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V. F. Syvokobylenko, Dr. Sc. (Tech.), Prof.

State Higher Educational Institution Donetsk National Technical University, Pokrovsk, Ukraine, e-mail: svf1934@gmail.com

DETERMINING EQUIVALENT CIRCUIT PARAMETERS OF INDUCTION MOTOR WITH DEEP BAR ROTOR USING CATALOG DATA

В. Ф. Сивокобиленко, д-р техн. наук, проф.

Державний вищий навчальний заклад „Донецький національний технічний університет“, м. Покровськ, Україна, e-mail: svf1934@gmail.com

ВИЗНАЧЕННЯ ПАРАМЕТРІВ ЗАСТУПНОЇ СХЕМИ АСИНХРОННОГО ДВИГУНА З ГЛИБОКОПАЗНИМ РОТОРОМ ЗА КАТАЛОЖНИМИ ДАНИМИ

Purpose. Development of the method for determining the equivalent circuit parameters of induction motor with deep bar rotor using catalog data.

Methodology. The methods of analysis, parameter identification, mathematical modeling, solving systems of nonlinear algebraic and differential equations are used.

Findings. The methods of taking into consideration the skin effect influence on rotor impedance are analyzed, which allowed adopting the rectangular cross-sectional shape of the rotor bar as a basis. Implication of two different heights for determination of rotor resistance and inductive reactance instead of one height is grounded. The analytical dependences for normalized heights are precised, where, in contrast to known approaches, these heights are determined as proportional to the slip in some unknown k degree, but not as proportional to square root of the slip. Method for selecting the variables of equivalent circuit and method for forming system of nonlinear equations for the numerical determining of variables values by the iterative method are proposed and investigated. The rotor resistance at rated slip, equivalent heights of the rectangular rotor bars, mutual inductance between stator and rotor, resistance of iron losses circuit and exponent for slip in the formula for determining the normalized height are accepted as variables. Using this method, the parameters of equivalent circuit for the deep bar induction motors of different types are calculated and their static characteristics are obtained. Calculated according to the equivalent circuit, the stator currents and moments coincided with the catalog data. The method of using the defined parameters of equivalent circuit for modeling start mode, short circuit and selfstart based on differential equations are presented.

Originality. For the first time during synthesis of the equivalent circuit parameters of the induction motor with deep bar rotor, the influence of the skin effect on the rotor impedance is suggested to be determined using not one, but two different heights of equivalent rectangular cross-section of the rotor bar, one for determining the resistance and the other for the inductive reactance.

Practical value. The proposed method for determining the equivalent circuit parameters of the induction motor with deep bar rotor the method for calculating of its static and dynamic characteristics is implemented as a program.

Keywords: *induction motor, deep bar rotor, catalog data, equivalent circuit*

Introduction. The induction motors with deep bar rotor (IMDB) or double cage rotor are widely used in power supply systems of industrial enterprises, because of their improved starting characteristics compared to conventional induction motors. The squirrel cage rotor bars of IMDB are manufactured in rectangular, trapezoidal shapes, bell-shaped etc. [1] in order to use the skin effect to increase the resistance, and therefore the torque, which is very important to facilitate the start mode and selfstart.

Unsolved aspects of the problem. To account for the impact of the skin effect on the IMDB equivalent circuit parameters, the knowledge of shape and sizes of the rotor slots and bars is required. Due to the lack of these data in factory catalogs, the approximate methods of determining the equivalent circuit parameters are used.

In this case the error of currents and torques calculation can reach 50 % or more. Therefore, the task of the method development for determining more reliable equivalent circuit parameters of IMDB based on catalog or updated from the experiment data is topical, which will allow defining static (operating) and dynamic (starting) characteristics of deep bar induction motor.

Analysis of the recent research. Methods for determining the IMDB equivalent circuit parameters are considered in many papers [2, 3], which utilize the known catalog or experimental data: nominal voltage U_n, stator current I_n, active power P_n, slip s_n, efficiency factor η_n, power factor $\cos\varphi_n$, as well as locked rotor current ratio I_p, starting torque-to-nominal torque ratio M_p and maximum torque-to-nominal torque ratio $M_{\max}$. Over the last years manufacturers have been specifying the minimum torque $M_{\min}$ in catalogs, consideration of the effect of which during synthesis IMDB parameters requires a special approach, but it is hardly discussed in the literature.

In most studies the authors use a *T*-equivalent circuit for the deep bar induction motor. This scheme represents a rotor as one circuit with resistance and inductive reactance, which depend nonlinearly on the slip [1, 2], or as two parallel-connected circuits with constant impedance [4]. The equivalent circuit with two rotor loops reflects the dynamic characteristics of the currents and torques more accurately, but it does not display static characteristics in slip range $s < s_n < 1$ accurately enough. Errors of equivalent circuits with single rotor loop substantially depend on the accuracy of skin effect considering by analytical dependences. For example, in [2] the ratio of nonlinear slip-dependent polynomials are used, but rotor inductive reactances in case of $s = 1$ sometimes turn out greater than in case of $s < 1$, which should not be this way. In [5] the exponential functions are used, but their values fitting is difficult and does not always lead to success.

Unsolved part of the problem. In [1] to take into consideration the skin effect influence on rotor resistance and inductive reactance, the coefficients $K_r(\xi)$ and $K_x(\xi)$ are used, which contain hyperbolic and trigonometric functions and depend on slip and depth of electromagnetic field penetration. These coefficients reflect the physical phenomena more accurately, but the method, which is used to determine equivalent and normalized rotor bars heights, requires further improvement and necessary corrections. [6] considers clarification of losses during calculation of transients, but only for induction motors of conventional type. Let us also note that we are not aware of works on methods of accounting the minimum torque, which value is contained in the catalog data. Therefore, issues of improving the methods for identification of the IMDB parameters are actual.

Objective of the research. It is required to develop a method for determining the parameters of the IMDB equivalent circuit based on catalog data, whereby the coincidence of calculated stator currents and torques with the catalog data is provided. It is also necessary to demonstrate the effectiveness of found parameters usage to determine the static and dynamic characteristics of IMDB.

Research materials and results. The following assumptions are accepted: voltage of the power source and the induction in the air gap of induction motor are sinusoidal, saturation of magnetic circuits is ignored, mechanical and additional losses are neglected. The idea of the proposed method is to clarify analytical dependencies, given in [1, 2], for equivalent and normalized rotor bar heights and current displacement coefficients that depend on these heights. The parameters will be found from the solution of systems of nonlinear equations by iterative numerical methods. In these equations the catalog values of currents and torques, and analytical expressions for them from the equivalent circuit are used. The skin effect and iron losses will be considered in the equivalent circuit (Fig. 1), accepted as the basis. All values will be given in per-unit system, commonly used for electrical machines [1, 4].

The resistance of the stator winding R_s, as in [4], will be taken equal to the nominal slip s_n, and leakage inductive reactance X_s – to the inverse of the double starting stator current $X_s = (2I_p)^{-1}$. To take into account iron losses, special loop with the leakage inductive reactance X_{fe} and resistance R_{fe} is provided in the equivalent circuit (Fig. 1), for which, according to [4], we assume that $X_{fe} = K_{fe} \cdot R_{fe}$, where $K_{fe} = 0.5 \div 0.6$.

Catalogues give no information about the form of the rotor slot, so we assume that the bars of squirrel cage rotor are rectangular. The equivalent heights h_r and h_x for determining resistance and inductive reactance of the bar, in contrast to [1, 2], are different, as well as normalized heights ξ_r and ξ_x, which, in contrast to [1], will not be defined as proportional to $\sqrt{s}$, but as proportional to s^k, where the exponent k is unknown and will be determined during the iterative calculation.

Then the normalized heights are determined in the following way

$$\xi_r(h_r, s, k) = h_r \cdot s^k; \quad \xi_x(h_x, s, k) = h_x \cdot s^k. \tag{1}$$

Taking into account (1), analytical expressions for rotor impedance and skin effect coefficients $K_r(h_r, s, k)$ and $K_x(h_x, s, k)$, known from [1, 2], are

$$R_r(s, h_r, k) = R_{r0} \cdot K_r(s, h_r, k); \quad X_r(s, h_x, k) = X_{r0} \cdot K_x(s, h_x, k); \tag{2}$$

$$K_r(s, h_r, k) = h_r \cdot s^k \cdot \frac{\mathrm{sh}(2h_r \cdot s^k) + \sin(2h_r \cdot s^k)}{\mathrm{ch}(2h_r \cdot s^k) - \cos(2h_r \cdot s^k)};$$

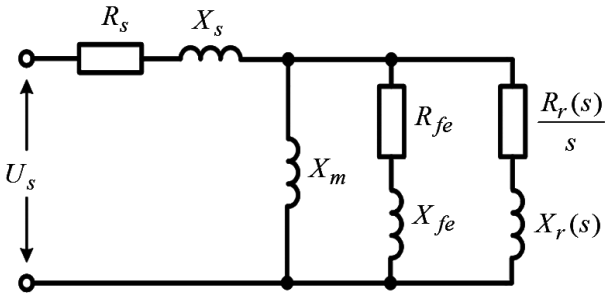

Fig. 1. T-equivalent circuit of a deep bar induction machine

$$K_x(s,h_x,k)=\frac{3}{2h_x\cdot s^k}\cdot\frac{\mathrm{sh}(2h_x\cdot s^k)-\sin(2h_x\cdot s^k)}{\mathrm{ch}(2h_x\cdot s^k)-\cos(2h_x\cdot s^k)}.$$

The skin effect in rotor practically is not significant for slips lower than nominal value. In this case the skin effect coefficients are equal to one, and the rotor resistance and inductive reactance are equal to R_{r0}, X_{r0}. To determine the rotor impedance for other slip values, unknown R_{r0}, X_{r0}, h_r, h_x, k are to be found first. Moreover, the R_{fe} and X_m will be the target values.

Let us consider now the method for determining the vector of unknown parameters for the entire equivalent circuit $V=(R_{fe}, X_m, h_r, h_x, R_{r0}, X_{r0}, k)^{tr}$. To do this, first we express stator and rotor current, and the torque by the required parameters and the corresponding slips

$$Z_s=R_s+jX_s;\quad Z_{fe}=R_{fe}+jX_{fe};$$

$$Z_r(s,V)=\frac{R_{r0}}{s}\cdot K_r(s,h_r,k)+jX_{r0}\cdot K_x(s,h_x,k);\quad (3)$$

$$I_s(s,V)=\frac{U_s}{Z_s+[X_m^{-1}+X_{fe}^{-1}+Z_r(s,V)^{-1}]^{-1}};\quad (4)$$

$$I_r(s,V)=[U_s-Z_s\cdot I_s(s,V)]\cdot Z_r(s,V)^{-1};\quad (5)$$

$$M(s,V)=|I_r(s,V)|^2\cdot R_{r0}\cdot K_r(s,h_r,k)\cdot s^{-1}.\quad (6)$$

The system of equations to determine the vector of unknown parameters can be obtained by writing the expression (3–6) for the stator currents and torques for slips s_n and $s_1=1$, as well as the maximum and minimum torque, and equating them to respective catalog data. Let us notice that complex value of the stator current at s_n is equal to $\cos(\varphi_n)-j\cdot\sin(\varphi_n)$, and the values of the maximum and minimum torques will be found by their sampling from the calculations using (6) for the corresponding ranges of slips $s_{var1}=(0\div 0.25)$ and $s_{var2}=(0.1\div 1.0)$. Then the system of equations to determine the parameters is given by

$$\begin{aligned}
&f_1(V)=I_s(s_n,V)-[\cos(\varphi_n)-j\cdot\sin(\varphi_n)]=0;\\
&f_2(V)=|I_s(s_n,V)|-I_n=0;\\
&f_3(V)=|I_s(s_1,V)|-I_p=0;\\
&f_4(V)=M(s_n,V)-M_n=0;\\
&f_5(V)=M(s_1,V)-M_p=0;\\
&f_6(V)=M(s_{var1},V)_{\max}-M_{\max}=0;\\
&f_7(V)=M(s_{var2},V)_{\min}-M_{\min}=0.
\end{aligned}\quad (7)$$

To solve the system of equations (7), one of the numerical methods for minimizing the sum of squared deviations (residuals) functions $F_{\min}(V)=\sum_{n=1}^{7}[f_n(V)]^2$ is used. To speed up the convergence of the calculations, the initial approximation for the variables is needed. To determine them, using known M_m, $\cos(\varphi_n)$ and η_n, mutual reactance can be found as

$$X_m=\left[\sin(\varphi_n)-(M_m-\sqrt{M_m^2-1})\cdot\cos(\varphi_n)\right]^{-1}.$$

The resistance R_{fe} and inductive reactance X_{fe} can be determined by calculating power loss in stator ΔP_S, in rotor ΔP_R, total losses ΔP_Σ and iron loss ΔP_{fe} for nominal mode

$$\Delta P_S=R_S\cdot I_n^2=R_s;$$

$$\Delta P_\Sigma=(1-\eta_n)\cdot\cos(\varphi_n);$$

$$\Delta P_R=\cos(\varphi_n)\cdot\eta_n\cdot s_n\cdot(1-s_n)^{-1};$$

$$\Delta P_{fe}=\Delta P_\Sigma-\Delta P_S-\Delta P_R;$$

$$R_{fe}=(1+K_{fe}^2)^{-1}\cdot\Delta P_{fe}^{-1};$$

$$X_{fe}=K_{fe}\cdot R_{fe}.$$

The rotor resistance R_{r0} and inductive reactance X_{r0} can be found using the known input impedance of the motor at nominal slip $Z_n=\cos(\varphi_n)+j\cdot\sin(\varphi_n)$. To determine the rotor resistance R_{r1} and inductive reactance X_{r1} for slip $s_1=1$, the values of starting torque M_p and starting current stator I_p are used

$$Z_{rn}(s_n)=[(Z_n-Z_s)^{-1}-(jX_m)^{-1}-Z_{fe}^{-1}]^{-1};$$

$$R_{r0}=\mathrm{Re}(Z_{rn}(s_n)\cdot s_n);\quad X_{r0}=\mathrm{Im}(Z_{rn}(s_n));$$

$$R_{r1}=M_p\cdot I_p^{-2};\quad X_{r1}=I_p^{-1}-X_s.$$

The initial value for the exponent k in (1) will be taken $k=0.5$, and for equivalent heights of rotor bars h_r and h_x, considering (2), the next equations can be obtained

$$h_r=\frac{R_{r1}}{R_{r0}};\quad h_x=\frac{3}{2}\cdot\frac{X_{r0}}{X_{r1}}.$$

All initial approximation is now known and from the solution of equations (7) the parameters of the equivalent circuit (Fig. 1) can be found. To evaluate the results of the parameters identification according to (3–6), the currents and torques should be calculated and compared with the original catalog data.

The proposed method is realized as program in Mathcad and MATLAB, which allows executing calculations for a large number of deep bar induction motors of different types (Table). The calculations have shown, that the calculated parameters nearly always provide a complete coincidence of catalog and calculated data (currents and torques for slips $s_н$ and $s=1$, and maximum and minimum torques).

For example, a complete coincidence of specified data received for IMDB of type 4AZM (power rating – 4000 kW), for which the catalog data and parameters of the equivalent circuit, calculated according to described method, are shown in Table. The currents and power losses in the nominal mode, calculated according to these parameters, are equal to: $I_s=1$; $I_r=0.915$; $I_m=0.234$; $I_{fe}=0.022$; $\eta=0.97$; $\Delta P_S=0.006$; $\Delta P_R=0.006$; $\Delta P_{fe}=0.018$; $\Delta P_\Sigma=0.03$. The calculated char-

Table

Catalogue data of the induction motors and calculation of equivalent circuits parameters

Type	2AZM	4AZM	2AZM-1	AOZ-400	4AZ55	Simens	4AH250	B180M4
a) catalog data								
P_n, kW	5000	4000	400	315	200	160	90	30
n, rpm	2985	2982	2980	2970	985	1487	367	1470
U_n, kV	6.0	6.0	6.0	6.0	6.0	0.4	0.4	0.4
s_n, %	0.5	0.6	0.667	1.0	0.5	0.87	2.0	2.0
η_n, %	97.4	97.3	94.7	95.0	94.0	96.0	93.0	91.0
$\cos\varphi_n$	0.92	0.89	0.9	0.9	0.9	0.85	0.92	0.88
M_p, pu	1.3	0.9	1.3	1.2	1.4	2.0	1.7	1.8
$M_{\max}$, pu	2.7	2.2	2.4	2.5	2.2	2.6	2.5	2.5
$M_{\min}$, pu	0.7	0.7	0.8	0.8	0.9	1.5	1.4	1.3
I_p, pu	6.5	5.7	7.0	7.0	6.5	7.2	6.8	6.5
b) stator and iron loss circuit parameters								
R_s, pu	0.005	0.006	0.00667	0.01	0.005	0.00867	0.02	0.02
X_s, pu	0.077	0.088	0.071	0.071	0.077	0.0694	0.074	0.077
X_m, pu	4.676	4.092	4.567	4.079	4.935	2.755	4.978	3.46
R_{fe}, pu	36.39	37.4	16.681	19.431	13.95	26.616	15.093	11.154
X_{fe}, pu	21.84	22.44	10.008	11.659	8.3728	15.969	9.056	6.693
c) rotor circuit parameters								
R_{r0}, pu	0.00516	0.00621	0.00712	0.011	0.00534	0.0096	0.021	0.022
X_{r0}, pu	0.119	0.159	0.159	0.145	0.178	0.148	0.133	0.142
h_r, sm	5.535	4.041	3.283	2.129	5.445	3.452	1.684	1.755
h_x, sm	2.436	2.778	3.427	3.152	3.588	3.429	3.084	3.125
K, pu	1.037	0.64	0.661	0.766	0.641	0.563	0.758	0.908
d) polynomial coefficients for determining the rotor parameters								
r_1, pu	–0.038	–0.0058	–0.024	–0.0035	–0.0052	–0.024	–0.0039	0.0150
r_2, pu	0.071	0.00704	0.043	0.018	0.00353	0.038	0.00940	0.0039
r_3, pu	–0.0093	0.018	–0.00238	–0.0034	0.026	0.00991	–0.0019	–0.0016
r_4, pu	0.0052	0.061	0.007138	0.011	0.00522	0.00948	0.021	0.022
x_1, pu	2.7	0.11	0.17	0.157	0.18	0.108	0.139	0.149
x_2, pu	0.026	–0.194	–0.264	–0.273	–0.264	–0.144	–0.244	–0.283
x_3, pu	0.7	0.011	0.004936	0.041	–0.019	–0.047	0.038	0.06
x_4, pu	0.286	0.159	0.159	0.145	0.179	0.148	0.132	0.141
$R_r(s) = r_1 \cdot s^3 + r_2 \cdot s^2 + r_3 \cdot s + r_4;\quad X_r(s) = x_1 \cdot s^3 + x_2 \cdot s^2 + x_3 \cdot s + x_4$								

acteristics for rotor resistance and inductive reactance, torque and current as a function of slip are shown in Figs. 2 and 3.

To calculate the modes of multimachine power-supply system, the parameters of IMDB equivalent circuits is convenient to store in a database. To do this, the rotor parameters are necessary to be approximated previously by next polynomials

$$R_r(s) = r_1 \cdot s^3 + r_2 \cdot s^2 + r_3 \cdot s + r_4;$$
$$X_r(s) = x_1 \cdot s^3 + x_2 \cdot s^2 + x_3 \cdot s + x_4.$$

The values of polynomial coefficients r, x can be found from condition of coincidence between resistance values for the four selected slip points, for example $s_1 = s_н$; $s_2 = 0.25$; $s_3 = 0.75$; $s_4 = 1.0$

$$\begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = \tilde{S} \cdot \begin{bmatrix} R_r(s_1, h_r, k) \\ R_r(s_2, h_r, k) \\ R_r(s_3, h_r, k) \\ R_r(s_4, h_r, k) \end{bmatrix};$$

$$\tilde{S} = \begin{bmatrix} s_1^3 & s_1^2 & s_1 & 1 \\ s_2^3 & s_2^2 & s_2 & 1 \\ s_3^3 & s_3^2 & s_3 & 1 \\ s_4^3 & s_4^2 & s_4 & 1 \end{bmatrix}^{-1};$$

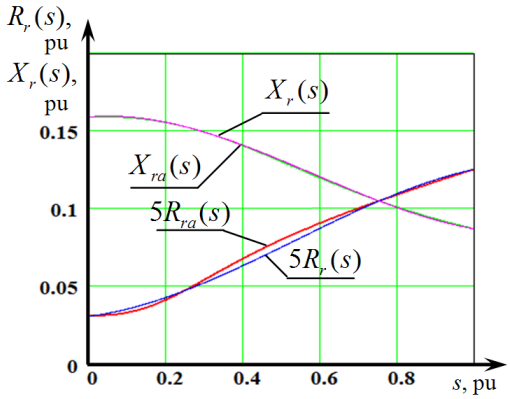

Fig. 2. Rotor resistance and inductive reactance as a function of slip for 4AZM induction motor

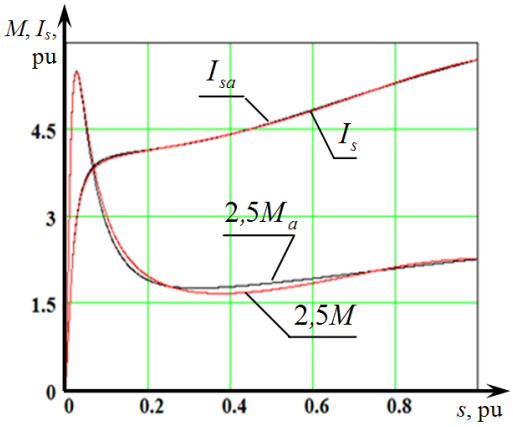

Fig. 3. Torque and stator current as a function of slip for 4AZM induction motor

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \tilde{S} \cdot \begin{bmatrix} X_r(s_1, h_r, k) \\ X_r(s_2, h_r, k) \\ X_r(s_3, h_r, k) \\ X_r(s_4, h_r, k) \end{bmatrix};$$

$$\begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \end{bmatrix} = \begin{bmatrix} -0{,}021 \\ 0{,}034 \\ 0{,}006162 \\ 0{,}006169 \end{bmatrix}; \quad \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} = \begin{bmatrix} 0{,}122 \\ -0{,}215 \\ 0{,}021 \\ 0{,}159 \end{bmatrix}.$$

The initial characteristics for rotor resistance and inductive reactance (R_r, X_r) as a function of slip and the results of their approximation (R_{ra}, X_{ra}) using polynomials are shown in Fig. 2, while those for stator currents (I_s, I_{sa}) and torques (M, M_a) are shown in Fig. 3. From the above data it follows that the approximation error does not exceed one percent, which indicates the desirability of its use.

The dynamic characteristics of IMDB during starting, short-circuit, selfstarting are defined using mathematical model, represented by a system of differential equations, defined in α, β coordinate system, fixed to the stator

$$p\psi_{s\alpha} = U_m \sin(t) - R_s \cdot i_{s\beta};$$

$$\begin{aligned} p\psi_{s\alpha} &= U_m \cos(t) - R_s \cdot i_{s\alpha}; \\ p\psi_{s\beta} &= U_m \sin(t) - R_s \cdot i_{s\beta}; \\ p\psi_{r\alpha} &= -R_r(s) \cdot i_{r\alpha} - \omega \cdot \psi_{r\beta}; \\ p\psi_{r\beta} &= -R_r(s) \cdot i_{r\beta} + \omega \cdot \psi_{r\alpha}; \\ p\psi_{fe\alpha} &= -R_{fe} \cdot i_{fe\alpha}; \\ p\psi_{fe\beta} &= -R_{fe} \cdot i_{fe\beta}; \\ p_\omega &= [M_e - M_c(\omega)]/J; \quad s = 1 - \omega; \\ M_e &= (\psi_{s\alpha} \cdot i_{s\beta} - \psi_{s\beta} \cdot i_{s\alpha})/X_s; \end{aligned} \tag{8}$$

$$X = \begin{bmatrix} X_s + X_m & X_m & X_m \\ X_m & X_{fe} + X_m & X_m \\ X_m & X_m & X_r(s) + X_m \end{bmatrix};$$

$$\begin{bmatrix} i_{s\alpha} \\ i_{fe\alpha} \\ i_{r\alpha} \end{bmatrix} = X^{-1} \cdot \begin{bmatrix} \psi_{s\alpha} \\ \psi_{fe\alpha} \\ \psi_{r\alpha} \end{bmatrix}; \quad \begin{bmatrix} i_{s\beta} \\ i_{fe\beta} \\ i_{r\beta} \end{bmatrix} = X^{-1} \cdot \begin{bmatrix} \psi_{s\beta} \\ \psi_{fe\beta} \\ \psi_{r\beta} \end{bmatrix}.$$

In the equations (8) M_e, M, J are electromagnetic torque, mechanical load torque, moment of inertia respectively; p is Laplace operator; ω is rotor rotational speed. The matrix X of inductive reactances and rotor resistances are the functions of slip and are adjusted for each calculation step.

For the 4AZM motor the simulation results for start mode, short-circuit and selfstart after a trip are shown in Fig. 4, which shows the behavior of the instantaneous values of the stator current module (I_s), the active power (P), the torque (M) and the rotational speed (ω). As it can be seen from the data, specified variables may substantially exceed the nominal values in dynamic conditions.

Conclusions and recommendations for further research.

1. The analytical dependences for finding skin effect coefficients, calculating iron losses and equivalent bar heights for induction motor with deep bar rotor have been defined more precisely.

2. The method for determining the parameters of equivalent circuit of the induction motor with deep bar rotor has been developed, where the parameters are

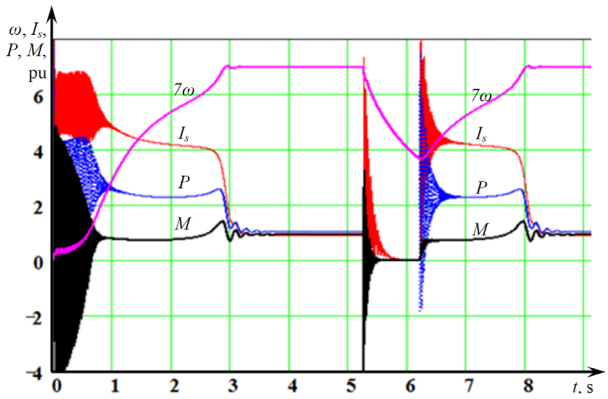

Fig. 4. The simulation results of dynamic characteristics of 4AZM induction motor during starting, short-circuit and subsequent self-starting

found by numerical solution of the system of equations, and the catalog values of the currents and the torques are expressed through the required parameters of the equivalent circuit.

3. The results of calculations for a large number of engines have confirmed that the values of the currents and torques, calculated using the equivalent circuit, coincide with the catalog values, including a minimum value for a given torque.

4. The further research is expedient to continue on determining the equivalent circuit parameters for induction motor with deep bar rotor when powered by frequency converters.

Referenses.

1. Voldek, A. I. and Popov, V. V., 2010. *Electrical machines. Alternative current machines: textbook for institutes of higher education*. St. Petersburg: Piter.

2. Moshinskiy, Yu. A., Bespalov, V. Ya. and Koriakin, A. A. Parameters of induction motor equivalent circuit estimation using catalogue data. *Elektrichestvo*, [online] Available at: <http://masters.donntu.org/2012/etf/sosedko/library/article3.pdf> [Accessed 11 May 20017].

3. Pedra J., 2008. On the determination of Induction Motor Parameters from Manufacturer Data for Electromagnetic Transient Programs. *IEEE Transactions on Power Systems*, 23(4), pp. 1709–1718.

4. Sivokobylenko, V. F., Tkachenko, S. N. and Derkachev, S. V., 2014. Defining the parameters of equivalent circuits and the characteristics of asynchronous motors. E*lectrichestvo*, 10, pp. 38–44.

5. Varenik, E. A., Fedorov, M. M. and Dennik V. F., 2006. Defining the parameters of the equivalent circuit of the induction motor on the catalog data. In: *Explosion-proof electrical equipment*. Donetsk: UkrNIIVE-Donetsk, pp. 123–127.

6. Boglietti, A., Cavagnino, A., Ferraris, L. and Lazzari, M., 2008. Induction motor equivalent circuit including the stray load losses in the machine power balance. *IEEE Transaction on Energy Conversion*, 23(3), pp. 796–803.

Мета. Розробка методу визначення параметрів схеми заміщення асинхронного двигуна з глибокопазним ротором за каталожними даними.

Методика. Використовуються методи аналізу, ідентифікації параметрів, математичного моделювання, рішення систем нелінійних алгебраїчних і диференціальних рівнянь.

Результати. Розглянуто методи врахування впливу витіснення струму на опори ротора, виконано їх аналіз і прийнята за основу прямокутна форма перетину стрижня обмотки ротора. Обґрунтовано застосування замість однієї загальної приведеної висоти стрижня двох різних наведених висот відповідно для визначення активного й індуктивного опорів ротора. Уточнені аналітичні залежності для приведених висот, в яких, на відміну від відомих підходів, їх визначають не як пропорційні кореню квадратному з ковзання, а як ковзанню у k-тому ступеню, що потім потрібно знайти. Запропоновано та досліджено спосіб вибору змінних схеми заміщення й спосіб формування системи нелінійних рівнянь для їх чисельного визначення ітераційним методом. В якості змінних прийняті опори ротора при номінальному ковзанні, еквівалентні висоти прямокутних стержнів ротора, взаємна індуктивність між статором і ротором, активний опір контуру втрат у сталі й показник ступеня для ковзання у формулі визначення приведеної висоти. За допомогою розробленого методу визначені параметри схем заміщення ряду різного типу глибокопазних двигунів і виконані розрахунки їх статичних характеристик. Отримано збіг розрахованих за схемою заміщення струмів статора та моментів з каталожними. Показано спосіб застосування визначених параметрів схеми заміщення для моделювання за допомогою диференціальних рівнянь режимів пуску, короткого замикання й самозапуску двигунів.

Наукова новизна. Уперше при розробці параметрів схеми заміщення глибокопазного асинхронного двигуна запропоновано вплив скін-ефекту на опори ротора визначати за допомогою не однієї, а двох різних еквівалентних висот прямокутного перетину стрижня ротора: однієї для визначення активного опору, а іншої – для індуктивного.

Практична значимість. Отримана програмна реалізація розробленого методу визначення параметрів схеми заміщення глибокопазного асинхронного двигуна й методу розрахунку його статичних і динамічних характеристик.

Ключові слова: *асинхронний двигун, глибокопазний ротор, каталожні дані, схема заміщення*

Цель. Разработка метода определения параметров схемы замещения асинхронного двигателя с глубокопазным ротором по каталожным данным.

Методика. Используются методы анализа, идентификации параметров, математического моделирования, решения систем нелинейных алгебраических и дифференциальных уравнений.

Результаты. Рассмотрены методы учета влияния вытеснения тока на сопротивления ротора, выполнен их анализ и за основу принята прямоугольная форма сечения стержня обмотки ротора. Обосновано применение вместо одной общей двух различных приведенных высот соответственно для определения активного и индуктивного сопротивлений ротора. Уточнены аналитические зависимости для приведенных высот, в которых их, в отличие от известных подходов, определяют не как пропорциональные корню квадратному из скольжения, а как скольжение в некоторой k-той искомой степени. Предложен и исследован способ выбора переменных схемы замещения и способ формирования системы нелинейных уравнений для их численного определения итерационным методом. В качестве переменных приняты сопротивления ротора при номинальном скольжении, эквивалентные высоты прямоугольных стержней ротора, взаимная индук-

тивность между статором и ротором, активное сопротивление контура потерь в стали и показатель степени для скольжения в формуле определения приведенной высоты. С помощью разработанного метода определены параметры схем замещения ряда различного типа глубокопазных двигателей и выполнены расчеты их статических характеристик. Получено совпадение рассчитанных по схеме замещения токов статора и моментов с каталожными. Показан способ применения определяемых параметров схемы замещения для моделирования по дифференциальным уравнениям режимов пуска, короткого замыкания и самозапуска двигателей.

Научная новизна. Впервые при синтезе параметров схемы замещения глубокопазного асинхронного двигателя предложено влияние скин-эффекта на сопротивления ротора определять с помощью не одной, а двух различных эквивалентных высот прямоугольного сечения стержня ротора: одной для определения активного сопротивления, а другой — для индуктивного.

Практическая значимость. Получена программная реализация разработанного метода определения параметров схемы замещения глубокопазного асинхронного двигателя и метода расчета его статических и динамических характеристик.

Ключевые слова: *асинхронный двигатель, глубокопазный ротор, каталожные данные, схема замещения*

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