Study of Winding Arrangement and Material Quality Effects on the Core Losses in High Speed Switched Reluctance Machines

Tiberiu Rusu, Adrian-Cornel Pop, Loránd Szabó, *Member, IEEE* and Claudia Marțiș, *Member, IEEE*

***Abstract*—The paper presents the analysis of losses of a three-phase, high speed 12/8 switched reluctance motor (SRM), intended to be used in automotive applications. The objective is to investigate by comparison the iron losses considering different types of short pitch winding arrangements, as well as different core laminations, and how much these affect the performance of a SRM having the same structure and working under the same conditions. The flux paths and static characteristics of several configurations are analyzed by means of 2D finite-element method (FEM). The effect of different lamination materials on the iron core losses are also studied. Dynamic simulation results were used to evaluate the performance of different SRM variants.**

***Index Terms*—Automotive, iron losses, switched reluctance machine, winding arrangement.**

I. Introduction

Switched reluctance motor (SRM) is one of the typical permanent magnet free motor that has received great attention in automotive applications [1]. It presents advantages, which are mainly related to the simple and robust construction, absence of magnets, hence eliminating some problems like demagnetization, temperature limitation and cogging torque.

The winding arrangement of the SRM plays an important role on the performance of the complete drive. Changing winding arrangement is a simple method that does not require machine structure to be changed and significant increase in performance can be achieved [2].

It was reported in [3], that with the full pitch winding configuration torque density can be increased. However, due to long end-windings, which result in higher copper losses and additional space and material requirement, this type of windings is not the best choice.

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Besides, distributed windings are more complicate to be manufactured which leads to higher costs of the motor.

Short pitch windings are the most used type of windings in SRM because they can be pre-wounded before mounting them on the stator poles, which results in low manufacturing costs [4].

This paper focuses on the performance evaluation of several short pitch winding configurations (known also as concentrated windings) as well as different iron laminations applied to the same 12/8 cross-section and presents results regarding iron losses for a SRM which targets a high speed application.

For choosing the topology suitable for a high speed SRM used in automotive industry, intensive investigation in the literature has been done. Therefore in [5], a comprehensive study and optimization of a 6/4 SRM targeting a high speed automotive application was made by the authors, because they presumed that iron losses are lower for this topology.

In [1], a comparative study was performed for 6/4 and 12/8 machines driving a compressor and it was concluded that the 6/4 topology is slightly better in efficiency specifically at high speed, due to the lesser commutation frequency, compared to that of 12/8. It was also reported that the 12/8 topology has less torque ripple than the 6/4. Regarding noise and vibration aspects, in [6] it was shown that the radial force of 6/4 SRM is more than two times as that one of 12/8 SRM at the same output power. Given that in the automotive industry a very important feature are the Noise, Vibration and Harshness (NVH) issues, the idea was to study a topology with lower torque ripple and to investigate iron losses in such a case considering different winding arrangements and lamination materials.

II. Motor Variants Taken into Study

In this paper, four single tooth, short-pitched winding arrangements of the three-phase 12/8 SRM are investigated (see Fig. 1).

Their design was performed via a 2D finite element (FE) model, due to its accuracy and to the possibility to consider also complex physical phenomena, such as core saturation. The geometry of the machine was optimized in order to maximize its torque density. The considered geometrical variables are given in the cross-sectional view of the SRM shown in Fig. 2.

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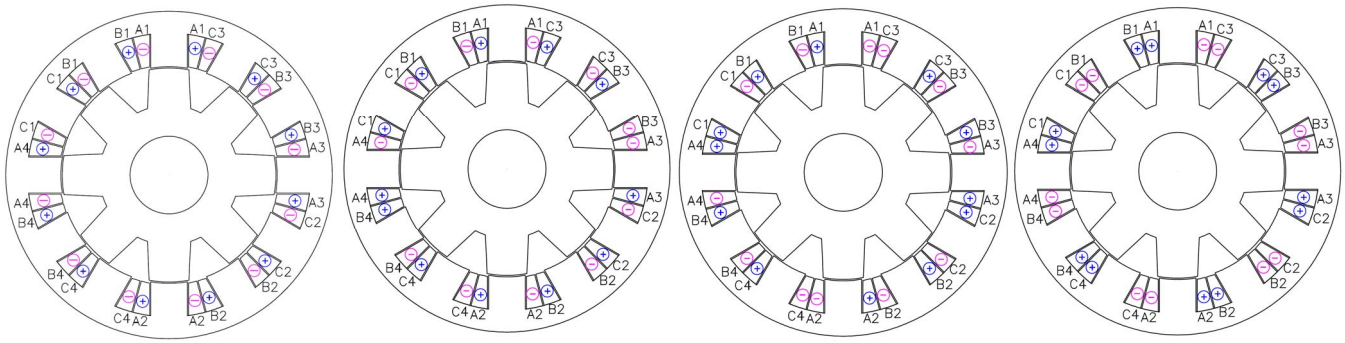


Fig. 1 The short-pitched winding arrangements of the SRM in study

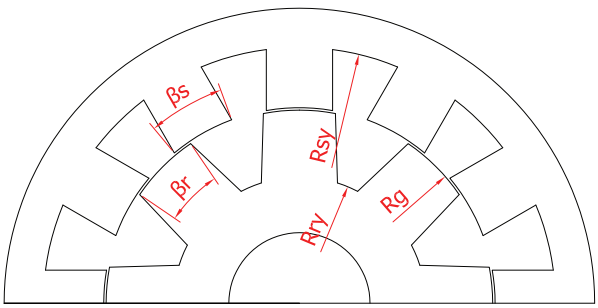


Fig. 2. The optimized dimensions of the SRM

In Fig. 2, R_g is the airgap radius, R_{sy} and R_{ry} are the stator and the rotor yoke radius, β_s and β_r the stator and rotor poles arcs.

The main rated values of the SRM are given in Table I.

TABLE I
SRM RATED VALUES

Rated speed	10,000 r/min
Rated torque	6.7 N·m
Rated output power	7 kW
DC bus voltage	270 V

III. FINITE ELEMENT ANALYSIS

A. Iron Losses Computation

The principles of the computation algorithm for iron-core loss implemented in the FE software are summarized below [7]. The total iron loss is given by:

$$P_v = P_h(f) + P_c(f) + P_e(f) \quad (1)$$

where the hysteresis loss is:

$$P_h = K_h f (B_m)^2 \quad (2)$$

The eddy-current loss is:

$$P_c = K_c \frac{1}{T}\int_0^T \left(\frac{dB}{dt}\right)^2 dt \quad (3)$$

and the excess one:

$$P_e = K_e \frac{1}{T}\int_0^T \left(\frac{dB}{dt}\right)^{1.5} dt \quad (4)$$

In the FE model the dB/dt is calculated for each element of the mesh during a transient simulation for given time variation of the current. The calculation procedure for the three coefficients is described hereafter.

The classical eddy current loss coefficient is computed directly considering the properties of the lamination, as:

$$K_c = \pi^2 \sigma \frac{d^2}{6} \quad (5)$$

where σ is the conductivity and d is the thickness of the lamination sheets.

The other two coefficients, K_h and K_e are calculated based on a fitting procedure, in which the following quadratic function having K_1 and K_2 as degrees of freedom is minimized:

$$err(K_1, K_2) = \sum[P_{vi} - (K_1 {B_{mi}}^2 + K_2 {B_{mi}}^{1.5})]^2 = min \quad (6)$$

where P_{vi} and B_{mi} are the ith point of the data on the measured loss characteristic curve.

In practice the manufacturers for steel lamination do not provide the above mentioned loss coefficients. They are only providing the loss curves in function of flux density for different frequencies. The specific core loss data of typical used electrical steel, namely M800-50A, provided from the supplier are given in Fig. 3.

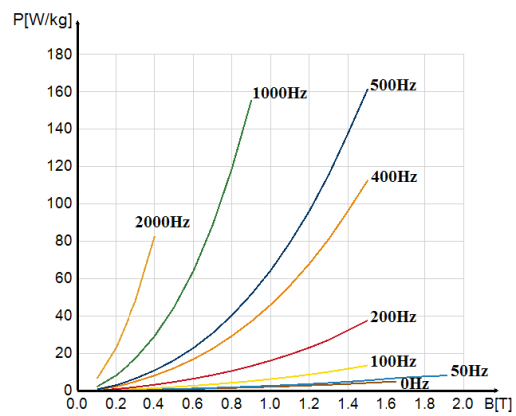


Fig. 3. Specific core loss versus flux density for M800-50A.

Finally based on K_1 and K_2 the K_h and K_e coefficients can be obtained as follows:

$$K_h = \frac{(K_1 - K_c {f_0}^2)}{f_0};\ K_e = \frac{K_2}{{f_0}^{1.5}} \quad (7)$$

where f_0 is the testing frequency for the B-H curve, B_m is the amplitude of the AC flux component, f the frequency, K_h is the hysteresis core loss coefficient, K_c the eddy current core loss coefficient and K_e the excess core loss coefficient.

The last step in the iron loss calculation is to multiply the obtained values with the iron volume, in order to calculate losses in W (since specific losses are expressed in W/m^3).

Due to the particular structure of the SRM, the developed analytical procedures for loss calculation are rather complicated because of different fundamental frequencies in different segments of the motor (tooth or yoke portion of two

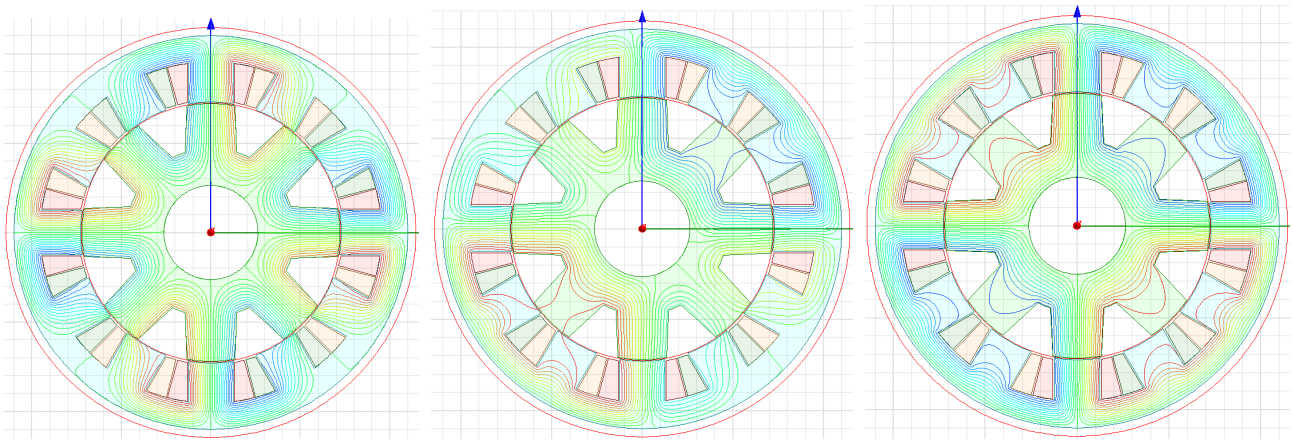
consecutive teeth), as well as the different number of minor loops and additional frequencies caused by switching of electronic devices [8]. Experimental procedures are very complex, and the loss separation is not straightforward. Upon all these, the iron losses estimation by means of using FEM based models seems to be a good trade-off.

However, it should be expected that the calculated iron losses in practice could be different than in the simulation, since as in the latter, effects such as lamination punching, tolerances in cutting the laminations and material anisotropy cannot be considered.

B. *Electromagnetic study for different winding arrangements*

In the Fig. 4, the flux lines in the studied machine in aligned position, having different short pitch winding arrangements, when single phase has unipolar excitation are shown.

In Fig 4a and 4b, the flux distribution for the SRM variants shown in Fig 1a and 1b are given. In Fig. 4c the flux path for the winding arrangement given in Fig. 1c and 1d is shown (these two SRM variants have the same sequence for phase *A*, thus the flux distributions inside the machines are obviously similar).



a) Short pitch category 1 b) Short pitch category 2 c) Short pitch category 3

Fig. 4. Flux lines for different short-pitched winding arrangements

C. *Static Characteristics*

In Fig. 5 the static torque of one phase for different short pitch winding categories fed with an ideal (DC) current of 75 A is given.

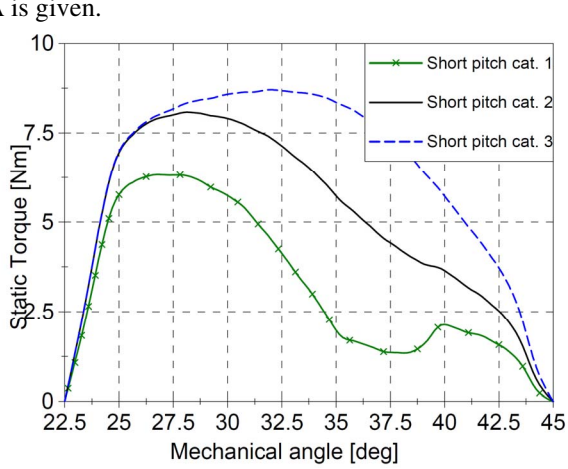


Fig. 5. Static torque of the studied SRM with different winding arrangements

For the first winding category (short pitch cat. 1) the motor has an average torque of 3.2 N·m. With the short pitch cat. 2 winding configuration, the average torque is 5.2 N·m. For the third category (the short pitch cat. 3) the greatest average static torque was obtained, 6.46 N·m. As for short pitch cat. 1 variant the static torque is very low, this was not further studied.

For short pitch winding cat. 3, two different winding arrangements were considered for future dynamic simulations, namely the short pitch 3, and the short pitch 3 modified (their winding arrangement are shown in Fig. 1c and 1d. The static torque characteristics are the same for both configurations, because the winding arrangement for phase *A*, remains unchanged. But different results are foreseen for dynamic simulation, due to the interaction of two neighboring phases.

IV. Dynamic Simulations

A. *SRM Dynamic Modeling*

The dynamic model of the SRM is based on the voltage equation [9]:

$$V = R_s i + \frac{d\lambda(\theta,i)}{dt} \tag{8}$$

where R_s is the phase resistance, and λ is the flux linkage of the phase, depending on the rotor position θ and current i.

Based on (8), the flux linkage is obtained through integration of the voltage after subtracting the voltage drop. The instantaneous variation of the current is obtained by interpolating the $i = f(\theta, \lambda)$ table at given flux λ and position θ.

In the dynamic model of the SRM two static characteristics (of the torque and flux) obtained via 2D FEM analysis performed by means of ANSYS Maxwell program are used:

$$T = f(i, \theta),\ \lambda = f(i, \theta) \tag{9}$$

The previously mentioned $i = f(\lambda, \theta)$ characteristic can be obtained by inversing the $\lambda = f(i, \theta)$ function.

The dynamic simulation program was implemented in MATLAB/Simulink. The average torque control strategy was applied, where firing angles were optimally calculated in a way to minimize the torque ripple of the machine [10]. The model of an asymmetric H-bridge converter was also

integrated in the SRM controller model [11].

B. Simulation Results

The simulation results obtained for the winding arrangements taken into study and for the different lamination materials were compared.

In Fig. 6 are shown the phase currents, while in Fig. 7 the torque variations are given. The computed average iron losses for each winding type are included in Table II. For this study M800-50 core material was considered.

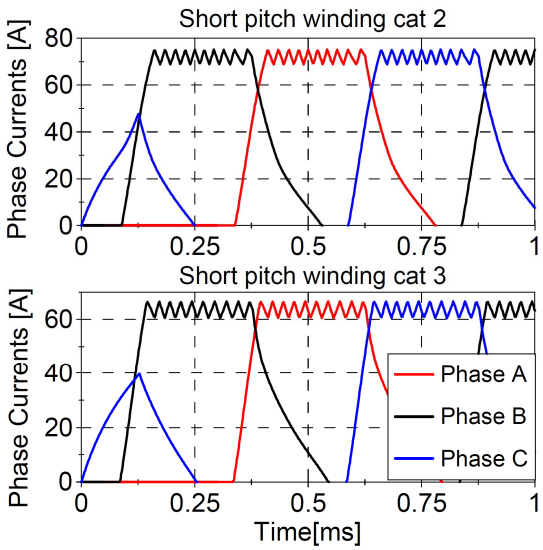


Fig. 6. Dynamic simulated currents at 10,000 r/min and 6.7 N·m for different winding arrangement

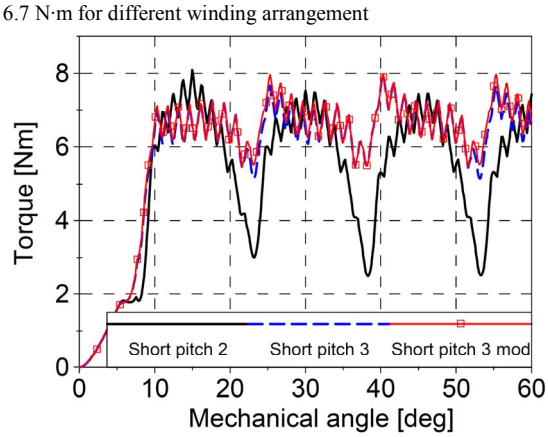


Fig. 7. Motor torque for different winding arrangement

TABLE II
IRON LOSSES FOR THE DIFFERENT SRMS

Winding Type	Average Iron Losses [W]
Short pitch 2	1,263
Short pitch 3	1,182
Short pitch 3 mod	1,229

C. Comparison of Different Materials

In this case the simulations were performed considering four lamination materials: M800-50A, M330-50A, M330-35A and Super E-Core 10JNEX900.The comparison of iron losses (shown in Table III) is made at the operating point of 10,000 r/min and 6.7 N·m for a fundamental period.

TABLE III
CALCULATED IRON LOSSES AT 10,000 R/MIN

Material	Average Iron Loss [W]
M800-50A	1,229
M330-50A	969
M330-35A	717
10JNEX900	153

V. CONCLUSION

In this paper, a comparative study was performed for a high speed SRM used in automotive applications. The analyses of the torque and iron losses based on the same motor structure were made, by considering different winding arrangements and different lamination materials.

It could be concluded, that the lamination material has the greatest impact on the iron losses. The simulations confirmed that using 10JNEX900 material, the iron losses of the machine can be substantially reduced, however with significant cost increase.

Regarding the winding arrangement, it was demonstrated that the modified short pitch 3 variant has the lowest torque ripple. Only small increase in the core losses was reported when using this winding configuration.

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