FORMULATION OF CHARACTERISTICS OF OPERATING MODES OF SWITCHED RELUCTANCE MOTORS WITH PERIODIC LOAD

**Purpose.** The purpose of the article is to create dependencies of efficiency on effective power when changing the supply voltage and switching angles, pulsation speeds of the rotor from the moment of inertia of the drive and mechanical characteristics of switched-reluctance motors with a periodic load, developing recommendations to ensure their effective and reliable operating modes in single-cylinder piston compressors. Methodology. To carry out research simulation mathematical modeling was used, to calculate the nonlinear inductance dependence on current and rotor angle, the finite element method. Results. The measures of improve the efficiency and reliability of drives single-cylinder piston compressors on the basis of the SRM has been proposed. Originality. Approaches that provide maximum efficiency values and a regulated level of ripple speeds of rotors SRM of single-cylinder reciprocating compressors in the operating frequency control range, with periodic load have been developed. Practical value. Algorithm for changing the supply voltage and switching angles of the SRM of single-cylinder compressors, which provides maximum efficiency values SRM when the rotational speed changes within the 1:6 range, has been developed. The minimum values of the moments of inertia of the drive of single-cylinder compressors, providing a regulated level of pulsations of the rotational speed of the rotor SRM with its regulation, were determined.

References 10, figures 5.

Key words: switched reluctance motor, periodic load, characteristics, efficiency, rotation frequency ripples.

**Problem definition.** Features of operation of compressor plants require the use of a regulated electric drive, which provides energy-efficient operating modes [1-4]. Promising are induction motors with short-circuited rotors and frequency converters, which carry out a smooth adjustment of the rotational speed. Alternatives for them are controlled synchronous motors with electromagnetic excitation or with excitation from permanent magnets, as well as switched reluctance motors with reactive rotor [5]. The use of regulated switched reluctance motors due to their high energy performance, starting and adjusting properties provides solution of the problem of increasing the efficiency and reliability of electromechanical equipment operating under variable load conditions.

In order to create a competitive switched reluctance motors drive of hermetic piston compressors (HPCs), usually of single-cylinder compressors with power up to...
500 W, with a significant reloading capacity (up to 3.0), it is necessary to provide efficient modes of their operation with the maximum values of efficiency in the range of 1:6 with the permissible level of the ripples of the rotor rotational speed and to reduce the weight and size indicators as well as costs of the main units of the machine.

Analysis of recent research and publications. The power indicators of electric drives with periodic loads are estimated using cyclic efficiency, which is determined in the period of one cycle of load variation. The long period of operation of the induction electric drive with periodic load with significant values of maximum and starting torques, in the mode of underloading leads to a decrease in energy efficiency and non-optimal energy use [6].

The level of the ripples of the rotation speed of motor rotors, traditionally induction, hermetically sealed piston compressors, is strictly regulated by standards and can not exceed 20%. To reduce the amplitude of these ripples, on the motor rotor an additional inertial mass is mounted – the flywheel [7]. An important step to increase the reliability of the HPC drive is to reduce the ripples of rotational speed of the rotor to a predetermined level when it is adjusted in the required range. Analysis of the research of the switched reluctance drive [8] shows that in steady-state modes, its efficiency decreases by 4% with a double load reduction, which is confirmed by the results [9]. In this paper [9] the authors give the characteristics of the SRM with switch with C-reset and vibrational energy return for change in supply voltage and switching angles at a constant load. The switch and its control circuit are simple enough, which is important for the mass production of compressors, pumps, etc.

Studies in this direction need to be continued for the purpose of evaluating the efficiency and ripples of the rotational speed of the SRM rotor at the change in the angles of switching, voltage and moment of inertia of the drive, taking into account the periodic load. This will allow the development of measures for adjusting the SRM rotor speed of rotation in the composition of compressor equipment and to reduce the costs of motor development.

The goal of the work is to form the dependencies of the efficiency on the power output at the changes in the supply voltage and switching angles, the ripples of the rotor rotation speed on the moment of inertia of the drive and the mechanical characteristics of the switched reluctance motors with periodic load, the development of recommendations for the provision of their efficient and reliable operating modes in the single-cylinder piston compressors.

Mathematical model of the switched reluctance drive. The object of the study is a SRM, which is developed on the basis of an induction motor 4AA56A4Y3 (nominal power of 120 W and rotational speed of 3000 rpm) with a number of poles of 6/4 and of phases m=3 phases with a switch with C-reset and a vibrational energy return [9]. A mathematical model [9] is used to study the modes of operation, the adequacy of which is confirmed by comparing the results of numerical and experimental studies. Its equations describe the structural elements of the motor and take into account their mutual influence.

For the phase of the switched reluctance machine, the following equation holds true

$$\frac{d\psi_{ph}}{dt} = u_{ph} - i_{ph} \cdot R_{ph},$$

where $u_{ph}, R_{ph}, i_{ph}, \psi_{ph}$ are the voltage at the output of the switch; resistance, current and flux linkage of the stator phase, respectively.

Phase current is determined as

$$\frac{di_{ph}}{dt} = \frac{1}{L_{ph}} \left( \frac{d\psi_{ph}}{dt} - i_{ph} \frac{\partial L_{ph}}{\partial \theta_{ph}} \right),$$

where $L_{ph}$ is the inductance of the stator phase, which is calculated by the finite element method [9] and is represented as a function of the current and the rotation angle of the rotor relative to the stator phase $L_{ph} = f(\theta_{ph}, i_{ph})$.

$\frac{\partial L_{ph}}{\partial \theta_{ph}}$ is the partial derivative of the tabular function $L_{ph}$ by the angle $\theta_{ph}$; $\omega$ is the angular rotor rotation speed; $\theta_{ph}$ is the rotation angle relative to the stator phase.

Electromagnetic moment formed by a single phase of the SRM

$$M_{ph} = \frac{1}{2} l_{ph} \frac{\partial L_{ph}}{\partial \theta_{ph}},$$

and the total torque $M$ of the switched reluctance motor from the action of $m$ phases

$$M = \sum_{k=1}^{m} M_{ph(k)}.$$

Differential equations of motion

$$\frac{d\omega}{dt} = \frac{1}{J} (M - M_e),$$

where $J$ is the compressor moment of inertia; $M_e$ is the load torque.

The angle of rotation of the rotor is obtained from the equation

$$\frac{d\theta}{dt} = \omega_R,$$

This angle relative to the stator phase

$$\theta_{ph} = \text{mod} \left( \theta_{ph} - \frac{2\pi}{Z_R} \right),$$

where $Z_R$ is the number of rotor teeth.

Mathematical modelling of the SRM is carried out in MATLAB – Simulink environment using the SymPowerSystems library. As the input parameters of the mathematical model, the angles $\theta_{on}$ of switching on and $\theta_{off}$ of switching off, the voltage of the DC link $U_d$ and the phase inductance dependencies on the angle of rotation of the rotor and the phase current are used.

The mathematical model takes into account the dependence of the load torque of the single-cylinder HPC of single action on the rotation angle of the motor rotor $M_t = f(\theta)$ applied in the range $7\pi/9$ on the period $2\pi$, the temporal dependence of which is shown in Fig. 1. To compare the calculations of operating modes with constant and periodic load, the average value $M_{(\text{mean})}$ of
the last one during the load period is used. For Fig. 1 – 0.33 N·m.

**Numerical experiment.** With the help of the mathematical model of the SRM, its efficiency is calculated taking into account losses in copper, magnetic and mechanical losses in operating modes at periodic loading. The calculation of the magnetic losses consisting of losses on hysteresis and eddy currents is based on the approach [10]. Mechanical losses are determined taking into account the change in rotor rotation speed and torque due to friction in bearings [9]. A method for controlling the SRM based on the change of the angle of switching on \((\theta_{on} = \text{var})\) in the range \(\theta_{on} = 36^\circ...51^\circ\) at a constant clock angle \((\theta = 30^\circ)\) and symmetric switching is used.

Dependencies of efficiency on the useful power \(P_2\) at changes in the supply voltage and switching angles at steady and periodic load, when \(M_{(\text{mean})} = 0.33\text{ N·m}\), are shown in Fig. 2. Each dependence is obtained at steady angles of switching on and switching off and change of voltage. The power of 103 W corresponds to the rotation speed of 3000 rpm, 52 W – 1500 rpm. The obtained dependencies of the efficiency with periodic loading with the moment of inertia \(J = 0.5 \times 10^{-3} \text{ kg·m}^2\) practically do not differ from the efficiency of the motor with a constant load at \(J = 1 \times 10^{-4} \text{ kg·m}^2\) (the constant torque equals the average value of the periodic load).

Shift of the switching zone towards the lowering of the angles of switching on and switching off leads to an increase in the motor efficiency, but the increase in efficiency is not observed throughout the entire range of loads. This allows to formulate an algorithm for changing the angles of commutation, which provides the maximum values of the efficiency of the switched reluctance motors of single-cylinder compressors on single action for the entire range of rotor rotation frequency control:

- in the range 3000...1500 rpm the SRMs should operate with commutation angles \(\theta_{on} = 36^\circ, \theta_{off} = 66^\circ\) and the voltage \(U_d = 133...77\text{ V}\);
- from 1500 to 1000 rpm – with angles \(\theta_{on} = 39^\circ, \theta_{off} = 69^\circ, U_d = 185...137\text{ V}\);
- from 1000 to 500 rpm – with \(\theta_{on} = 42^\circ, \theta_{off} = 72^\circ, U_d = 149...88\text{ V}\).

The influence of the moment of inertia of the drive of a hermetic piston single-cylinder compressor on the ripples of the rotation speed of the SRM rotor for the range of regulation of the rotation speed of 1:6 at constant angles of commutation is investigated. It is shown that the regulated level of ripple \(\delta n = 20\%\) with frequency regulation in the range of 1:3 (3000...1000 rpm) can be provided at the moment of inertia of the drive \(J = 5 \times 10^{-4} \text{ kg·m}^2\), in the range of 1:4 (3000...750 rpm) – \(1 \times 10^{-3} \text{ kg·m}^2\) (Fig. 3). Increasing the moment of inertia leads to a reduction of ripples and expansion of the range of regulation.

**Fig. 1.** Temporal dependence of the load torque of the single-cylinder compressor.

**Fig. 2.** Dependencies of efficiency on the useful power at changing the supply voltage for different switching angles at steady state \(M_{(\text{mean})} = \text{const} (a)\) and periodic \(M_{(\text{mean})} = f(\theta) (b)\) load for moments of inertia \(J = 1 \times 10^{-4} \text{ kg·m}^2\) and \(J = 1 \times 10^{-3} \text{ kg·m}^2\), respectively.

**Fig. 3.** Dependence of the ripples of the SRM rotor rotational speed on the moment of inertia of the drive of a single-cylinder HPC at steady angles \(\theta_{on} = 42^\circ, \theta_{off} = 72^\circ\).

Extension of the range (up to 1:6) under this condition can be implemented:
• for pulsating load of a two-cylinder compressor ($M_{c(mean)} = 0.33 \text{ N.m}$, moment of inertia of the drive $1 \cdot 10^{-3} \text{ kg.m}^2$), which provides ripples of frequency in the range of $0.3 \ldots 12.8 \%$
• for less than twice the load at steady angles of switching due to a change in supply voltage.

Figure 4 shows the mechanical characteristics of the SRM at constant switching angles ($\theta_{on} = 42^\circ$, $\theta_{off} = 72^\circ$) at changing the supply voltage in the range $31 \ldots 121 \text{ V}$, which makes it possible to regulate the frequency of rotor rotation in the range of $1:6$ with periodic load $M_{c(mean)} = 0.165 \text{ N.m}$.

It is found that at the nominal rotational speed at $M_{c(mean)} = 0.165 \text{ N.m}$, the highest efficiency is provided by switching angles $\theta_{on} = 36^\circ$, $\theta_{off} = 66^\circ$, at rotation frequencies in the range of $750 \ldots 500 \text{ rpm}$ – by angles $\theta_{on} = 42^\circ$, $\theta_{off} = 72^\circ$, which allow to increase the efficiency by $2 \ldots 5 \%$ in comparison with the angles $\theta_{on} = 36^\circ$ and $\theta_{off} = 66^\circ$.

Conclusions.

1. Using the mathematical model, the operating modes of the switched reluctance motors with a switch and C-reset and a oscillatory return of energy of single-cylinder piston compressors at the changes in the supply voltage, switching angles and moment of inertia, taking into account the periodic load are investigated, which allowed to form the characteristics of the motors that provide an increase their energy efficiency and reliability.

2. The algorithm for changing the supply voltage and switching angles of the SRM is proposed, which provides the maximum values of efficiency at change in the frequency of rotation in the range of $1:6$.

3. The values of moments of inertia of SRM of hermetic piston compressors are determined, which provide the recommended level of ripples of the rotational speed of the rotor of $20 \%$ in the ranges: $1:4$ – for single-cylinder compressors, $1:6$ – for double-cylinder ones.

4. The results of the research can be used for the creation of SRMs that operate in compressors and pumps in the areas of municipal and industrial use.

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