IMPROVEMENT OF THE COMPUTER SIMULATION MODEL OF A FREQUENCY-REGULATED INDUCTION MOTOR IN THE MATLAB SOFTWARE PACKAGE

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The article is devoted to improving the well-known computer simulation model of a three-phase squirrel-cage induction motor with frequency control (which is present in the MATLAB software package). This improvement the simulation model consists in expanding its functionality (in particular, carrying out a refined calculation of the instantaneous values of all types of basic power losses, basic active power consumption, and energy indicators of the motor) and increasing the precision of finding the instantaneous values of the basic harmonic components of the motor's phase stator currents in steady-state and start-braking modes. This task was solved by supplementing the abovementioned well-known model from the MATLAB software package with refined analytical dependencies for calculating the main energy parameters of a frequency-regulated induction motor and as because of obtaining new refined analytical calculation dependencies for determining the instantaneous value of the modulus of the generalized stator current vector of this motor. To confirm the capacity for work of the improved computer simulation model, the following parameters were calculated using it (for a squirrel-cage induction motor loaded with a centrifugal fan) in steady and start-braking modes of the motor: its basic power losses and basic active power consumption, efficiency and power coefficients. The practical value of the improved computer simulation model consists in increasing the precision of calculating the electromagnetic and energy processes of a frequency-regulated induction motor in steady and start-braking modes under scalar control. References 18, figures 4, tables 2.
Keywords: induction motor, frequency regulation, computer simulation model, electromagnetic and energy processes.

Introduction. Considering the widespread use of frequency-regulated (f-r) squirrel-cage induction motors (IM) in various industries today and taking into account the rising cost of electricity in the world and Ukraine, it has become relevant and in demand in practice to refine the definition and study of the energy characteristics of these motors. It is particularly important now to create computer simulation models (CSM) for research energy processes in these motors, since these computer models (unlike direct experimental research) allow for the rapid and relatively less labor-intensive to optimizate of the control of IM operating modes in operation, thereby reducing overall power losses or minimizing the power consumption of these motors in the steady and start-braking modes.

Currently, the most well-known and widely used in practice is the IM computer simulation model, which is presented in the Simulink library of the MATLAB software package [1]. It should be noted that according to international standards: IEEE112 for the USA, IEC34-2 for Europe, and IEC37 for Japan, five types of basic power losses must be taken into account in an induction motor (mechanical, electrical in the stator and rotor windings, magnetic, and additional [2–4]). However, in the mentioned well-known motor CSM from the MATLAB software package only takes mechanical power losses into account in full, while magnetic and additional power losses are not taken into account at all. In addition, the idealized computer simulation model of IM from [1] does not fully take into account the electrical power losses in its stator winding, since the calculation of the electromagnetic processes of this motor in its model does not take into

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account the increments in the motor stator current caused by a transportation of magnetic and additional power losses to the magnetization circuit or through the motor air gap, respectively. Thus, the well-known CSM from the MATLAB software package does not contain any calculation dependencies for determining the instantaneous energy processes of the IM, and the mentioned low actual precision of calculating its stator current does not meet the required precision for determining the energy processes of this motor.

Taking into account the above, the purpose of the proposed article is to improve the existing well-known (from the MATLAB software package) computer simulation model of a frequency-regulated induction motor. This improvement consists in expanding its functional capabilities (aimed at more precise determining the instantaneous values of all types of basic power losses, energy processes and indicators of the induction motor) and increasing the precision of the model in finding the instantaneous values of the basic harmonic components of stator currents in the steady and start-braking modes of this motor under scalar control.

Next, we will evaluate the possibility of realization the above-mentioned improvement of the known CSM, based on a preliminary analysis of existing publications, devoted to the refined calculation of energy and electromagnetic processes. In publications [5–7] there are set refined analytical dependencies for determining electrical power losses in the stator and rotor windings of the f-r IM in the steady modes through the controlled phase values of the stator and rotor currents of the motor, respectively, and through the known values of the active resistances of its stator and rotor windings (where values of this active resistances are set by the corresponding steady-state mode of the motor or determined for a concrete motor in operation using identification devices [8]). To increase the precision of determining electrical power losses in the stator and rotor windings of the f-r IM during start-braking modes, in publications [1, 9, 10] are used calculations from [11] of the mentioned power losses through the projections of generalized vector of the IM stator current.

The known refined analytical dependencies for calculating magnetic power losses in IM from publications [5, 12–14] take into account the simultaneous influence of hysteresis and eddy currents on these losses. The increase of the stator current of the IM (caused by the transfer of magnetic power losses to its magnetization circuit) is determined in articles [12–14] from the substitution scheme of this motor, supplemented by a resistor (connected in parallel to the magnetization inductance of the IM). This resistor simulates the electrical losses in it, which are equaled to the instantaneous magnetic power losses of the motor. Calculations of the increase in the stator current of the IM (caused by the mentioned transfer of magnetic power losses) are significantly complicated in start-braking modes, since the resistance value of the simulating resistor in the motor substitution scheme changes with a variation the instantaneous values of its frequency, speed, main flux linkage and torque of the f-r IM.

The change in the instantaneous value of additional power losses for the IM powered by a voltage source with a constant frequency (equal to the nominal frequency) is characterized by a variation in the motor load, according to [5], a quadratic dependence on the modulus of the generalized vector of its stator current, created by the basic (first) harmonic components of its phase stator currents. With regard to the f-r IM motors, the following other analytical dependencies have been proposed in known publications for determining the refined instantaneous values of additional power losses, which are characterized by: in [15] – a quadratic dependence on the motor torque, as well as a directly proportional change from the modulus of the generalized stator flux linkage vector; in [16] – a directly proportional change from the frequency of the first harmonic of the phase stator voltage and a quadratic dependence on the modulus of the generalized stator current vector of the motor, created by the basic (first) harmonic components of its phase stator currents. To determine the increase in stator current caused by the transportation of additional power losses through the air gap, additional resistors (simulating additional power losses) are installed in the electrical substitution scheme of this motor in known publications: in [14] – in the rotor or in [17] – in the stator link of the motor, which significantly complicates the calculations of its electromagnetic and energy processes. A known refined calculation of the instantaneous mechanical losses of the IM is given in article [5].

The above carry out analysis of known publications shows that there are currently sufficient refined analytical dependencies for calculating all types of basic power losses in the f-r IM, which can be used to create on a basis of the known idealized model of the f-r IM with scalar control from the MATLAB software package [1] (the block diagram of which is shown in Fig.1) an improved computer simulation model of the f-r IM. This improved simulation model will provide refined calculations of the electromagnetic and energy processes of this motor. However, it is desirable to simplify (in particular, without changing the idealized substitution scheme of the IM and the corresponding CSM from [1]) the determination of the instantaneous

increments of the stator current, which are caused by the transportation (transfer) of additional power losses through the motor air gap, and magnetic power losses – to the motor magnetization circuit.

1. Initial assumptions. The following assumptions and designations are accepted for an IM:

a) three-phase stator and rotor windings for different motor phases are symmetrical and structurally identical;

b) the motor air gap is the same along the inner circle of the stator;

c) the motor is powered (according to the block diagram in Fig. 1) from a three-phase stator voltage source with continuously adjustable frequency f_1 [Hz] and amplitude u_{sm} [V] of phase stator voltages $u_{sa}(t)$, $u_{sb}(t)$, $u_{sc}(t)$ sinusoidal shape (with displacements from each other by 120 and 240 electrical degrees
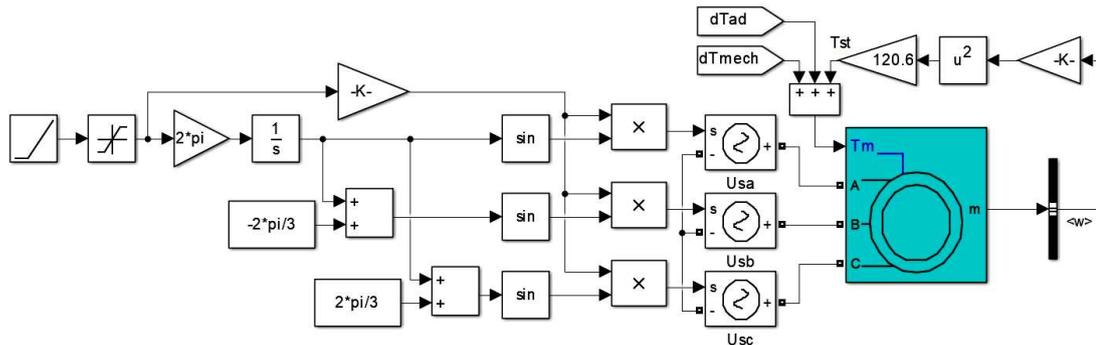

Fig. 1

for these voltages). In the improved model to the input «Tm» of the IM model are supplied (unlike the well-known CSM [1]): static torque T_{st}, mechanical torque losses ΔT_{mech} and torque losses ΔT_{ad} IM (the latter are caused by the influence of additional motor power losses); the values of the above quantities are determined from the analytical dependencies given in the further content of the proposed article.

Substitution scheme for the three-phase IM in the MATLAB software package [1] is shown in Fig. 2 and is composed of projections V_{ds}, V_{qs} of the generalized stator voltage vector $\overline{V}_s$, projections i_{ds}, i_{qs} and i'_{dr}, i'_{qr} of the generalized vectors of the stator $\bar{i}_s$ and rotor $\bar{i}'_r$ currents, projections φ_{ds}, φ_{qs}, and φ'_{dr}, φ'_{qr} generalized vectors of stator $\overline{\psi}_s$ and rotor $\overline{\psi}'_r$ flux linkages of the motor on the axis of the immobile orthogonal coordinate system (OCS) «q–d», connected by the real axis «q» with the direction of the geometric axis of the stator winding of phase «A» of the motor; here and further, the hat symbol for short-circuited IM denotes its rotor values, reduced to the equivalent three-phase rotor winding of the motor.

Electromagnetic processes in the IM substitution scheme in the Fig. 2 are described by mathematical relations [1]:

$$
\begin{aligned}
V_{qs} &= R_s \cdot i_{qs} + d\varphi_{qs}/dt + \omega \cdot \varphi_{ds}, \\
V_{ds} &= R_s \cdot i_{ds} + d\varphi_{ds}/dt - \omega \cdot \varphi_{qs},
\end{aligned}
\qquad
\left.
\begin{aligned}
V'_{qr} &= R'_r \cdot i'_{qr} + d\varphi'_{qr}/dt + (\omega - \omega_r) \cdot \varphi'_{dr}, \\
V'_{dr} &= R'_r \cdot i'_{dr} + d\varphi'_{dr}/dt - (\omega - \omega_r) \cdot \varphi'_{qr}, \\
T_e &= 1.5 p \cdot (\varphi_{ds} \cdot i_{qs} - \varphi_{qs} \cdot i_{ds})
\end{aligned}
\right\}
\qquad (1)
$$

where T_e is the instantaneous value of the rotating electromagnetic torque IM; p is the number of motor pole pairs.

In the substitution scheme in Fig. 2 and formula (1) are used the following symbols: ω is the angular frequency [rad/s] of the «q–d» coordinate system (for the immobile «q–d» OCS equal to zero angular frequency: $\omega=0$ corresponds); ω_r is the instantaneous value of angular frequency [rad/s] of rotor rotation (speed) of the motor; for a squirrel-cage induction motor, the projections V'_{dr}, V'_{qr} of the generalized rotor voltage vector $\overline{V}'_r$ are equal to zero: $V'_{dr}=V'_{qr}=0$.
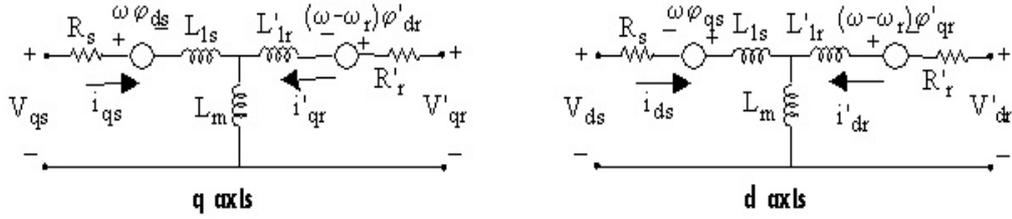
Fig. 2

Internal parameters of the motor substitution scheme: active resistances [Ohm] of the stator R_s and rotor R'_r phase windings (which are brought to the operating temperature of the motor) and magnetizing inductance L_m [H], as well as the leakage inductances [H] of the stator $L_{1\mathrm{s}}$ and rotor $L'_{1\mathrm{r}}$ windings of the motor, were considered constant.

Based on the substitution scheme in Fig. 2 and formula (1), it is possible to determine for the f-r IM in the immobile OCS «q–d» the instantaneous values of the projections φ_qm, φ_dm and the modulus φ_m [Wb] of the generalized vector of the main flux linkage $\overline{\varphi}_\mathrm{m}$ (which is equal to the magnetic flux in the air gap of the motor), as well as the instantaneous values of the projections $e_\mathrm{qm}, e_\mathrm{dm}$ and the modulus e_m [V] of the generalized vector $\overline{e}_\mathrm{m}$ of the electromotive force (EMF), the instantaneous values of the modulus i'_r of the generalized vector of the rotor current $\overline{i'_\mathrm{r}}$ [A] and the angular frequency of rotation of the rotor (speed) ω_r [rad/s] of the motor in steady and start-braking modes using known analytical dependencies [1, 11]:

$$\left.\begin{array}{l}\varphi_\mathrm{dm}=L_\mathrm{m}\cdot\left(i_\mathrm{ds}+i'_\mathrm{dr}\right), \quad \varphi_\mathrm{qm}=L_\mathrm{m}\cdot\left(i_\mathrm{qs}+i'_\mathrm{qr}\right), \quad \varphi_\mathrm{m}=\sqrt{\varphi_\mathrm{dm}^2+\varphi_\mathrm{qm}^2}, \quad i'_\mathrm{r}=\sqrt{\left(i'_\mathrm{qr}\right)^2+\left(i'_\mathrm{dr}\right)^2}, \\[3mm] e_\mathrm{dm}=-\dfrac{d}{dt}\left(\varphi_\mathrm{dm}\right), \quad e_\mathrm{qm}=-\dfrac{d}{dt}\left(\varphi_\mathrm{qm}\right), \quad e_\mathrm{m}=\sqrt{e_\mathrm{dm}^2+e_\mathrm{qm}^2}, \quad \omega_\mathrm{r}=\dfrac{1}{J}\displaystyle\int_0^t\left[T_\mathrm{e}-\left(T_\mathrm{st}+\Delta T_\mathrm{mech}+\Delta T_\mathrm{ad}\right)\right]\cdot dt\end{array}\right\}, \quad (2)$$

where J is the total moment of inertia [kg·m^2] of the drive; t is the value [s] of instantaneous time.

Calculating in an immobile OCS «q–d» harmonic functions from the instantaneous argument of the generalized magnetic flux vector $\overline{\varphi}_\mathrm{m}=\varphi_\mathrm{m}\cdot e^{j\Theta_\Phi}$ IM in the form [18]:

$$\cos\left(\Theta_\Phi\right)=\varphi_\mathrm{qm}/\varphi_\mathrm{m} \qquad \text{and} \qquad \sin\left(\Theta_\Phi\right)=\varphi_\mathrm{dm}/\varphi_\mathrm{m}, \qquad (3)$$

use them to determine the instantaneous values of the motor's rotating electromagnetic torque T_e and orthogonal projections i_us and i_vs, φ_um and φ_vm, e_um and e_vm [18]:

$$\left.\begin{array}{l}T_\mathrm{e}=1.5\cdot p\cdot\left(\varphi_\mathrm{um}\cdot i_\mathrm{vs}-\varphi_\mathrm{vm}\cdot i_\mathrm{us}\right), \\ i_\mathrm{us}=i_\mathrm{qs}\cdot\cos\left(\Theta_\Phi\right)+i_\mathrm{ds}\cdot\sin\left(\Theta_\Phi\right), \\ i_\mathrm{vs}=i_\mathrm{qs}\cdot\sin\left(\Theta_\Phi\right)-i_\mathrm{ds}\cdot\cos\left(\Theta_\Phi\right),\end{array}\right. \quad \left.\begin{array}{l}\varphi_\mathrm{um}=\varphi_\mathrm{qm}\cdot\cos\left(\Theta_\Phi\right)+\varphi_\mathrm{dm}\cdot\sin\left(\Theta_\Phi\right), \\ \varphi_\mathrm{vm}=\varphi_\mathrm{dm}\cdot\cos\left(\Theta_\Phi\right)-\varphi_\mathrm{qm}\cdot\sin\left(\Theta_\Phi\right), \\ e_\mathrm{um}=e_\mathrm{qm}\cdot\cos\left(\Theta_\Phi\right)+e_\mathrm{dm}\cdot\sin\left(\Theta_\Phi\right), \\ e_\mathrm{vm}=e_\mathrm{dm}\cdot\cos\left(\Theta_\Phi\right)-e_\mathrm{qm}\cdot\sin\left(\Theta_\Phi\right)\end{array}\right\} \quad (4)$$

accordingly, generalized vectors of stator current $\overline{i}_\mathrm{s}$, main flux linkage $\overline{\varphi}_\mathrm{m}$ and EMF $\overline{e}_\mathrm{m}$ IM on the axis of rotational OCS «u–v», oriented by the real axis «u» in the direction of the generalized vector $\overline{\varphi}_\mathrm{m}$ of the main flux linkage of the motor.

From the theory of frequency control of IM [4, 10, 18] it is known, that when the rotational orthogonal OCS «u–v» is oriented with the real axis «u» by the generalized vector of the main flux linkage $\overline{\varphi}_\mathrm{m}$: the projection i_us of the generalized vector $\overline{i}_\mathrm{s}$ of the stator current on the axis «u» sets the level of magnetization of the motor (in particular, the instantaneous value of the modulus φ_m of the main flux linkage), and the projection of this vector onto the axis «v» sets the active (torque-producing) projection i_vs of the motor stator current, which creates its rotating torque and consumed active power (including compensating for power losses and increments of the stator currents of the IM caused by the transportation of magnetic and additional power losses to the magnetization circuit or through the air gap of the motor, respectively). Moreover, for the steady operating modes of the f-r IM the values of the projections φ_um, φ_vm

and e_{um}, e_{vm} of the generalized vectors of the main flux linkage $\overline{\varphi}_m$ and EMF $\overline{e}_m$, are equal to their modules φ_m, e_m or zero, respectively:

$$\varphi_{um} = \varphi_m, \qquad \varphi_{um} = 0 \quad \text{and} \quad e_{um} = 0, \quad e_{vm} = e_m. \tag{5}$$

However, in very rapid start-braking modes, deviations from formula (5) are possible, therefore, in this article, the following calculations of electromagnetic and energy processes will be executed in the general case using the calculated instantaneous values of the projections φ_{um}, φ_{vm} and e_{um}, e_{vm} of the above-mentioned generalized vectors $\overline{\varphi}_m$ and $\overline{e}_m$ on both axes of the rotational OCS «u–v».

An important distinguishing feature of the proposed calculation of electromagnetic and energy processes is, according to [16], the assumption about a directly proportional change of the instantaneous basic additional power losses ΔP_{ad} as a function of the angular frequency of rotation of the stator magnetic field ω_s (or the instantaneous rotor speed ω_r) of the f-r IM.

For a more refined calculation of the instantaneous values of the basic (caused by the first harmonic components of the phase stator voltages and currents of the motor) electrical power losses in the stator $\Delta P_{e.s}$ and rotor $\Delta P_{e.r}$ windings, magnetic ΔP_{ir}, additional ΔP_{ad} and mechanical ΔP_{mech} power losses, total ΔP_m and electromagnetic ΔP_{em} power losses, useful on a shaft P_2 and consumed active P_1 motor power, electromagnetic P_{em} and mechanical P_{mech} power of the f-r IM, the following known analytical dependencies were selected [3–5, 10, 12, 17]:

$$\left.\begin{aligned}
&\Delta P_{e.s} = \frac{3}{2} R_s \cdot \left(i_s^*\right)^2, \ \Delta P_{e.r} = \frac{3}{2} R_r' \left(i_r'\right)^2, \ \Delta P_{ir} = \Delta P_{ir.n} \cdot \left(\frac{\varphi_m}{\varphi_{mn}}\right)^2 \cdot \left(\frac{f_1}{f_{1n}}\right)^\lambda, \ \lambda = 1.3, \ C_{ad} = \frac{3}{2} R_{ad}, \\
&\Delta P_{ad} = C_{ad} \cdot \left(\frac{\omega_s}{\omega_{sn}}\right) \cdot i_s^2 \approx C_{ad} \cdot \left(\frac{\omega_r}{\omega_{rn}}\right) \cdot i_s^2, \ R_{ad} = \frac{2}{3} \cdot \frac{\Delta P_{ad.n}}{I_{s.n}^2}, \Delta T_{mech.n} = \frac{\Delta P_{mech.n}}{\omega_{rn}}, \ \omega_s = \frac{2\pi f_1}{p}, \\
&\omega_{sn} = \frac{2\pi f_{1n}}{p}, F_r = G_r + (F+G) \cdot \left(1 + \frac{l+2a}{L}\right) + \left|\frac{G_r}{2} - (F-G) \cdot \left(1 + \frac{l+2a}{2L}\right)\right| + \left|\frac{G_r}{2} - (F-G) \cdot \frac{l+2a}{2L}\right|, \\
&C = 0.3, \ F = C \cdot \left|T_{us}\right|/R_e, \quad \Delta P_f = 3.75 \cdot 10^{-4} \omega_r F_r, \quad \Delta T_f = \Delta P_f / \omega_r, \quad \Delta P_{mech} = \Delta P_f + \Delta P_{sv}, \\
&\Delta P_{ad.n} = 0.005 \cdot P_{2n}/\eta_n, \quad \Delta P_m = \Delta P_{e.s} + \Delta P_{e.r} + \Delta P_{ir} + \Delta P_{ad} + \Delta P_{mech}, \quad \Delta P_{em} = \Delta P_m - \Delta P_{mech}, \\
&P_2 = \omega_r \cdot T_{us}, P_1 = P_2 + \Delta P_m, T_{us} = T_{st} + J \cdot (d\omega_r/dt), \Delta T_{mech} = \Delta T_f + \Delta T_{sv}, T_e = T_{us} + \Delta T_{mech} + \Delta T_{ad}, \\
&\Delta P_{sv.n} = \Delta P_{mech.n} - \Delta P_{f.n}, \Delta P_{sv} = \Delta P_{sv.n} \cdot \left(\frac{\omega_r}{\omega_{r.n}}\right)^3, \Delta T_{sv} = \Delta P_{sv.n} \cdot \left(\frac{\omega_r^2}{\omega_{r.n}^3}\right), s = \frac{\omega_s - \omega_r}{\omega_s}, \beta = \frac{\omega_s - \omega_r}{\omega_{sn}}, \\
&n = \frac{30 \cdot \omega_r}{\pi}, \ \cos(\varphi) = \frac{2P_1}{3 \cdot u_s^* \cdot i_s^*}, \quad \eta = \begin{cases} P_2/P_1 \ \text{at} \ T_e \geq 0, & P_{em} = \omega_s T_e = P_1 - \Delta P_{e.s} - \Delta P_{ir}, \\ P_1/P_2 \ \text{at} \ T_e < 0; & P_{mech} = \omega_r T_e = P_2 + \Delta P_{mech} + \Delta P_{ad}. \end{cases}
\end{aligned}\right\} \tag{6}$$

The following symbols are used in formula (6): φ_m and φ_{mn} are the instantaneous and nominal values [Wb] of the generalized vector of the main flux linkage $\overline{\varphi}_m$ respectively; ω_s and ω_{sn} is the instantaneous and nominal values [rad/s] of the angular frequency of the phase stator flux linkages of the IM respectively; n and ω_{rn} is the instantaneous value of speed [rpm] and nominal value [rad/s] of angular frequency of motor rotor rotation, respectively; f_1 and f_{1n} are the instantaneous and nominal values [Hz] of frequency of phase stator voltages of the IM, respectively; $\Delta T_{mech.n}$ is the nominal value [Nm] of mechanical torque losses of the motor; T_{us} and C_{ad} are the useful torque [Nm] on the motor shaft and constant coefficient for calculating additional losses, respectively; G_r and G are the weight of the IM rotor and half-coupling [N]; F and F_r are the radial force applied to the protruding end of the shaft (caused by the reaction of a transmission and the weight of the half-coupling) and equivalent radial force acting on the motor bearings; $d = 0.048$ and $R_e = 0.069$ are the diameter of the outer end of the motor shaft and radius of the transmission of the force in the МУВП-8 elastic coupling [m]; ΔP_f and $\Delta P_{f.n}$ are the instantaneous and nominal values of power losses due to friction in the motor bearings [W]; ΔP_{sv} and $\Delta P_{sv.n}$ are the

instantaneous and nominal values of IM power losses due to self-ventilation (including friction between the rotor and the air inside the motor) [W]; ΔT_f and ΔT_{sv} are the instantaneous friction torque losses in bearings and self-ventilation of the IM [Nm]; l, $l+a$, L are the length of the protruding end of the shaft, distances from the end of the shaft to the front bearing and between bearings [m]; $\Delta P_{ad.n}$ and $\Delta P_{mech.n}$ are the nominal values [W] of additional and mechanical power losses of the IM, respectively; s and β are the relative and absolute slip [%] of the IM, respectively; η and η_n are the instantaneous and nominal values [%] of the motor efficiency, respectively; i_s^* and u_s^* are the refined calculated instantaneous values of the modules of generalized vectors of stator current [A] and voltage [V] of the f-r IM, respectively; $\cos(\varphi)$ is the instantaneous value of the motor power factor.

2. Theoretical research. At *the first stage*, we obtain an analytical dependence for determining the increment $\Delta i_{v.ad}$ of stator current in the rotational OCS «u–v». This increments leads to a change of the instantaneous value of the orthogonal projection i_{vs} of the IM stator current and is caused by the transfer (transportation) of additional power losses of the f-r IM through the air gap of the motor. To increase the precision of determining additional power losses ΔP_{ad}, we will calculated them differently from the calculated expression for them in formula (6). Namely, taking into account the inclusion of additional losses in the mechanical power P_{mech} IM [4] and also taking into account the last ratio for the mentioned power from formula (6), we will establish that, physically, additional power losses ΔP_{ad} are not affected by electrical losses in the stator $\Delta P_{e.s}$ and rotor $\Delta P_{e.r}$ windings, as well as magnetic power losses ΔP_{ir} of the motor. Therefore, we will find additional power losses not directly proportional to the square i_s^2 of the modulus of the generalized stator current vector $\bar{i}_s$, but directly proportional to the square of the modulus $i_{s\Sigma}^2$ of another generalized stator current vector $\bar{i}_{s\Sigma}$ from the following expressions:

$$\Delta P_{ad} = 1.5 \cdot R_{ad}^* \cdot (\omega_r / \omega_{rn}) \cdot i_{s\Sigma}^2 = 1.5 \cdot R_{ad}^* \cdot (\omega_r / \omega_{rn}) \cdot \left(i_{us}^2 + i_{vs\Sigma}^2 \right), \quad \bar{i}_{s\Sigma} = i_{us} + j i_{vs\Sigma},$$
$$R_{ad}^* = 2 \cdot \Delta P_{ad.n} / \left[3 \cdot \left(i_{us.n}^2 + i_{vs\Sigma.n}^2 \right) \right] = 2 \cdot \Delta P_{ad.n} / \left(3 \cdot i_{s\Sigma.n}^2 \right) = R_{ad} \cdot (i_{s.n} / i_{s\Sigma.n})^2 \quad (7)$$

through the instantaneous values of the modulus $i_{s\Sigma}$ or longitudinal $i_{u.s}$ and transverse $i_{v.s\Sigma}$ projections of the generalized vector $\bar{i}_{s\Sigma}$ on the axes of the previously mentioned rotational OCS «u – v». In formula (7): R_{ad}^* is the the refined value of the equivalent (intended for calculating additional power losses) active resistance of the motor, which is calculated using the nominal (i.e., corresponding to the nominal mode of the motor) value of additional power losses $\Delta P_{ad.n}$, as well as using the nominal values of the module $i_{s\Sigma.n}$, of the longitudinal $i_{us.n}$ and transverse $i_{vs\Sigma.n}$ projections of the generalized stator current vector $\bar{i}_{s\Sigma.n}$ of the motor on the orthogonal axes of the OCS «u–v».

Let us compile (taking into account (7) and the calculated relations from formula (6) for useful power P_2 and mechanical power losses ΔP_{mech} IM) the energy balance for its mechanical power P_{mech} [4]:

$$P_{mech} = \omega_r \cdot T_e = \omega_r \cdot (T_{us} + \Delta T_{mech}) + 1.5 \cdot R_{ad}^* \cdot (\omega_r / \omega_{rn}) \cdot i_{s\Sigma}^2, \qquad i_{s\Sigma}^2 = \left(i_{us}^2 + i_{vs\Sigma}^2 \right), \quad (8)$$

where the instantaneous value of the electromagnetic moment T_e is determined from the first relation in (4) without taking into account or taking into account (5), respectively, using known dependencies [1, 11]:

$$T_e = 1.5 \cdot p \cdot (\varphi_{um} \cdot i_{vs\Sigma} - \varphi_{vm} \cdot i_{us}) = 1.5 p \cdot \varphi_m \cdot i_{vs\Sigma}. \quad (9)$$

Let us obtain, by analogy with (9), calculated relations (through orthogonal projections $i_{u.s}$ and $i_{v.s}$ of the motor stator current) for a determining the sum of moments $(T_{us} + \Delta T_{mech})$ of the f-r IM:

$$T_{us} + \Delta T_{mech} = 1.5 p \cdot (\varphi_{um} \cdot i_{vs} - \varphi_{vm} \cdot i_{us}) = 1.5 p \cdot \varphi_m \cdot i_{vs}. \quad (10)$$

Based on the known relation for torque T_e from formula (6), dependence (10) also determines the instantaneous value of the electromagnetic torque T_e IM in the known CSM [1], which does not take into account additional power losses ($\Delta P_{ad} = 0$) of the IM and created by it the torque losses ($\Delta T_{ad} = 0$).

From formula (8), taking into account (9) and (10), we find the calculated dependence for additional power losses of the f-r IM:

$$\left. \begin{array}{l} \Delta P_{\rm ad} = 1.5 \cdot R_{\rm ad}^* \cdot (\omega_{\rm r} / \omega_{\rm r\,n}) \cdot \left(i_{\rm us}^2 + i_{\rm vs\Sigma}^2 \right) = \omega_{\rm r} \cdot T_{\rm e} - \omega_{\rm r} \cdot (T_{\rm us} + \Delta T_{\rm mech}) = \omega_{\rm r} \cdot [T_{\rm e} - (T_{\rm us} + \Delta T_{\rm mech})] = \\ = 1.5 \cdot p \cdot \omega_{\rm r} \cdot [\varphi_{\rm um} \cdot (i_{\rm vs\Sigma} - i_{\rm vs}) - \varphi_{\rm vm} \cdot (i_{\rm us} - i_{\rm us})] = 1.5 \cdot p \cdot \omega_{\rm r} \cdot \varphi_{\rm m} \cdot \Delta i_{\rm v.ad}, \qquad \Delta i_{\rm v.ad} = i_{\rm vs\Sigma} - i_{\rm vs} \end{array} \right\} \qquad (11)$$

through the instantaneous value of the modulus $i_{\rm s\Sigma}$ of the generalized vector $\bar{i}_{\rm s\Sigma}$ of the stator current and the increment $\Delta i_{\rm v.ad}$ of the projection $i_{\rm v.ad}$ of the generalized vector of the stator current of the f-r IM (which is caused by the transportation of its additional power losses $\Delta P_{\rm ad}$ through the air gap of the motor).

Let us transform the left and right expressions from the first dependence in formula (11) to the form:
$$\Delta P_{\rm ad} = 1.5 \cdot R_{\rm ad}^* \cdot (\omega_{\rm r} / \omega_{\rm r\,n}) \cdot \left(i_{\rm us}^2 + i_{\rm vs\Sigma}^2 \right) = 1.5 \cdot p \cdot \omega_{\rm r} \cdot \varphi_{\rm m} \cdot \Delta i_{\rm v.ad}, \qquad (12)$$
composed of the module $\varphi_{\rm m}$ of the generalized vector $\bar{\varphi}_{\rm m}$ of the main flux linkage and the above-mentioned projections $i_{\rm us}$, $i_{\rm vs\Sigma}$ and increment $\Delta i_{\rm v.ad}$ of the stator current.

From the last relation in formula (11) we determined the instantaneous value of the projection $i_{\rm v.s\Sigma}$ of the generalized vector $\bar{i}_{\rm s\Sigma}$ in the form:
$$i_{\rm v.s\Sigma} = i_{\rm v.s} + \Delta i_{\rm v.ad} \qquad (13)$$
and after substitution it into formula (12), we obtain the following equation:
$$R_{\rm ad}^* \cdot (\omega_{\rm r} / \omega_{\rm r\,n}) \cdot \left[i_{\rm us}^2 + (i_{\rm vs} + \Delta i_{\rm v.ad})^2 \right] = p \cdot \omega_{\rm r} \cdot \varphi_{\rm m} \cdot \Delta i_{\rm v.ad}, \qquad (14)$$
which after equivalent algebraic transformations we will reduce to the usual quadratic equation with respect to the variable value $\Delta i_{\rm v.ad}$:
$$\Delta i_{\rm v.ad}^2 + \Delta i_{\rm v.ad} \cdot \left(2 \cdot i_{\rm vs} - p \cdot \omega_{\rm r\,n} \cdot \varphi_{\rm m} / R_{\rm ad}^* \right) + i_{\rm us}^2 + i_{\rm vs}^2 = 0. \qquad (15)$$

The solution to this equation (relative to the increase $\Delta i_{\rm v.ad}$) is the following relation:
$$\Delta i_{\rm v.ad} = \left(0.5 \cdot p \cdot \omega_{\rm r\,n} \cdot \varphi_{\rm m} / R_{\rm ad}^* - i_{\rm vs} \right) - \sqrt{\left(0.5 \cdot p \cdot \omega_{\rm r\,n} \cdot \varphi_{\rm m} / R_{\rm ad}^* - i_{\rm vs} \right)^2 - i_{\rm us}^2 - i_{\rm vs}^2}, \qquad (16)$$
which allows to calculate the mentioned instantaneous increment $\Delta i_{\rm v.ad}$ in the function of the instantaneous values of the modulus $\varphi_{\rm m}$ of the main flux linkage vector $\bar{\varphi}_{\rm m}$ and orthogonal projections $i_{\rm us}$, $i_{\rm vs}$ of the stator current vector $\bar{i}_{\rm s}$ of the f-r IM. After calculating in the relations (16) and (13) the instantaneous values of the increment $\Delta i_{\rm v.ad}$ and projection $i_{\rm vs\Sigma}$ of the stator current, the instantaneous value of the additional power losses $\Delta P_{\rm ad}$ of the IM are found from formulas (7) and (11).

To estimate the instantaneous error δ between the angular frequency ratios: $(\omega_{\rm r} / \omega_{\rm r\,n})$ and $(\omega_{\rm s} / \omega_{\rm s\,n})$, as well as to determine, based on formula (8) and the relation for torque $T_{\rm e}$ from formula (6), the instantaneous value of torque losses $\Delta T_{\rm ad}$ (caused by the influence of additional motor power losses $\Delta P_{\rm ad}$), the following analytical expressions are proposed:
$$\delta = (\omega_{\rm r} / \omega_{\rm r\,n}) - (\omega_{\rm s} / \omega_{\rm s\,n}) \qquad \text{and} \qquad \Delta T_{\rm ad} = 1.5 R_{\rm ad}^* \cdot \left[i_{\rm us}^2 + (i_{\rm vs} + \Delta i_{\rm v.ad})^2 \right] / \omega_{\rm r\,n}. \qquad (17)$$
A complete coincidence between the instantaneous values of the rotating electromagnetic torque $T_{\rm e}$ calculated using formulas (1), (6) and (9) has been revealed, which, in turn, confirms the precision of the calculations obtained with using the improved CSM.

In *the second stage,* we will obtain analytical dependencies for determining the instantaneous increments $\Delta i_{\rm u.ir}$ and $\Delta i_{\rm v.ir}$ of the stator current in the rotating OCS «u–v», which lead to a change in the orthogonal projections of the generalized stator current vector and are caused by the transportation of magnetic power losses of the f-r IM to the motor magnetization circuit. According to publications [12–14], the mentioned increments of the stator current of the IM motor, caused by the influence of instantaneous magnetic power losses $\Delta P_{\rm ir}$, are simulated in the known electric substitution schemes of this motor by introducing in it an additional resistor $R_{\rm ir}$, which connected in parallel to the magnetization inductance $L_{\rm m}$.

Taking this into account, the instantaneous value of the resistance $R_{\rm ir}$ of the mentioned resistor (which is selected from the condition that the instantaneous electrical power losses in it are equal to the instantaneous value of the magnetic power losses of the IM) is found from the analytical dependencies:
$$\Delta P_{\rm ir} = 1.5 \cdot e_{\rm m}^2 / R_{\rm ir}, \qquad R_{\rm ir} = 1.5 \cdot e_{\rm m}^2 / \Delta P_{\rm ir}, \qquad (18)$$

where e_m is the instantaneous value of the motor EMF module, determined from (2). Using the instantaneous projections e_um and e_vm of the generalized motor EMF $\bar{e}_\mathrm{m}$ vector calculated in formula (4) and taking into account the expression, given in formula (6) for determining the instantaneous magnetic power losses ΔP_ir, we obtain, taking into account (18), the analytical dependencies for finding the increments $\Delta i_\mathrm{u.ir}$ and $\Delta i_\mathrm{v.ir}$ longitudinal and transverse projections of the stator current of the f-r IM:

$$\left.\begin{array}{l} \Delta i_\mathrm{u.ir} = \dfrac{e_\mathrm{um}}{R_\mathrm{ir}} = \dfrac{2e_\mathrm{um}}{3e_\mathrm{m}^2}\cdot\Delta P_\mathrm{ir} = \Delta P_\mathrm{ir.n}\cdot\dfrac{2e_\mathrm{um}}{3e_\mathrm{m}^2}\cdot\left(\dfrac{\varphi_\mathrm{m}}{\varphi_\mathrm{mn}}\right)^2\cdot\left(\dfrac{f_1}{f_\mathrm{1n}}\right)^\lambda, \\[3mm] \Delta i_\mathrm{v.ir} = \dfrac{e_\mathrm{vm}}{R_\mathrm{ir}} = \dfrac{2e_\mathrm{vm}}{3e_\mathrm{m}^2}\cdot\Delta P_\mathrm{ir} = \dfrac{2}{3}\cdot\dfrac{\Delta P_\mathrm{ir}}{e_\mathrm{m}} = \Delta P_\mathrm{ir.n}\cdot\dfrac{2e_\mathrm{vm}}{3e_\mathrm{m}^2}\cdot\left(\dfrac{\varphi_\mathrm{m}}{\varphi_\mathrm{mn}}\right)^2\cdot\left(\dfrac{f_1}{f_\mathrm{1n}}\right)^\lambda \end{array}\right\}. \qquad (19)$$

Based on (13), (16), and (19), we obtain refined dependencies for determining the instantaneous values of the longitudinal i_us^* or u_us^* and transverse i_vs^* or u_vs^* projections, modules i_s^* or u_s^* respectively of the generalized vectors of stator current $\bar{i}_\mathrm{s}^*$ or voltage $\bar{u}_\mathrm{s}^*$ of the f-r IM:

$$\left.\begin{array}{ll} \bar{i}_\mathrm{s}^* = i_\mathrm{us} + j\cdot i_\mathrm{vs}^*, & i_\mathrm{us}^* = i_\mathrm{us} + \Delta i_\mathrm{u.ir} \approx i_\mathrm{us}, \quad \Delta i_\mathrm{u.ad} = 0, \\[2mm] \bar{u}_\mathrm{s}^* = u_\mathrm{us}^* + ju_\mathrm{vs}^*, & i_\mathrm{vs}^* = i_\mathrm{vs\Sigma} + \Delta i_\mathrm{v.ir} = i_\mathrm{vs} + \Delta i_\mathrm{v.ad} + \Delta i_\mathrm{v.ir}, \\[2mm] i_\mathrm{s}^* = \sqrt{(i_\mathrm{us})^2 + (i_\mathrm{vs}^*)^2}, & u_\mathrm{us}^* = e_\mathrm{um} + R_\mathrm{s}\cdot i_\mathrm{us} - p\cdot\omega_\mathrm{s}\cdot L_\mathrm{1s}\cdot i_\mathrm{vs}^* + L_\mathrm{1s}\cdot\dfrac{d}{dt}(i_\mathrm{us}), \\[3mm] u_\mathrm{s}^* = \sqrt{(u_\mathrm{us}^*)^2 + (u_\mathrm{vs}^*)^2}, & u_\mathrm{vs}^* = e_\mathrm{vm} + R_\mathrm{s}\cdot i_\mathrm{vs}^* + p\cdot\omega_\mathrm{s}\cdot L_\mathrm{1s}\cdot i_\mathrm{us} + L_\mathrm{1s}\cdot\dfrac{d}{dt}(i_\mathrm{vs}^*). \end{array}\right\} \qquad (20)$$

These dependencies simultaneously take into account the presence in the f-r IM model of all basic types of power losses, as well as current increments $\Delta i_\mathrm{v.ad}$ and projections $\Delta i_\mathrm{u.ir}$, $\Delta i_\mathrm{v.ir}$ of stator currents caused by the transportation of additional and magnetic power losses of this motor through its air gap or to its magnetization circuit, respectively. Finding the instantaneous values of the modulus u_s and projections u_us, u_vs of the generalized stator voltage vector $\bar{u}_\mathrm{s}$ of the motor on the rotational axis OCS «u–v» in the improved the f-r IM model can be carry out from the last three expressions in formula (20), if we substitute: u_s^* – to u_s, u_us^* – to u_us, u_vs^* – to u_vs and i_vs^* – to i_vs respectively.

According to the dependencies from (20), we will compile a distribution diagram of increments $\Delta i_\mathrm{u.ir}$, $\Delta i_\mathrm{v.ir}$ and $\Delta i_\mathrm{v.ad}$ of the stator current between the generalized vectors of stator currents $\bar{i}_\mathrm{s}^*$, $\bar{i}_\mathrm{s\Sigma}$ and $\bar{i}_\mathrm{s}$ f-r IM on Fig. 3 for the improved model.

3. Modeling results. Results of modeling (shown in Fig. 4) of steady and start-braking modes of the f-r IM (using the example of a 4A160M4U3 motor with nominal parameters from Table 1), which is loaded with a BP217-30-6.3 centrifugal fan with a moment of inertia $J_\mathrm{fan} = 1.44$ kg·m^2 and is characterized by a to-tal moment of inertia J of the drive and an instantaneous static moment T_st according to the dependencies:

Fig. 3

$$J = J_\mathrm{m} + J_\mathrm{fan}, \quad T_\mathrm{st} = T_\mathrm{st.n}\cdot(n/n_\mathrm{n})^2; \quad T_\mathrm{st.n} = T_\mathrm{us.n} = 120.6 \text{ (Nm)}. \qquad (21)$$

Formula (21) uses the following symbols: $T_\mathrm{st.n}$ and $T_\mathrm{us.n}$ are the corresponding to the nominal speed n_n IM values of static torque T_st and useful torque T_us on the IM shaft; J_m is the moment of inertia of the motor rotor from Table 1. In the modeling there was applied the well-known scalar law of frequency
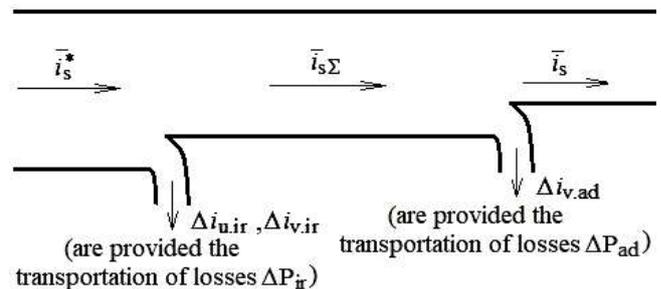
control: $U_s / f_1 = \text{const}$, which is widely used in practice for f-r IM loaded with centrifugal fans or pumps. In the existing CSM of the f-r motor from the MATLAB software package, there were set the frequency $f_1(t)$ and amplitude $u_{sm}(t)$ of the instantaneous phase stator voltages u_{sa}, u_{sb}, u_{sc} for the induction motor (but in the improved model there were set the frequency $f_1(t)$ and amplitude $u_{sm}^*(t)$ of the instantaneous phase stator voltages u_{sa}^*, u_{sb}^*, u_{sc}^* for the refined model of this motor), which varied linearly over time: during accele-ration – in the range from zero to the nominal frequency (equal to f_{1n} =50Hz) and to the nominal effective
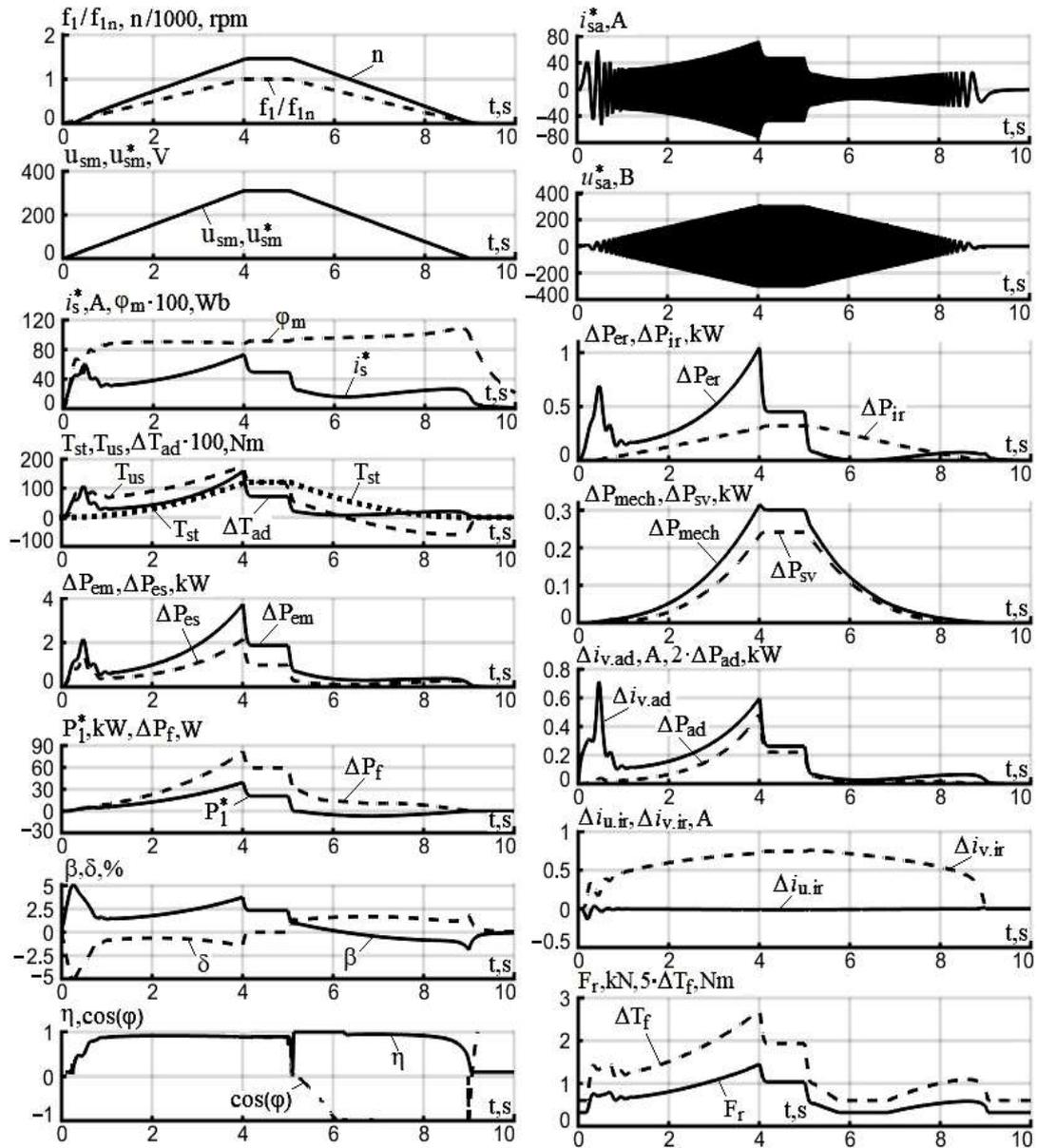

Fig. 4

voltage value $U_{sn} = 220\,\text{V}$ (at which the amplitude value u_{smn} of the phase stator voltage is equaled to $U_{sn} \cdot \sqrt{2} \cdot 220 = 311.1\,\text{V}$); during the braking mode, on the contrary, this values change from the above-mentioned frequency f_{1n} and nominal voltage amplitude u_{smn} = 311.1 V – to their zero values.

The offered refined analytical calculation dependencies (1) – (4), (6), (7), (16), (17), (19) and (20) for determining the instantaneous values of stator current and voltage, instantaneous values of torque and

power losses, and energy indicators of the f-r IM were realized in an improved simulation model using standard Simulink library blocks from the well-known MATLAB software package (the calculation discreteness automatically coincides with the IM calculation, which is present in the same existing Simulink simulation model [1] and is equal to 0.0001 s). The graphs of the electromagnetic and energy processes (which are shown in Fig. 4) of the researched f-r IM, loaded with the fan, were calculated using the improved CSM, and correspond to the acceleration and deceleration times equal to 4 s. The designation of the instantaneous calculated values in Fig. 4 fully corresponds to their conditional designation previously considered in the text of this article.

Table 1

I. Nominal parameters, dimensions	Value	I. Nominal parameters of the 4A160M4U3 asynchronous motor, dimensions		Value
Useful active power, kW	18.5	Useful torque T_n, Nm		120.6
Effective phase stator voltage, V	220	Motor rotor moment of inertia, kg·m²		0.13
Amplitude of phase stator current, A	50.35	II. Parameters of the T-shaped substitution scheme:	Value	
			r.u.	SI
Frequency of phase stator voltage, Hz	50	- active resistance of the stator phase winding R_s, Ohm	0.042	0.7416
Number of pole pairs	2	- active resistance of the phase stator winding R'_r, Ohm	0.024	0.1483
Motor speed, rpm	1465			
Efficiency, %	89.5	- magnetizing inductance L_m, mH	4.3	84.58
Power factor	0.88	- stator winding leakage inductance L_{1s}, mH	0.086	1.672
Maximum torque ratio	2.3	- rotor winding leakage inductance L'_{1r}, mH	0.13	2.557

Using the offered improved CSM, the following calculations were also accomplished over a time interval: $4s < t < 5s$ electromagnetic and energy processes of the researched 4A160M4U3 motor in its nominal steady-state mode of operation (at a nominal stator frequency f_{1n} =50Hz, nominal amplitudes u_{smn} of phase stator voltages and with a load in the form of a centrifugal fan BP 217-30-6.3) with respect to the following three variants: I, II and III of the IM model (the results of these calculations are given in Table 2).

Table 2

Var.	Electromagnetic parameters of the motor									
	n	s	T_{us}	ΔT_{ad}	$\Delta i_{v.ir}$	$\Delta i_{v.ad}$	i_{sm}	i_{sm}^*	u_{sm}	u_{sm}^*
Unit	rpm	%	Nm	Nm	A	A	A	A	V	V
I	1465.3	2.316	119.88	0	0	0	49.13	–	311.1	–
II	1465.0	2.333	119.84	0.7110	0	0	49.40	–	311.1	–
III	1465.0	2.333	120.62	0.7191	0.7443	0.2617	49.44	50.35	310.8	311.1

Var.	Energy parameters of the motor									
	ΔP_{es}	ΔP_{er}	ΔP_{ir}	ΔP_{ad}	ΔP_{mech}	ΔP_f	ΔP_{em}	δ	η	$\cos(\varphi)$
Unit	kW	kW	kW	kW	kW	kW	kW	%	%	–
I	0.9389	0.4456	0.3221	0	0.3006	0.0590	1.7067	0.0183	90.22	0.8954
II	0.9490	0.4510	0.3219	0.1091	0.3005	0.0590	1.8310	-0.0030	89.67	0.8956
III	0.9862	0.4519	0.3212	0.1103	0.3008	0.0593	1.8697	-0.0023	89.50	0.8800

Variant I corresponds to the IM model from the existing MATLAB software package (in which the basic magnetic and additional power losses, as well as electrical losses during their transportation, are not taken into account in the motor); in variant II the model of the motor additionally takes into account the basic magnetic and additional power losses, but does not take into account the losses, associated with their transportation; variant III corresponds to the proposed improved CSM of the frequency-regulated IM (when all the basic power losses present in the motor (including magnetic and additional ones) are taken into account at the same time, as well as electrical power losses caused by the transportation of magnetic and additional losses. The analysis of Table 2 shows that, firstly, in variant III there is a complete coincidence of the values of efficiency η, $\cos(\varphi)$ and current i_{sm}^* with the corresponding reference data from Table 1;

secondly, the greatest deviations from the reference data correspond to variant I (in which, due to the highest degree of «idealization» of the IM model, the efficiency value η is unreasonably overestimated by more than 0.77%, and, conversely, the stator current i_s and electromagnetic power losses ΔP_{em} – are underestimated by 2.43% and 8.72%, respectively. Moreover, the detected decrease in electromagnetic power losses ΔP_{em} in variant I (compared to the reference data in Table 1 or the improved model in variant III) leads to an incorrect verification of this motor for permissible heating during operation, if its instantaneous heating is monitored through the abovementioned electromagnetic power losses. Thirdly, for variant II of the IM simulation model (compared to variant III) the errors in calculating the efficiency and electromagnetic power losses of the motor do not exceed 0.19% and 2.1%, respectively.

Conclusions. An improvement has been made to the computer simulation model of an induction motor from the MATLAB software package, which allows to accomplish the refined calculation of the instantaneous values of all basic types of power losses, as well as the active power consumption, efficiency and power coefficients of the f-r IM. Compared to all known existing models of the f-r IM from the MATLAB software package, the offered improved model takes into account for the first time all the basic power losses present in this motor, as well as the electrical losses caused by transporting magnetic and additional power losses to the magnetization circuit or through the air gap of the motor, respectively. New refined analytical dependencies (7), (16), (17), (19), and (20) have been obtained for calculating instantaneous values of stator currents and their components, as well as torque losses caused by additional power losses of the motor in steady and start-braking modes. The theoretical results, presented in the article are confirmed by the results of modeling a general-industry induction motor, loaded with a centrifugal fan, in the MATLAB software package at the researched modes.

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УДК 621.313.13

УДОСКОНАЛЕННЯ КОМП'ЮТЕРНОЇ ІМІТАЦІЙНОЇ МОДЕЛІ ЧАСТОТНО-РЕГУЛЬОВАНОГО АСИНХРОННОГО ДВИГУНА В ПАКЕТІ ПРОГРАМ MATLAB

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Роботу присвячено удосконаленню відомої імітаційної моделі комп'ютерного моделювання трифазного короткозамкненого асинхронного двигуна з частотним керуванням у програмному комплексі MATLAB, що полягає у розширенні її функціональної можливості (зокрема, здійсненню уточненого розрахунку поточних значень всіх видів основних втрат потужності, основної споживаної активної потужності, енергетичних показників двигуна) і підвищенню точності знаходження поточних значень основних гармонійних компонентів фазних статорних струмів і напруг в усталеному і пуско-гальмівному режимах двигуна. Це завдання вирішено шляхом доповнення відомої моделі з програмного комплексу MATLAB уточненими аналітичними залежностями задля розрахунку основних енергетичних параметрів частотно-регульованого асинхронного двигуна та внаслідок отримання нових уточнених аналітичних розрахункових залежностей задля визначення поточних значень модулів узагальнених векторів статорних струмів й напруг цього двигуна. Задля підтвердження працездатності вдосконаленої комп'ютерної імітаційної моделі були з її використанням обчислені (стосовно до загальнопромислового короткозамкненого асинхронного двигуна, навантаженого відцентровим вентилятором) в усталених і пуско-гальмівних режимах двигуна його основні втрати потужності і основна споживана активна потужність, коефіцієнт корисної дії та потужності. Практична цінність створеної удосконаленої комп'ютерної імітаційної моделі полягає у підвищенні точності розрахунку електромагнітних та енергетичних процесів асинхронного двигуна з частотним регулюванням в усталеному та пуско-гальмівних режимах за скалярного керування. Бібл. 18, рис. 4, табл. 2.

Ключові слова: асинхронний двигун, частотне регулювання, комп'ютерна імітаційна модель, електромагнітні та енергетичні процеси