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SIMULATION OF INDUCTION MACHINES WITH COMMON SOLID ROTOR

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A simulation model is developed and transient modes of a double-module induction machine with a common external solid rotor are researched. It is established, that with the counter rotation of magnetic fields, a gearless mode of the steady operation of a double-module induction machine is provided at low rotational speeds of the solid hollow rotor, combined with a screw actuator. References 14, figure 1, table 1.
Key words: simulation model, induction machine, solid rotor, transient mode.

One of the perspective directions of increasing energy efficiency and productivity of technological systems for the processing of coarse substances is the structural and thermal integration of separate elements of equipment, the use of a double-motor system with a common rotor-shaft and a dissipative component of the energy of these elements, as well as the application of the principle of low-speed low rotation speed and multiple amplification torque [1, 2]. In the papers [3–6] double-stators converters are considered and an analytical approach using an equivalent circuit for replacing an induction machine (IM) with a solid rotor (SR), as well as calculations using a finite element model is presented. For the generalized electromechanical converter (GEC) the known equations are equitable [7–10, 14], but the simulation of induction machines with a common rotor-shaft is carried out without mutual coordination of processes in individual machines, standard but not interconnected substitution schemes are used, which leads to the analysis of electromechanical processes in transient modes of operation to significant errors. There is no single approach in modeling of IM with SR, on the basis of which it would be possible to form a simulation model (SM) by the method of inheritance, based on the initial generalized SM. This is especially true for induction machines with a common rotor, which is also has a function of an executive mechanism.

Therefore, the aim of the work is the development of a simulation model and the study of transient modes of operation of induction machines with a common external solid rotor.

Consider the formation of a simulation model of an electromechanical converter with a SR from a well-known generalized model, given in a two-phase coordinate system αβ. The equations system of IM with SR in a steady state mode, according to the *T*-shape substitution circuit [9], taking into account the presents of short-circuit winding inside a solid rotor [10], has the next view:

$$\begin{cases} \dot{U}_1 = -\dot{E}_0 + \dot{I}_1\left(r_1 + jx_1\right) \\ 0 = \dot{E}_0 - \dot{I}_2'\left(r_2' + jx_{20}'\right)\dfrac{1}{\sqrt{s}} - \dot{I}_2'\, jx_{20}'' \\ \dot{I}_0 = \dot{I}_1 + \dot{I}_2', \end{cases} \quad (1)$$

where U_1 is the stator voltage; E_0 is the EMF; r_1 is the stator winding resistance; x_1 is the stator winding reactance; r'_2 is the rotor reduced resistance; x''_{20} is the rotor reactance; I_0 is the idle mode current; I_1 is the stator current; I'_2 is the rotor reduced current; s is the slippery.

The second equation of the system (1), written for the rotor circuit, differs from the one for induction motor with short circuit rotor, since the transformations for the stator circuit are analogous to those, known for the generalized electric machine [11].

After transformations the second equation of sysytem (1), described in detail in [10], we write the expression for the instantaneous values in the two-phase coordinate system α, β. Considering $x''_{20} = 0$ for IM with SR without a short-circuited winding for the given problem [2], we obtain

$$0 = r_r i_{r\alpha} + \frac{d}{dt}\left(L_r i_{r\alpha} + M i_{s\alpha}\right) + \frac{d}{dt} L_{r\sigma} i_{r\alpha}\omega_s - \left(L_r i_{r\beta} + M i_{s\beta}\right)\omega_0\omega_s, \quad (2)$$

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where r_r is the rotor resistance; L_r is the rotor self-inductance; $L_{r\sigma}$ is the rotor leakage inductance; M is the mutual inductance; $i_{s\alpha}$, $i_{s\beta}$ are the α, β axes stator currents; $i_{r\alpha}$, $i_{r\beta}$ are the α, β axes rotor currents; $\omega_s = 1-\sqrt{s}$ is the rotor reduced speed.

In (2) expression $\frac{d}{dt}\left(L_r i_{r\alpha} + M i_{s\alpha}\right)$ is linkage differential $\frac{d}{dt}\Psi_{r\alpha}$ on axis α and $\left(L_r i_{r\beta} + M i_{s\beta}\right)$ is rotor linkage $\Psi_{r\beta}$ on axis β [11].

In the final form for AM with SR the equations system for the instantaneous values in a two-phase coordinate system that rotates with the rotor speed, considering (2) has the form [10, 11]

$$\begin{aligned} &\frac{d\Psi_{s\alpha}}{dt} = u_{s\alpha} - r_1 i_{s\alpha} + \omega_e \Psi_{s\beta}; \qquad \frac{d\Psi_{s\beta}}{dt} = u_{s\beta} - r_1 i_{s\beta} - \omega_e \Psi_{s\alpha}; \\ &\frac{d\Psi_{r\alpha}}{dt} = -r_r i_{r\alpha} - \frac{d}{dt} i_{r\alpha} L_{r\sigma}\omega_s - \Psi_{r\beta}\left(\omega_e - \omega_0\omega_s\right); \qquad \frac{d\Psi_{r\beta}}{dt} = -r_r i_{r\beta} - \frac{d}{dt} i_{r\beta} L_{r\sigma}\omega_s + \Psi_{r\alpha}\left(\omega_e - \omega_0\omega_s\right), \end{aligned} \tag{3}$$

where $\psi_{s\alpha}$, $\psi_{s\beta}$ are the α, β axes stator linkages; $\psi_{r\alpha}$, $\psi_{r\beta}$ are α, β axes rotor linkages; $u_{s\alpha}$, $u_{s\beta}$ are the α, β axes stator windings sine voltages; r_s is the stator winding resistance; ω_0 is the field synchronous speed; ω_e is the coordinate system rotation speed; ω_s is the rotor rotation speed.

Stator flux linkages for model axes α, β can be obtained by the next equations [12]:

$$\begin{aligned} \Psi_{s\alpha} &= L_s i_{s\alpha} + L_m i_{r\alpha}; \\ \Psi_{s\beta} &= L_s i_{s\beta} + L_m i_{r\beta}, \end{aligned} \tag{4}$$

where L_m is the magnetic circuit inductance.

Rotor flux linkages for model axes α, β can be obtained by the analogical equations [12]

$$\begin{aligned} \Psi_{r\alpha} &= L_r i_{r\alpha} + L_m i_{s\alpha}; \\ \Psi_{s\beta} &= L_r i_{r\beta} + L_m i_{s\beta}. \end{aligned} \tag{5}$$

Parameters of the stator winding (active resistance and inductance) are based on known equations for three-phase windings of induction motor [11]. Parameters of the ferromagnetic rotor are according to the equations given in [9] and specified in [13]. Supplementing the system (3) with known equations of motion and torque [11, 12], we obtain a complete system of differential equations for IM with SR.

Using system (3) we can make the following conclusions: the total resistance of the rotor differs by the magnitude of the ferromagnetic body leakage inductance, taking into account the speed approximation factor ω; nonlinear change of machine parameters is taken into account by the introduction of a speed approximation factor ω_s. By completing the system with equations of motion and moment, we obtain a complete system of differential equations for IM with SR.

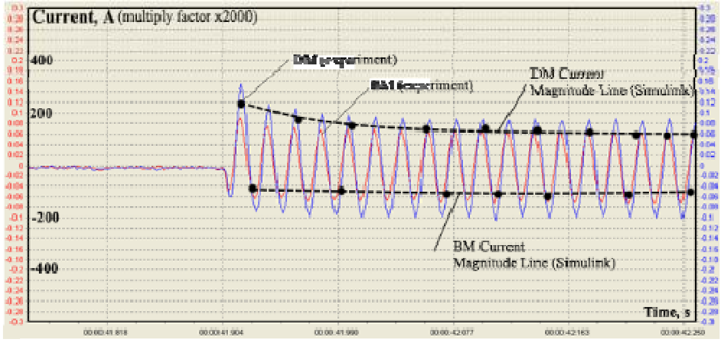
Let's consider an example of forming an induction motor with solid rotor model in the *Simulink MatLab* package, using (3) for double-stator IM with SR [3-6]. In such machine, the two stators are located inside the steel rotor tube and operate in the counter mode, forming the motor module and the brake module. To study the transient characteristics of GES with SR in the *Simulink MatLab* package, it is convenient to develop a model for rotation of the coordinate system with rotor speed $\omega_e = \omega_r$. For simulation, the parameters of the electric motor of the screw type EDSH-1, shown in the Table, are used. It should be noted that the EDSH-1 stator is structurally similar to a rotor of induction motor with a phase rotor. This feature should be considered while finding the parameters of the three-phase stator winding [13].

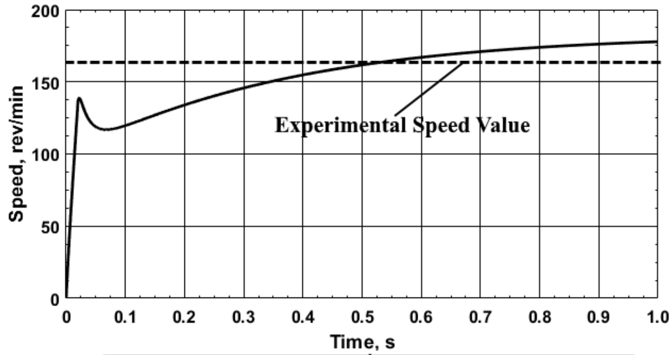
In the considered mathematical model, a two-mass model of an electric drive with rigid constraints is calculated. In the dynamics calculation subsystems, a model for calculating the electromagnetic part is compiled for each of the two machines (driving module and braking module). The electromagnetic torque of both machines is summed and applied to the mechanical part. As a result of integration, we obtain the resulting speed with a time constant equal to the sum of the time constants of both machines. The resulting speed is applied to both machines to calculate the EMF. The advantage of the developed model is that it is adequate even for the machines with different powers, i.e. you can see how the load is distributed between them. To the load of each of the modules, the transporting substance loading torque is also added.

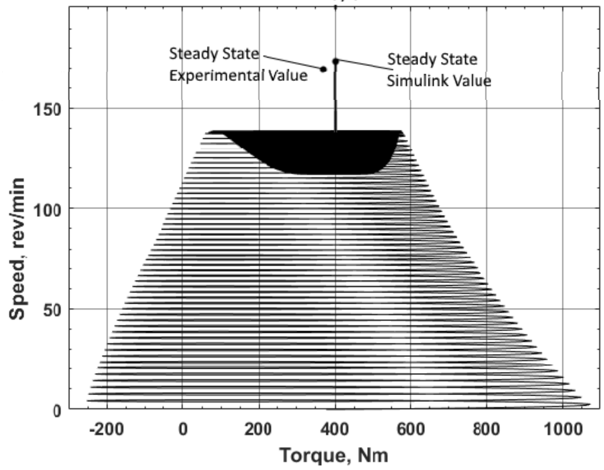
The mode of consonant rotation of the fields is used only in cases when the EDSH-1 is switched on when the screw is blocked or the high viscosity mass is transported. Thus, the main mode should be considered to be the reciprocal rotation of the fields, under which the BM operates with slip $s_b > 1$, i.e. in the electromagnetic BM. For the EDSH-1 driving module, the given output power is selected based on the sum of the thermal and the mechanical power. For the EDSH-1 braking module, operating in the resistance mode, only the thermal power is considered.

The subsystem for supplying the BM has the following features: a) the supply begins to be applied from the time 25 ms, when the DM at idling mode is accelerated to 1/5 of its synchronous speed; b) the sign of phase voltages is changed to the opposite in comparison with the power supply system of the DM. The simulation results of a double-module GES with SR (DM and BM stator currents, rotor rotation speed) are shown on Figure.

Name	Driving Module	Braking Module
Output power, kW	50	33
Line voltage, V	380	380
Number of pole pairs	8	8
Stator resistance, Ohm	0.11	0.127
Stator leakage resistance, Ohm	1.424	2.04
SR reduced resistance, Ohm	1.671	1.926
SR reduced leakage resistance, Ohm	1.021	1.177
Magnetizing resistance, Ohm	6.256	8.888
Rotor weight, kg	250	
Rotor diameter, m	0.374	
Rotor thickness, m	0.012	







The initial starting torque, fixed experimentally is 670 Nm for DM. At the time of BM connecting, the value of the DM electromagnetic torque, obtained in the simulation, practically coincides with the experimental one. The electromechanical process is completed within 0.2 s. The steady-state value of the resultant GES torque (400 Nm) with a deviation of 9.8% corresponds to the experimental value (365 Nm). The simulation results have a satisfactory similarity to the data obtained for a similar machine experimentally – the average calculation error does not exceed 10%.

Conclusions.

A mathematical model of an induction machine with a solid rotor is developed, which takes into account the dependence of the solid rotor parameters on its rotational speed. The resulting mathematical model was used in constructing a mathematical model of a double-stator induction motor with a common hollow solid rotor.

It is established that, with the counter rotation of magnetic fields, a gearless mode of the steady operation of a double-module IM is provided at low rotational speeds of the solid rotor combined with a screw actuator.

A sufficiently high convergence of the simulation results for the IM with SR start mode with experimental one is demonstrated. The error in the simulation results in comparison with the data, obtained experimentally does not exceed 10%.

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МОДЕЛЮВАННЯ АСИНХРОННИХ МАШИН ІЗ ЗАГАЛЬНИМ ЗОВНІШНІМ МАСИВНИМ РОТОРОМ

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Розроблено математичну модель і досліджено динамічні режими двохмодульної асинхронної машини з загальним зовнішнім масивним ротором. Встановлено, що при зустрічному обертанні магнітних полів забезпечується безредукторний режим стійкої роботи двохмодульної асинхронної машини на низьких частотах обертання ротора, поєднаного з шнековим виконавчим механізмом. Бібл. 14, рис. 1, табл. 1.
Ключові слова: математична модель, асинхронна машина, масивний ротор, динамічний режим.

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МОДЕЛИРОВАНИЕ АСИНХРОННЫХ МАШИН С ОБЩИМ ВНЕШНИМ МАССИВНЫМ РОТОРОМ

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Разработана математическая модель и исследованы динамические режимы двухмодульной асинхронной машины с общим внешним массивным ротором. Установлено, что при встречном вращении магнитных полей обеспечивается безредукторный режим устойчивой работы двухмодульной асинхронной машины на низких частотах вращения ротора, совмещенного с шнековым исполнительным механизмом. Библ. 14, рис. 1, табл. 1.
Ключевые слова: математическая модель, асинхронная машина, массивный ротор, динамический режим.

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