Electromagnetic Design of Synchronous Reluctance Motors for Electric Vehicles Considering Mechanical Stress

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Abstract

This paper focuses on the Electromagnetic Design of Synchronous Reluctance Motors for Electric Vehicle Considering Loss Minimization with the saturation effect (saturated case) and rotor ploes. The SynRM is considered as a special case of the interior Permanent Magnet Synchronous Machine (PMSM) without permanent magnet excitation. The paper presents an analysis of the performance of an electrical machine used for electric traction in automotive applications. The machine under study is a 8-pole, 72-slot SynRM. The study includes analytical analysis using the SPEED program and numerical analysis to obtain the performance of the proposed machine. The geometry parameter optimization of the machine is also presented in detail and analyzed.

Keywords: Synchronous Reluctances Machine-SynRM, Traction motors, Electric vehicle, Torque ripple, Control strategy.

1. Introduction

The synchronous reluctance machine (SynRM) is very similar to other induction and permanent magnet assistant machines. The main differences are the rotor topolgies of flux barriers or pole shape desiges. Contrary to the rotor of other machines, there is no conduction or permanent magnet on the rotor of the SynRM therefore optimal rotor design is the most important factor. Various rotor configurations with multi layer U and V shapes have influences on electromagnetic performances in M. Ferrari, 2015, X. Y. Zhu 2017, W. Wang2015. For electric vehicle application, the most important parameters of this machine is the provided torque of SynRM, which is dependent on the inductance difference between d- and q- axis and saliency ratio, respectively in N. Bianchi, 2018. This parameter can be improved by optimizing the geometrical parameters of the rotor and stator of SynRM and the combination of slots/number of poles. Another important parameter is speed in the context of the major drawback of the SynRm, the ribs and bridges areas of the rotor would fail because of the high centrifugal forces. The solutions to increase the maximum speed of the SynRM are: change the thickness value of ribs and bridges (strong influence in torque value), fill the barriers with non magnetic materials with high Young's Module value, involving non-magnetic rings mounted in the air-gap, non magnetic insertions in the barriers, increasing the number of ribs, all showing a good potential without technological constraints. The paper will develop the analytical bases software SPEED and finite elements method (Flux 2D) in order to study the influence of different parameters of the rotor on the machine performances. In order to obtain the best performances (torque ripple, efficiency) and one control strategy are detailed in this paper.

2. Analytical Design of SynRM

Electromagnetic torque has been calculated based on the stator, rotor diameter, and power inverter voltage and currents. The electromagnetic parameters can inertial calculated as:

$$T = \frac{\pi}{2} D^2 L_{stk} \sigma,$$

where T is the electromagnetic torque, D is the rotor diameter, L_{stk} is the stack length and $\sigma = \frac{L}{D}$ is defined from 0.8 to 1.25 for the inner rotor.

Torque prediction is carried out for any stator-rotor relative position and the finite element grid is automatically adjusted when the rotor is rotated. The influence of mesh has been investigated to get satisfactory accuracy avoiding inaccuracies due to the element distortion. Only one pole is simulated, due to the motor symmetry. The steady-state stator voltage equations written in the d-q rotating reference frame are:

$$\begin{aligned} v_d &= Ri_d - \omega L_q i_q \\ v_q &= Ri_q + \omega L_d i_d + \omega L_q i_q \end{aligned} \tag{2}$$

where: i_d , i_q , v_d and v_q are the d and q axis components of the armature current and terminal voltage respectively, R is the winding resistance per phase, L_d and L_q are the axis inductances and Φ is the magnets flux linked with the armature winding. The electromagnetic torque is calculated using the well-known equation.

$$T = \frac{3}{2} p\left[\phi_M i_q + \left(L_d - L_q\right) i_d i_q\right] \tag{3}$$

The study concerns the design for a three-phase SynRM 120 kW, 8 poles, 72 slots, synchronous reluctance motor. The cross-section of the stator and rotor core is shown in Fig. 1. The rotor presents one barrier per pole and the magnet material is inserted into this cavity. The stator and rotor consist of a stack of laminated high permeability non-oriented grain silicon steel. Three-phase double-layer distributed windings are inserted in the 48 stator slots. The set of parameters x used in the optimization procedure are listed in Table 1. The motor has 9 variables (thickness layer, outer stator diameter, airgap, slot depth and magnet angles) that vary in a discrete way. For good electromagnetic performance, it should be necessary to minimize irreversible demagnetization. The centrifugal force on steel bridges should be considered with maximum mechanical stress in high-speed operation. From a preliminary analysis a minimum value of 2 mm is imposed. This value is consistent with the maximum speed and mechanical stress.

Table 1 Min and max variables

Parameters	Discrete variables	Min	Max	step
Thickness layer 1 (mm)	X1	1	4	0.5
Thickness layer 2 (mm)	X6,7,8	0.5	2	0.1
Bridge Thickness (mm)	X5	0.5	2	0.1
Tooth depth (mm)	X4	1.5	4.5	0.3
Tooth width (mm)	X3	18	20	0.2
Layer width (mm)	X2	7	10	0.2
Post thickness (mm)	X9	1	2	0.1

The design optimization needs to satisfy several constraints to guarantee the reliability and feasibility of the final design. The main design constraint is the value of the back EMF at maximum speed which has not been allowed to exceed the rated terminal voltage and maximum current density.

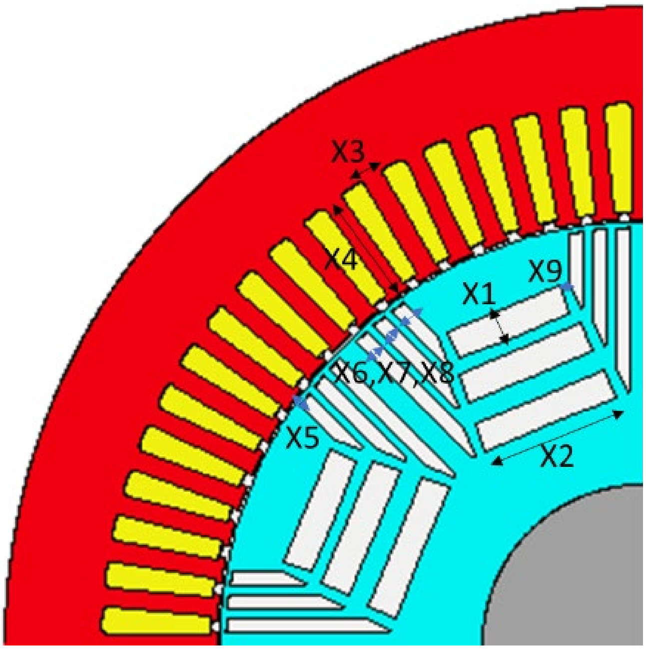

Figure 1. Design variables of 72Slot/8poles

The main constraints are ratios of inner, outer stator/rotor, stator tooth and stator yoke and stack length.
Multi-Objective Function:

Maximize average torque
Minimize Torque Ripple

Constraints:

Efficiency ≥ 91%
Torque ripple≤10%

The design procedure was started according with the performance requirements presented in Fig.2, and the geometrical constraints: stack length (L = 150 mm), stator outer diameter (D_{out}= 205 mm)

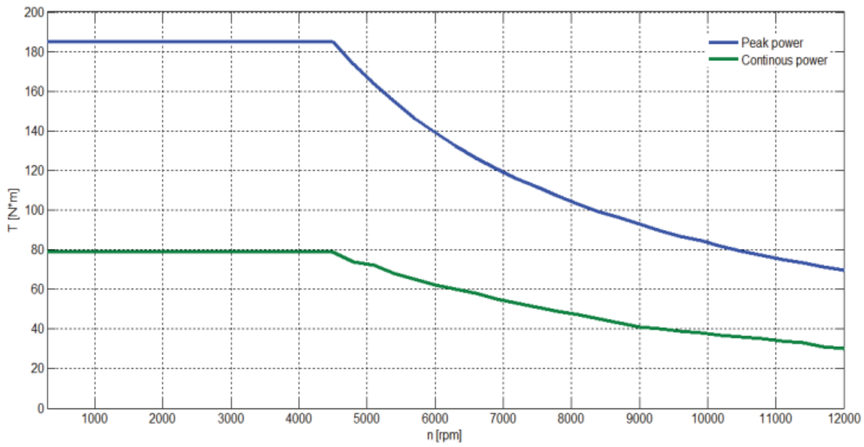

Figure 2. SynRM performance requirements.

Having designed the machine, the following step is to validate the structures using FEA software. For this purpose, FEMM 2D is used. The results of FEA simulation proved that the saturation in the machine core is acceptable. the results showed that the saturation in the core was acceptable, with the maximum flux density only reaching undesirable limits during peak power.

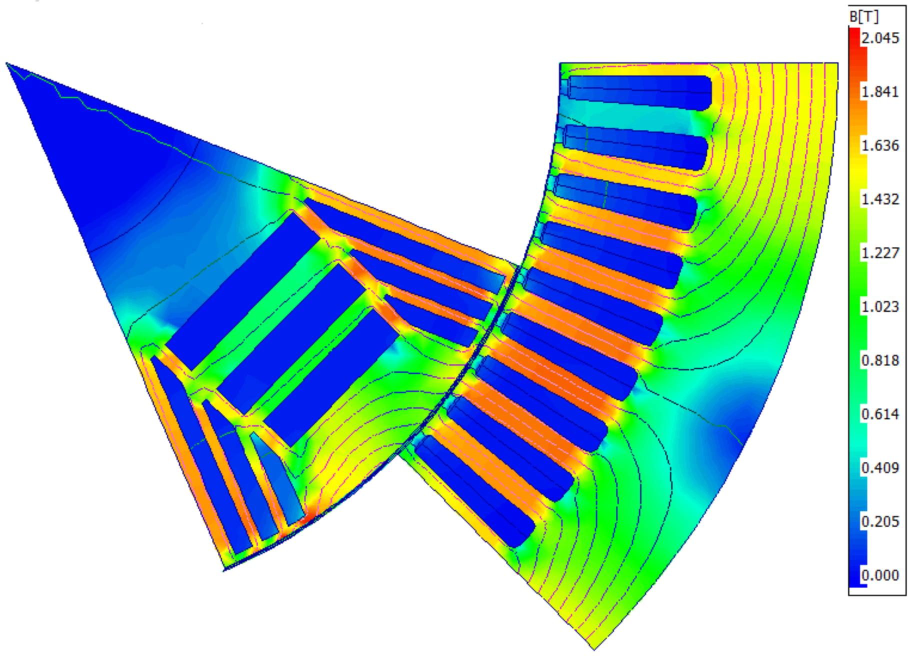

Figure 3. Flux density result by FEM

Finite Element Analysis (FEA) is used in motor design to determine the optimal design that meets performance and design requirements. It does so by mathematically representing the design problem as a minimization problem that takes the motor parameters as variables. The FEA program computes the objective function and constraints of the problem, which is then used by the optimization procedure to iteratively update the parameters and find the best trade-off between them to achieve an optimal motor design.

Table 2 Geometry parameters

1	72 Slots, 12 Poles
2	Shaft diameter = 60mm
3	Rotor outer diameter = 142.8 mm
4	Stator inner diameter = 144.2 mm
5	Airgap length = 0.7 mm
6	Stator stack length = 140 mm
7	Rotor stack length = 141.6 mm
8	Average stack = 140.8 mm

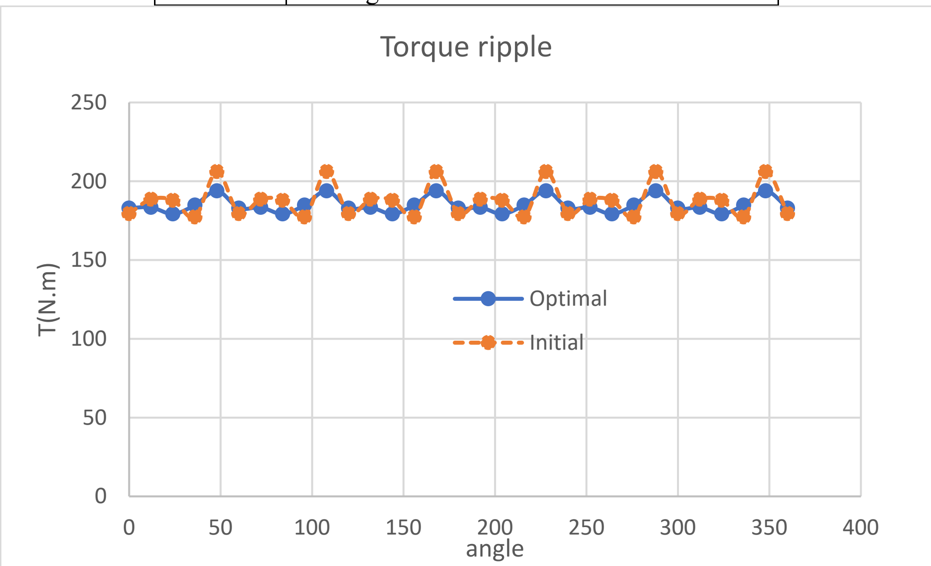

Figure 4. Torque waveforms of the initial and optimal models

The figure 4 shows that the optimal model has an average torque of 185 Nm, which is 7% higher than the initial model. The torque ripple of the optimal model is 7.5%, which is slightly lower than that of the initial model but still within the constraint of 10%.

In order to check the torque production, the machine was fed with currents and the position of the rotor was determined to find the maximum torque. The mean value of the torque was plotted in Figure 4, and it was noted that the structure had a low torque ripple, meaning that the torque was relatively smooth. This is an advantage because it eliminates the need to use skewing, which is a technique used to reduce torque ripple. However, increasing the current value may be necessary to achieve the desired torque, as skewing reduces the mean value of the torque.

Table 3. Electromagtic results of the initial and optimal designs

Parameters	**Optimal**	**Initial**	**Unit**
Maximum torque possible	217.96	217.28	Nm
Average torque (virtual work)	184.89	167.15	Nm
Average torque (Maxwell stress)	188.25	171.35	Nm
Average torque (DQ)	185.48	167.62	Nm
Average torque (loop torque)	184.12	166.39	Nm
Torque Ripple (MsVw)	14.127	17.997	Nm
Torque Ripple (MsVw) [%]	7.5717	10.634	%
Speed limit for zero q axis current	12536	11347	rpm
Electromagnetic Power	97687	88617	Watts
Input Power	1.03E+05	93612	Watts
Total Losses (on load)	8610.7	8686.9	Watts
Output Power	94113	84925	Watts
System Efficiency	97.546	97.369	%

The efficiency of the machine over the entire current and speed range (0-15.000 rpm, with 500 rpm steps) is presented in Fig. 5 in the form of an efficiency map. Efficiency values lower than 94% are obtained for high currents and low speed because of the high current density required producing the desired torque, at high speeds the efficiency is higher than 95% because of the low iron losses.

The variation of total (copper and iron) losses with the motor speed are presented in Figure 5&6.

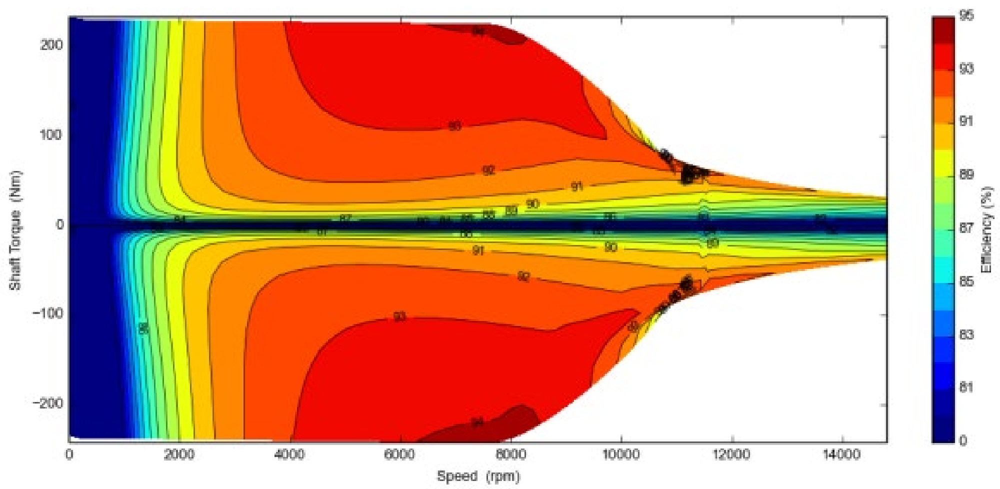

Figure 5. Torque map

The continuous power requirement of 80kW is also available between 4,500rpm to 1500rpm. The continuous peak power is close to the 165kW. The machine is operating within the thermal limits for all speed range.

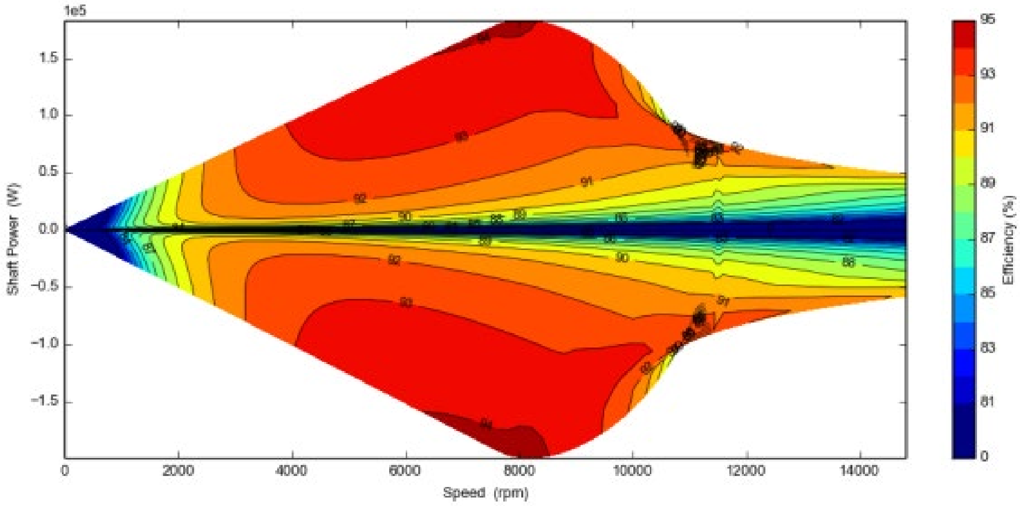

Figure 6. Power map

3. Mechanical Stress Analysis

An initial modeling and parametric analysis setting for the automatic change of design variables was performed using the FEM Program. By creating Matlab files and batch files, electromagnetic analysis was automatically performed in CAD. Analytical analysis results were transferred to Matlab, and the responses of multi-objective functions and constraints were automatically calculated. In addition, when the computational analysis for one experimental point was finished, the shape design parameters were automatically changed in FEM with the aid of CAD tools by receiving the MATLAB command.

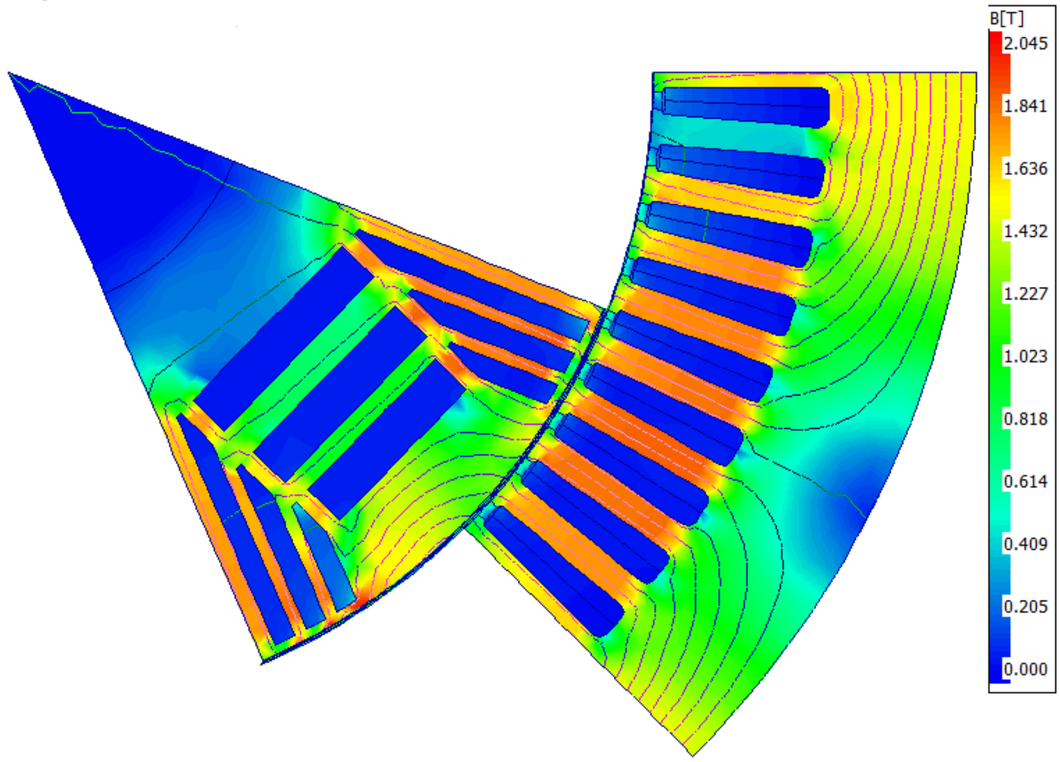

Figure 7. Flux density result by FEM

With Silicon steel of M250-35A the yield stress is 455 MPa, mechanical stree analysis was implemented to evaluate the Maximum stress value, Averaged stress value and Safety ratio with respect to the material yield strength.

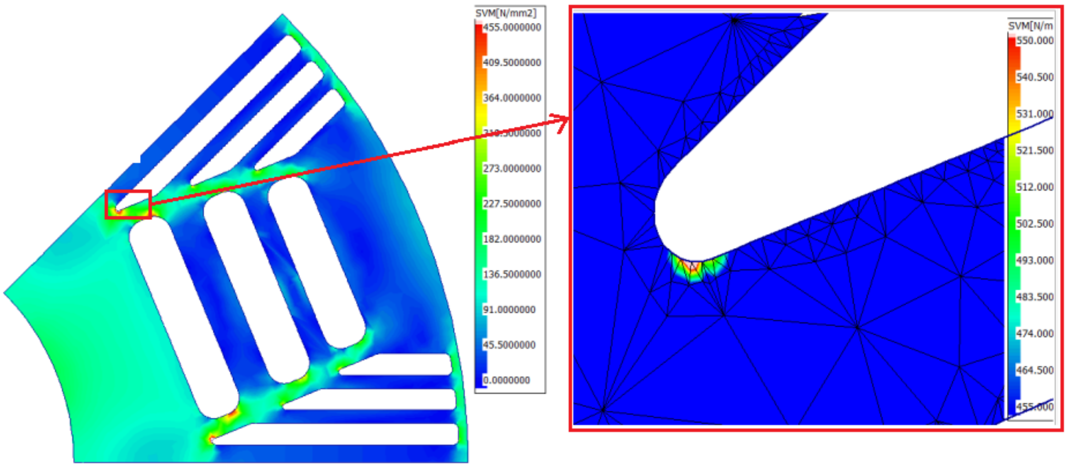

Figure 8. Mechanical stress results

To visualise the area with Von Mises stress above Yield stress (455MPa). The stress values of Layer 1 of rotor barriers can be observed there are just few elements of the mesh. These regions can be adapted via dedicated mechanical design.

4. Conclusion

This paper presents the shape optimization of a SynRM using multi optimization of geometry parameters of rotor poles. To maximize the performance of the SYNRM, the average torque, torque ripple was set as the multi-objective function, and efficiency and torque ripple were set as constraints. FEM was used to improve the accuracy of the design results. Efficiency was performed based on changes of the design variables. As a result of the parametric study, the layer thickness, rib thickness, stator depth and with parameters were determined to be design variables. The result of optimization shows the efficiency of the entire approach. The influence of stator slot/pole number combinations in average value of torque and torque ripples has been investigated in this paper. The configuration with 27 slots and four layer flux-barrier has the lowest torque ripple. Also this configuration has been numerically evaluated, and the obtained performances has presented in this paper. In continuous power the efficiency is 95% and in peak power condition is 90% at rated speed.

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