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THEORETICAL AND EXPERIMENTAL RESEARCH OF SYNCHRONOUS RELUCTANCE MOTOR

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The paper presents the research on evaluation of accuracy of magnetic field calculations of synchronous reluctance motor in comparison with the results obtained in experiments. Magnetic field calculations are performed with the finite element method to determine values of the magnetic flux and electromagnetic torque according to the current value in motor stator and load angle between the rotor direct-axis and axis of stator magnetomotive force (MMF). Experimental values of magnetic flux and electromagnetic torque are obtained on motor with locked rotor while equivalent direct current is applied to the stator windings. The research shows that the results obtained from the magnetic field calculations coincide well with the experimental data.

Keywords: *electromagnetic torque, magnetic field calculations, magnetic flux, synchronous reluctance motor*

1. INTRODUCTION

Nowadays it is obvious that the intensity of usage of electrical machines increases as well as specific electromagnetic loads. It sets higher requirements for accuracy of calculations for electrical machines, as well as for the study of magnetic field that can be achieved taking into account detailed geometry of the machine and magnetic circuit saturation. It is also important to determine whether the results of magnetic field numerical calculations comply with real experimental data.

Various methods can be applied for magnetic field calculation in electrical machines, but the simplest way for considering magnetic circuit saturation is to perform numerical calculations based on Maxwell equations [1]. Since the energy conversion process mainly takes place in the active part of the electrical machine, it allows performing magnetic field calculations in two-dimensional space, i.e., magnetic field induction B and intensity H vary in radial and tangential directions, while in axial direction of machine their values remain constant.

The most frequently used method for magnetic field calculation is the finite element method FEM [2]–[10]. The benefits of FEM compared to other methods are the following: the possibility to define the object of any form; the ability to change the discretization for different areas in order to obtain higher accuracy of calculations with finer mesh, and the possibility to define the boundary conditions of any length limits.

Magnetic field calculation using the finite element method allows determining the main parameters of electrical machine – magnetic flux, electromagnetic torque, values of magnetic induction in different parts of magnetic circuit, armature reaction inductive reactance and other parameters.

In the paper magnetic field calculations are performed for the synchronous reluctance motor (SRM), and in order to determine their accuracy the obtained results are compared to the experimental data.

2. THEORETICAL RESEARCH OF SYNCHRONOUS RELUCTANCE MOTOR

Within the framework of the research, low-speed synchronous reluctance motor SRM presented in Fig. 1 is used as the experimental object. Such motors are used in control systems of nuclear power stations if the motor is connected to 1–1.5 Hz AC power supply [11]. Parameters of the experimental motor are listed below:

the stator outer diameter	$D = 110$ mm;
the stator package length	$l = 222$ mm;
the air gap value	$\delta = 1.3$ mm;
the Carter coefficient	$k_c = 1.2$;
the number of pole pairs	$p = 2$;
the number of phases	$m = 3$;
the number of windings in phase	$w = 200$;
the winding coefficient	$k_w = 0.935$;
the number of stator teeth	$Z = 24$;
the value of nominal current	$I_1 = 10.8$A.

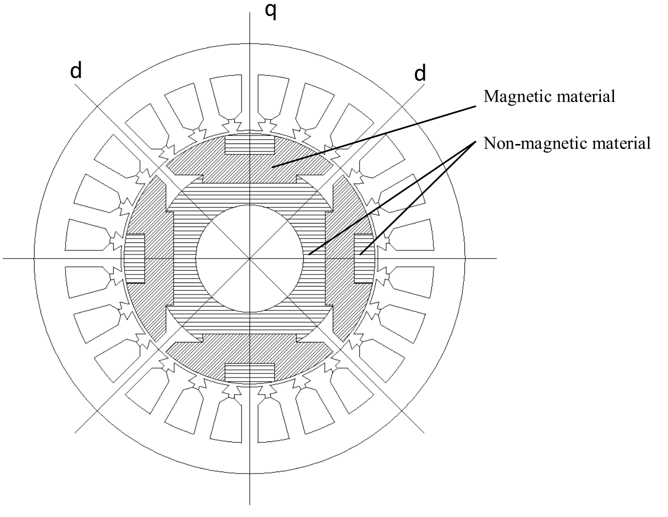

Fig.1. SRM construction.

All the required information about magnetic field of the electrical machine, including real saturation of magnetic circuit, can be obtained performing magnetostatic field calculations based of Maxwell equations [2], [12].

Magnetostatic fields are produced by steady state currents, and magnetic field can be described using the following equations:

$$rot\overline{H} = \bar{j} \; ; \tag{1}$$

$$div\overline{B} = 0 \; ; \tag{2}$$

$$\overline{B} = \mu\mu_0\overline{H} \; , \tag{3}$$

where H is the magnetic field intensity;
B is the magnetic field induction;
j is the current density;
μ is the magnetic permeability;
μ_0 is the permeability constant (μ_0=4$\pi\cdot10^{-7}$, H/m).

Magnetic flux of one pole of electrical machine can be defined as integral (4) in air gap for area S_1 which corresponds to one pole of electrical machine.

$$\Phi = \int_{S_1} B_1 dS_1 \; , \tag{4}$$

where B_1 is the magnetic induction in air gap;
S_1 is the surface corresponding to one pole.

The magnetic flux Φ curves for different values of current can be used to calculate voltage U_1 by using the amplitude values of the first harmonic of the magnetic flux Φ_1

$$U_1 = E_1 = 4.44 fwk_w\Phi_1 \; , \tag{5}$$

where E_1 is the phase EMF generated by the first harmonic of the magnetic flux;
f is the frequency of the current I_1;
w the number of windings in phase;
k_w is the winding coefficient.

Functions $\Phi=f(I_1)$ that are obtained for load angles $\Delta=0^o$ and $\Delta=90^o$ between the rotor direct-axis and axis of stator MMF represent magnetization curves respectively by direct-axis and quadrature-axis of the machine. Using these curves, it is possible to calculate direct-axis and quadrature-axis armature reaction inductive reactance x_{ad} and x_{aq}, respectively. Armature reaction inductive reactance x_{ad} and x_{aq} can be used in order to calculate electromagnetic torque value T_{em} using equation (6) [11], [13].

$$T_{em} = \frac{mI_1^2}{2\Omega}(x_{ad} - x_{aq})\sin(2\Delta) = \frac{mI_1^2}{2 \cdot 2\pi \cdot f_1}(x_{ad} - x_{aq})\sin(2\Delta), \tag{6}$$

where x_{ad} is direct-axis armature reaction inductive reactance;
x_{aq} is quadrature-axis armature reaction inductive reactance;
Ω is the angular rotation frequency.

Numerical calculation of two-dimensional magnetic field is based on a grid surface that is perpendicular to the shaft of the machine. The assumption is used that the length l of the machine is divided into n layers. Each layer has a thickness b_{sl} equal to l divided by n. Since the stator slots are skewed by a stator tooth pitch those layers are rotated by an angle α/n relative to one another, where α corresponds to a total angle of the slot skew (Fig. 2).

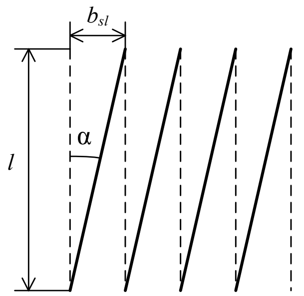

Fig.2. Graphical illustration of the skewed stator teeth (l – stator package length, α – total angle of the slot skew, b_{sl} – thickness of the skew corresponding to tooth pitch). Magnetic field calculations for the current task are performed by using calculations based on the finite element method. These calculations are performed through magnetostatic field simulations in *QuickField* software. This is a two-dimensional finite element analysis system from *Tera Analysis* [14].

In Fig. 3, the results of magnetic field calculations in *QuickField* software are represented as magnetic field lines corresponding to direct-axis when load angle $\Delta=0^{\circ}$ and to quadrature-axis when load angle $\Delta=90^{\circ}$.

a) b)

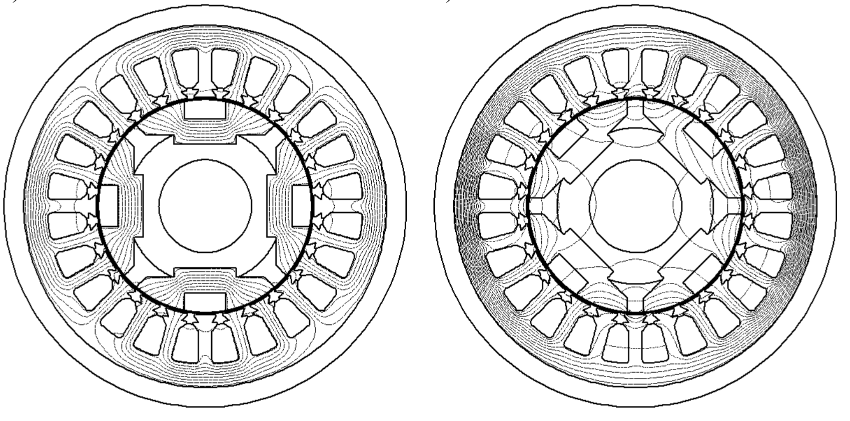

Fig.3. Depiction of magnetic field of SRM corresponding to (a) direct-axis and (b) quadrature-axis.

Figure 4 demonstrates magnetic flux curves for current values I_1=4 A and I_1=12 A, where load angle Δ varies within the range of 10° to 80°. These curves show both theoretically obtained values and experimental values measured with measuring windings 1–13. Experimental research of synchronous reluctance motor is described in Chapter 3 of the paper.

Curves given in Fig. 4 indicate that magnetic flux of the electrical machine depends not only on current value I_1, but also on the operation mode, which is represented in form of angle Δ.

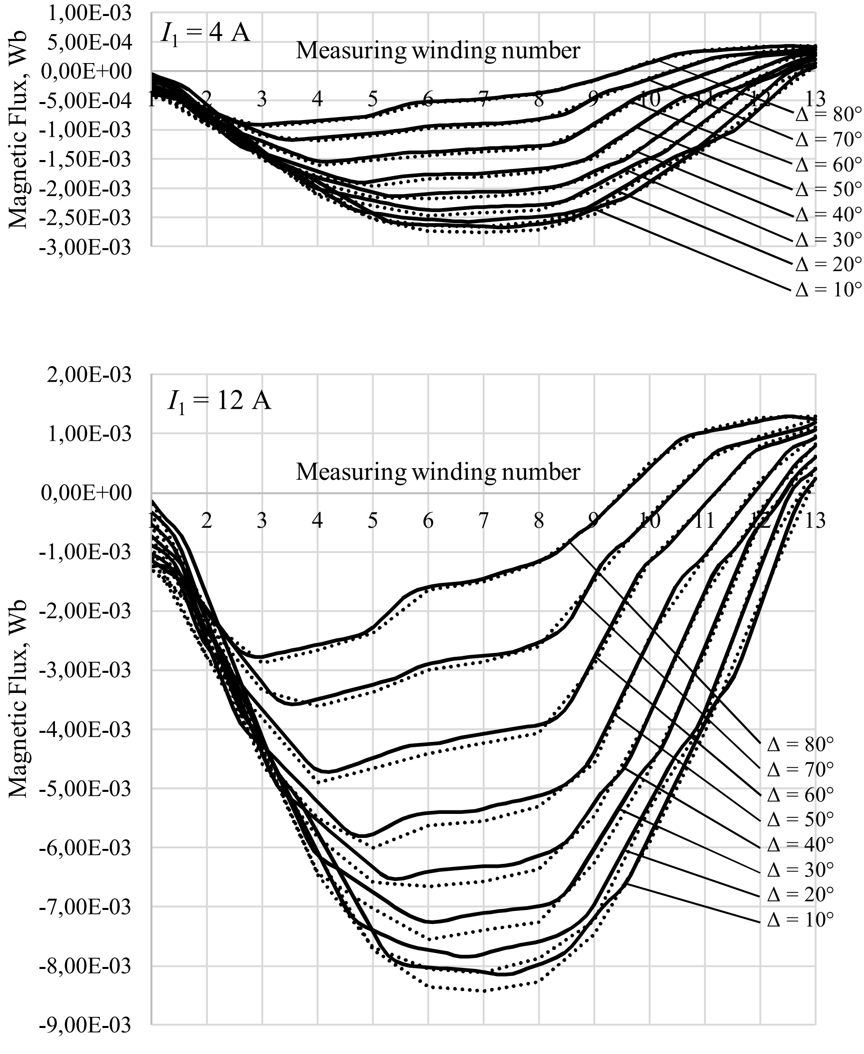

Fig.4. Values of magnetic flux for different values of current I1 and load angle Δ
——— calculated values, ··········· experimental values.

Magnetic flux curves for different values of current I_1, when load angle Δ=0° and Δ=90°, are shown in Fig. 5 and can be used to calculate direct-axis and quadrature-axis armature reaction inductive reactance x_{ad} and x_{aq}, respectively.

Theoretical and experimental values of electromagnetic torque are presented in Fig. 6.

Values of electromagnetic torque are calculated using Maxwell stress tensor [15]. The electromagnetic torque is described with surface integral (7) over the closed surface S in the middle of the motor air gap.

$$T_{em} = \oint_S \left(\bar{r} \times \left[\frac{1}{2\mu_0} \left(B_n^2 - B_t^2 \right) \times \bar{n} - \frac{1}{\mu_0} B_n B_t \bar{t} \right] \right) dS \,, \tag{7}$$

where T_{em} is the electromagnetic torque;
$\bar{n}$ is the normal vector of the point on the closed surface S;
$\bar{r}$ is the radius-vector of the point on the closed surface S;
$\bar{t}$ is the tangent vector of the point on the closed surface S;
B_n is the normal component of the magnetic flux density;
B_t is the tangential component of the magnetic flux density.

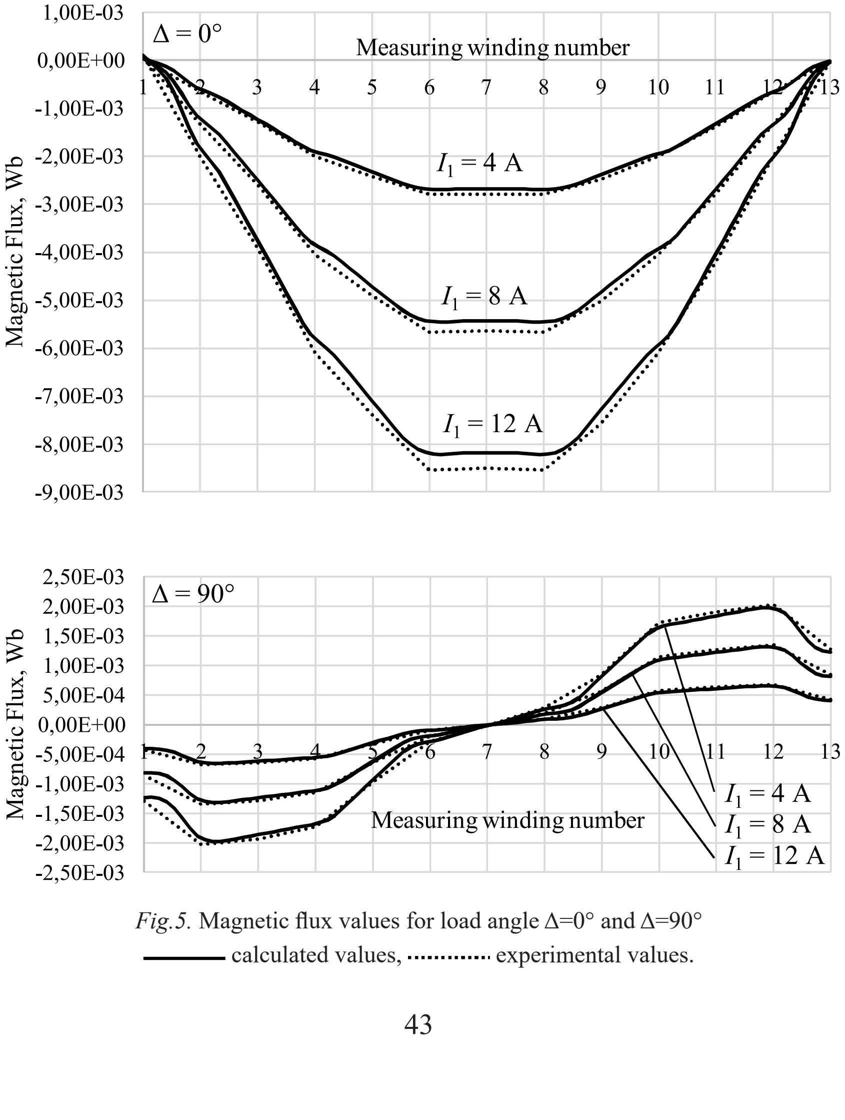

Fig.5. Magnetic flux values for load angle Δ=0° and Δ=90°
——— calculated values, ··········· experimental values.

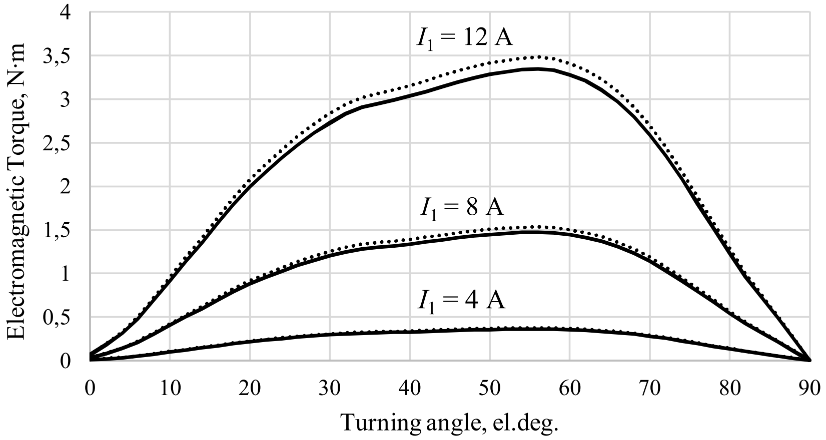

Fig.6. Electromagnetic torque curves for different values of current I_1 for SRM with locked rotor calculated values, experimental values.

3. EXPERIMENTAL RESEARCH OF SYNCHRONOUS RELUCTANCE MOTOR

Theoretical calculation results obtained earlier can be confirmed by conducting experiment on the motor with locked rotor. Magnetic flux is measured with miliwebermeter. For the machine with rotating magnetic field magnetic flux Φ and voltage U_1=E_1 are periodically variable parameters that can be determined by using measuring windings, placed on pole pitch τ where EMF E_1 is induced. In order to obtain the variation in time of magnetic flux Φ which is generated by the EMF, it is required to place *n* measuring windings on rotor as it is shown in Fig. 7.

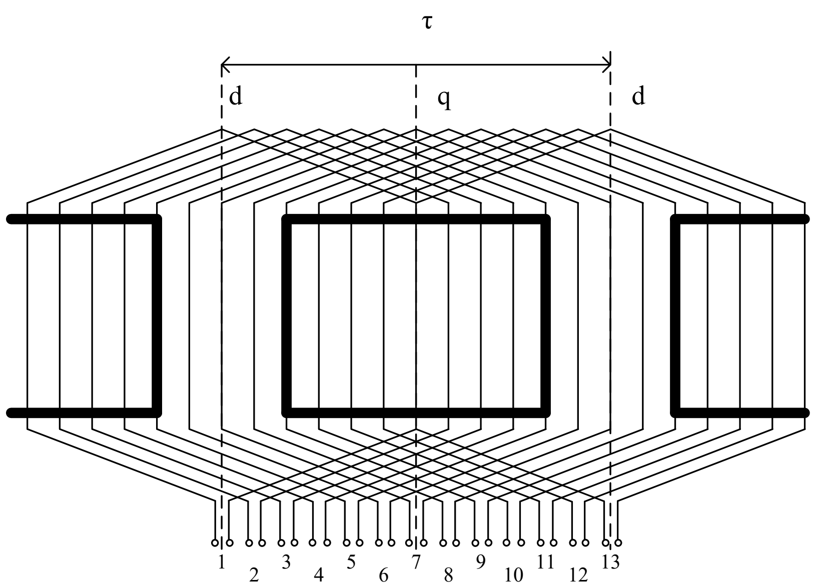

Fig.7. Experimental SRM measuring winding placement scheme.

Equivalent direct current $I_{=} = \sqrt{2} \cdot I_1$ is applied to the stator phase windings of researched SRM with locked rotor. The first harmonic of magnetomotive force generated by the direct current $I_{=}$ for the motor with locked rotor must be equal to the first harmonic of the magnetomotive force generated by the alternating current I_1 flowing in all 3 phases of the stator phase windings when the rotor rotates [13], [16].

By measuring magnetic flux Φ passing through areas 1–13 covered by measuring windings (Fig. 7) for different I_1 values, variable magnetic flux Φ for one half-period is obtained. Curves corresponding to magnetic flux Φ obtained by calculations and experiments are shown in Figs. 4 and 5.

Electromagnetic torque curves as function $T_{em}=f(\Delta)$ can be experimentally obtained by using motor with locked rotor, when stator windings are supplied with DC current $I_{=}$. Direct current $I_{=}$ flowing through the stator windings creates magnetic flux that interacts with permanent magnets and holds the rotor in the certain position. For the creation of static moment on the rotor the weight is applied to the rotor. Under the impact of the torque the rotor rotates at a certain angle that can be read from a disk with graduated scale. The value of rotor rotating angle depends on the weight suspended to the rotor.

Calculated and experimental electromagnetic torque curves are shown in Fig. 6. These curves show that theoretical and experimental results have decent compatibility.

4. CONCLUSIONS

Based on the results obtained within the framework of conducted research, the following conclusions can be drawn:

1. Magnetic flux curves and electromagnetic torque curves, as well as armature reaction inductive reactance and other parameters can be conveniently determined for synchronous reluctance motor with locked rotor.
2. Values of magnetic flux and electromagnetic torque obtained from numerical calculations of magnetic field with the finite element method coincide well with the experimental data. Results differ by 3 % to 7 % depending on the saturation level of magnetic circuit.
3. If magnetic circuit saturation is low, in order to determine load angle curves of synchronous reluctance motor it is possible to use values of armature reaction inductive reactance obtained from the magnetic field calculations with theoretical formulas of electrical machines.

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SINHRONĀ REAKTĪVĀ DZINĒJA TEORĒTISKĀ UN EKSPERIMENTĀLĀ IZPĒTE

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K o p s a v i l k u m s

Novērtēta sinhronā reaktīvā dzinēja magnētiskā lauka aprēķinu precizitāte, salīdzinot to rezultātus ar eksperimentāliem mērījumiem. Magnētiskā lauka aprēķini veikti ar galīgo elementu metodi, nosakot magnētiskās plūsmas un elektromagnētisko griezes momentu atkarībā no dzinēja statora strāvas lieluma un slodzes leņķa starp rotora garenasi un statora MS asi. Plūsmas un momenta eksperimentālie mērījumi veikti dzinējam ar nobremzētu rotoru, barojot tā statora tinumus ar ekvivalento līdzstrāvu. Parādīts, ka no magnētiskā lauka aprēķiniem iegūtie rezultāti labi sakrīt ar eksperimentu datiem.

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