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Design influence on torque ripple in Switched Reluctance Motor (SRM)

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Anotácia:
Tento článok sa zaoberá vplyvom konštrukčnej úpravy SRM na zmenu zvlnenia momentu. Konštrukčne sa menia šírka pólu statora, rotora a zmena ich tvarov. Veľkosť jarma statora, rotora a vzduchovej medzery ostávajú nezmenené. Na základe dobrej zhody merania a simulácie v metóde konečných prvkov, sú všetky konštrukčné úpravy a ich vplyv na zvlnenie momentu SRM urobené prostredníctvom MKP v programe FEMM. Bol vytvorený parametrický model na rýchlu zmenu jednotlivých konštrukcií. Pomocou FEMM boli vypočítané statické parametre motora a aj zvlnenie momentu. Kombináciou jednotlivých úprav sa získalo nižšie zvlnenie momentu ako v reálnom stroji.

Annotation:
This paper deals with design influence of SRM on its torque ripple. The construction, size and width of stator and rotor poles are changed. The size and construction of stator and rotor yokes and air gap are without changes. On the base of good coincidence between measurements and simulations by means of Finite Element Method (FEM), all construction designs are simulated and calculated by means of FEM under program FEMM. The parametric model of SRM has been created for quick design changes of mentioned parameters. The static parameters of SRM have been calculated by means of FEM and also its torque ripple. The combination of various construction changes, the design with lower torque ripple has been obtained than in real SRM.

INTRODUCTION

Many scientific papers deal with torque ripple minimization in Switched Reluctance Motor. It is one of SRM disadvantages which causes the noise [1]. Torque ripple of SRM is in some applications ineligible, so exists many techniques to minimize it by control and/or optimization of its construction [2]. The construction covers: number of phases, size and shape of stator and rotor poles, the quality of ferromagnetic circuit and air gap.

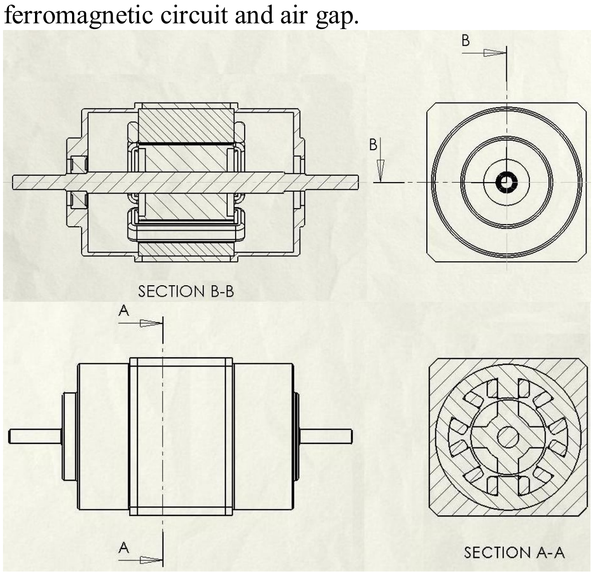


Fig. 1: Cross-section area of investigated 6/4 SRM

Some possibilities to minimize torque ripple have been described in [3], [4], [5]. In these papers a real 3-phase 12/8 SRM has been investigated. This paper deals with a real 3-phase 6/4 SRM. Its cross-section area is in greater detail shown in Fig.1 and its nameplate is in the Table I.

TABLE I
THE NAMEPLATE OF INVESTIGATED SRM

MEZ	EM Brno	TYPE SR 40N
3x 10V	28,5A	5000rpm

The paper [6] deals with Finite Element Method (FEM) identification of SRM parameters by means of program FEMM 2D version 3.4. This paper continues in this investigation by creating of LUA script using. It means, that SRM is described by parametric equations. In this case is very simple to change each construction dimension or parameter and then to calculate all static parameters as: phase inductance, flux linkage, coenergy and developed electromagnetic torque versus rotor position and phase current. The last parameter is very important from point of view torque ripple minimization. The outer diameter, air gap in aligned position and stator and rotor yoke width have been kept constant. The following parameters and dimensions have been changed:

- width of stator and rotor pole in accordance with feasible triangle, which can be seen for this SRM in the Fig.2.
- length of stator and rotor pole,

- the shape of stator and rotor pole, if the pole arcs have been kept constant as in real SRM (see Fig.2).

In the Fig.2 there is so called feasible triangle with correspond pole arcs of stator and rotor.

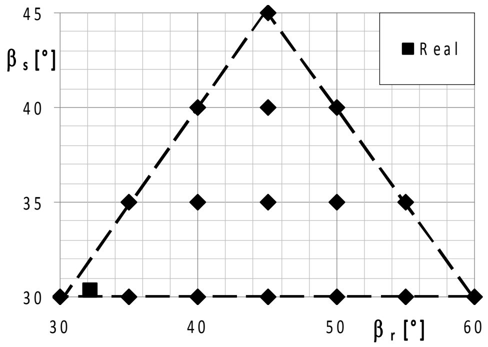


Fig.2: Feasible triangle for 6/4 SRM

All described construction changes are calculated, investigated and discussed.

SIMPLIFIED MODEL OF SRM

To investigate torque ripple of SRM both of models are needed. The first is model created under FEM (influence of construction changes on static parameters) and the second is mathematical model of SRM for transient analysis (various switched ON and OFF angles and their influence on SRM torque ripple) [2]. This combination could take a long time for solving this problem. On the base of these facts the simplified model is used.

This simplified model is given and is investigated for one phase only, because the phase symmetry is supposed. The total torque is given as the sum of all three phases for constant phase current shifted in accordance with 6/4 three phase SRM topology. This methodology corresponds to switched ON angle in unaligned rotor position and switched OFF in aligned rotor position. The static torque of one phase is calculated from following equation:

$$dT_1 = 1/2(H(B\cdot n) + B(H\cdot n) - (H\cdot B)n) \qquad (1)$$

where *n* denotes the direction normal to the surface at the point of interest.

The total instantaneous torque is given:

$$T = T_1 + T_2 + T_3 \qquad (2)$$

The average value of static torque is given as:

$$T_{av} = \frac{m \cdot N_r}{2\pi} \cdot W \qquad (3)$$

Where W is coenergy obtained from FEM analysis and N_r is rotor poles number. The torque ripple can be calculated from following equation:

$$dT = \frac{T_{max} - T_{min}}{T_{av}} \qquad (4)$$

The torque ripple depends also from the phase current. In this case the current was kept constant *I*=14A for pole pair, because one phase consists of two parallel windings, so total current is 28A as it can be seen from nameplate of SRM. In the Fig.3 there can be seen the total instantaneous torques for different currents of a real 6/4 SRM.

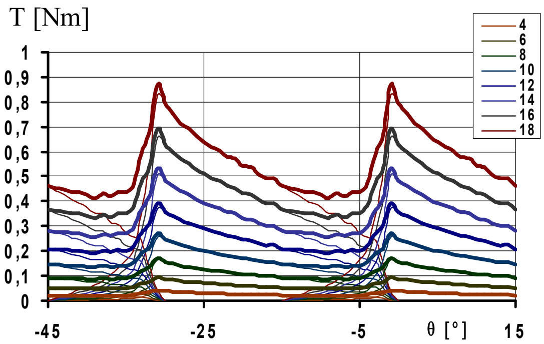


Fig.3: Total static torque of a real 6/4 SRM

TORQUE RIPPLE FOR DIFFERENT SRM CONSTRUCTIONS

This simplified mathematical model with FEM combination can be used for various constructions of SRM to identify its torque minimization. Also average torque will be investigated versus construction changes.

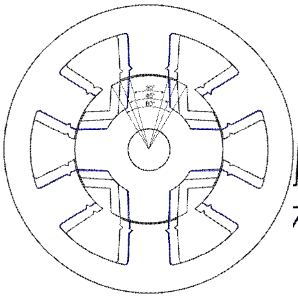
The construction changes are following:

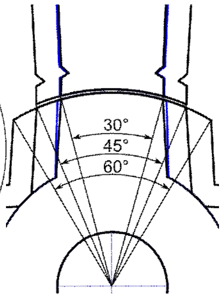
- width of stator and rotor poles limited by feasible triangle for given SRM and for constant air gap (Fig.2, Fig.4a,b),
- length of rotor and stator poles for their constant widths and constant air gap (Fig.5a,b),
- shape of rotor and stator poles, mainly size of arcs between poles and yokes in stator and rotor. Stator and rotor arcs are equal as for real SRM (Fig.6a,b)
- skewing of rotor and stator poles, stator and rotor arcs are equal as for real SRM (Fig.7a,b).

The torque ripple for real investigated SRM given by simplified model is d*T* = 80,36%. The torque ripple investigation will by analyzed in following chapters for constructions changes mentioned above.

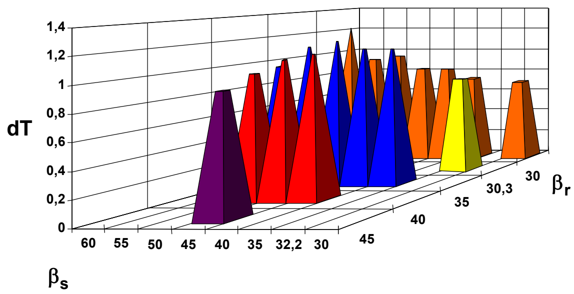
The change of stator and rotor pole widths

The limitation for this construction design is the feasible triangle. But not only this limitation is taken into account. To keep constant outer dimensions, following parameters are constant: width of rotor and stator yokes, the same number of turn for phase and the same area for coils. The construction changes are shown in Fig. 4a and detail is shown in Fig. 4b.





a) b)



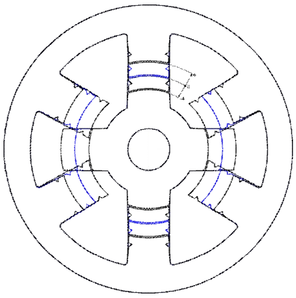
c)

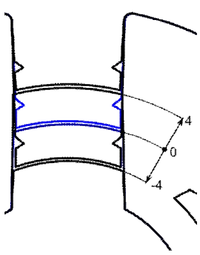
Fig.4: a) The construction changes of rotor and stator width, b) detail of changes, c) calculated torque ripples in triangle graph

The calculated values can be shown in the Fig. 4c in triangle graph for feasible triangle. The real torque ripple is 0.8 (see purple color) and the smallest torque ripple is 0.701 for β_r = 30°, β_r = 30° (see yellow color).

The change of stator and rotor pole lengths

The limitation of this construction change is shown in the Fig. 5a and in greater detail in Fig. 5b, respectively. All outer dimensions, number of turns per coil, phase current and air gap have been kept constant as in the real SRM. Calculates values of torque ripples, average torque, minimal and maximal torques are shown in the Table II, bold values correspond to real SRM.





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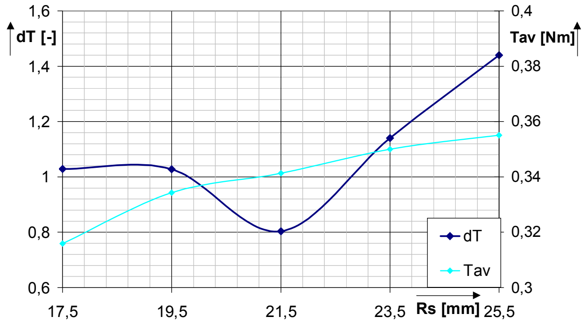

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Fig.5: a) The construction changes of rotor and stator lengths, b) detail of changes, c) calculated torque ripples and average torque

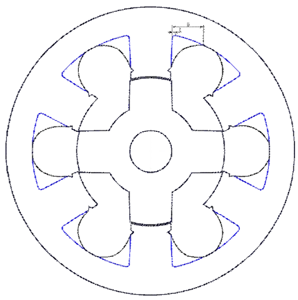
TABLE II

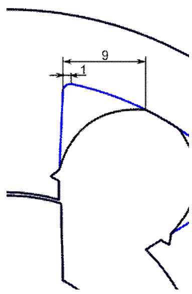
change	T_{max} [Nm]	T_{min} [Nm]	T_{av} [Nm]	dT [-]	I [A]
-4	0,527735	0,202596	0,315944	1,029101	14
-2	0,587965	0,244247	0,334329	1,028081	14
0	**0,532011**	**0,257715**	**0,341325**	**0,803623**	**14**
2	0,561905	0,162816	0,34997	1,140353	14
4	0,621958	0,110922	0,355036	1,43939	14

As it can be seen from Fig. 5c, this change is not suitable for torque ripple minimization, because torque ripple is higher as for real SRM. In opposite, the average torque is increasing.

The change of stator and rotor pole shapes

The limitation of these construction changes are shown in the Fig. 6a and 6b in detail.





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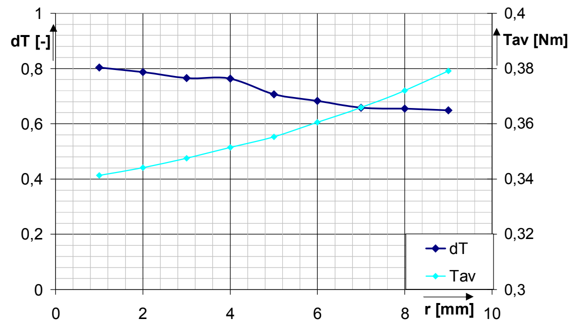


c)

Fig.6: a) The construction changes of rotor and stator shapes, b) detail of changes, c) calculated torque ripples and average torque

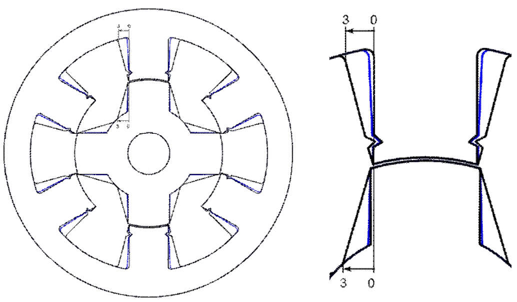
All outer dimensions, number of turns per coil, phase current and air gap have been kept constant as in the real SRM. By these changes a high influence on phase inductance versus rotor position can be achieved and finally average torque. Calculates values of torque ripples, average torque, minimal and maximal torques are shown in the Table III, bold values correspond to real SRM. These results are very good, because torque ripple is decreasing and average torque is increasing (see Fig.6c).

TABLE III

change	T_{max} [Nm]	T_{min} [Nm]	T_{av} [Nm]	dT [-]	I [A]
1	**0,532011**	**0,257715**	**0,341325**	**0,803623**	**14**
2	0,532603	0,261606	0,34414	0,787462	14
3	0,532446	0,266387	0,347532	0,765565	14
4	0,539985	0,271531	0,351487	0,763766	14
5	0,526615	0,275528	0,3553	0,706691	14
6	0,526937	0,280657	0,360487	0,683185	14
7	0,526391	0,285659	0,365897	0,657921	14
8	0,536975	0,29346	0,371992	0,654625	14
9	0,55066	0,304512	0,379162	**0,649189**	14

Skewing of rotor and stator poles

The limitation of this construction change is shown in the Fig. 7a and in greater detail in Fig. 7b, respectively. All outer dimensions, number of turns per coil, phase current and air gap have been kept constant as in the real SRM. Calculates values of torque ripples, average torque, minimal and maximal torques are shown in the Table IV, bold values correspond to real SRM.



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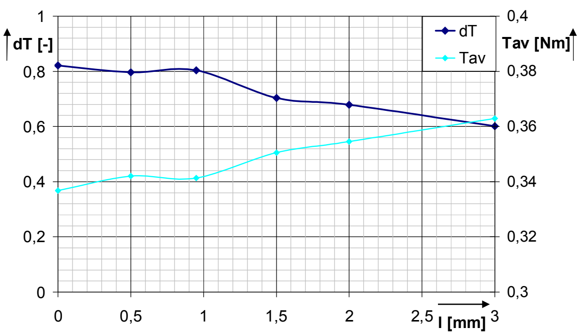

c)

Fig.7: a) Skewing of rotor and stator poles, b) detail of changes, c) calculated torque ripples and average torque

TABLE IV

change	T_{max} [Nm]	T_{min} [Nm]	T_{av} [Nm]	dT [-]	I [A]
0	0,528646	0,252153	0,33682	0,820891	14
0,5	0,530093	0,257733	0,341999	0,796374	14
0,95	**0,532011**	**0,257715**	**0,341325**	**0,803623**	**14**
1,5	0,511451	0,264818	0,350555	0,703548	14
2	0,515866	0,275349	0,354578	0,678319	14
3	0,49843	0,280399	0,362878	**0,600838**	14

As it can be seen from Fig.7c, if the skewing is increasing, also average torque is increasing and torque ripple is decreasing. Minimal torque ripple achievd in this simulation is 0.6.

Combination of several changes

In the Fig.8 can be seen combinations of several changes mentioned above. The results are shown in the Table V.

TABLE V

change	T_{max} [Nm]	T_{min} [Nm]	T_{av} [Nm]	dT [-]	I [A]
βs=βr=30 **Arc** r=9mm	0,52545	0,30299	0,374666	0,593769	14
βs=βr=30 **skewing** 3mm on rotor	0,49796	0,268113	0,340814	0,674412	14
βs=βr=30 **Arc** r=9mm **skewing** 3mm on rotor	0,51860	0,314304	0,379798	**0,537917**	14

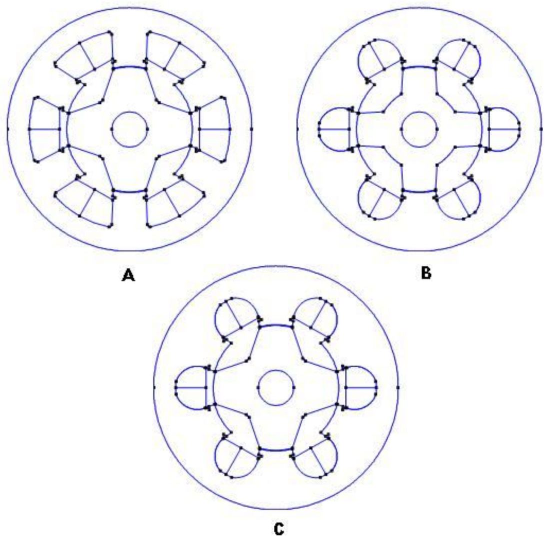

Fig.8: Combination of several changes

As it can be seen from results, to make some combinations of changes a minimal torque ripple can be achieved. The torque ripple is decreased from 80% (real SRM) to 53,79% for βs = βr = 30^{o}, arc between stator and yoke with diameter 9 mm and skewing 3 mm (Fig.8c).

IV. CONCLUSION

The influence of construction design on the SRM torque ripple has been analyzed and calculated. FEM program and simplified mathematical model have been used for static SRM parameters investigation, mainly average torque and torque ripple. Several construction changes have been carried out to achieve minimal torque ripple. Strong torque ripple minimization has been obtained using of several changes combination. The results of this optimization is torque ripple decreasing about 30%. This methodology of SRM torque ripple minimization mentioned in this paper, can be used also for other types of SRM.

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