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IMPROVEMENT OF THE METHOD OF CALCULATING THE PARAMETERS OF THE INDUCTION MOTORS REPLACEMENT SCHEME

В. Пліс. **Удосконалення методу розрахунку параметрів заступної схеми асинхронних двигунів.** Подано оптимізацію параметрів заступної схеми трифазного асинхронного двигуна з еквівалентним двоконтурним ротором. Початкові параметри еквівалентної схеми оцінюються із застосуванням методу, відомого як інженерний, на основі даних, зазначених у технічному паспорті виробника. Мета цієї роботи спрямована на підвищення точності розрахунку струмів та моментів при використанні двоконтурної заступної схеми асинхронного двигуна за рахунок удосконалення методу визначення параметрів заступної схеми. Розроблено порядок оптимізації параметрів, що дозволяє зменшити похибки між розрахунковими та фактичними значеннями моменту та струму двигуна. Досягнення мети забезпечується за рахунок використання авторської методики урахування нелінійностей двигуна, а саме насичення магнітного кола по основному шляху і шляхах розсіювання. Для аналізу характеристик асинхронного двигуна та прогнозування його поведінки у випадку несправностей та різних режимів експлуатації необхідно створити математичну модель цього двигуна. Для забезпечення адекватності розрахунків моделі необхідно враховувати різноманітні нелінійності асинхронного двигуна, такі як ефекти витіснення струму і насичення машини, втрати у сталі та інші. Вибір конкретної нелінійності для врахування, а також методики її урахування визначаються складністю завдань, що ставляться перед моделлю. Глибина врахування нелінійних параметрів асинхронного двигуна залежить від вимог до точності аналізу та обов’язково включає у себе урахування найбільш вагомих факторів, що впливають на робочі характеристики машини. Створено універсальну математичну модель, яка описує асинхронний двигун у системі координат, що є нерухомою відносно статора і враховує нелінійності його параметрів. Оцінено параметри заступної схеми дванадцяти промислових асинхронних двигунів без та з оптимізацією. Зроблено порівняння отриманих результатів з інженерним методом та фактичними даними виробника для перевірки ефективності запропонованого методу.

Ключові слова: асинхронний двигун, нелінійність параметрів АД, дані виробника, оптимізація, оцінка параметрів, біляча клітка, математичне моделювання, експериментальні дослідження

V. Plis. **Improvement of the method of calculating the parameters of the induction motors replacement scheme**. The optimization of the equivalent circuit parameters of a three-phase induction motor with an equivalent double-circuit rotor is presented. The initial parameters of the equivalent circuit are estimated using a method known as engineering, based on the data provided in the manufacturer’s data sheet. The purpose of the work is aimed at increasing the accuracy of calculating currents and torques when using a double-circuit equivalent circuit of an induction motor by improving the method for determining the parameters of the equivalent circuit. A procedure for optimizing parameters has been developed to reduce errors between the calculated and actual values of the motor torque and current. Achieving the goal is ensured through the use of the author’s method of taking into account the nonlinearities of the motor, namely saturation of the magnetic circuit along the main path and scattering paths. To analyze the characteristics of an induction motor and predict its behavior in the event of faults and various operating modes, it is necessary to create a mathematical model of this motor. To ensure the adequacy of model calculations, it is necessary to take into account various nonlinearities of an induction motor, such as the effects of current displacement and machine saturation, steel losses, and others. The choice of a specific nonlinearity to take into account, as well as the methodology for taking it into account, are determined by the complexity of the tasks posed to the model. The depth of taking into account the nonlinear parameters of an induction motor depend on the requirements for the accuracy of the analysis and necessarily includes taking into account the most significant factors affecting the performance of the machine. A universal mathematical model has been created that describes an induction motor in a coordinate system that is stationary relative to the stator and takes into account the nonlinearity of its parameters. The parameters of the equivalent circuit of twelve industrial induction motors without and with optimization were assessed. A comparison was made of the results obtained from the engineering method and the actual data of the manufacturer to verify the effectiveness of the proposed method.

Keywords: induction motor, nonlinearity of IM parameters, manufacturer’s data, optimization, parameter estimation, squirrel cage, mathematical modeling, experimental studies

Introduction

Three-phase induction motors (IMs) with a short-circuited rotor are still the dominant motor technology in modern enterprises. The main advantages are their strength, simplicity of construction and minimal maintenance due to the absence of brushes. An important advantage is also their price compared to synchronous motors with permanent magnets, which are the main competitors of IM. It is these advantages that make them an attractive choice for a wide range of industrial and manufacturing applications. All over the world, IMs consume more than 50% of electricity [1]. Improvement of the starting characteristics of IM with a voltage of 6...10 kV is achieved due to the manufacture of a rotor with deep grooves or two cages. In the starting modes of such IMs, due to the effect of displacement

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of the current in the rotor, the active resistance increases and the dissipation inductance decreases, which leads to an increase in the electromagnetic moment.

The lack of information about the shape and dimensions of the rotor grooves and rods in the factory catalogs for engines does not allow to take into account the influence of this effect in the IM substitute circuits and forces the use of approximate methods for determining the parameters of the substitute circuits, which can lead to errors in the calculations of currents and moments, in some cases 30% or more. During the design and operation of the power supply systems of many enterprises, a large number of powerful IMs are used, while the errors in the calculations of the parameters of their operating modes should not exceed 5%, which requires a more perfect definition of the parameters of the backup circuit. Despite the long-discussed topic of determining the values of IM parameters, it remains relevant and important.

Analysis of recent research and publications

The analysis of the mathematical model is fundamental for understanding the behavior of the machine in order to implement a certain type of control. To analyze IM characteristics and predict its behavior in the event of malfunctions and different operating modes, it is necessary to create an adequate mathematical model of this engine [2 – 5]. The accuracy of this analysis depends on the adopted alternate scheme of the mathematical model of IM.

Currently, the method of mathematical modeling is the most common method of researching induction electric motors. Due to the high accuracy and practically unlimited possibilities for taking into account nonlinearities of any nature, research conducted using a mathematical model is often called an experiment on a model.

All known electric machines, including induction ones, can be described according to the principles of a generalized machine, which is an idealized two-phase implicitly poled machine, on the stator and rotor of which there are two symmetrical windings. The axes of the windings are at an angle of 90° and can rotate in space. The speed of rotation of the coordinate system is chosen in accordance with the purpose and tasks of the study. Due to the fact that the stator and rotor windings do not move relative to each other, the mutual inductances between them remain constant and do not change with the position of the rotor. This approach allows you to abstract from specific technical details and simplifies the understanding of the operation of various types of electric machines. The simplest mathematical description of IM can be implemented using two-phase orthogonal coordinates. This led to the widespread use of the following orthogonal coordinate systems of axes:α, β, 0, which are stationary relative to the stator windings; x, y, 0, which rotate relative to the stator at synchronous speed; d, q, 0, which are stationary relative to the rotor windings and u, v, 0, whose axes rotate in space at an arbitrary speed [6]. Taking into account the nonlinearities of IM parameters depend on the requirements for the accuracy of the study and necessarily involves taking into account the most influential on the working characteristics of the machine. They need to be weighed so that the model reflects real electrotechnical processes properly [7]. Researchers recommend taking into account the effects of machine saturation and current displacement, steel loss and operating temperature fluctuations on changes in active and reactive resistances [8]. Determination of heterogeneity of the considered parameter and methods of taking into account its individual characteristics depend on the complexity of the tasks envisaged by the model. As some sources indicate, it is enough to take into account the effects of saturation of the machine's magnetic circuits and current displacement [9].

Papers [10 – 14] are devoted to the issue of identification of IM parameters, which mainly consider motors of general industrial purpose with an insignificant effect of current displacement in the rotor. In addition, the authors, as a rule, do not take into account magnetization losses (in IM steel), which reduces the accuracy of calculations for modeling steady-state and transient modes. The calculated values of currents and moments according to the substitute scheme synthesized by the specified methods may differ from the original ones, which are declared by 30…40% or more [15].

The method of determining the parameters of the substitute IM scheme with a multi-link rotor based on catalog data is proposed in [16].

In [17], a two-stage optimization of the parameters of the IM substitute circuit is presented, which allows to minimize the errors between the estimated and actual values of the motor torque and current. The alternate scheme is shown in Fig. 1. The initial parameters of this equivalent circuit are estimated by the engineering method using the data given in the manufacturer's passport [16].

The equivalent circuit of IM with a short-circuited rotor is modeled by two parallel-connected resistive-inductive circuits, which are denoted by indices 1 and 2, respectively. The specified method implies the availability of the following data: nominal slip or IM speed, power factor, efficiency, the ratio of starting and maximum moments to the moment of full load, as well as the ratio of starting current to rated current. To evaluate the parameters in actual values, the nominal voltage and power of the motor will also be needed, if necessary. The results obtained by the authors in work [17] satisfy the set requirements when using the specified engines. However, in relation to IM series, which are most widely used in the enterprises of our country, the proposed optimization of the selection of additional coefficients does not provide the necessary indicators.

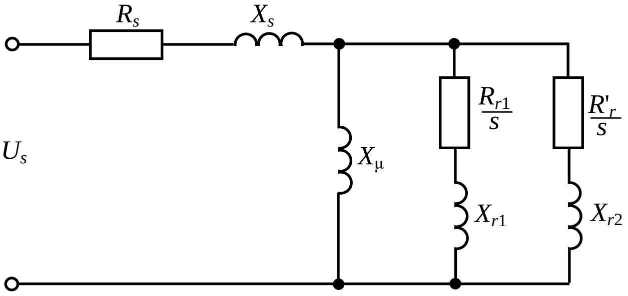

Fig. 1. Alternate diagram of a three-phase induction motor

The purpose of this work – to increase the accuracy of the calculation of currents and moments when using a two-circuit substitute circuit of IM due to the improvement of the method of determining the parameters of the substitute circuit.

Tasks of work:

– to improve the method of calculating the parameters of the IM substitute circuit, which allow, as derivatives, to form currents and torques that coincide as closely as possible with the catalog passport values;

– to create a universal mathematical model of IM, which takes into account the nonlinearity of its parameters and can function when using semiconductor converters.

An overview of the main material

Both foreign and domestic manufacturers are engaged in the production and commissioning of high-voltage machines of large capacity. Today's offer on the electric scooter market is very diverse: starting from expensive foreign machines (German, Italian, USA) and ending with domestic engines, both new and used. Domestic alternating current motors (depending on the design, number of revolutions, power, etc.) of general industrial purpose cost approximately 1.2…1.7 times cheaper than similar imported ones, while they are not inferior in quality, and sometimes even surpass them. The enterprises of our country are characterized by the use of low-voltage IM series 4A, 6АМУ, high-voltage - А4, ВАО2, АОДА, ДАЗО, А5К.

These series of engines are the most widely used in the enterprises of our country and are accepted as objects of further research (Table 1). Calculations were made for IMs of the specified series and standard sizes, the results of which are shown in the Table 2.

When developing asynchronous machines in order to reduce their mass, the operating point of the nominal mode is used, which is chosen on the non-linear part of the magnetization characteristic, which means that the machine is in saturation mode.

Table 1

Technical characteristics of induction motors

№	Engine type	Output power, kW	Nominal voltage, V	Nominal current, A	Nominal speed, rev/min	Efficiency, %
1	АОДА-800-6-2	800	6000	94.5	985	95
2	4А280S4	110	380	206	1470	91.0
3	4А355М2	315	380	565	2970	93.0
4	6АМУ315М8	110	380	217	738	93.3
5	6АМУ315М2	200	380	357	2967	94.5
6	6АМУ315S4	160	380	292	1480	94.5
7	ДАЗО4-400Х-4У1	400	6000	47	1485	94.2
8	ВАО2-560М4	630	6000	56.3	1487	95.0
9	2АЗМУ4	1000	6000	112.5	2975	95.77
10	4А355S2	250	380	459	2970	92.5
11	ДАЗО4-560Х-10У1	500	10000	40	595	94.1
12	А5К-355-400-2	400	6000	46	2980	94.1

Table 2

Coefficients of starting current, starting and maximum torques, calculated by the engineering method and by the factory

№	Engine type	Data source	$K_{I\,\text{start}}$	$K_{M\,\text{start}}$	$K_{M\,\text{max.}}$	Relative error, δ, %		
						$K_{I\,\text{start}}$	$K_{M\,\text{start}}$	$K_{M\,\text{max.}}$
1	АОДА-800-6-2	catalog	6.000	1.000	2.400	1.010	0.990	7.941
		calculat.	5.940	1.010	2.607			
2	4А280S4	catalog	5.500	1.200	2.000	1.010	0.990	11.073
		calculat.	5.445	1.212	2.249			
3	4А355М2	catalog	7.000	1.000	1.900	1.010	0.990	23.784
		calculat.	6.930	1.010	2.493			
4	6АМУ315М8	catalog	6.500	1.600	2.500	1.010	0.990	10.779
		розрах.	6.435	1.616	2.802			
5	6АМУ315М2	catalog	7.800	1.700	3.300	1.010	0.990	1.227
		calculat.	7.722	1.717	3.341			
6	6АМУ315S4	catalog	6.500	2.600	3.300	1.010	0.990	5.163
		calculat.	6.435	2.626	3.138			
7	ДАЗО4-400Х-4У1	catalog	7.000	1.300	2.800	1.010	0.990	9.209
		calculat.	6.930	1.313	3.084			
8	ВАО2-560М4	catalog	6.500	1.300	2.500	1.010	0.990	3.919
		calculat.	6.435	1.313	2.602			
9	2АЗМУ4	catalog	5.300	1.000	1.900	1.010	0.990	5.425
		calculat.	5.247	1.010	2.009			
10	4А355S2	catalog	7.000	1.000	1.900	1.010	0.990	24.633
		calculat.	6.930	1.010	2.521			
11	ДАЗО4-560Х-10У1	catalog	6.000	1.300	2.200	1.010	0.990	8.410
		calculat.	5.940	1.313	2.402			
12	А5К-355-400-2	catalog	7.000	0.900	2.500	1.010	0.990	10.363
		calculat.	6.930	0.909	2.789			

In order for the model being developed to take into account the change in the inductive resistance of the magnetization circuit in the entire range of the magnetization current, saturation is taken into account using the $X_\mu = f(I_\mu)$ curves given in [18].

These dependencies for the studied IM are not sufficiently described in the technical literature, so it is necessary to use experimental data. The experiments were carried out at the National Research Center "ELKOM" of the Odessa National Polytechnic University. During simulation, it is convenient to use the relationship between the change in the parameters of the IM magnetization circuit and the magnetization current, expressed in relative units. To compensate for saturation, using the main magnetic flux, it is necessary to determine a new value of the resistance of the magnetic circuit using the correction factor X_μ^*:

$$X_{\mu N} = X_\mu^* \cdot X_\mu, \tag{1}$$

where X_μ is the inductive resistance of the magnetization loop without taking saturation into account.

The ratio of the current value of the magnetizing current amplitude to its nominal value determines the multiplicity of the magnetizing current [18]:

$$I_\mu^* = \frac{I_{\mu\,\max}}{I_{\mu\,\text{rated}}}. \tag{2}$$

Accordingly, the nominal value of the magnetizing current is found as:

$$I_{\mu\,\text{rated}} = \frac{U_\text{rated}}{\sqrt{(X_\mu + X_s)^2 + R_s^2}}, \tag{3}$$

where U_rated is the nominal voltage of IM, V;

R_s, X_s – active and inductive resistance of the IM stator winding, Ohm; X_μ is the inductive resistance of the IM magnetization branch, Ohm.

When calculating according to the engineering method [16], the active resistance of the stator in relative units is equal to the nominal slip. We adjust the value of the active resistance of the stator by entering the coefficient K_1:

$$R_s = K_1 \cdot s_{\text{rated}} . \tag{4}$$

We present this approximation as $K_1 = \pm 2\%$.

It is also stated in [16] that the correction of starting current and torque ratios during start-up occurs by using additional coefficients $K_2 = 0.99$ and $K_3 = 1.01$, respectively. To increase the accuracy, we assume that they change a little more, the range of changes is from 0.98 to 1.02, and the ratio of starting torque to full load torque ($K_{M\,\text{start}}$.) and the ratio of starting current to rated current ($K_{I\,\text{start}}$.) are corrected as:

$$K_{I\,\text{start}}^{\text{corr}} = K_2 \cdot K_{I\,\text{start}} ; \tag{5}$$

$$K_{M\,\text{start}}^{\text{corr}} = K_3 \cdot K_{M\,\text{start}} . \tag{6}$$

To reduce errors in calculations, it is also necessary to adjust the parameters of the rotor of the substitute circuit, which is done by introducing additional coefficients $K_4 - K_7$ [17]:

$$R_{r_1} = K_4 \cdot \frac{g_r^{s_н}}{(g_r^{s_н})^2 + (b_r^{s_н})^2} \cdot s_н , \tag{7}$$

$$X_{\sigma r_1} = K_5 \cdot \frac{b_r^{s_н}}{(g_r^{s_н})^2 + (b_r^{s_н})^2} , \tag{8}$$

$$R_{r_2} = K_6 \cdot \frac{g_{r_2}}{g_{r_2}^2 + b_{r_2}^2} , \tag{9}$$

$$X_{r_2} = K_7 \cdot \frac{b_{r_2}}{g_{r_2}^2 + b_{r_2}^2} . \tag{10}$$

Applying the given steps to optimize the calculation to the engines listed in the table. 1, we obtain the following calculation results (Table 3).

Table 3

Coefficients of starting current, starting and maximum torques, calculated by the engineering method and by the factory

№	Engine type	Data source	Relative error, δ, %		
			$K_{I\,\text{start}}$	$K_{M\,\text{start}}$	$K_{M\,\max}$
1	АОДА-800-6-2	eng.	1.010	0.990	7.941
		optim.	0.498	0.027	1.072
2	4А280S4	eng	1.010	0.990	11.073
		optim.	0.128	0.151	1.834
3	4А355М2	eng.	1.010	0.990	23.784
		optim.	0.488	0.092	4.810
4	6АМУ315М8	eng.	1.010	0.990	10.779
		optim.	0.870	0.230	2.468
5	6АМУ315М2	eng	1.010	0.990	1.227
		optim.	0.206	0.000	0.242
6	6АМУ315S4	eng.	1.010	0.990	5.163
		optim.	0.170	0.154	0.733
7	ДАЗО4-400Х-4У1	eng.	1.010	0.990	9.209
		optim.	0.029	0.077	0.356
8	ВАО2-560М4	eng.	1.010	0.990	3.919
		optim.	0.062	0.154	0.596
9	2АЗМУ4	eng.	1.010	0.990	5.425
		optim.	0.151	0.498	0.423
10	4А355S2	eng.	1.010	0.990	24.633
		optim.	0.474	0.100	5.237
11	ДАЗО4-560Х-10У1	eng.	1.010	0.990	8.410
		optim.	0.050	0.386	2.048
12	А5К-355-400-2	eng.	1.010	0.990	10.363
		optim.	0.029	0.334	3.051

By mapping the generalized vector from the model of the generalized machine onto the coordinate axes that remain fixed with respect to the stator [6], a model of the IM in the α-β coordinate system is obtained, which also remains fixed with respect to the stator:

$$\begin{cases} \dfrac{d\Psi_{s_\alpha}}{dt} = U_{s_\alpha} - R_s \cdot i_{s_\alpha}; \\ \dfrac{d\Psi_{r_{1\alpha}}}{dt} = -R_{r_1} \cdot i_{r_{1\alpha}} - \omega_r \cdot \Psi_{r_{1\beta}}; \\ \dfrac{d\Psi_{r_{2\alpha}}}{dt} = -R_{r_2} \cdot i_{r_{2\alpha}} - \omega_r \cdot \Psi_{r_{2\beta}}; \\ \dfrac{d\omega_r}{dt} = \dfrac{1.5 p L_\mu (i_{s_\beta} i_{r_\alpha} - i_{s_\alpha} i_{r_\beta}) - M_c}{J}; \\ \dfrac{d\Psi_{s_\beta}}{dt} = U_{s_\beta} - R_s \cdot i_{s_\beta}; \\ \dfrac{d\Psi_{r_{1\beta}}}{dt} = -R_{r_1} \cdot i_{r_{1\beta}} - \omega_r \cdot \Psi_{r_{1\alpha}}; \\ \dfrac{d\Psi_{r_{2\beta}}}{dt} = -R_{r_2} \cdot i_{r_{2\beta}} - \omega_r \cdot \Psi_{r_{2\alpha}}; \\ \dot{\alpha}_0 = \omega_0, \end{cases} \tag{11}$$

where α, β – indices reflecting the projections of variables onto the corresponding axes;

$d\Psi_{s_\alpha}$, $d\Psi_{s_\beta}$, $d\Psi_{r_{1\alpha}}$, $d\Psi_{r_{2\alpha}}$, $d\Psi_{r_{1\beta}}$, $d\Psi_{r_{2\beta}}$ – flux coupling of stator and rotor;

U_{s_α}, U_{s_β} – voltage on the motor stator, projections on the corresponding axes $U_{s_\alpha} = |\vec{U}_s| \cdot \cos(\alpha_0)$, $U_{s_\beta} = |\vec{U}_s| \cdot \sin(\alpha_0)$;

α_0 – the angle at which the flux vector turns;

i_{s_α}, i_{s_β}, $i_{r_{1\alpha}}$, $i_{r_{2\alpha}}$, $i_{r_{1\beta}}$, $i_{r_{2\beta}}$ – currents in the stator and rotor windings;

R_s, R_{r_1}, R_{r_2} – active supports of the stator and rotor;

ω_r – angular speed of rotation of the rotor;

p – the number of pairs of poles;

L_μ – mutual inductance between the stator and rotor windings;

M_c – moment of resistance on the shaft;

J – moment of inertia of the rotor.

The IM model, which uses a two-phase generalized machine, is based on the ability to decompose the generalized three-phase vector of any variable onto the projection of any coordinate system that can rotate at any speed.

Results

The suitability of the developed mathematical model for the IM under study was evaluated by comparing the simulation results with the experimental results. Modeling was carried out for electric motors with power from 1.5 to 500 kW. Fig. 2 shows the experimental and calculated oscillograms of the IM during idle start-up.

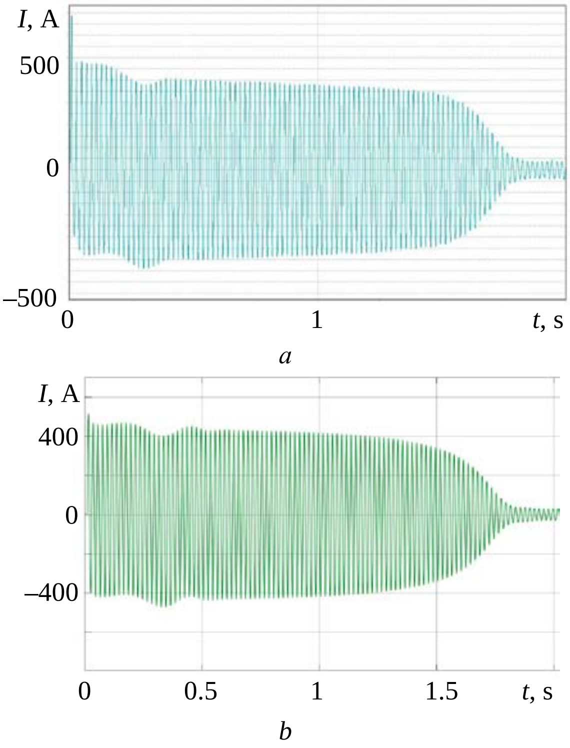

Fig. 2. Oscillograms during start-up of the idle IM with a capacity of 447 kW, a voltage of 6 kV:
a – experiment; *b* – calculation

Conclusion

1. The method of determining the parameters of the IM substitute circuit for the calculation of electromagnetic and electromechanical transient processes was further developed, in which the passport data, as well as the data of the oscillograms of the start-up and coasting modes, are used as output data. Increasing the accuracy of calculating currents and moments is achieved due to the use of the author's method of taking into account motor nonlinearities, namely the saturation of the magnetic circuit along the main path and scattering paths. Differences between catalog and calculated parameters are no more than 5%.

2. A universal mathematical model of IM was created, in which saturation is taken into account using curves that determine the dependence of the resistance of the magnetization circuit on the magnetization current, based on experimental data. In static modes of operation, the discrepancies between calculation and experimental data are 5…10%, and in dynamic modes – 16…21%. Such a model makes it possible to obtain results that accurately reflect the electromechanical and electromagnetic processes of a real engine and allows conducting research on static and dynamic modes of operation of electromechanical systems.

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