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DISC SWITCHED RELUCTANCE MOTOR WITH HIGH DYNAMICS

SILNIK RELUKTANCYJNY Z PRZEŁĄCZANIEM TARCZOWYM O WYSOKIEJ DYNAMICE

Abstract: The paper presents the disc switched reluctance motor as a possible constructional modification of this type of motor. Disc motor with bidirectional pull is described based on the theory of SRM. In the first chapter behaviours of inductance, magnetic flux and torque, depending on the current and rotor position as well as the influence of geometric dimensions on these values are investigated. In the following parts suggested are the dimensions and described is constructional configuration of the electromagnetic circuit of disc SRM that recognizes its technical implementation.

Streszczenie: W artykule przedstawiono silnik reluktancyjny z przełącznikiem tarczowym jako możliwą modyfikację konstrukcyjną tego typu silnika. Silnik tarczowy o dwukierunkowym ciągnięciu opisany jest w oparciu o teorię SRM. W pierwszym rozdziale badane są zachowania indukcyjności, strumienia magnetycznego i momentu obrotowego, w zależności od prądu i położenia wirnika oraz wpływ wymiarów geometrycznych na te wartości. W kolejnych częściach sugerowane są wymiary i opisana jest konfiguracja konstrukcyjna obwodu elektromagnetycznego dysku SRM, która rozpoznaje jego techniczną realizację.

Keywords: *Switched reluctance motor, disk rotor, high dynamics, magnetic flux*
Słowa kluczowe: *przełączany silnik reluktancyjny, wirnik tarczowy, wysoka dynamika, strumień magnetyczny*

1. Introduction

The development of motors and drives, referred as "modern", is currently underway, although their principle was described and used as early in the 19th century. One example of such motor is the switched reluctance motor (SRM). SRM was first time published until 1969, when S. A. Nasar published his article entitled "D.C.-Switched Reluctance Motor" [1]. Progress in the development of SRM was also published in the next articles, e.g. in literature [2], [3] and [4]. SRM represent interesting alternative to induction motor, because opposite to induction motor it has a simpler construction, which also results in simpler and cheaper series production and lower maintenance requirements [5], [6]. Inverters for SRM are necessary too, but they are much simpler than inverters for induction motors [7], [8].

Modern control systems require fast, dynamic drives with a precisely defined position. At drives with low power output and with high dynamics, it is possible to design motors with a disc rotor and axial direction magnetization. At present DC and induction motors, BLDC and BLAC motors, permanent magnet motors with a disc rotor known and all of these motors have very good dynamic properties, due to the low moment of inertia of the machine rotor. The design of SRM with an axial air gap results from these fact, which would combine the advantageous control properties of cylindrical type of SRM with the dynamic properties of motors with disc rotor [9].

The core of article is disc switched reluctance motor with a number of poles 2p1/2p2 = 8/6. The article presents the courses of inductance, magnetic flux, motor torque, influence of geometric dimensions on these quantities and the determination of the optimal dimensions of disc switched reluctance motor with regard to achieving the highest possible dynamics.

2. Switched reluctance motor

The switched reluctance motor (SRM) structurally represent rotating electric machine with expressed poles on the stator and rotor. Its principle was described as early as 1838, but only with the development of power electronics does it become a serious rival of drives with induction motors [10], [11].

The switched reluctance motor has the following advantageous compared to other drives:

- simple construction, low price, which results from the fact that the rotor has no windings (electrical circuit) or magnets,

- effective motor cooling, as all windings are only on stator,
- little effect of temperature to motor properties in a wide range,
- use for the high speed range, from facts rotor does not contain a commutator, rings or carbons,
- relatively small inertial masses and a high ratio of motor torque and inertial masses,
- simple power converters for power supply which are characterized by high efficiency and reliability, only one polarity current is required in motor phase (unipolar power supply),
- wide range of angular velocity control,
- excellent motor control,
- there is no risk of a direct short circuit in the inverter branch, because in all inverters for reluctance motors there is a phase winding in series with the main power element,
- motor is reversible and can also step.

Disadvantages of a switched reluctance motor:

- converter with adequate control is necessary,
- for precise control, SRM needs a rotor angle sensor or other corresponding solution, that identifies the angle,
- torque profile is wavy, which results in higher motor noise, higher stress on bearings and other mechanical parts of the drive.

SRM main advantages was reason for research activity in order to use this drive in a wide range of applications and power in industry [12]. Drives with SRM are also use in aviation, for automatic drives, for driving fans, pumps, household appliances, machine tools and traction equipment. [13]

The basic division of switched reluctance motors we can made by type of movement:

- rotary,
- linear.

Linear SRMs are used in servodrives. Rotary SRMs are next distinguished according to the direction of magnetic flux [14], we know motors with radial and axial magnetic fields. Axial magnetic field motors have a disc rotor. They can be made as single-disc or multi-disc. [15].
The direction of rotor rotation is give only by the switching sequence of the individual SRM phases. The motor phase must be switched on and off depends of defined mutual position between rotor and stator, according to the selected switching strategy. For this reason, position sensor (or indirect position sensing) is required and it is an integral part of the SRM drive.
A typical electromagnetic circuit of reluctance motor (SRM) with a cylindrical rotor is shown in Figure 1. It is design of 4-phase motor with 2p1/2p2=8/6.

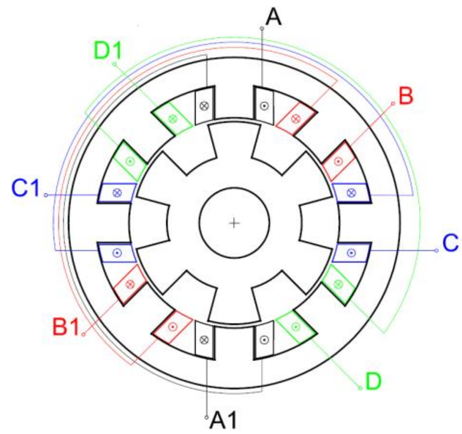

Fig. 1. Electromagnetic circuit of cylindrical SRM with 2p1/2p2=8/6

The SRM torque is achieve by tendency of the magnetic circuit to take position of smallest magnetic resistance (reluctance) for magnetic flux of switched on phase, which means that rotor aligns with stator poles so that inductance of excited coils is as large as possible. To obtain torque function $m = f(\theta,i)$, where θ je is angle of rotation of stator pole axis and rotor pole axis and i is immediate value of current in the supplied phase, relatively complex derivation based on basic voltage equation and energy balance is required. It is possible to derive a simplified relationship for torque, depending on angle of rotation θ rotor compared with stator, neglecting magnetic nonlinearity:

$$M(\theta) = \frac{1}{2} I^2 \frac{\partial L}{\partial \theta} \qquad (1)$$

From relation (1) follows, that it does not matter direction of current and polarity of motor torque is determine only by increase or decrease of phase inductance. So unipolar power supply we only need, which results in simple converter construction for SRM.
By gradually switching of phases of multi-phase switched reluctance motor, it is possible to ensure an uninterrupted output torque. Its value for different rotor positions is not constant in facts. Motor output torque shows ripple due to saturation. Approximate shape of output torque depending on position of rotor is show in Figure 2. Output motor torque is given by sum of individ-

ual torques produced by phases individually, when only one phase is switch on at time.
The output torque ripple is undesirable and affects the smooth running of the switched reluctance motor, especially at low speeds.

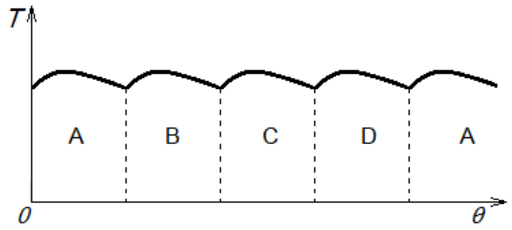

Fig. 2. Output torque of 4-phase SRM

This limits the use of the motor in applications that require smooth running in the low speed range [16]. By eliminate of the output torque ripple as possible we can reach improve of SRM properties, including the reduction of noise and vibration and thus expand its possibilities of use.

Fig. 3 shows a linearized course of inductance and current of one phase as a function of the angle rotation of the rotor pole to the stator pole. The course of the current corresponds to the motor high speed, when the value of the current is limited by a short line interval at a given time constant of the circuit (exponential increase of the current) and a sharp increase of the electrical circuit inductance. At low speeds, discontinuous power supply must be used to keep the current within the required limits I_{MIN} and I_{MAX}, as shown in Fig. 4.

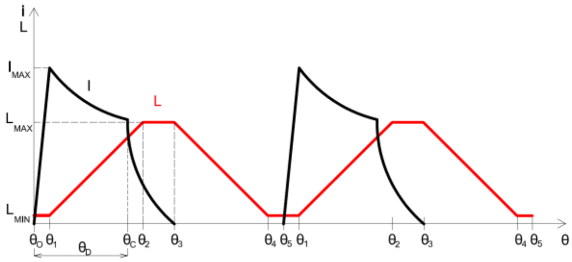

Fig. 3. Current and inductance of one phase depending on rotor position at high speed torque of 4-phase SRM

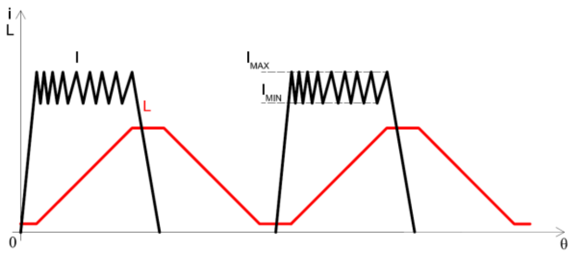

Fig. 4. Current and inductance of one phase at discontinuous power supply and low speed torque of 4-phase SRM

The mean value of the current determines the magnitude of the torque. The maximum torque corresponds to the maximum current value. These values are given by the inverter properties or limit is thermal factor [17].

3. Construction of a disc switched reluctance motor with double-sided traction

The cross section of the designed magnetic circuit of the discs SRM with an axial air gap and with double-sided thrust is shown in Figure 5. 3D model of SRM is in Figure 6.

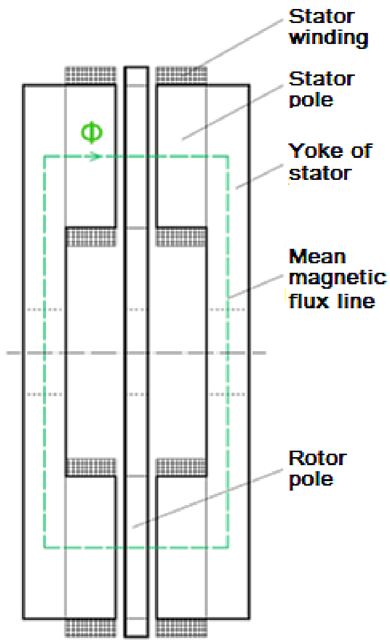

Fig. 5. Magnetic circuit of SRM with discs rotor

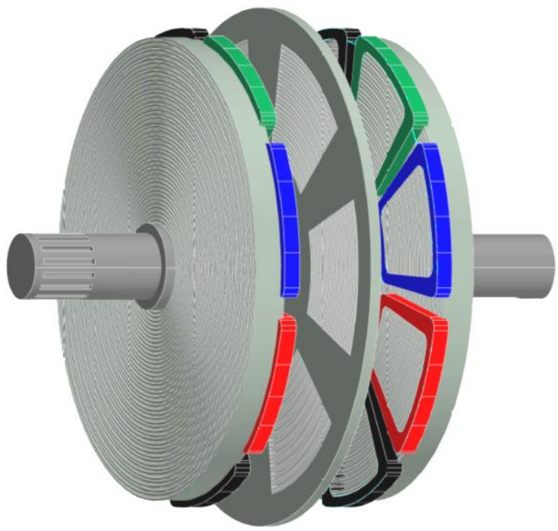

Fig. 6. 3D model of SRM 8/6 with discs rotor

The stator consists of two opposite parts and is made of yoke and poles. The rotor is disc-shaped with recessed poles from a non-magnetic material. Coils on the stator poles excite the magnetic flux. The coils of the motor one phase are connected to series so, as to generate a magnetic flux in the same direction. The magnetic flux is closed by the stator and rotor poles and four times by an air gap.

The magnetic circuit of the stator (Figure 7) is made from electrotechnical sheets. The stator magnetic circuit production technology is similar with disc synchronous and induction motors. The self-supporting stator coils are wound on trapezoidal former and after winding, they are slid onto the pole pieces. The stator yoke and stator poles are one unit.

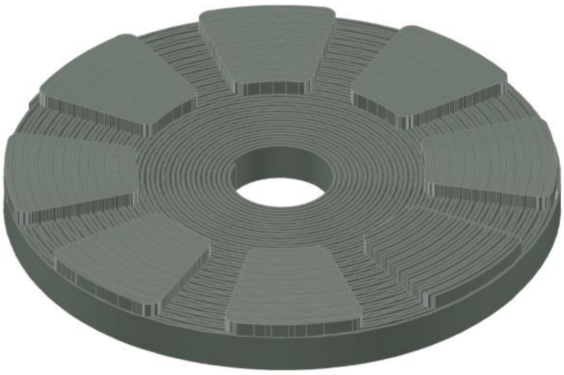

Fig. 7. 3D model of the stator magnetic circuit

The rotor has the shape of a thin disc. The rotor poles are cut from a toroid wound from an electrical sheet and placed parallel to the longitudinal axis of the motor (Fig. 8). The size of the rotor arc is given by the best course of inductance, depending on the angle rotation of the rotor and stator. The rotor poles are regularly placed in the annulus, encapsulated in a suitable and solid non-magnetic material. By this, we achieves a lower weight of the rotor disc, which also reduces the moment of inertia and increases the overall dynamics of the motor.

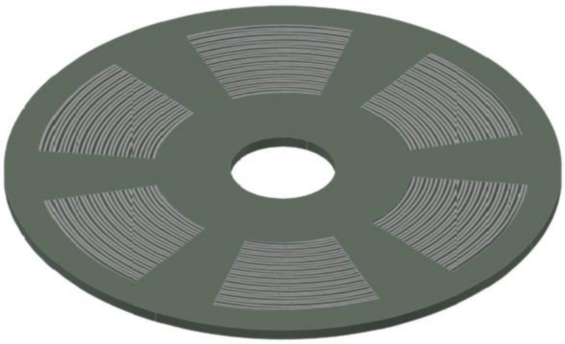

Fig. 8. 3D model of the rotor magnetic circuit

The proposed nominal motor parameters: P=400 W, U=60 V, I_f=8 A, n=1000 rpm. The proposed dimensions of the stator magnetic circuit and rotor disc of the motor are listed in the table 1.

Table 1. Magnetic circuit construction parameters

Parameter	Value
Outer diameter of the rotor disc (D1)	160.10^{-3} m
Inner diameter of the rotor disc (d1)	24.10^{-3} m
Length of rotor (lr)	7.10^{-3} m
Outer diameter of the rotor pole (D)	150.10^{-3} m
Inner diameter of the rotor pole (d)	70.10^{-3} m
Height of rotor pole (D)	40.10^{-3} m
Size of air gap (δ)	$0.15.10^{-3}$ m
Width of stator yoke (s)	12.10^{-3} m
Width of stator pole (ls)	18.10^{-3} m

4. Calculation of basic quantities of disc SRM

Inductance $L(\theta,i)$, magnetic flux $\Psi(\theta,i)$ and torque $M(\theta,i)$ are the basic quantities of SMR. All these quantities are two-parametric, their value depends not only on the instantaneous current value, but also on the overlap angle of the stator and rotor poles. Their calculation is based on the dimensions and material of the magnetically parts of the rotor and stator. The basis is the calculated magnetic flux of this part of the circuit and the magnetic circuit other parts dimensions are selected. The number of winding of the stator excitation coil is calculated from the magnetic voltages of the magnetic circuit individual parts and the magnetic voltage in the air gap.

The inductance values for different rotor positions are calculated from values of the magnetic conductivities of the magnetic circuit individual parts and the magnetic conductivity in the air gap, which changes depending on the angle of rotation of the stator and rotor poles. Figure 9 show the calculated dependence of the inductance on the position of the rotor at a constant current 8A.

Inductance in the angles range 0°-3,75° is minimal and practically constant, so-called aligned inductance. The stator and rotor poles do not overlap in this position. Inductance increases in angle range from 3,75° to 26,25°, because the pole overlap increases. This part is 22,5° wide, which corresponds to angle of the stator pole. The overlap of the poles does not change in the range of angles 26,25° to 33,75° and therefore the inductance changes only slightly. The inductance at this position is known as non-aligned. The poles move away from each other from an angle of 33,75° to 56,25°, which reduces the inductance up to the angle 56,25°. The inductance hardly changes again from this position up to an angle of 60°, as the poles do not overlap.

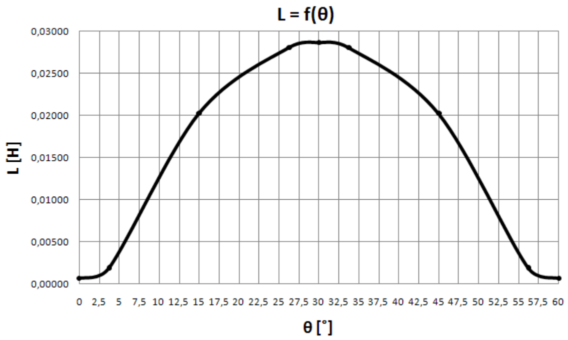

Fig. 9. Course of inductance depending on rotor position at constant current I = 8A

Figure 10 shown the courses of Inductance, depending on rotor position and size of current.

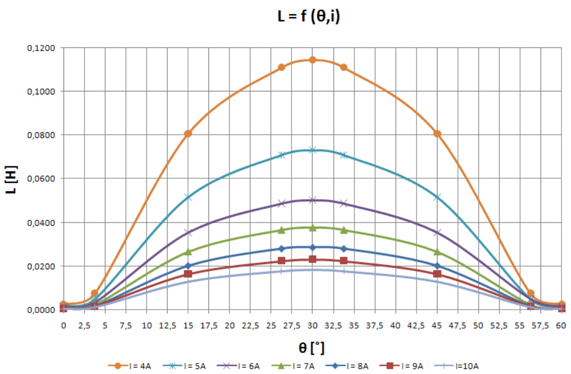

Fig. 10. Course of inductance depending on rotor position and current

The Simulink toolbox in the Matlab program is used to calculate the course of the magnetic flux. The maximum value of the magnetic flux is calculated from the maximum induction in the stator pole and its area. The maximum current is I = 8A. Figure 11 showns the course of the magnetic flux.

The individual curves show the course of the magnetic flux with increasing angle of overlap of the stator and rotor poles from the initial aligned position to the non-aligned position. Its value increases with increasing angle of overlap. We calculate the torque values for the disc SRM depending on the size of the current from the basic relation (1), but we replace the change of inductance (L) by changing the magnetic resistance (R_m) according to the relation $L=N^2/R_m$, where N is the number of windings of the excitation coil.

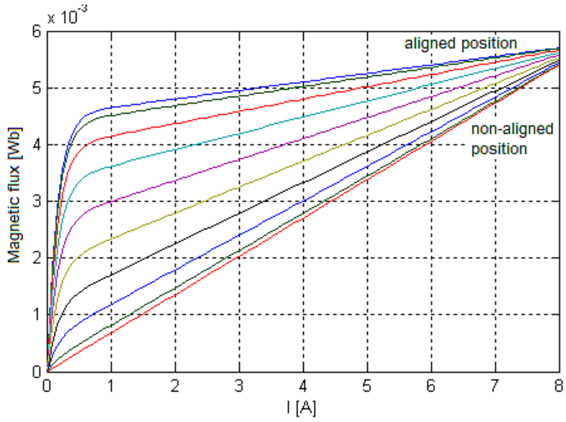

Fig. 11. Magnetic flux courses depending on current and angle

Table 2 shows the calculated torques of the proposed disc SRM as a function of the current when the rotor and stator are rotated from the non-aligned position by an angle $\theta=30°$.

Table 2. The size of torque of the proposed disc SRM depending on the current

***I* [A]**	1	2	3	4	5
***T* [N·m]**	0,059	0,236	0,531	0,944	1,475
***I* [A]**	6	7	8	9	10
***T* [N·m]**	2,123	2,890	3,7746	4,777	5,898

If we compare the value of nominal torque T_N=3.82 N·m, calculated from the specified motor parameters (P=400 W, n=1000 ot.min^{-1}), so the calculated value of torque at current I=8 A is T=3,77 Nm and reaches 98,7% from the given nominal value.

5. Optimization of geometric dimensions of disc SRM

This section describes the influence of the geometric dimensions of the motor (the disc width, the air gap size and the stator pole width), on the course of inductance and magnetic flux. The new optimal dimensions of the electromagnetic circuit are proposed after evaluating the results, respect to the improvement of the dynamic properties of the motor. Table 3 shows the calculated values of the inductance L_{MIN} and L_{MAX} against the change in the thickness of the rotor disc l_r.

Table 3. Influence of rotor disc thickness lr to values L_{MIN} and L_{MAX}

l_r [mm]	3	4	5	6
L_{MIN} [H]	0,000568	0,000577	0,000625	0,000651
L_{MAX} [H]	0,0286	0,0286	0,0286	0,0286
l_r [mm]	7	8	9	10

L_{MIN} [H]	0,000675	0,000698	0,000719	0,000739
L_{MAX} [H]	0,0286	0,0286	0,0286	0,0285
l_r [mm]	11	12	13	14
L_{MIN} [H]	0,000759	0,000777	0,000795	0,000812
L_{MAX} [H]	0,0285	0,0285	0,0285	0,0285
l_r [mm]	15	16	20	25
L_{MIN} [H]	0,000828	0,000844	0,000900	0,000961
L_{MAX} [H]	0,0285	0,0285	0,0284	0,0284

In table 3 we can see that when the thickness of the rotor disc changes, the value of the maximum inductance practically invariable and only the size of the minimum inductance to change. The thinner the disc, the higher the L_{MAX}/L_{MIN} ratio, the moment of inertia also decreases, which improves the dynamics of the motor.

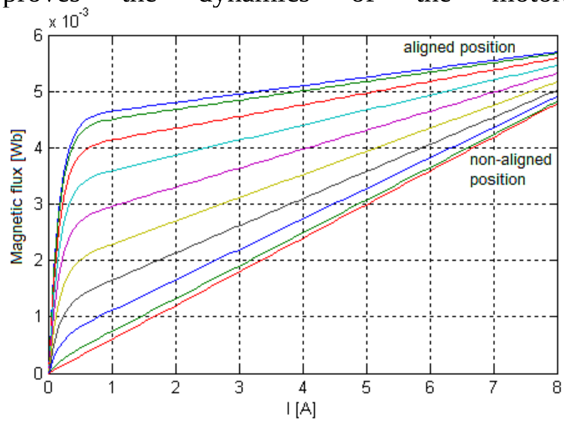

Fig. 12. The course of magnetic flux at the thickness of the rotor disc l_r = 4 mm

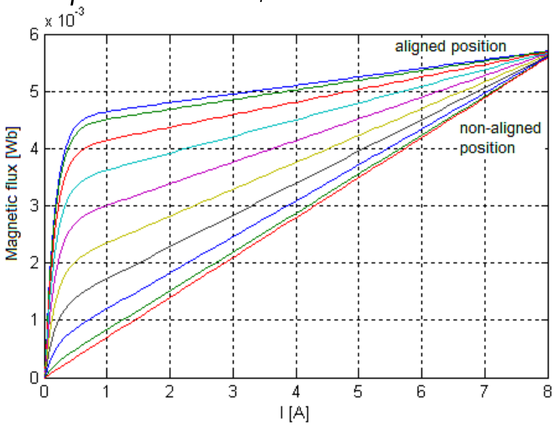

Fig. 13. The course of magnetic flux at the thickness of the rotor disc l_r = 8 mm

Considering into the technological implementation of disc processing, we choose the thickness l_r=5 mm. Figures 12 and 13 show the current-dependent magnetic flux curves at different rotor disc thicknesses lr.

The magnetic flux increases with the thickness of the rotor disc increases in the aligned position. The effect of disc thickness is minimal in the non-aligned position.

Table 4 shows the calculated values of the inductance L_{MIN} and L_{MAX} when changing the size of the air gap δ.

Table 4. Influence of air gap width δ on values L_{MIN} and L_{MAX}

δ [mm]	0.1	0.15	0.2	0.25
L_{MIN} [H]	0,00049	0,000675	0,000888	0,0011
L_{MAX} [H]	0,0241	0,0286	0,0331	0,0362

The change of the air gap size affects the values of maximum and minimum inductance, but the air gap size can significantly affect the dynamics of the motor. The smaller air gap, produce the more motor torque. Therefore, the size of the air gap δ = 0.15 mm, is chosen, which is still structural realizable. The magnetic flux, in the non-aligned position, changing very little, when changing the width of the air gap.

Table 5 shows the calculated values of the inductance L_{MIN} and L_{MAX} when changing the size of the stator pole l_S.

Table 5. Influence of stator pole width l_S on values L_{MIN} and L_{MAX}

l_S [mm]	13	14	15	16
L_{MIN} [H]	0,000494	0,000541	0,000589	0,000607
L_{MAX} [H]	0,0262	0,0273	0,0283	0,0279
l_S [mm]	17	18	19	20
L_{MIN} [H]	0,000657	0,000675	0,000727	0,000743
L_{MAX} [H]	0,0290	0,0286	0,0296	0,0292

The width of the stator pole has the least effect on the size of the minimum and maximum inductance. However, it is substantial that at the selected width of stator pole must be space for the required number of the excitation coil winding to achieve the desired motor torque. The height of the excitation coil should not be greater than 5 to 6 mm in our case. From structural point of view, that respects the width and height of the wound coil, the stator pole width of is designed l_S = 14 mm.

The calculations show that as the stator pole width increases, the magnetic flux increases from aligned position to non-aligned position. The magnetic flux does not change with the stator pole width in the non-aligned position. Figure 14 shows the course of the magnetic flux as a function of the current at the stator pole width l_S = 14 mm.

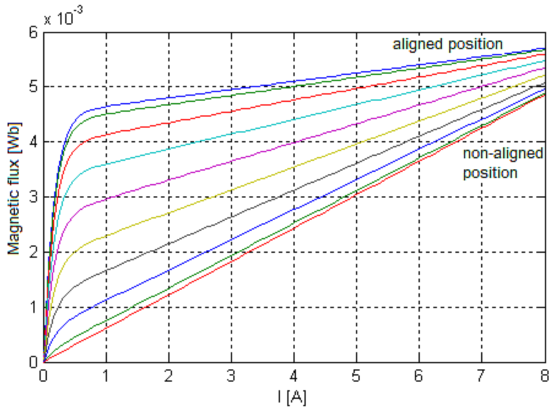

Fig. 14. The course of magnetic flux at the width of the stator pole l_S = 14 mm

New optimal dimensions of the motor electromagnetic circuit for the expected producing of a functional sample are proposed after evaluating the results based on the above-described influences of the geometric dimensions of the motor magnetic circuit on the course of inductance and magnetic flux. The proposed new parameters of the electro-magnetic circuit are shown in the table 6.

Table 6. Optimal construction parameters of the magnetic circuit

Parameter	Value
Outer diameter of the rotor disc (D1)	160.10^{-3} m
Inner diameter of the rotor disc (d1)	24.10^{-3} m
Length of rotor (lr)	5.10^{-3} m
Outer diameter of the rotor pole (D)	150.10^{-3} m
Inner diameter of the rotor pole (d)	70.10^{-3} m
Height of rotor pole (D)	40.10^{-3} m
Size of air gap (δ)	$0.15.10^{-3}$ m
Width of stator yoke (s)	12.10^{-3} m
Width of stator pole (ls)	14.10^{-3} m

6. Conclusions

The design of the electromagnetic circuit of a disc switched reluctance motor is based on the construction realization of coiled toroidal circuits and self-supporting stator coils. The basic spatial configuration of the magnetic circuit arrangement was determined after iterative calculations, which is based on angular and pole symmetry. The optimal dimensions of the electromagnetic circuit were determined by investigating the influence of geometric dimensions on the course of inductance and magnetic flux. The article does not deal with the overall design of the motor. The analyses show that the size of the air gap has the most significant effect on the size of the motor torque.

The required disc thickness and air gap width are technologically achievable. The production of the stator's magnetic circuit and rotor poles will be more difficult on the technology. The dynamic properties of the designed disc switched reluctance motor will be possible to verify by measurement only after its construction realization.

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