DESIGN AND PARAMETER ANALYSIS OF SWITCHED RELUCTANCE MOTOR WITH PERMANENT MAGNETS

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Summary This paper deals with Switched Reluctance Motor (SRM) parameter investigation, if permanent magnets are suitable inserted in stator parts to increase magnetic flux. The analysis is made on the base of input geometrical dimensions and materials of a real SRM without permanent magnets (PM). The calculation of PMSRM static parameters is made by means of Finite Element Method (FEM) and by analytical approach. The output parameters of PMSRM analysis are phase inductance, flux linkage and electromagnetic torque versus phase current and rotor position. These calculated parameters are compared with measured and FEM calculated parameters of SRM without PM. The recommendations for PMSRM design configuration are given.

1. INTRODUCTION

The optimizing of electrical machines design is very actual task from a point of view of electromagnetic torque improvement. The electromagnetic torque increasing is possible by using new materials, by new construction design or by inserting of permanent magnets (PM). PM are often used in DC and synchronous machines. However, they are used more and more in other electrical machines, to improve their performances. This paper is focused on the improvement of Switched Reluctance Motor (SRM) torque by means of PM.

The SRM construction is very simple. The both stator and rotor have salient poles and only stator carries winding coils, which are suitable connected to create phase. The magnetic flux is provided by phase current to develop a reluctance torque [1].

This paper deals with new design of SRM, where PM are used to support magnetic flux in the stator yoke. The analysis is focused on determination of SRM static parameters, mainly phase linkage flux, phase inductance, co-energy and electromagnetic torque versus phase current and rotor position. The PM are placed into stator yoke of SRM (see Fig.1) and obtained parameters are compared with SRM without PM. For calculation of these parameters, FEM analysis is used and also analytical approach for comparison of results. The analytical approach of SRM is in greater details shown in [4]. The FEM applicability has been verified by measurement [3], so it is also used for SRM with PM. A 3-phase 12/8 SRM, 3.7kW, 3000rpm, 11.8Nm is investigated (see Fig. 1).

2. PERMANENT MAGNET LOCATION IN SRM

As it is known, the PM produces constant magnetic flux. That means, in SRM is necessary to find place or cross-section area, when during SRM operation, the magnetic flux is approximately constant, and doesn't change its direction. The place for PM location is there, where PM magnetic flux supports main magnetic flux of all phases. To find suitable place, a deeper analysis of the magnetic flux waveforms in individual parts of the machine was found out [3]. When the working rotor point P is followed in Fig.1, in all rotor parts the magnetic flux is changed if rotor rotates. At stator parts, the magnetic flux is varying versus rotor position in stator tooth, but no at all parts of stator yoke. For here investigated 3-phase 12/8 SRM, stator yoke can be divided onto 12 parts, see Fig.1. The stator yoke flux waveforms are obtained from analytical analysis [3], and it can be seen in Fig.2. From Fig.2 it is clear, that in stator yoke parts 1, 4, 7, 10, the magnetic flux is constant during SRM operation. The switching sequence of SRM phases has to be successively, in this case A, C, B. So only these segments are suitable for PM location. This fact is valid only for 3 phase 12/8 SRM, if the switching phase sequence is A,C,B. As it is seen in Fig.2, the flux linkage in stator yoke, parts 2,3,5,6,8,9,11,12 changes its polarity.

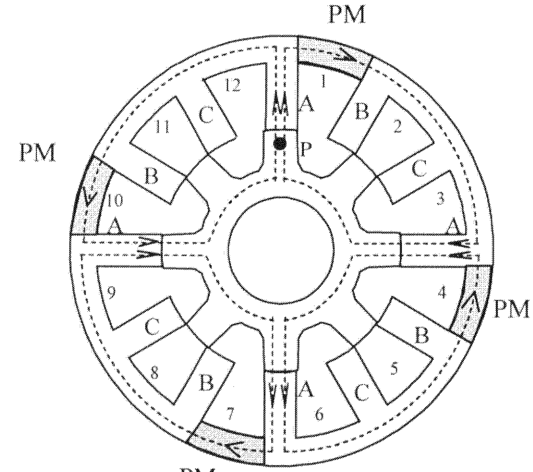


Fig. 1. The cross-section area of the 3-phase 12/8 SRM with PM in stator yoke.

In many other cases, the precise location of PM is different and depends on number of phases, stator and rotor poles and sequence of phase winding excitation.

In this paper, the SmCo27MGOe was used with follow parameters: relative permeability 1.103, coercivity 772kA/m, electrical conductivity 1.176 MS/m.

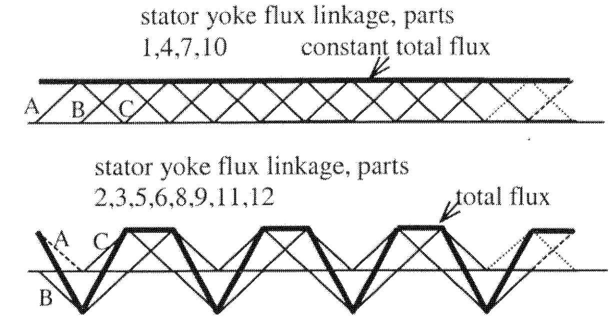
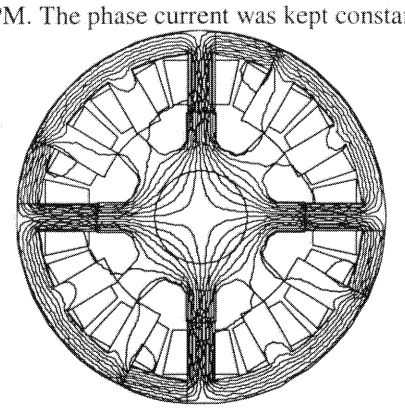


Figure 2. Flux linkage waveform in stator yoke as the sum of the individual phase contributions.

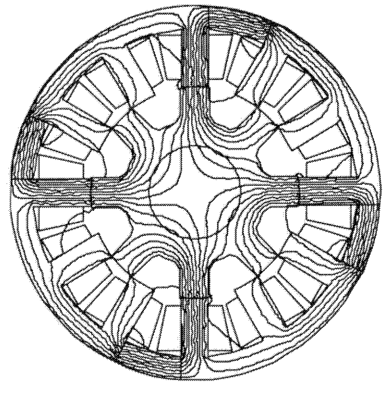
In the future, the influence some other kinds of PM should be investigated.

2. FEM ANALYSIS

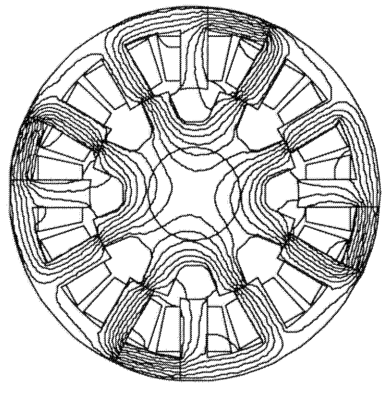
For FEM analysis the next input data are needed: geometrical dimensions, current density of one phase, material constants (winding conductivity and relative permeability, B-H curve of SRM ferromagnetic circuit material and permanent magnet constants) and boundary conditions. The accuracy of the result depends on the size of FEM mesh and accuracy of the input parameters. In this paper, 9984 nodes have been used. The calculation was carried out for each individual rotor position and current under static condition. The rotor position ϑ was moved from aligned to unaligned position in 1 mechanical degree and at each position the current was changed from 1 to 30A, because it is its working range. In Fig. 3a,b it can be seen the distribution of magnetic flux lines of PMSRM for aligned position, in Fig.3c for unaligned rotor position and in Fig.3d for unaligned rotor position of SRM without PM. The phase current was kept constant 10A.



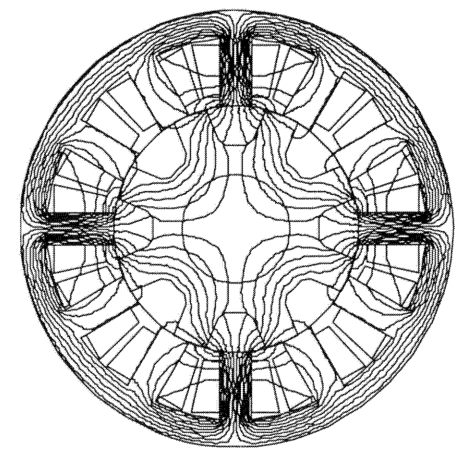
a) PMSRM in aligned rotor position for current 10A and for other higher values of phase current. The same figure for SRM without PM.



b) PMSRM in aligned rotor position for 1A and other lower phase currents.



c) PMSRM in unaligned rotor position, 10A.



d) SRM without PM in unaligned rotor position, 10A.

Fig.3 Magnetic flux distribution in cross-section area for phase current 10A and 1A.

In the aligned rotor position for higher currents, the magnetic flux line distribution is the same for both SRM without PM (Fig. 3a) and SRM with PM. For lower currents from 1 to 7A, the magnetic flux distribution is different, because the permanent magnet flux is higher than the magnetic flux created by phase current, and the PM location is not symmetrical with regard to stator coils of phase A (see Fig.1 and 3b).

In the unaligned rotor position (and in other rotor positions around unaligned position), the flux line distribution is different for PMSRM and SRM without PM (see Fig. 3c, 3d). The main reason is the presence of PM (Fig.3c), which causes lower leakage flux, and the phase inductance in this rotor position will be higher. The comparison of phase inductance versus rotor position of both SRM is shown in Fig.5 for phase current 10 and 20 A.

3. ANALYTICAL APPROACH OF SRM

The analytical approach has to be based on a set of implicit and explicit analytical expressions involving the motor dimensions and inputs to performance variables in a similar way as in FEM. This method is described in greater details in [5].

In the analytical model, the quarter of a real SRM cross-section area (Fig. 1) is used because of machine symmetry. The magnetic flux lines are assumed on the base of FEM. The flux lines distribution depends not only on rotor position, but also on phase current, because of PM presence. So, the analytical model is more complicated as for SRM without PM. In this paper, the flux line lengths are calculated analytically for aligned and unaligned rotor position only and for current I=20, 25, 30A to verify results from FEM. The total magnetomotive force F applied to a phase winding is given by:

$$F = NI = \sum H_\delta l_\delta + \sum H_i l_i - H_{cPM} l_{PM}, \qquad (1)$$

where N is number of turns of the quarter of SRM, I is phase current, H_δ and l_δ are magnetic field intensity and length of air gap, respectively, H_i and l_i are magnetic field intensity and length of iron parts and H_{cPM} is coercitivity of used PM and l_{PM} is length of PM. Every flux path has been described by equivalent reluctance circuit [5] and the reluctance is given as:

$$R_{kj} = \frac{H_{kj} l_{kj}}{B_{kj} A_{kj}}, \qquad (2)$$

where k is order of flux line path, j is part of stator or rotor (stator or rotor yoke or tooth), B is flux density in part j due to k flux path and A is cross-section area. Then the flux linkage of k flux path is:

$$\psi_k = \frac{F}{\sum R_{jk}} \qquad (3)$$

and the phase inductance is:

$$L = \sum \frac{\psi_k}{I} = \sum L_k. \qquad (4)$$

The calculated values of flux linkage and phase inductance for aligned and unaligned position are compared by FEM and it can be seen in Fig. 4 and Fig. 5.

The coincidence between analytical approach and FEM for SRM with PM in unaligned position is very good and the difference is no greater than 5%. In aligned position is the coincidence also very good. This analytical method doesn't seems to be suitable for design of SRM with PM, because takes a lot of time to create and calculate new magnetic flux lines for every rotor position and phase current.

4. MAGNETIC FLUX

The static parameters of SRM are very important for its design, dynamic simulations, losses and efficiency calculations. The first parameter is flux linkage versus phase current for different rotor position $\psi = f(I, \vartheta)$. The area bounded by maximal phase current and by both ψ-I curves for aligned and unaligned position is equal to mechanical energy, which is converted to electromagnetic torque [1]. In the Fig. 4 can be seen these curves obtained by means of FEM for both SRM with PM and without PM.

The values are verified by analytical calculation for current 20, 25 and 30A. From the Fig. 4 is clear, that for SRM with PM is the area higher as for SRM without PM, because of PM presence, mainly for lower current. It means, that the electromagnetic torque will be higher. When the phase current is zero, the flux linkage is not zero, because it is created by PM (Fig. 4).

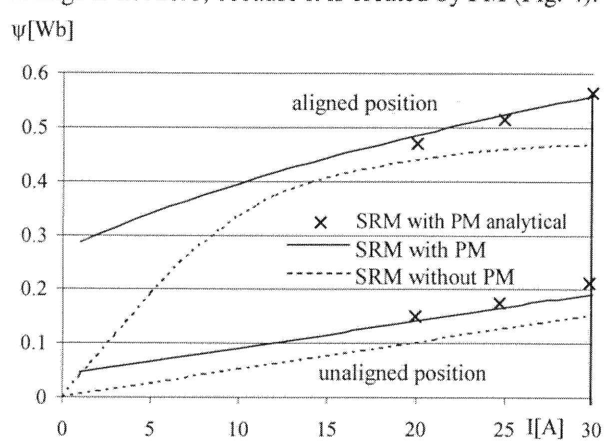


Fig. 4 Flux linkage curves versus phase current for aligned and unaligned rotor position.

5. PHASE INDUCTANCE

The phase inductance versus rotor position for full current range is static parameter, which is needed in SRM mathematical model for dynamic simulations. The analysis was made for the whole working range. In the Fig. 5, the phase inductance profiles are shown, where 0° corresponds to aligned position and 22.5° to unaligned position only for phase current 10 and 20A because of better transparency. The results are obtained by means of FEM for SRM with and without PM and compared by analytical approach for current 20A for aligned and unaligned position only. But as it is seen, the coincidence is very good.

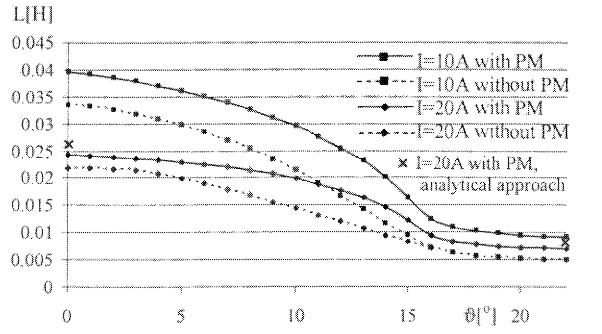


Fig. 5. The phase inductance versus rotor position for phase current I=10 and 20A.

6. ELECTROMAGNETIC TORQUE

The electromagnetic torque was calculated by means of FEM only. The static torque characteristics were obtained for the whole working range. The static torque values are calculated from co-energy W', which is given as:

$$W' = \int_{\Omega} \left(\int_0^i \psi di \right) d\Omega \,, \qquad (5)$$

where Ω is a region on which a co-energy is integrated (whole cross-section area of SRM) and $\int \psi di$ is calculated on the base of Fig.4.. Then the static instantaneous electromagnetic torque is:

$$T = \left[\frac{\partial W'}{\partial \vartheta} \right]_{i=const.} \qquad (6)$$

The calculated values are shown in Fig. 6 for both SRM with and without PM and for phase current 10 and 20A. It is clear, that the maximal torque of SRM with PM is higher approximately two times.

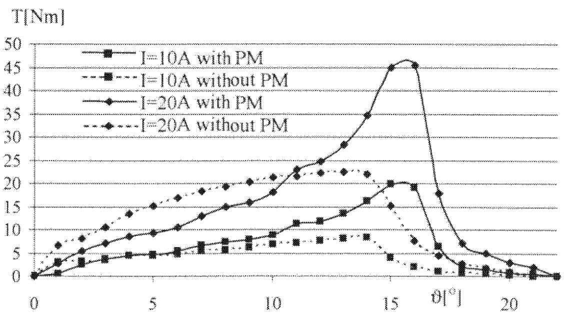


Fig.6. The static instantaneous electromagnetic torque versus rotor position for phase current 10 and 20A.

For more complex analysis, the average torque T is necessary to know. So the average torque is given as:

$$T_{av} = \frac{1}{\Delta\vartheta} \int_{\vartheta_a}^{\vartheta_u} T d\vartheta \,,$$

where $\Delta\vartheta$ is defined as $\Delta\vartheta = \vartheta_a - \vartheta_u$ and it is difference between aligned rotor position ϑ_a and unaligned rotor position ϑ_u. In this case the difference is 22.5°. The phase current was kept constant I=5,10,15,20,25,30 and average electromagnetic torque for SRM with and without PM versus current is shown in Fig. 7. From this figure is clear, that the torque increases in the whole range of the current. For rated current 18A the average torque increasing is about 43%.

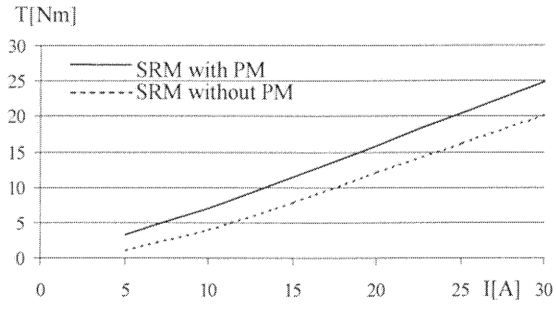


Fig. 7. Average electromagnetic torque versus phase current.

7. CONCLUSION

In this paper, the analysis of PMSRM static parameters are given. The flux linkage, phase inductance and electromagnetic torque versus rotor position and current are calculated. The values for the both SRM, with and without PM have been compared. The FEM and analytical approach was used and results have been compared. The increasing of maximal torque is about 2 times and average torque about 43% for SRM with PM. The conclusion is that PM inserting to the SRM stator yoke is a good method to increase a developed electromagnetic torque and hence to improve its qualitative parameters.

Acknowledgement

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