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Investigation study of geometric dimensions of the magnetic system of the switched-reluctance machine influence on magnetic moment

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Abstract. The article deals with the investigation concentrated to optimizing the active part of the switched-reluctance motor with the aim of increasing the value of the average electromagnetic torque. Susceptibility of the average value of the electromagnetic torque to changes of the geometric dimensions of the magnetic system found in the optimization process was set.

1. Introduction

Electromechanical converters of energy (EMC) are the basis of modern industrial production. Constantly increasing requirements to dynamic, the energy and mass-dimensional characteristics of EMC require the improvement of all components and active parts involved in electromechanical energy conversion.

EMC switched-reluctance type having a sufficiently high technical and economic indicators is one of the most promising at present. In the world practice, a switched-reluctance electric machines (SRM), composed of switched-reluctance electric drives (SRD) are used in many fields. The main reason for the expansion of their application is a number of advantages such as design simplicity, reliability, relatively low cost to manufacture and a high energy performance and mass-dimensional indicators. In this regard there is a need to improve their design, in particular magnetic systems with the aim of improving technical and economic indicators. Due to the availability of powerful computers and software, it is possible to improve the active part of SRM through the use of optimization algorithms.

In most cases, three-phase and multiphase SRM are used there some areas where a single-phase SRM application is rational. For example: for household appliances [1], for machines and mechanisms with ventilation load, for operation in generator mode, in the cases where there is requirements no high to the starting point and the major argument is the low cost. The switched-reluctance motor (SRM) in some cases is used as an embedded object in the technological machine, which may entail a number of design restrictions for the magnetic system. This study was conducted in order that the designer had the opportunity to choose certain parameters for optimization that have the greatest influence on the magnitude of the electromagnetic torque.

2. The objectives of the investigation

The main aim of the study was optimization of single-phase SRM 6/6 magnetic system (fig. 1) according to the criterion of maximum of average value of the electromagnetic torque and the determination of the susceptibility of electromagnetic torque value to the geometric dimensions of the magnetic system changes found in the optimization process.

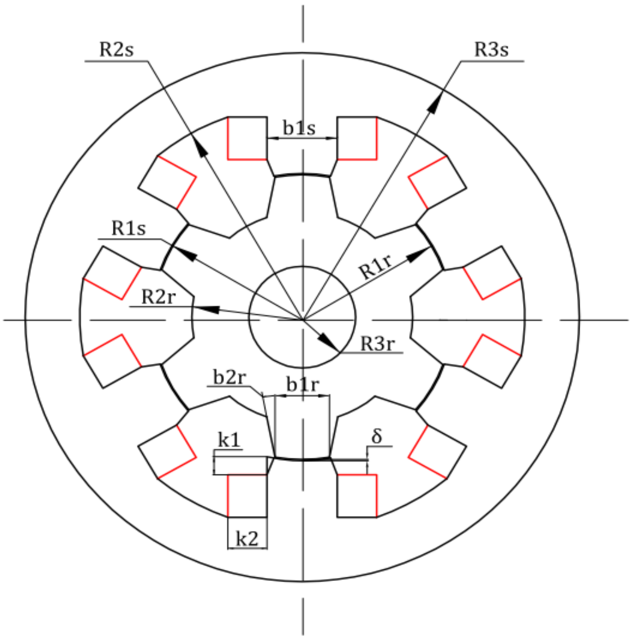

Figure 1. Magnetic system SRM 6/6

3. The solution of the problem

The object of the investigation is SRM (fig. 2), which was manufactured at the plant "Horizont" (Rostov-on-Don) and it was tested as part of the ventilation unit successfully.

Figure 2. Single-phase SRM

Basic dimensions and nominal values are presented in the table 1, 2. As a tool for the automated design and optimization process the program "Optimization of SRM" developed by the authors was used [2]. It had already been used for optimization of SRM with other types of magnetic systems [3–6].

To determine the dynamic characteristics of the single-phase SRM under consideration the known relations [7]

$$\frac{di}{dt} = \frac{1}{L_d(i,\theta)} \cdot \left(u - i \cdot R - \omega \cdot \frac{\partial \psi(i,\theta)}{\partial \theta} \right),$$

$$\frac{d\omega}{dt} = \frac{1}{J} \cdot (M_e - M_s).$$

where i is the phase current, t is the time, L_d is differential phase inductance, u is the phase voltage, R is active resistance of the phase winding, ω is frequency of rotation of the rotor, ψ is flux linkage of phase, θ is the angle of rotation of the rotor, J is reduced moment of inertia of the rotor, M_e is the electromagnetic moment on the shaft, M_s is reduced moment of resistance on the shaft.

The calculation of the electromagnetic torque was performed through a derivative of coenergy [8, 9].

Table 1. Basic dimensions of the studied SRM 6/6

The name of the parameter	Value
The number of teeth of the stator	6
The number of teeth of the rotor	6
Number of phases	1
The packet length of the stator (rotor), mm	50
Outer radius of stator ($R3s$), mm	44,2
The radius of the stator in the grooves ($R2s$), mm	35,5
The radius of the bore of the stator ($R1s$), mm	24
The width of the tooth of the stator ($b1s$), mm	11,2
The angle of the side surface of the tooth of the stator ($b2s$), grad.	0
The air gap (δ), mm	0,2
The outer radius of the rotor ($R1r$), mm	23,8
The radius of the rotor grooves ($R2r$), mm	17,6
The radius of the hole under the shaft ($R3r$), mm	8,5
The tooth width of the tooth of the rotor ($b1r$), mm	8,7
The angle of the side surface of the tooth of the rotor ($b2r$), grad.	11
Coil width ($k2$), mm	6,25
The elevation of the tooth of the stator on the coil ($k1$), mm	3,02
The number of turns, n	130

Table 2. The nominal value of the studied SRM 6/6

Name of engine parameters	Value
Power, W	234
Moment, N·m	1,492
Rotation frequency, min^{-1}	1500
The effective value of current, A	4 A
The voltage pulse DC, V	310

The table 3 with the results obtained in the study is presented below. Optimization was performed in two stages (for a more accurate determination of numerical values of time): first fragments of the magnetic system was optimized by Monte-Carlo method (to avoid finding a local extremum), and then by using of Nelder – Mead method (for the Refine value). Five parameters highlighted in the table 1 were taken as the base as optimizing geometric elements.

Table 3. The results of the optimization

Optimized parameters	The method of Monte-Carlo, mm The average torque *M*, N·m	The method of Nelder – Mead, mm The average torque *M*, N·m	The increase of torque (from source), %

*b*2*s*, *b*1*s*, *R*2*r*, *b*2*r*, *b*1*r*	*b*2*s* = 8,35;
	*b*1*s* = 12,59;
	*R*2*r* = 17,86;
	*b*2*r* = 14,84;
	*b*1*r* = 9,92
	M = 2,14
		*b*2*s* = 6,62;
		*b*1*s* = 13,86;
		*R*2*r* = 16,48;
		*b*2*r* = 14,26;
		*b*1*r* = 10,69
		M = 2,143
			30,37

The Monte-Carlo method is referred to the methods of static testing because of the need for a sufficiently large number of calculations. The definition of the method is to simulate a random variable in order to calculate the characteristics of their distributions. A detailed description of the application of this method as well as its advantages and disadvantages are considered in the work [10].

The method of Nelder – Mead (or deformable polyhedron) is a continuation of the simplex method Spindle, Hexta and Hemsworth. This method applies to deterministic methods of unconditional optimization of functions of several variables and does not use the derivative (gradient) of the function. A detailed and descriptive description of this method is presented in [4].

Are showed in figure 3 for two geometries: the black color shows the geometry of the source engine, and red – optimized. Demonstration of the final result.

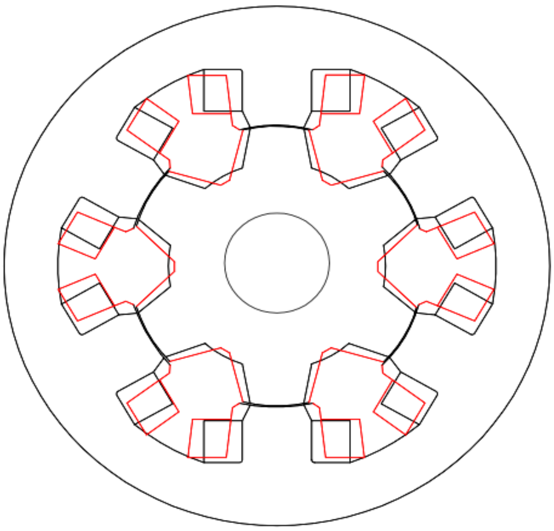

Figure 3. Cross-sections of the original and optimized active part of the SRM 6/6

It can be seen from figure 3 that the zone for the passage of magnetic flux in teeth area of the optimized version of the SRM is wider than the initialone. It is a reason of the decrease of the magnetic resistance, the degree of saturation of the magnetic system and the increase in the average electromagnetic torque. However, further extension of this zone leads to a decrease in the difference between the phase inductance in coordinated and miscoordinated positions that lead to decrease in the average electromagnetic torque.

Due to the fact that the optimization process involves a number of SRM parameters the physical basis of the geometry obtained in the result of the optimization must be coordinated with these parameters. Finite element method, which is the basis of FEMM [11, 12] program allows to estimation so SRM calculations the geometry of the machine obtained after optimization of provides a maximum objective function, in this case contradictory requirements are coodinated.

To determine the sensitivity of the electromagnetic torque to changes in the geometrical quantities of the five parameters (see table 3, column 3) magnetic system SRM 6/6 was carried out the following steps:

1 In the "Optimization SRM" the calculation of the average electromagnetic torque when one of the five parameters (the other four dimensions are without changes) on the value of ± 1–5 % (1 % increments) was carried out.

2 The dependence of the variations of the values of the considered geometrical parameter was built.

According to this investigation we obtained the following values of the average torque and the geometric dimensions (table 4).

Thanks to the data given in table 4, the dependences presented in figure 4. Were obtained reference values of the electromagnetic torque and resizable fragment of the magnetic system are pointed by the red dots on the chairs data.

The dependences obtained are arranged in the order of reducing the effect of size changes on the value of the moment. This is an analysis of data graphs.

Table 4. The average electromagnetic torque when changing the geometric dimensions of the fragments of the magnetic system

	-5%	-4%	-3%	-2%	-1%	**Initial value**	1%	2%	3%	4%	5%
b*1*r	10.156	10.263	10.37	10.477	10.584	**10.69**	10.79	10.903	11.01	11.117	11.224
M	1.697	1.86	1.95	2.076	2.104	**2.143**	2.114	2.113	2.102	2.086	2.046
b*1*s	13.177	13.316	13.454	13.59	13.73	**13.87**	14.00	14.147	14.28	14.424	14.563
M	1.785	1.889	2.061	2.088	2.107	**2.143**	2.116	2.085	2.069	2.066	2.038
b*2*s	6.289	6.356	6.422	6.488	6.554	**6.62**	6.686	6.752	6.818	6.884	6.95
M	1.789	1.94	2.054	2.086	2.105	**2.143**	2.119	2.089	2.075	2.065	2.04
R*2*r	15.656	15.821	15.986	16.151	16.316	**16.48**	16.64	16.81	16.97	17.139	17.304
M	2.141	2.1415	2.142	2.1425	2.1428	**2.143**	2.142	2.1425	2.142	2.141	2.139
b*2*r	13.557	13.7	13.842	13.985	14.128	**14.27**	14.41	14.55	14.69	14.84	14.98
M	2.139	2.14	2.1405	2.141	2.142	**2.143**	2.142	2.1423	2.142	2.141	2.14

In figure 4, *a* the dependence of the average electromagnetic torque on the values of the fragment magnetic system b1r in intervals of ± 1–5 % is presented. The graph shows that the optimal point is the point with such coordinates (10,69; 2,143), and any deviation from the value $b1r$ = 10,69 mm to the left or right leads to the reduction of the moment. The largest slope is observed the at values period –1 % to –5 % b1r. This means that the reduction in the width of the tooth of the rotor ($b1r$) may lead to a reduction in the numerical values of moment of approximately 20 %, and increasing the value of $b1r$ 4,5 %.

Figure 4, *b*, *c* shows the dependence of the width of the tooth and the angle of inclination of the side surface of the tooth of the stator ($b1s$ and $b2s$). The forms of these curves are almost similar to figure 4, *a*. It suggests that the decrease in the values of $b1s$ and $b2s$ leads to the greatest reduction of value of time (17 % – $b1s$ and 16 % – $b2s$), rather than increasing the value of this parameter (at the 5 % *b*1*s* and 4,7 % – *b*2*s*). Changes of to dimensions of these parameters have a lower impact on the average time, which is evident from the results obtained at ± 5 % of the size of the considered fragments.

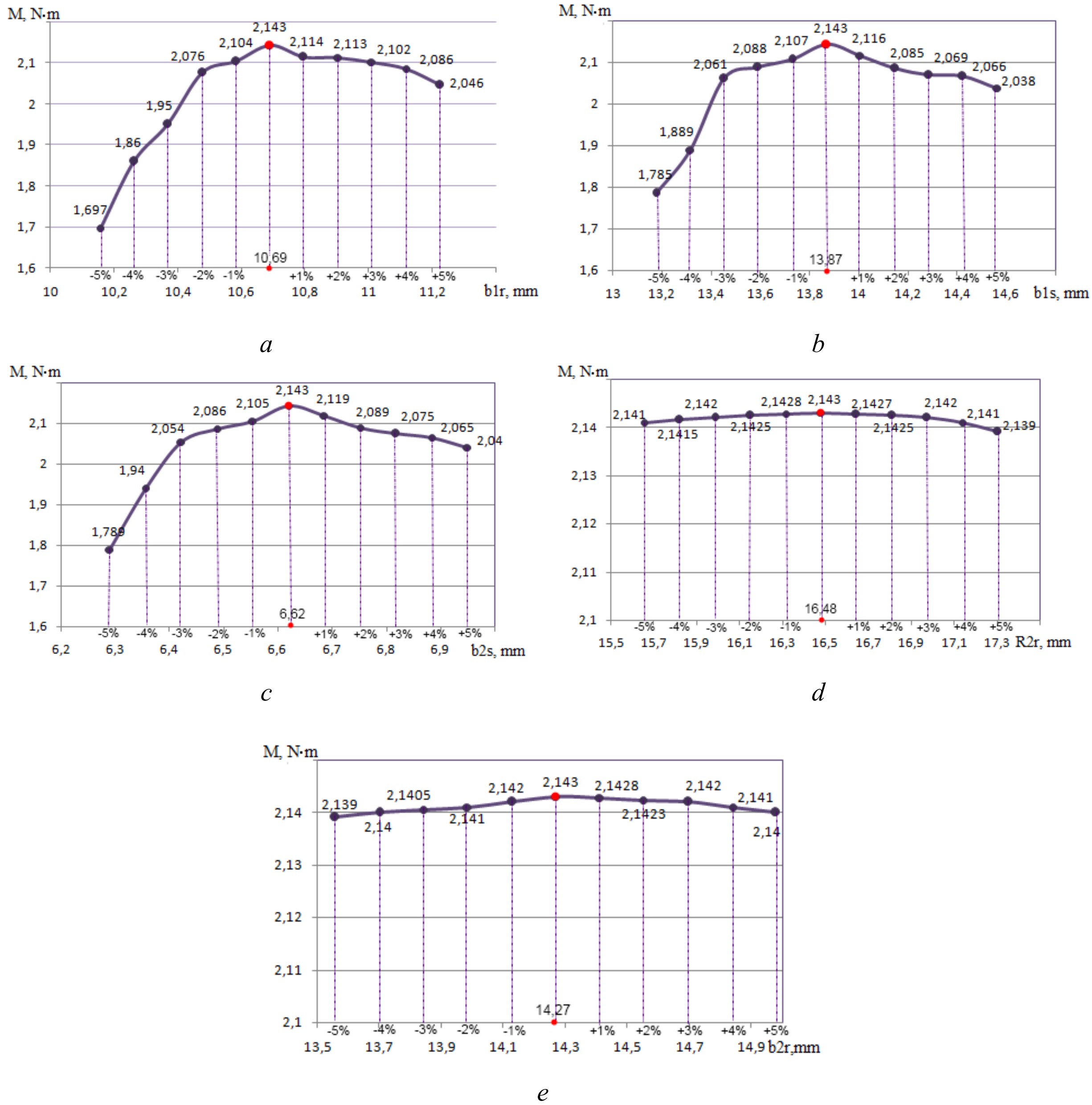

Figure 4. The dependence of the average values of the electromagnetic torque on the variations of the geometric dimensions of the magnetic system SRM 6/6:
a – *b*1*r*; *b* – *b*1*s*; *c* – *b*2*s*; *d* – *R*2*r*; *e* – *b*2*r*

Are presented in figure 4, *d*, *e* the curves of the dependency of the average time from *R*2*r* and *b*2*r*, having a virtually flat form. Are presented it suggests that the variation of data values of parameters of the magnetic system has a minor influence on the formation of the average value of time (± 0,2 %).

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4. Conclusions

The result of the optimization algorithm applying was the increase in the average electromagnetic torque by 30,36 % while maintaining the outer diameter and length of the magnetic circuit, which indicates the effectiveness of the application of optimization algorithms in order to improve performance.

The research carried out on the susceptibility of the electromagnetic moment to the change in the geometric parameters of the magnetic system of the object under consideration demonstrates that the greatest influence on the magnitude of the moment is caused by a change in the element $b1r$ (the width of the rotor's tooth).

The value of the torque to the change of parameters $b1s$ and $b2s$ is less sensitive and is the variation of the elements of $b2r$ and $R2r$ very little influenced. These results can be used by the designers in the conditions, when the magnetic system is embedded and the change of any geometrical parameter of the active part is the reason for increase or decrease in operational performance.

In addition, of revealed link between changes of geometric dimensions and the magnitude of the mean electromagnetic moment can be used in the development of the SRM manufacturing technology and the designation of tolerances in design documentation for structural elements.

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