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ASSESSMENT OF EFFICIENCY OF ELECTRIC DRIVE OF STOP VALVES

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Проаналізовано особливості функціонування електропривода запірної арматури. Встановлено, що привод запірної арматури, реалізований на базі асинхронних двигунів, характеризується низькою енергоефективністю. Для цілеспрямованого поліпшення енергетичних показників електроприводу розроблено метод оцінки енергетичної ефективності модуля арматури. Необхідність розробки метода викликана тим, що оцінки енергоефективності, засновані на міжнародних стандартах, справедливі для сталих режимів роботи, за умови нехтування часом перехідних процесів.

На відміну від традиційних типів приводів, привод запірної арматури характеризується низькими швидкостями обертання. Використання механічних редукторів не дозволяє істотно знизити швидкість приводу, тому доводиться здійснювати імпульсне керування двигуном або переходити на безредукторний привод.

Ефективність альтернативних типів двигунів оцінюється за допомогою запропонованого метода, який базується на моделюванні процесу позиціонування запірної арматури. Траєкторія переміщення формується відповідно до керуючих імпульсів, які подаються на обмотки двигуна, що входить до складу мехатронного модуля.

Апробація методу проведена відповідно до паспортних даних асинхронного двигуна типу АIP56А4, потужністю 120 Вт, що входить до складу однооборотного мехатронного модуля, та випускається серійно. Для порівняння енергетичних показників обрано 3-х фазний синхронний двигун з ротором, що котиться, у якого параметри обмотки статора аналогічні параметрам обмотки двигуна АIP56А.

Порівняння оцінок енергетичної ефективності показало перевагу і перспективність використання безредукторних синхронних двигунів в приводі запірної арматури.

Розроблені моделі дозволяють досліджувати і оптимізувати характеристики електроприводу на базі двигунів, що досліджуються, а також формулювати вимоги до конструктивно-технологічних параметрів двигуна на основі одержуваних оцінок енергоефективності.

Запропонована методика оцінки енергоефективності є основою для реалізації комплексу технічних засобів, що забезпечують оцінку енергоефективності приводу в реальних промислових умовах, при виконанні конкретної технологічної задачі

Ключові слова: асинхронний двигун, безредукторний електропривод, енергоефективність модуля запірної арматури, синхронний реактивний двигун

1. Introduction

The operational characteristics of stop valves (SV) depend on the type of actuator used. The requirements that are imposed on the SV drive in alternating load cycles are contradictory. A compromise between the minimum response time of the valves and the need to keep the load torque, which varies over a wide range, is usually achieved as a result of the search for the optimum.

The widespread use of pneumatic actuators for the SV in various industries was based on the idea of insufficient dynamics of the SV drive. Expansion of the nomenclature and required ranges of developed power of commercially available types of electric motors made it possible to solve

the problems of improving the dynamics of the SV, not only in terms of optimizing its design, but also in the direction of improving the energy performance of the equipment used.

Thus, the choice of the type of SV drive, apart from the resolution of a compromise between the SV speed and positioning accuracy, implies an assessment of the energy efficiency of the used SV, whose parameters are determined by the characteristics of the components of the composable drive.

Operational safety of SV is achieved by balancing the force, which ensures the closure rate of the valves and the force achieved when the valve seal is broken. Assessment of the energy efficiency of maintaining the balance of forces is relevant in the aspect of selecting progressive solutions to the problems of electric drive control.

Drive operation at maximum capacity increases heat loss, which limits the running time and switching frequency (SF) of the motor.

To ensure accurate positioning of the drive shaft of pipe fittings, a low motor speed (units of rpm) is required, while commercially available electric motors are characterized by a nominal speed of thousands rpm. Reducing the speed of the shaft, coupled with the working body is achieved through the use of a mechanical gearbox, which together with the motor used forms the mechatronic control module of SV.

The advantage of the gear mechatronic module is a significant increase in torque on the SV drive shaft and the ability of self-braking.

The disadvantages of this module are manifested in the increase in mass and dimensional parameters, the moment of inertia, as well as the decrease in the efficiency of the mechatronic module.

Thus, the choice of the direction for improving the SV electric drive is formulated as the search for the best combination of electric motor and mechanical gearbox compatible with it based on the evaluation of the energy parameters of the SV mechatronic module, which determines the relevance of this work.

2. Literature review and problem statement

Test methods for electric drives related to energy efficiency assessment are governed by relevant standards. The work [1] discusses the factors that influence the values of the measured efficiency of electric drive systems. To assess the efficiency of several electric drive systems from different manufacturers, the supply voltage, operating conditions, and power meter settings were changed. The research results confirm the need to improve the methods of efficiency assessment, in particular, the effect of the drive on the motor, and vice versa.

To improve the method of evaluating the efficiency of the electric drive, it is proposed in [2] to describe the losses and energy efficiency depending on the motor speed factor and load moment. Then, as a result of comparing the dependencies obtained, it becomes possible to objectively evaluate the energy efficiency of various types of motors and system implementations.

The desire to obtain an objective assessment of energy efficiency implies the creation of similar test conditions for steady-state modes, which does not correspond to the operation modes of the SV drive.

The specifics of the SV drive is to achieve the specified torques at various points of the movement path of the work-

ing member of the mechatronic module. In accordance with the changing operation modes of the electric motor and the energy consumed E_{elec} from the supply network to create the necessary mechanical energy E_{mech} spent for holding the specified position of the working body of SV, the efficiency of the SV mechatronic module η_a will vary with time. Therefore, to assess the drive efficiency η_a, which varies over time, you need to use the integral indicators given in [3]:

$$
\left.
\begin{aligned}
\eta_a &= \frac{E_{mech}(t)}{E_{elec}(t)}, \\
E_{mech} &= \int_{ts}^{te} M(t)\omega(t)\mathrm{d}t, \\
E_{elec} &= \int_{ts}^{te} U(t)I(t)\mathrm{d}t,
\end{aligned}
\right\}
\tag{1}
$$

where ω – the angular velocity of the motor achieved; M – developed moment; $U(t)$, $I(t)$ – the voltage of the power source and the current consumed from it.

In [4], the possibility of energy saving is shown with an uneven load curve of the electric drive of a periodic pipe rolling mill. The results of the analysis allow us to purposefully improve the elements of the electric drive, the methods and control systems in its established operating modes.

International standards IEEE 112-B, IEC 34-2, and JEC 3 are also used for the practical assessment of the energy efficiency of electric drives; they determine the methods for taking into account the effect of load on stationary modes of electric drives. However, the estimates adopted in the international standards are valid under the condition of neglecting the time of transient processes, which does not allow us to correctly characterize drive operation. This is due to the predominance of transient modes, which are observed when the SV working body is moved from one position to another.

The described approaches to energy efficiency assessment stimulate the search for solutions to positioning problems in the field of motion optimization along a given trajectory. At the same time, it is proposed in [5], by optimizing the movements along a given trajectory, to minimize not only the energy consumed, but also to ensure acceptable dynamic characteristics of the drive. This approach allows significant energy savings without additional equipment costs.

Thus, the expediency of resolving the contradiction between the need to ensure the required SV speed and the desire to obtain the highest possible efficiency is confirmed.

The compromise on the formulated contradiction is achieved by choosing the type of electric motor that could, when changing the SV position, provide the necessary torque at the minimum starting current.

However, up to now, squirrel cage induction motors (IM), are used in the SV drive, which are characterized by reasonable cost and reliability.

The disadvantages of IM include:
– non-linear dependence of the angular velocity (angle of rotation) of the mechanical characteristics of IM;
– uncontrolled transient in moment and current during the direct start of IM, which leads to large values of shock moments and currents;
– type of mechanical characteristics, reflecting the difference between the nominal and starting moments by two or three times.

As a result of using a mechanical gearbox to achieve a regulatory speed of the mechanism shaft, its dynamic parameters

deteriorate and the efficiency of mechanism control decreases. In addition to the decrease in speed caused by an increase in the total moment of inertia of the module, its operational characteristics deteriorate. The use of special devices that choose the backlash and soften the blows reduces the rigidity of transmission. This leads to the need to introduce additional corrective devices and increase the mass and overall dimensions of the mechatronic module.

These drawbacks of the electric drive based on the IM with a mechanical gearbox determine the search for alternative options of SV mechatronic modules. The choice of options relates to motor types, such as brushless DC motors or synchronous reluctance motors (SRM). Fundamentally, shortcomings of the electric drive based on IM are eliminated by using a gearless drive, which was considered in [6].

To control electric power consumption, discrete switching of stator windings is used, which is combined with pulse-width modulation (PWM) and variations of switching angles of the switches of the inverter that feeds the motor.

The choice of the motor, providing an increase in the SV electric drive efficiency, is determined by the tasks that are solved by these modules:

– ensuring high torque when opening or closing the valve;

– keeping a stable torque in the process of moving it;

– fixing the force at the end of the movement of the working body.

The fulfillment of the requirements arising from the formulated tasks was made possible by the introduction of low-speed, high-torque electric motors and electronic frequency converters based on IGBT transistors.

The gearless drive is implemented on the basis of switched motors, which are permanent magnet synchronous machines (PMSM), synchronous reluctance motors (SRM), brushless DC motors (BLDC).

As one of the alternative options for building the SV gearless drive, the experimental rolling rotor motor (RRM) is considered, which was studied in [7]. RRM is a high-torque low-speed synchronous reluctance electric motor synchronous.

RRM has the following properties:

1) high specific torque of 5–0.5 N m/kg with a low of 2–200 rpm and ultra-low speed – 0.05–1 rpm;

2) low starting current and short-circuit current is 1.1–1.3 of the nominal value of the stator winding current (the ability to work «for a stop» for a long time);

3) high speed (acceleration and stopping time 0.01–0.05 s), no self-propelled drive, «run out», ability to work in the electromagnetic brake mode (holding moment is 3 times higher than the nominal one).

Taking into account the advantages of SV IM-based electric drives, it should be noted that the improvement of the gearless (direct) drive on the basis of IM has not exhausted its potential [8]. Improvement of SV actuators, produced by AUMA (Germany), ZRA PECKY, A.S, (Czech Republic), Rotork (England), is on the way of using soft-start microcontroller devices or frequency converters that improve the energy characteristics of IM.

All this suggests that the lack of a method for evaluating the drive energy efficiency, which takes into account the specifics of the SV drive, eliminates the possibility of obtaining adequate quantitative estimates of the drive under study. Existing international standards do not provide an answer to the question of choosing an efficient engine, as well as ways to optimize the operation modes of the SV drive. The requirement to optimize the modes arises from the operation conditions of SV associated with changes in mechanical loads on the drive over time. Testing the method for evaluating the efficiency of alternative options for the SV drive creates conditions for searching for reserves to increase the drive energy efficiency.

3. The aim and objectives of the study

The aim of the study is to test the method for estimating the energy efficiency of SV drives on the basis of IM and RRM. This task is associated with the evaluation of the efficiency, which is achieved by an electric drive based on these motors, when positioning the SV module.

To achieve the aim, the following objectives were set:

– to develop a model of the SV drive based on IM with a gearbox;

– to develop a model of the SV drive based on the RRM;

– to test the efficiency evaluation method in real time;

– to obtain quantitative estimates of the drive energy efficiency in the process of positioning the drive actuator.

4. Building models of the stop valve drive

Taking into account the specifics of the SV electric drive, the subject of the analysis is the transient modes of the module, that is, start-up, braking and movement of the modules of the module at a given speed. These movements are made either periodically, at various time intervals, or briefly, as dictated by the process control algorithm. In this case, situations are possible when the SV cannot provide the specified sealing of the channel, or vice versa, with insufficient torque, move off due to valve jamming.

Consider changes in efficiency, determined by the relation (1) at a given time interval in the model load cycle. Since there are no special requirements for the parameters of the transition process in the SV actuator, it is not necessary to detail these parameters.

4. 1. Model of the stop valve electric drive on the basis of IM

Further, the model of the module is represented by a combination of the electric drive based on the IM, connected to the gearbox interface of SV (Fig. 1).
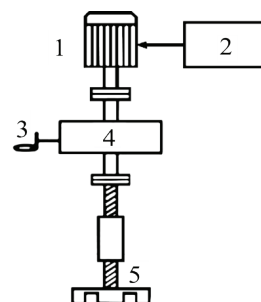

Fig. 1. SV module structure:
1 — IM; 2 — SV module control unit; 3 — override;
4 — Gearbox; 5 — load interface

Simulation of IM in the SimPowerSystems™ MATLAB Simulink library is performed by building a simulation mathe-

matical model based on the coordinate transformation *d, q* [9]. The model consists of four main parts:

– power supply;

– conversion of variables in the *abc* coordinates to variables in the *d, q* system, which rotates synchronously with the motor rotor;

– obtaining motor speed, currents and electromagnetic torque as output variables;

– conversion of variables from the *d, q* coordinate system to the *abc* system for obtaining stator, rotor and current voltages.

The inverse transformation of the description of the IM model into three-phase coordinates makes it possible to solve the problem of studying its modes, corresponding to actual operating conditions. This takes into account the expressions of instantaneous values of voltages and currents of phases *A*, *B* and *C*.

Initially, the representation of a three-phase symmetric power supply of IM is converted from a three-phase system into the *d, q* coordinate system, which rotates at a synchronous speed

$$\omega_e = d\Theta/dt,$$

where Θ – the output angle.

The stator winding voltage U_s is represented by the equations:

$$\left. \begin{aligned} U_{dS} &= -\frac{1}{\sqrt{3}}(U_B - U_C)\cos\Theta + U_A\sin\Theta, \\ U_{qS} &= \frac{1}{\sqrt{3}}(U_B - U_C)\sin\Theta + U_A\cos\Theta, \end{aligned} \right\} \quad (2)$$

where U_A, U_B, U_C – IM phase voltages.

IM parameters – L_S, L_R, L_{SR}, stator, rotor inductance, mutual inductance of the stator and rotor windings, as well as the active resistance of the stator winding R_S and the rotor winding R_R determine the corresponding flux linkages Ψqs and Ψds:

$$\left. \begin{aligned} \Psi_{dS} &= \int_0^t U_{dS}dt - \frac{R_S}{L_S}\int_o^t\Psi_{dS}dt + \frac{L_{Sr}R_S}{L_S}\int_0^t i_{dr}dt + \omega_e\int_0^t\Psi_{qS}dt, \\ \Psi_{qS} &= \int_0^t U_{qS}dt - \frac{R_S}{L_S}\int_o^t\Psi_{qS}dt + \frac{L_{Sr}R_S}{L_S}\int_0^t i_{qr}dt - \omega_e\int_0^t\Psi_{dS}dt, \end{aligned} \right\} \quad (3)$$

where i_{qr} and i_{dr} – rotor currents in the *d, q* coordinates, which can be obtained as a result of solving equations (3).

These currents form an electromagnetic moment M_{EM}:

$$M_{EM} = \frac{3}{2}L_{SR}(i_{qS}i_{dr} - i_{dS}i_{qr}). \quad (4)$$

The dynamics of the rotor is modeled by the classical equation of mechanics:

$$J\frac{d\omega}{dt} = M_{EM}(t) - M_C(t), \quad (5)$$

where J – total moment of inertia of moving masses of the electric drive, reduced to the rotor shaft of the induction motor; $\omega(t)$ – rotor speed; $M_C(t)$ – moment of resistance on the IM shaft.

The ratio between the speed of the coordinates of the model ω_e and the rotor speed ω is bound by the relation:

$$\omega_e = p\omega,$$

where p – the number of pairs of poles.

Representation of the description of the IM model in the form of (3)–(5) makes it possible to study the behavior of an induction motor in transients, which are characteristic of changes in IM modes [9, 10], especially load parameters. Nevertheless, it is possible to use known IM models to evaluate the SV drive efficiency after appropriate revision.

Publications assessing the efficiency of the electric drive based on IM are mainly devoted to studies of stationary and steady-state operating modes of the IM, since most of the industrial drives operate in these modes. Comparison of efficiency estimation methods based on different national standards [11] shows that such methods are unacceptable for evaluating drive efficiency under cyclic loading.

The development of works to improve the energy efficiency of IM operating in acceleration/deceleration modes is the studies of IM dynamics [12], which include optimization of soft starter settings that reduce the starting currents during acceleration of the drive to the rated speed.

In the currently used gearbox drives of the SV modules, it is difficult to achieve the required reduction in the shaft speed, therefore the IM control signals are pulsed in nature. The period of control pulses is dictated by the time it takes to achieve the adjustable parameter (displacement or rotation angle) of a given value, and the duration of the pulses determines the minimum increment of the adjustable parameter.

To implement the simulation model of the SV module, based on equations (3)–(5), the IM block from the SimPowerSystems ™ MATLAB library is used. The three-phase power supply in the model is implemented by three single-phase AC voltage sources. Since, when evaluating the energy performance of the SV module drive, the goal of improving its characteristics is not set, the simulated control circuit fulfills the direct start mode.

The feature of the model shown in Fig. 2, is a unit that implements the pulsed nature of the flow of control signals into the windings of the three-phase IM. Using the Switch blocks, the supply voltage pulses are supplied to obtain the angular displacement of the IM shaft in real time.

The simulation of the gearbox, which provides the required speed of movement and is part of the SV module, is performed by the ideal integrating element with the corresponding reduction factor and efficiency.

The efficiency of the SV mechatronic module depends on the efficiency of the electric motor and gearbox. It is known that the efficiency of the AIR56A4 induction motor from different manufacturers is in the range of 55–60 % at the rated power on the shaft, and the efficiency of the worm gear is 60–90 %. Since the resulting efficiency of the mechatronic module in the mode of rated power on the shaft is determined by the product of the mentioned efficiency, the value of the efficiency estimate will be in the range from 33 % to 54 %. However, with frequent starts/stops that accompany the SV operation, the efficiency will be lower than for the nominal steady-state operation, which is explained by the presence of starting currents of the induction motor.

The MEO-250/10 module includes the commercially available IM of the AIR56A4 series. To set the parameters of the model, we will use its data sheet.
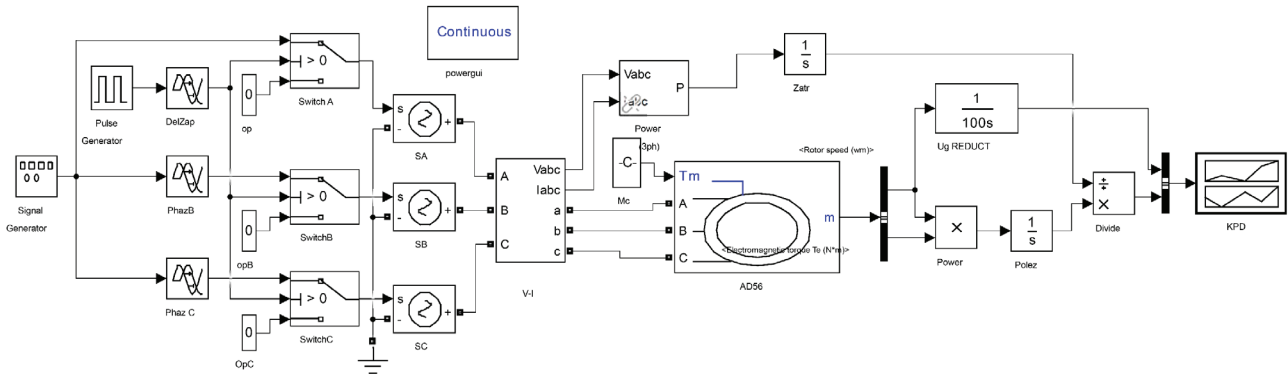
Fig. 2. Scheme of modeling of the SV module in MATLAB

4. 2. Model of the stop valve electric actuator on the basis of RRM

Comparative evaluation of the energy efficiency of the drive on the basis of IM and RRM can be carried out in the presence of an appropriate RRM model, which is absent in the MATLAB library. Therefore, the problem of testing the estimation method can be solved on the basis of the RRM model [13], which allows to investigate its dynamic parameters. Improvement of the model of the SV drive module based on the RRM is performed by clarifying the description of its model, as well as by complementing the measurement, switching and control units, which will allow for the power consumed by the SV drive motor.

The RRM model is based on the representation by the switched reluctance motor (SRM) with a smooth stator. The unipolar power supply circuit of the stator windings provides the displacement of the force F of one-sided magnetic attraction (FOMA) in accordance with the stator winding switching algorithm.

Given that the eccentric cylindrical rotor (Fig. 3) participates in the formation of the SRM magnetic field, the basic equation of the RRM model can be represented as [14]:

$$U = I \cdot R + L(I,\Theta)\frac{dI}{dt} + I\frac{dL(I,\Theta)}{d\Theta}\frac{d\Theta}{dt}, \qquad (6)$$

where U – voltage applied to the winding; R – active phase winding resistance; I – winding current; $L(I, \theta)$ – mutual inductance depending on the winding current and the angular position of the rotor θ.

Equation (4) reflects the dependence of the voltage applied to the winding on the self-induction force e_E and rotational speed ω_m:

$$U = I \cdot R + L(I,\Theta)\frac{dI}{dt} + I \cdot K_b \cdot \omega_m, \qquad (7)$$

where $K_b = dL(I, \theta)/d\theta$, $\omega_m = d\theta/dt$, $e_E = K_b \omega_m I$.

The torque of a single-toothed rotor SM depends on the current of the switched winding $I(t)$, the instantaneous value of the winding inductance $L(I, \theta)$ [12] and on the angular position of the rotor $\Theta(t)$:

$$M_e = \frac{1}{2}\frac{\partial L(\Theta,I)}{\partial \Theta}I^2 = \frac{1}{2}K_b I^2. \qquad (8)$$

The structure of the investigated RRM model is determined by the method of presenting the description of the winding inductance changes from the rotor position.

Consideration of various options of SRM models shows that most of the proposed models do not aim at the practical use of simulation results [15], especially for the implementation of control devices.
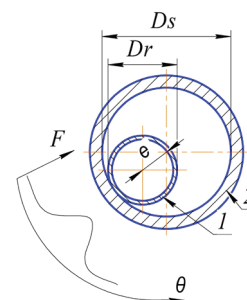

Fig. 3. FOMA distribution:
1 — rotor eccentrically located to the RRM stator; F — FOMA; e — rotor/stator eccentricity; Θ — angle of rotation

Based on the goals of the simulation, it can be assumed that to evaluate the efficiency of the SV module based on RRM, there is no need to accurately display the nonlinearities of the magnetic field. Therefore, the use of quasilinear descriptions of changes in inductance K_b allows an analytic representation of changes in magnetic field energy, which greatly simplifies the considered RRM model.

Referring to the values of the magnetic field in the RRM stator/rotor gap [13], which change when the rotor moves within 8 %, we take a linear approximation of the inductance function of the rotor angle. The limited range of currents in the RRM windings also confirms the possibility of linearizing the flux linkage function.

These considerations allow us to present the general scheme of modeling the SV module on the basis of RRM as shown in Fig. 4.

The scheme contains: rotor angle identification unit; inverter (switch block); torque and motor shaft displacement simulation unit; mechanical reduction element and power consumption estimation unit.

It should be noted that among the RRM, practically used at present, 6- and 8-winding motors predominate. However, in this work, to obtain results comparable in energy consumption to IM, the model of 3-phase RRM is used, in which the parameters of the stator winding are similar to the parameters of IM windings. In accordance with the simulation tasks, the model, has the rotor angle identification unit, which tracks the switching position of the next RRM winding after the rotor rotates 120°.
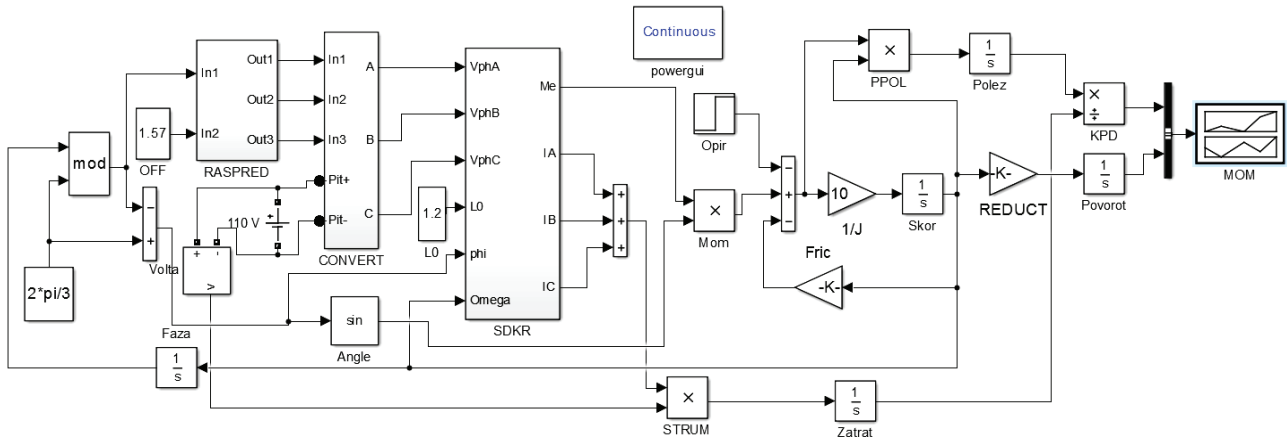
Fig. 4. Scheme of modeling the SV module on the basis of RRM in MATLAB

The model of formation of currents of the RRM stator winding, which is included in the torque simulation unit (Fig. 5), reflects the linear variation of the switched winding inductance from the rotor angle. The input data for this unit is the maximum value of the winding inductance and rotor angle.
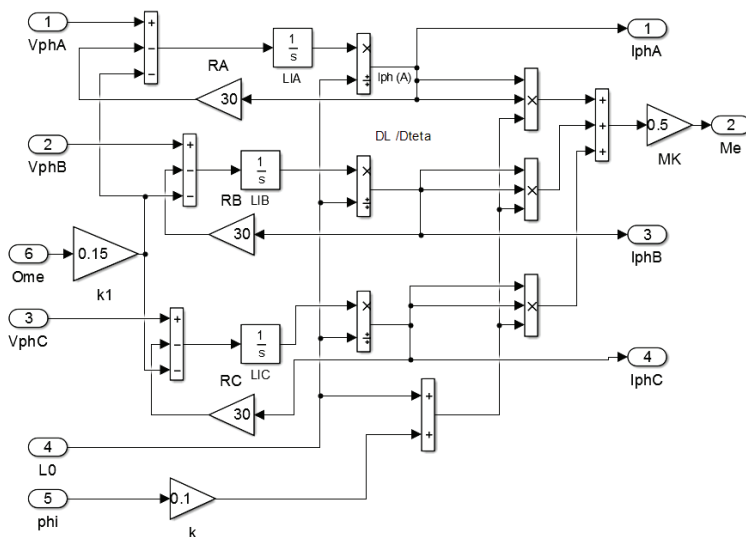

Fig. 5. Torque simulation scheme

The diagram shows the components of equations (7), (8) the change in flux linkage with the change in inductance; self-induction force e_E, as well as the formation of the electromagnetic moment M_e.

5. Testing of the actuator efficiency estimation method

For a comparative assessment of the energy efficiency of SV electric actuators based on IM and RRM, the developed models of mechatronic modules are used, which include models of the motors mentioned.

5. 1. Mathematical modeling of the valve closing process

The test procedure consists in obtaining the trajectories (angles of rotation) of the SV module shaft as a function of time for both types of electric drive. The net power of the module is determined by the shaft rotation process by the ex-

pression (1). Power consumption is estimated by the current consumed by the SV motor.

The SV module is produced in the form of a single-turn actuator (MEO), the time of shaft displacement from one extreme position to another is taken as the time constant of the actuator.

The study uses data of AIR56A4 IM: 3 phase, 50 Hz, 120 W, $n=1,500$ rpm, efficiency$=56.6$ %, $\cos\varphi=0.66$, $U_{nom}=220$ V, $I_{nom}=0.5$ A, which is part of the MEO. The parameters of the stator winding of the 3-phase RRM, taken for comparison, are similar to the winding parameters of the described IM.

In the model of the MEO module, data are accepted that correspond to a virtual gearbox with a reduction factor of $i=100$, which is taken to be equal to the RRM reduction coefficient. This takes into account that the real reduction coefficient of RRM is much larger, while the real mechanical gearbox for the IM-based module with the corresponding reduction coefficient of RRM becomes technically inexpedient.

The efficiency estimates we are interested in are obtained as a result of calculating its instantaneous values using the relation (1) in relation to the time function of the angle of rotation of the RRM and MEO shaft.

The results of testing the specified angle of shaft rotation of the MEO based on AIR56A4 IM are shown in Fig. 6, and Fig. 7 shows the same process for the RRM-based module.

The obtained oscillograms illustrate the change in the efficiency of the electric drive during the rotation of the SV module shaft. The prerequisite for comparing the positioning characteristics is the correspondence of the rotation angles of the RRM shaft and MEO gear shaft. The motor speeds, and accordingly winding switching moments, are set from the condition of making one revolution in 10 seconds.

The oscillogram of the MEO efficiency (Fig. 6) shows that at the time the module starts, the efficiency of the IM-based module reaches 26 % and in the cycle of movement to the specified position has the value of 22 %.

The performance of the same cycle of movement by the RRM-based SV module (Fig. 7) is characterized by the efficiency of 20 %. Thus, it is clear that the efficiency of the RRM-based module is slightly inferior to the MEO efficiency.
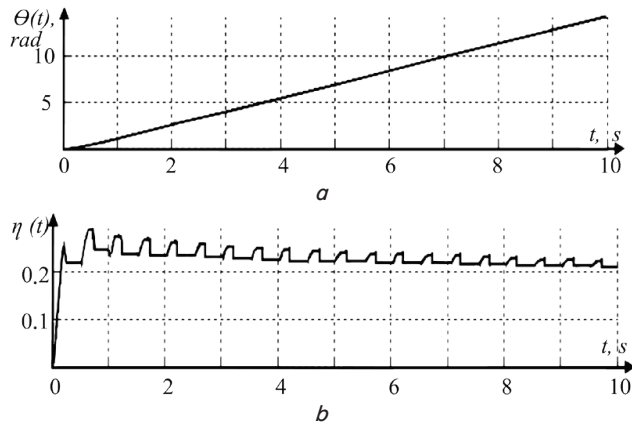
Fig. 6. MEO oscillograms:
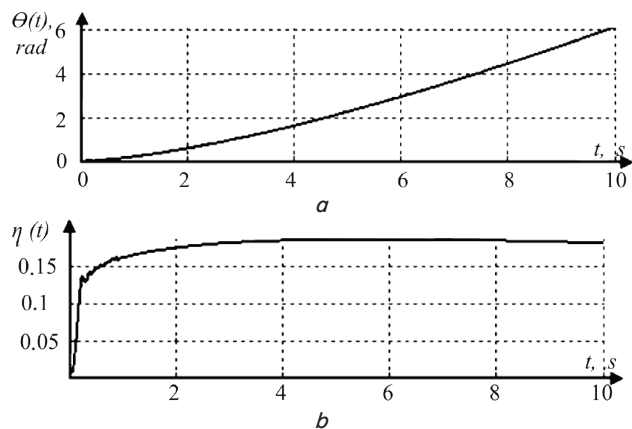*a* — change of the angle of rotation; *b* — efficiency

Fig. 7. RRM oscillograms:
a — change of the angle of rotation; *b* — efficiency

5. 2. Experimental evaluation of the SV actuator efficiency

Experimental tests of the developed efficiency evaluation method are based on the results of the study of the electromechanical rolling rotor transducer [16]. To estimate the useful mechanical power P_{mech}, a disk attached to the end of the shaft of the electromechanical transducer is used in research. A steel cable with a weight G is attached to the shaft. After starting the motor, the load G rises to a certain height h in time t.

In this case, the effective mechanical power P_{mech} will be determined by the ratio:

$$P_{mech} = \frac{g \cdot G \cdot h}{t}, \qquad (9)$$

where g – gravitational acceleration [m/s^2].

This approach is further used in the test facility (Fig. 8) in the study of experimental RRM operating from a three-phase AC network of an industrial network [17]. A disk is rigidly fixed on the motor shaft fixed to the bracket, on the external diameter of which there is a steel cable. One end of the cable is fixed on the disk, and loads of different mass are attached to the second one. The three-phase supply voltage through the circuit breaker is supplied to the measuring devices (voltmeter, ammeter, phase meter, wattmeter), and then to the stator winding terminal block.

Thus, with the help of instruments we measure the power consumption, which is used in motor efficiency evaluation.
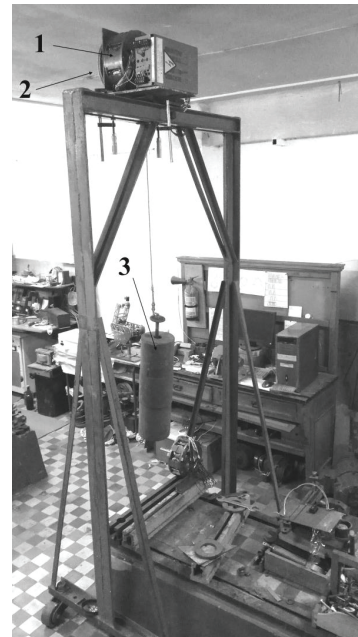

Fig. 8. Test installation: 1 — motor; 2 — disk; 3 — load

The useful power P_{mech} is estimated using equation (9), for this the installation (Fig. 8) is provided with sensors which record the passage of the distance h (Fig. 9). The RIGOL SDS 1022DL oscilloscope is used as a time meter.

An experimental sample of synchronous reactive RRM and MEO module are alternately connected to the AC three-phase network of the industrial network.
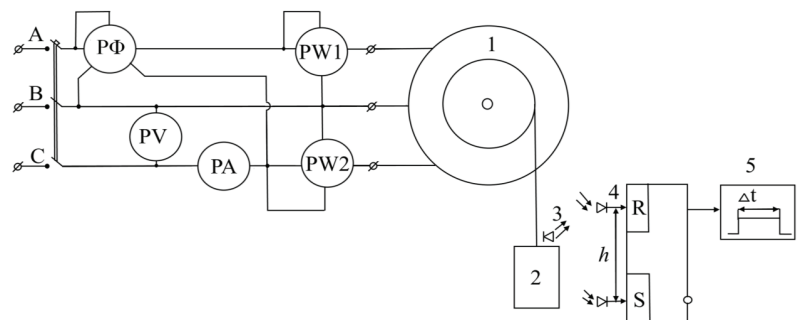

Fig. 9. Power measurement circuit:
1 — motor; 2 — load; 3 — laser; 4 — photodiodes; 5 — time meter

The essence of the tests for a particular type of engine comes down to measuring the values of power consumption over a period of time fixed by the signals at the end and the beginning of measurements.

Drive efficiency is obtained in accordance with the relation (1) using the values of consumed and calculated power.

6. Discussion of the results of testing the energy efficiency assessment method

Features of the operation of the SV drive limit the use of cost-effective and reliable IM due to the required low speeds

of the working body of the module. Although the IM-based SV drive is constantly being improved, but so far no quantitative estimates of the efficiency of IM as part of the SV drive have been obtained. The characteristics of the drive provide data that correspond to the passport data of IM operating in stationary modes, which gives the impression of deliberately high energy indices. Accordingly, the models investigating the start/stop modes of the motors do not provide energy efficiency data corresponding to the pulse operation modes of the drive. The main attention in such models of the electric drive is paid to the description of the modes of the converters that provide power to the electric motors.

In this work, we completed the revision of the drive models, which made it possible to take into account the power consumed by the converter and the useful power consumed in the mechanical load. The feature of the method of efficiency evaluation of the drive lies in the possibility of registering the actuator trajectory in accordance with changes in the useful and consumed power over time.

The adequacy of the proposed models was evaluated on the test facility (Fig. 8, 9), using the IM with the RRM gear. The experiment consisted of two experiments for both motors. In the first experiment, the electric drive was tested in the mode of repeated starts (SF) with the cycle time $t_c=2$ s, that is, 2 s on, 2 s off (SF-50).

In the second experiment – the mode is non-stop, when the end of the output shaft moves by 90° in 10 seconds (1.5 rpm). To ensure the constancy of the moment of shaft resistance, a weight of 85 kg was lifted on the disk with a diameter of 0.6 m.

The results of measurements of the electrical parameters of the phase currents I_{ph}, cosφ at the supply voltage $U_1=380$ V=const, network frequency $f=50$ Hz=const are summarized in Table 1.

As can be seen from Table 1, the lifted load travels a different distance at one time, which indicates a change in the speed of the output shaft under load. Changes in speed under load are natural, both for IM and RRM.

The result of the adequacy assessment is formed on a relative comparison of the efficiency values obtained as a result of its measurements (Fig. 9) and modeling, in fact, to the powers P_{mech} and P_{elec}.

From the oscillogram of modeling the SV closing process (Fig. 6), it can be seen that the efficiency of the MEO type electric drive varies from 21–26 %. The range of the efficiency of the IM-based electric drive, obtained according to Table 1, characterizing the load lifting process, is estimated as 18–24 %. Thus, the relative error of efficiency estimation for the measured and modeled values is 12 %.

The simulation data are compared in the same way (Fig. 7), where the efficiency of the RRM-based electric drive is estimated to be 18 % and the data in Table 1, which characterize the process efficiency, at the level of 19.8 %. In this case, the relative error of efficiency estimation is 10 %.

The errors of adequacy assessment consist not only of the errors of the used measuring devices and the errors of modeling in the MATLAB environment. When building the model, passport data of devices are used (for example, a gearbox), the exact value of which is difficult to take into account. Using expert values of model parameters in mathematical modeling reduces the accuracy of adequacy assessment, and their influence on the accuracy of the model is a separate problem.

The experiments carried out confirmed the absence of starting currents of the RRM, which made it possible to achieve a high efficiency in the SF-50 mode. The mode of without stops and frequent starts, which is typical for the «open/closed» control task, showed that the efficiency of the MEO-250/10 type electric drive is higher than the RRM.

The studies performed show a decrease in the energy efficiency of serial samples of electric motors that are part of the SV drive in the mode of frequent starts, in particular SF-50. The nominal number of switchings per hour for the MEO is 630 (according to passport data), and the maximum is 1,200. Based on these data, it is clear that the MEO is experiencing frequent starts/decelerations, and therefore the efficiency value will be low. For the mode of frequent starts and adjustment mode, the experimental RRM has the best efficiency.

It should be noted that the tried and tested method of evaluating the efficiency of the SV drive is a tool that allows you to solve problems of increasing energy efficiency based on the choice of advanced technical means. In particular, this study shows that the RRM-based SV drive, which refers to synchronous motors, is slightly inferior to the IM-based drive. This circumstance justifies the use of synchronous motors in the SV drive, especially gearless.

To estimate the energy characteristics of the alternative types of motors to be used in the SV drive, it is needed to modify the existing models of these motors in terms of providing the power consumption data.

The disadvantage of the proposed energy efficiency assessment method is the need to ensure comparable conditions for testing different types of engines in general, and gearless drive in particular. The absence of comparable conditions requires the development of additional comparison criteria to ensure the objectivity of assessment.

The development of technical means to measure parameters of the SV module in real time when performing a technological task can eliminate this drawback. This approach transfers the task of drive efficiency evaluation from a specific area to a typical design area. Then, regardless of the drive type, the task of efficiency evaluation comes down to processing and visualizing data obtained from the sensors installed on the actuators of the module under test. However, due to the variety of drives used in industry, it is difficult at this stage to recommend universal sensors and data processing tools. The priority of the implementation of the proposed test method is metrological certification of sensors to be used in tests. The second task is presented as an interpretation of the resulting estimates in relation to well-known international standards.

Table 1

Test results

Drive type	Mode: start, rotation	Load, kg	t, s		h, m	P_{mech}	P_{elec}, W	I_{ph}, A	cosφ, o. e.	Efficiency, %
			t_c	$t\Sigma$						
RRM	start/rotation		2	10	0.45	37.5	197.4	0.43	0.7	19.8
MEO-250/10	start	85	2	10	0.48	40	222	0.56	0.6	18
	rotation		2	10			167	0.42	0.6	24

7. Conclusions

1. The model of the IM-based SV drive has been developed, taking into account the parameters of the mechanical gearbox – efficiency,

moment of inertia and reduction coefficient, as well as the switching modes of the windings. The proposed model displays the change in power consumption when moving the working body in space and time.

2. The known dependence of the RRM moment on the winding flux linkage parameters (8) shows the possibilities of increasing the useful mechanical power of the SV drive by increasing the inductance and reducing the resistance of the RRM winding. However, the time constant of the winding, at which the required torque is achieved, causes an increase in the rise/fall time of the winding current, respectively, a decrease in the SV drive efficiency. Optimization of the winding switching modes for the selected type of RRM, which takes into account the time constant of the windings, allows to increase the energy efficiency of the RRM-based SV drive.

3. The test method was tested for SV drives, which consists in comparing the power consumed by different types of drives in real time when they perform the same useful work. The existing standards for evaluating the electric drive efficiency do not take into account the operation specifics of the SV drive, associated with a change in drive efficiency when moving the SV working body. The proposed method involves tracking the trajectory of the working body with fixing the useful mechanical and consumed power of the compared drives in time.

4. Quantitative estimates of the efficiency of SV actuators on the basis of IM and RRM were obtained, which characterize the process of moving the valves. The efficiency of the mathematical model of the SV module on the basis of IM at the time of start-up quickly reaches 26 %, and in the cycle of movement to a given position has a value of 22 %. The efficiency of the mathematical model of the SV module based on the RRM is characterized by a value of 20 %. Experimental estimates of the efficiency of the tested drives show that when imitating the valve closing mode, the efficiency of the IM-based drive is 18–24 %, and that of the RRM-based drive is 19 %.

Thus, with the use of IM in the SV drive, there is a decrease in its efficiency from passport 60 % to experimental 22 % (taking into account the gearbox efficiency). The gearless drive based on synchronous reluctance motors, including the RRM, is slightly inferior to the IM-based drive in terms of energy efficiency, having an efficiency = 19 %. Comparability of the realized efficiency values of the studied drives, with the advantage of mass and dimensional RRM parameters, allows using the latter in the SV drive.

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