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OPTIMIZATION OF THE CALCULATION OF SYNCHRONOUS RELUCTANCE MOTOR FOR A COAL HARVESTER 180 KW

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Annotation. *Three-phase induction motors are the most common type of motor in the mining industry, but there is currently interest in new types of IM motors, one of which is the synchronous reluctance motor (SRM).*

SRM are a step up from permanent magnet motors in terms of cost and magnet system design. SRMs do not have permanent magnets and, therefore, they are much cheaper to manufacture and operate than synchronous and induction classical machines. However, there are problems in the design of this type of engine, especially in the issues of developing the optimal geometry of the SRM magnetic system. Thus, on the basis of the above, the relevance of the research topic is determined by the need to create synchronous reluctance motor with high energy characteristics, which are advantages over competitors. The article investigated a synchronous reluctance motor with a power of 180 kW, with the number of poles 4, which is supposed to be used on new coal harvesters of the type UDC200-400, UDC200-500.

Keywords*: synchronous reluctance motor, magnetic wire geometry, magnetic induction, inductive resistance, efficiency, mechanical characteristics.*

Introduction.

Today, the world's leading manufacturers of electric motors show a special interest in synchronous jet electric motors, although the first versions were patented as early as the end of the 19th century. The fact is that the efficiency of synchronous jet electric motors is fundamentally much higher than the efficiency of induction electric motors.

There are no energy losses in the rotor, but usually 30% of the losses fall on the rotor itself. In this way, the service life of the electric motor is also increased - harmful heating is reduced. The mass of a synchronous jet electric motor and its dimensions are 20% less than that of an induction motor of the same capacity.

In this regard, the aim of the scientific work is to show that by modeling electromagnetic processes, choosing the geometric dimensions of the magnetic system of the engine, it is possible to obtain high energy characteristics.

Analytical review.

In the mining industry, electric drive systems are the largest consumer of electrical energy. They account for up to 70% of consumption. Examples of mining equipment that use AC motors are pumps, fans, compressors, crushers, conveyor line drives, centrifuges, presses, lifting and transport mechanisms, and more. Today, in the mines of Ukraine, cleaning combines of a new technical level of construction of JSC "Dongiprovuglemash" are used for working out gentle and inclined layers: on layers with a thickness of 0.85 - 1.5 m: with a raised feeding system UKD200, UKD200-400, UKD200-500,

One of the alternative ways to obtain electric motors of a high energy efficiency class (IE3 and higher), which does not require a significant complication of the production technology, an excessive increase in size and weight, and does not require the use of expensive permanent magnets, is the use of a reluctance motor (SRM). SRM has no electrical losses in the rotor winding, and can meet the highest energy efficiency classes.

From other energy-efficient motors (synchronous motors with permanent magnets), SRM is advantageously distinguished by the simplicity of the design of the rotor of the machine, the absence of expensive permanent magnets in the design of the machine, which significantly complicate the manufacture, maintenance and repair, and the maximum unification of the technology of the production of such a motor with the production of IM.

The absence of losses in the rotor winding means a higher efficiency, a smaller amount of SRM overheating at the same load, compared to IM. In particular, smaller amounts of overheating of the stator winding and bearing assemblies are achieved. The absence of a short-circuited winding in the rotor and magnets leads to a decrease in the moment of inertia of the rotor, which is necessary when it is used in mining combines (Fig. 1).

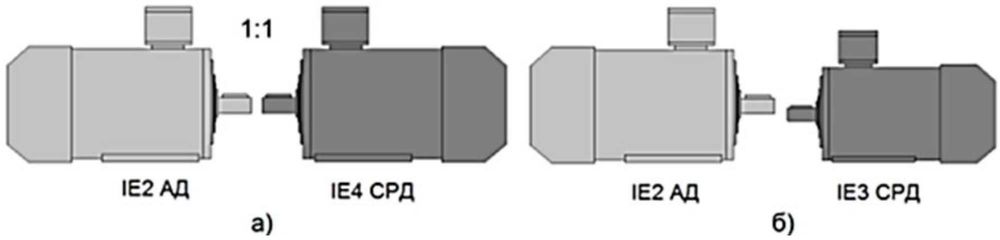


Fig. 1 - Comparison of energy and dimensional parameters of IM and SRM of the same capacities *a) IM and high-efficiency SRM b) IM and small-sized SRM*

Analytical part. The complexity of SRM modeling in a stationary coordinate system consists in accounting for changes in the parameters (inductance) of the stator phases when the rotor rotates. For this reason, the equations of synchronous motors with $L_d \neq L_q$ are usually considered in a coordinate system rotating with the rotor. The axis *d* in the paper is understood as the axis of the greatest magnetic conductivity of the rotor. Below *the q axis* is the axis of the smallest magnetic conductivity of the rotor (Fig. 2).

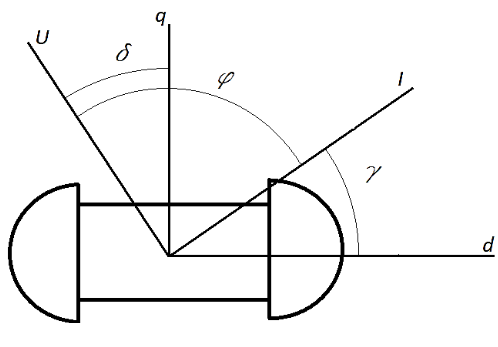


Fig. 2 - Determination of the ratio between angles ϕ, δ, and γ

Expressions for the analysis of synchronous motors of various designs are usually obtained by simplifying the general form of the Park-Horev equations.

When writing the equations of the established mode, the SRM must determine the load factor, which will determine the magnitude of the loading moment. In the literature, models of SRM are described, where the value of the angle δ or the value of the angle γ is used as a load factor [1-3]. Rice. 4 shows the relationship between the phase angles of the machine in the form of a vector diagram:

$$\varphi = \frac{\pi}{2} + \delta - \gamma \quad (1)$$

where φ is the phase angle between the current and voltage vectors; $\delta = arctg(Ud/Uq)$ is the phase angle between the *q axis* and the voltage vector; $\gamma = arctg(Iq/Id)$ is the phase angle between the *d axis* and the current vector.

The characteristics of the SRM depending on the angle γ are of interest. Let's describe the equation of the SRM when powered from a voltage source depending on the angle γ. Under the assumptions described above, the system of SRM equations in rotating *dq* axes has the form [4]:

$$\begin{aligned} L_d \frac{di_d}{dt} &= U_d - Ri_d + L_q \omega i_q \\ L_q \frac{di_q}{dt} &= U_q - Ri_q + L_d \omega i_d \\ T &= \frac{m}{2} p(L_d - L_q) i_d i_q \\ \frac{d\omega}{dt} &= \frac{T - T_j}{J} \end{aligned} \quad (2)$$

where U_d, U_q, i_d, i_q are, respectively, the voltages and currents of the stator winding along the axes *d* and *q;* L_d, L_q - total inductances of the stator along the *d* and *q axes* ; *R* - active resistance of the stator phase; ω - mechanical speed (angular frequency) of engine shaft rotation; *p* - number of pairs of poles; *m* =3 - the number of motor phases; *T* - electromagnetic moment of the engine; T_i - load moment, *J* - resulting moment of inertia of the engine, which is driven by the mechanism.

In the established mode of operation of the engine, the equation of electrical balance will turn into the form:

$$\begin{aligned} U_d &= Ri_d - L_q \omega i_q \\ U_q &= Ri_q + L_d \omega i_d \end{aligned} \quad (3)$$

The equation of electrical balance at a fixed frequency for one phase of the DC stator in the established mode of operation can be written as:

$$U = jI_d x_d + jI_q x_q + Ir \tag{4}$$

In expression (4), the magnitudes of the current complexes are equal to:

$$\dot{I}_d = I_d e^{-i(\delta+\frac{\pi}{2})}$$
$$\dot{I}_q = I_q e^{-i\delta}$$
$$\dot{I} = \dot{I}_d + \dot{I}_q \tag{5}$$

where *d* - internal load angle - angle between axis *q* and the vector *Ui* .

Then the motor currents can be found as:

$$I_d = \frac{U_i}{x_d}\cos(\delta)$$
$$I_q = \frac{U_i}{x_q}\cos(\delta) \tag{6}$$

Taking into account the ratio between the angles ***δ*** and ***γ*** resulting from the SRM vector diagram can be written:

$$tg(\delta) = \frac{x_q}{x_d} tg(\gamma)$$
$$\delta = arctg(\frac{x_q}{x_d} tg(\gamma)) \tag{7}$$

Substituting (6) and (7) into (5), we obtain:

$$\dot{I} = U_i(\frac{(x_d - x_q)tg\gamma}{x_d{}^2 + x_q{}^2 tg^2\gamma} - j\frac{x_d + x_q tg^2\gamma}{x_d{}^2 + x_q{}^2 tg^2\gamma}) =$$
$$= U_i(\frac{(x_d - x_q)tg\gamma}{x_d{}^2 + x_q{}^2 tg^2\gamma} - j\frac{x_d + x_q tg^2\gamma}{x_d{}^2 + x_q{}^2 tg^2\gamma} - \frac{j}{x_d} + \frac{j}{x_d}) \tag{8}$$

Expression (8) can be rewritten in the form:

$$\dot{I} = \frac{U_i}{jx_d} + \frac{U_i}{\frac{r_\gamma}{tg\gamma} + jx_\gamma} \tag{9}$$

The SRM impedance equation represented by expression (9) can be depicted in the form of a substitution scheme (Fig. 8). Parameters r_g *and* L_g are given by the expressions:

$$r_\gamma = \frac{\omega L_d}{(1-\frac{L_q}{L_d})}$$

$$L_\gamma = \frac{L_d L_q}{L_d - L_q} \tag{10}$$

The analysis of scientific and technical materials on this topic showed that the development of power conversion electronics made it possible to approach the creation of highly efficient SRMs. In [4], a new analytical method for calculating inductive resistances along the longitudinal and transverse axes was proposed. Prior to this study, obtaining high efficiency and ultimately higher torque was arbitrary. In the works on the optimization of the rotor design [5], an analysis of the influence of the SRM rotor parameters on its efficiency and torque was made. In the article on design criteria for synchronous jet engines [6], it was concluded that SRM can develop a torque 20-40 % higher compared to an induction engine at an increased rated current and the same amount of losses.

Different optimization methods were evaluated by researchers in [7]. In [8], the optimization of the barrier shape and the issue of reducing torque ripples were considered.

Research part.

For more accurate calculations of the operating characteristics of the SRM, you can use models that take into account such effects as saturation, magnetic and mechanical losses. When building a model in modern numerical modeling packages (for example, Ansys Maxwell, MATLAB, Simulink), it is easy to immediately implement a model of the dynamics of the object in question, which also allows calculations of established modes. If it is necessary to reduce the calculation time, it is possible to easily obtain a model of the established regime from the dynamic model by equating to zero the corresponding terms in the equations of the system elements [4].

Several variants of rotor designs were investigated

Graphical illustrations of the number and shape of the rotor barriers and the shape of the barriers considered for the numerical analysis are shown in fig. 3. The influence of the inductance ratio L_d was analyzed and L_q on the efficiency of the motor, the magnitude of the stator current, and torque pulsations. Finite element analysis was performed for four versions of the SRM rotor.

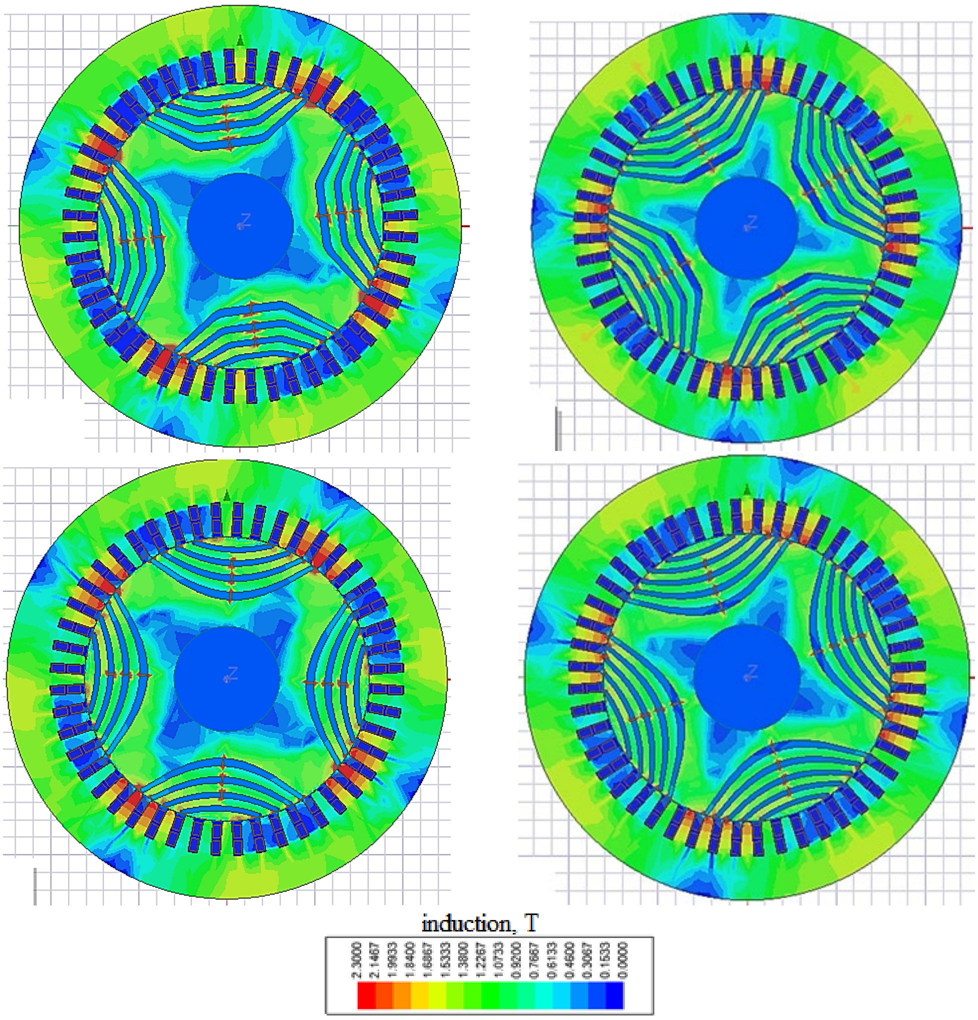
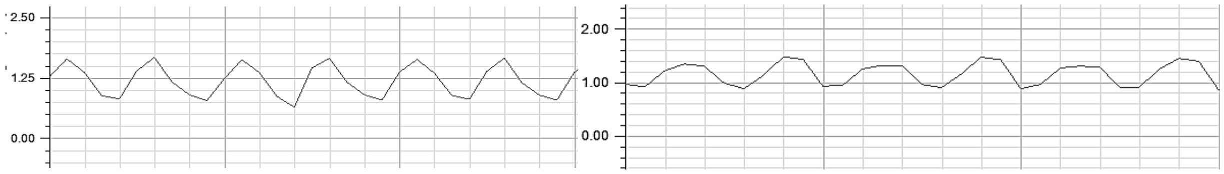


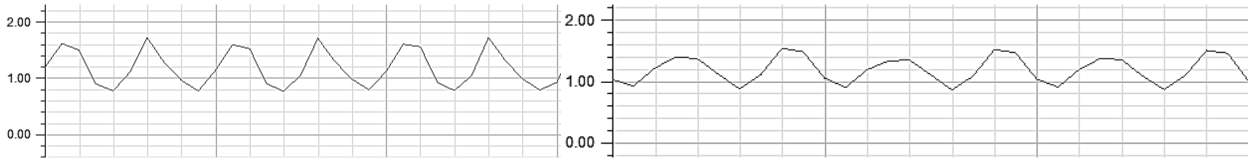
Fig. 3 - Investigated variants of SRM rotors with definition of induction in the nominal mode of operation

In fig. 4 presents the results of the calculation experiment for the four studied options for the torque on the rotor shaft.

After analyzing the results of the calculation experiment of four versions of the SRM rotors, we can conclude that the best parameters were shown by option *b*. The motor with such a configuration and number of air barriers has the lowest losses, and therefore the highest efficiency, a smaller reactive component of the stator current, which is determined by the ratio L_q to L_d, and the smallest compared to other variants of torque pulsation on the shaft.



a b



in

Fig. 4 - The value of the torque on the SRM shaft and pulsations for the four tested rotor variants.

The replacement scheme of synchronous jet engines (Fig. 5) contains a primary branch that branches into a branch with parameters independent of the load ("magnetization circuit") and a branch whose parameters depend on the value of the load factor γ.

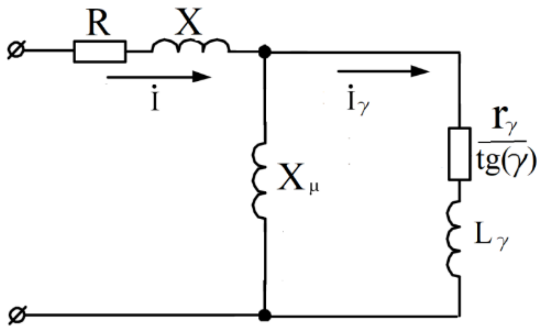


Fig.5 - Scheme of substitution of SRM with parameters depending on the angle γ

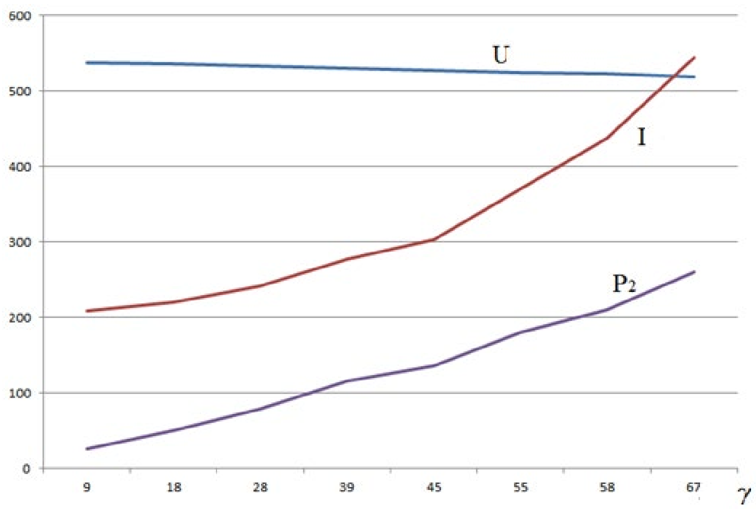


Fig. 6 – Energy characteristics depending on the angle γ

Calculations were carried out to determine the mechanical characteristics of the SRM of a coal harvester with a capacity of 180 kW.

Based on the results of the calculations, the mechanical characteristics were constructed depending on the angle γ. They are presented in Fig. 6, 7.

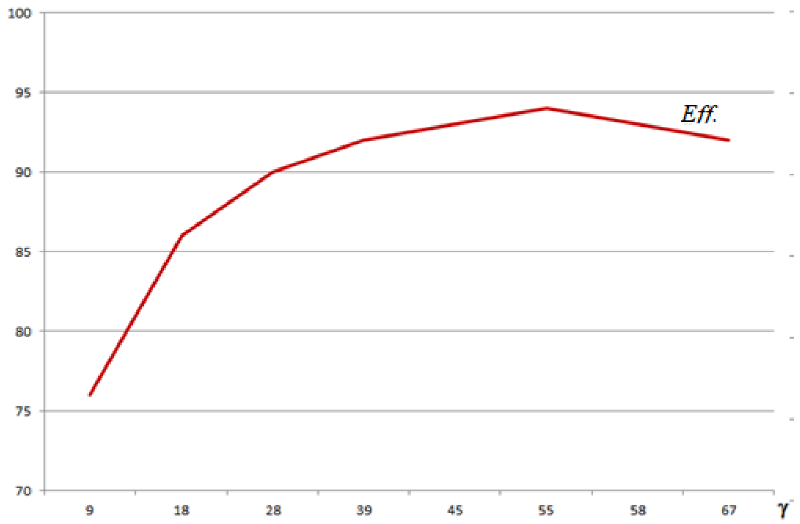


Fig. 7 – Engine efficiency depending on the angle γ

Conclusions.

The calculations made in the scientific work make it possible to conclude that to control the operation of the SRM, it is necessary to change the angle γ and the supply voltage. Using modern converters today, it is easy to set the control algorithm for the operation of the electric drive on the UDC200 coal harvester.

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