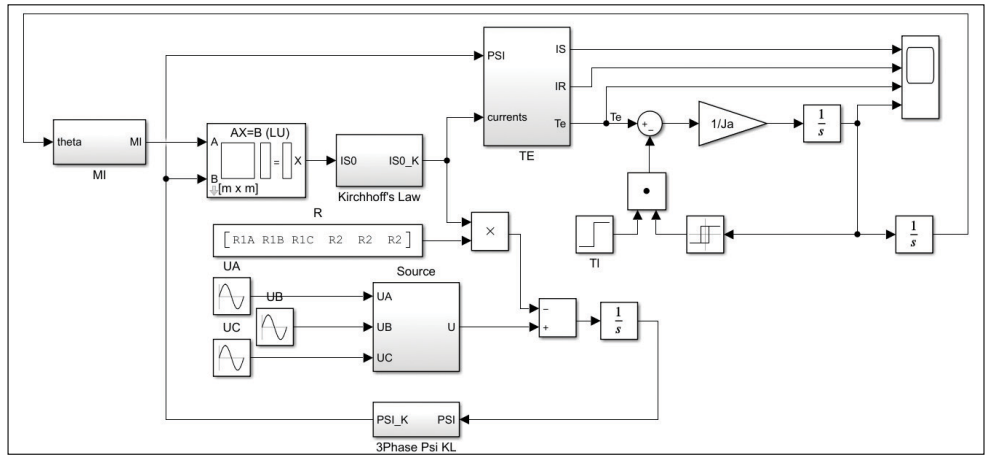

Fig. 1. Model of an induction motor with parametric electromagnetic asymmetry of windings

To conduct research and perform calculations using the model, all parameters must be set in the Model Properties block, where the parameters are configured (Fig. 2).

Let us consider how the load on the induction motor shaft affects the service life of the insulation when the electromagnetic parameters are asymmetrical.

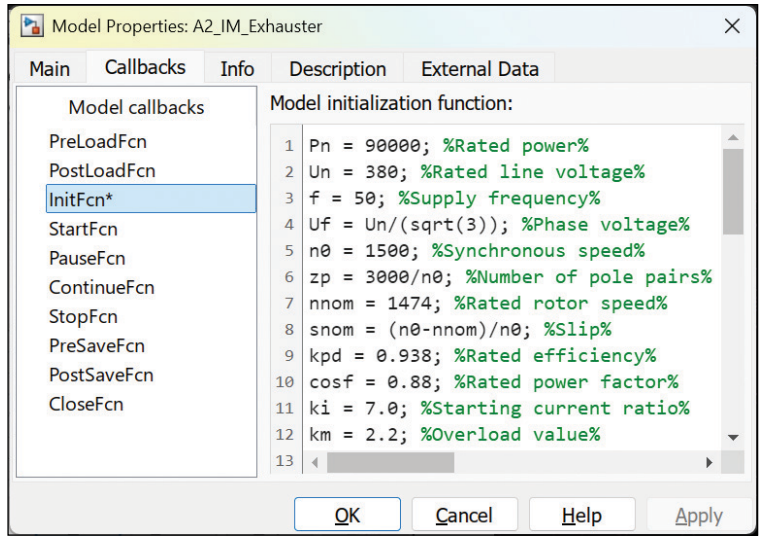

Fig. 2. Model Properties for debugging parameters

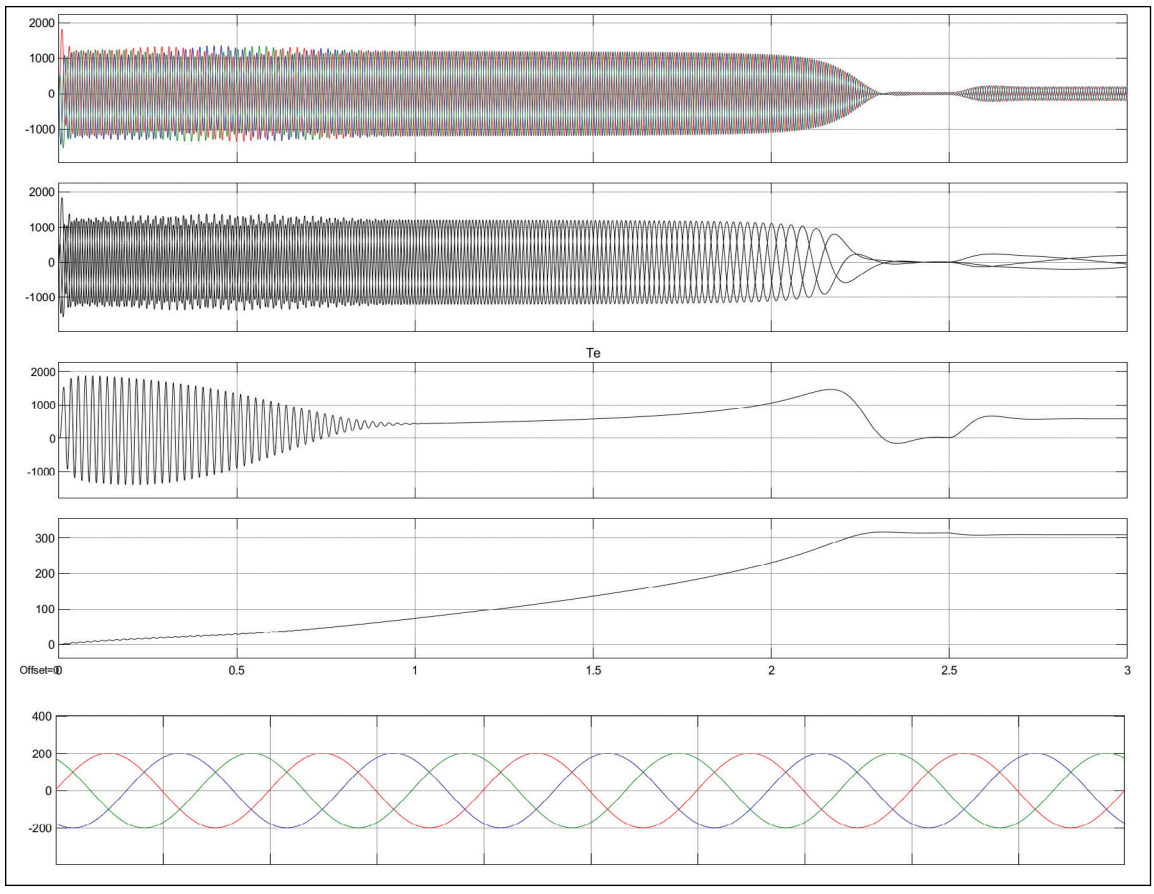

Fig. 3. Time processes during the induction motor start-up: stator phase currents, rotor phase currents, electromagnetic torque, angular frequency of rotation and stator phase currents (fragment, at an interval of 0.1 s) for a symmetrical motor

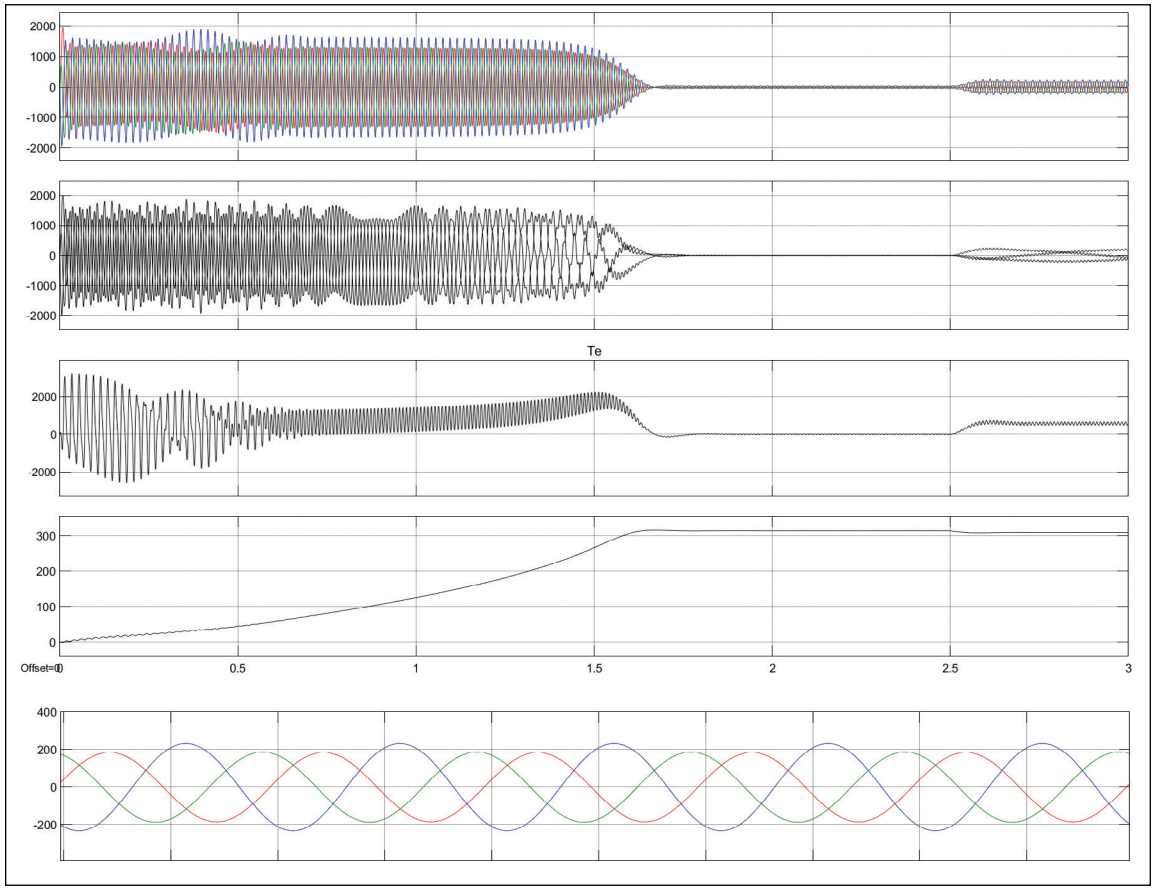

Fig. 4. Time processes during the induction motor start-up: stator phase currents, rotor phase currents, electromagnetic torque, angular frequency of rotation and stator phase currents (fragment, at an interval of 0.1 s) with a winding asymmetry coefficient of 0.5

A study will be performed to assess the asymmetry in the active resistance of phase B at the rated load of the motor. Moreover, the asymmetry coefficient ranges from 0.5 to 1.5. The calculations are summarised in Table 1.

The relative service life of the insulation is calculated as:

$$z = e^{-b\left(i^2-1\right)\vartheta_H}, \tag{18}$$

Table 1. **Calculations of performance indicators for resistance asymmetry**

Coefficient asymmetries	Phase current, A	Phase current, relative units $\frac{I_1}{I_{1nom}}$	Electrical losses, relative units $\frac{\Delta p_1}{\Delta p_{1m.nom}}$	Relative service life of insulation, *z*	Multiplicity of reduction in insulation life, γ
0.5	233.2	1.157	1.339	0.046	21.9
0.6	227.6	1.13	1.276	0.081	12.282
0.7	222.2	1.102	1.215	0.142	7.059
0.8	215.5	1.069	1.144	0.271	3.696
0.9	207.2	1.03	1.06	0.577	1.733
1.0	201.5	1	1	1	1
1.1	205.5	1.02	1.04	0.694	1.44
1.2	210	1.042	1.086	0.457	2.189
1.3	214.7	1.066	1.135	0.292	3.422
1.4	219.5	1.089	1.187	0.183	5.458
1.5	225	1.117	1.247	0.106	9.437

where b = 0.0866 – coefficient, $i = \frac{I_1}{I_{1nom}}$ – stator current multiplicity, ϑ_H – nominal temperature for this insulation class.

The multiplicity of insulation life reduction will be determined as:

$$\gamma = \frac{1}{z}. \tag{19}$$

As presented in Table 1 and Fig. 5, even moderate resistance deviations of ±20–30% (asymmetry coefficient values of 0.7–0.8) lead to a noticeable increase in currents and losses in the faulty phase.

Considering that the work is carried out in the working, rigid section of the mechanical characteristic, which is practically linear up to the load moment that does not exceed the nominal one, we write the dependence between the electromagnetic moment and the stator current in the form of a straight line equation:

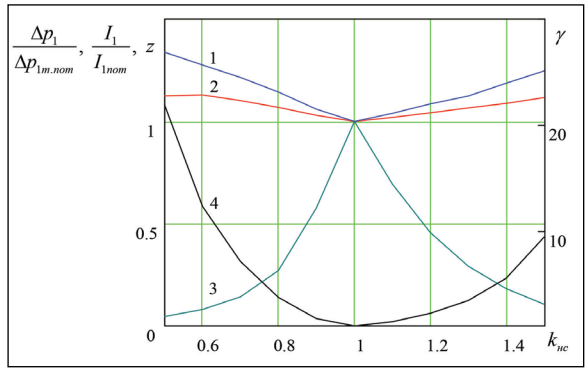

Fig. 5. Performance indicators of the induction motor with asymmetry of electromagnetic parameters: 1 – relative electrical losses in the stator copper; 2 – relative stator current; 3 – relative insulation service life; 4 – multiplicity of reduction in insulation life

$$I_1 = \left(I_{1(1.0)} - I_0\right)\frac{M_1}{M_H} + I_0, \tag{20}$$

where I_1, $I_{1(1.0)}$, I_0 – current at the moment of load M_1, current at rated torque, no-load current.

Let us calculate the multiplicity of the reduction in insulation life for other values of the load moment and show the results in Table 2.

From the fragment of Fig. 6 (b) it is clear that the multiplicity of the insulation resource can be reduced when the load is reduced.

Let us solve the problem of finding such a load moment at which, with a real asymmetry coefficient, the rate of resource reduction would not exceed unity.

Using the least squares method (LSM), we will estimate the model and its coefficients from the data in Table 2. We will take the equation as the model:

$$\gamma = ae^{bk_{ns}}. \tag{21}$$

The coefficients for different load moments are summarised in Table 3.

Let us find the equation that relates the model coefficients.

Table 3. **Coefficients of the insulation life reduction factor model for different load moments**

Load moment, a.o., $\frac{M_1}{M_{nom}}$	**a**	**b**
1	414.111	–5.872
0.975	221	–5.61
0.95	122.26	–5.391
0.9	36.2	–4.84

Table 2. **Multiplicity of reduction in insulation life at different values of load moment**

Coefficient asymmetries	**Phase current, relative units $\frac{I_1}{I_{1nom}}$**				**Multiplicity of reduction in insulation life, γ**			
Load moment	1.0	0.975	0.95	0.9	1.0	0.975	0.95	0.9
0.5	1.157	1.133	1.11	1.062	21.9	13.287	8.202	3.222
0.6	1.13	1.107	1.084	1.038	12.282	7.772	4.917	2.026
0.7	1.102	1.08	1.057	1.013	7.059	4.516	2.929	1.266
0.8	1.069	1.048	1.026	0.983	3.696	2.424	1.617	0.739
0.9	1.03	1.01	0.989	0.948	1.733	1.19	0.82	0.399
1.0	1	0.98	0.961	0.921	1	0.701	0.495	0.252

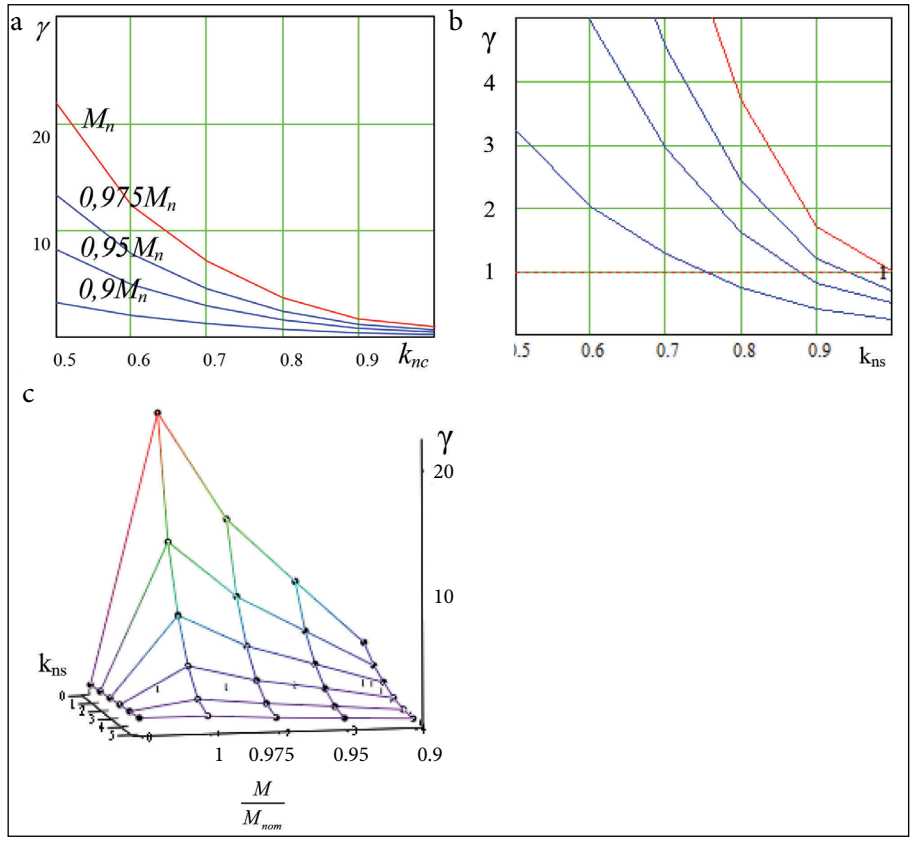

Fig. 6. Multiplicity of reduction in insulation life for different load moments: (a) – in the entire range; (b) – fragment; (c) – three-dimensional graph

Coefficient a we will search in the form $a = a_0\left(\frac{M_1}{M_{nom}}\right)^{b_0}$.

Coefficient b we will search in the form $b = a_1 + b_1\left(\frac{M}{M_{nom}}\right)$.

The values of the coefficients are summarised in Table 4.

Table 4. **Coefficients of the coupling equations**

a_0	b_0	a_1	b_1
411.23	24.55	4.39	–10.27

The final equation for the insulation life, taking into account the load moment and the asymmetry coefficient, will take the form:

$$\gamma = a_0\left(\frac{M}{M_{nom}}\right)^{b_0} e^{k_{ns}\left(a_1+b_1\left(\frac{M}{M_{nom}}\right)\right)}. \qquad (22)$$

Let us solve the equation relative to the load moment, for γ = 1:

$$\frac{M}{M_{nom}} = \exp\left(\frac{1}{b_0}\ln\left(\frac{1}{a_0}\right) - \right. \qquad (23)$$
$$\left. -LambertW\left(\frac{b_1}{b_0}k_{ns}e^{\frac{1}{b_0}\left(\ln\left(\frac{1}{a_0}\right)-a_1k_{ns}+1\right)}\right) - \frac{a_1}{b_0}k_{ns} + \frac{1}{b_0}\right).$$

where $LambertW$ (•) – the Lambert exponential function, which can only be calculated by numerical methods.

To find an analytical solution, we expand the relative momentum equation into a Taylor series in the neighbourhood of the point k_{ns}:

$$\frac{M}{M_{nom}} = A - \frac{k_{ns}A(a_1+b_1A)}{b_0} +$$
$$+k_{ns}^2A\left(\frac{(a_1+b_1A}{2b_0^2} + \frac{b_1^2A_1}{b_0^2} + \frac{a_1b_1A}{b_0^2}\right), \qquad (24)$$

where $A = e^{\frac{1}{b_0}\left(\ln\left(\frac{1}{a_0}\right)+1\right)}$, $A_1 = e^{\frac{2}{b_0}\left(\ln\left(\frac{1}{a_0}\right)+1\right)}$.

Let us build a dependence $\frac{M}{M_{nom}} = f(k_{ns})$.

The resulting equation (24) makes it possible to calculate the required load torque at which, for a given asymmetry factor, the factor of insulation service life reduction does not exceed unity. As shown in Fig. 7, under conditions of parametric deviations, reducing the load torque by 5–10% from the rated value allows the insulation service life to be restored to an acceptable level.

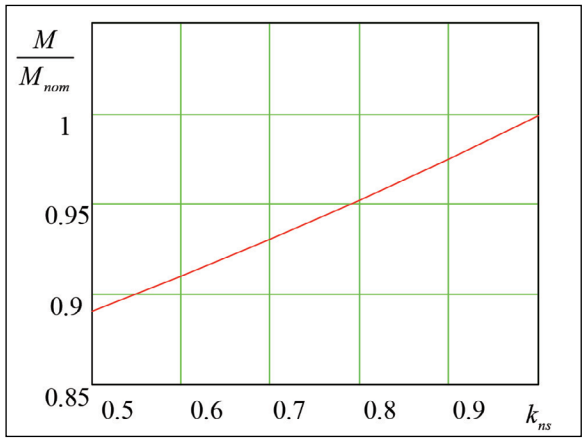

Fig. 7. Dependence of the required load moment on the parametric electromagnetic asymmetry of the induction motor phases

CONCLUSIONS

A complete model of an induction motor in ABC–abc coordinates, which takes the three-phase structure of the stator and rotor windings, the connection of the stator windings in a star with an isolated neutral, and the parametric electromagnetic asymmetry of one phase due to changes in active resistance and inductance into account, is constructed. It is shown that such a model allows for the correct description of current redistribution and changes in electromagnetic torque when the phase parameters deviate from the nominal values.

Based on numerical simulation in Simulink of steady-state and transient modes, the dependences of the relative currents of the most loaded phase and the relative losses in the stator copper on the unbalance coefficient of the active resistance in the range kR = 0, 5…1,5. It has been shown that even moderate deviations in resistance (±20–30%) lead to noticeable increases in currents and losses in the damaged phase.

Using the temperature-exponential model, the relative insulation life and the rate of reduction in service life were calculated as a function of the current rate. The results obtained demonstrate that at an asymmetry factor of k_R = 0, 5…0,7. The insulation life can be reduced by an order of magnitude or more, even while maintaining the nominal load moment, which confirms the criticality of early detection and consideration of parametric defects.

Based on tabular simulation results, the dependence of the insulation resource reduction multiplicity on the asymmetry coefficient and the load moment was approximated using the least-squares method. An analytical equation was proposed, the parameters of which were obtained for several load-moment levels and then generalised into a final model. This allowed us to move from purely numerical results to a compact formula for calculation.

Based on the final equation, a method is proposed to determine the load moment at which, for a given asymmetry coefficient, the multiplicity of the insulation resource reduction does not exceed unity. It is shown that, for parametric deviations, a reduction of the load moment by 5–10% of the nominal value can restore the insulation resource to an acceptable level.

As a result of combining the phase model of the induction motor with parametric asymmetry and its analytical generalisation, an engineering methodology has been proposed that, based on the estimated asymmetry coefficient (for example, from diagnostics), allows the permissible range of shaft loads to be quickly determined. The methodology can be used to make decisions regarding the further operation of partially damaged motors, the correction of operating modes of electric drives, and the planning of repairs, taking into account the actual state of insulation.

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LEISTINOSIOS APKROVOS SKAIČIAVIMAS ASINCHRONINIAM VARIKLIUI SU PARAMETRINE APVIJŲ ASIMETRIJA

Santrauka

Šio straipsnio tikslas – pristatyti parengtą inžinerinę metodiką, skirtą trifazio asinchroninio variklio su parametrine statoriaus apvijų elektromagnetine asimetrija leistinajam apkrovos momentui nustatyti, užtikrinant, kad izoliacijos tarnavimo laikas išliktų priimtinas.

Tyrimas atliktas remiantis pilnuoju faziniu (ABC–abc) asinchroninio variklio matematiniu modeliu, kuriame aiškiai įvertintos vienos iš statoriaus fazių asimetrinės aktyviosios varžos ir induktyvumo vertės. Skaitinis modeliavimas atliktas „MATLAB Simulink“ aplinkoje. Taikant temperatūrinį eksponentinį izoliacijos senėjimo modelį, nustatyta santykinio tarnavimo laiko priklausomybė nuo srovės kartotinumo. Mažiausiųjų kvadratų metodu gauta analitinė izoliacijos resurso sumažėjimo kartotinumo aproksimacija, išreiškiama kaip asimetrijos koeficiento ir apkrovos momento funkcija.

Nustatyta, kad net ir santykinai nedidelė statoriaus fazės aktyviosios varžos asimetrija (±20–30 %) sukelia reikšmingą srovių ir vario nuostolių padidėjimą, taip pat kelis kartus sumažina izoliacijos resursą esant vardinei apkrovai. Parodyta, kad tikslingai sumažinus apkrovos momentą 5–10 % nuo vardinės vertės, galima kompensuoti neigiamą asimetrijos poveikį ir atkurti santykinį izoliacijos resursą iki vieneto.

Pasiūlytas apibendrintas analitinis izoliacijos resurso mažėjimo modelis, kuris leidžia vienu metu įvertinti parametrinės asimetrijos koeficientą bei mechaninės apkrovos lygį. Juo remiantis parengta inžinerinė metodika, skirta leistinajai apkrovai apskaičiuoti iš dalies pažeistiems asinchroniniams varikliams.

Gauti rezultatai leidžia operatoriams priimti pagrįstus sprendimus dėl tolesnio variklių su aptikta parametrine asimetrija eksploatavimo ir koreguoti apkrovą, siekiant išvengti spartesnio terminio izoliacijos senėjimo bei neplanuotų gedimų.

Reikšminiai žodžiai: asinchroninis variklis, parametrinė asimetrija, leistinoji apkrova, izoliacijos tarnavimo laikas, vario nuostoliai, fazinis modelis