Comparison of Axially and Transversally Laminated Synchronous Reluctance Motors by Using FEM Based Analysis

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Abstract: The rotor design of a Synchronous Reluctance Motor (SynRM) has a significant effect on its efficiency, torque ripple and maximum torque. In order to achieve a good compromise between these three goals, optimized rotor design is necessary. Due to nonlinear characteristics of magnetic materials, finite element method (FEM) is considered to be a better approach for rotor optimization of the SynRM. The two most crucial design parameters of a SynRM are position and width of flux-barriers for the torque output and torque ripple. This paper proposes an approach to obtain the optimized values of the above mentioned parameters. So in order to achieve design with a low torque ripples and enhanced torque output for a SynRM with full pitch distributed windings in 24 slots on stator. This method is valid for a wide range of SynRMs. It also provides insight into the behaviour of the machine as a function of position and width of flux barriers. Furthermore, the torque and torque ripple of SynRMs having an axially and transversally laminated rotor are compared.

Keywords: Axially, Electrical, Motor, Ripple, Transversally, Reluctance and Synchronous.

I. INTRODUCTION

Electric motors considered as workhorse of the modern industries, consume about 70% of the industrial electrical demand. Hence there is an increasing demand for motors which are highly efficient, economical and provides high output per unit volume. A few newly adopted machines like permanent magnet and reluctance machines have replaced the conventional dc and induction motors in many applications. But the permanent magnets being made up of costly rare earth materials have now given way for more reliable and satisfactory reluctance machines [1].

Besides being simpler and robust the SynRM offer several other advantages such as improved efficiency and reduced cost compared over other prominent machine configuration like induction and permanent magnet synchronous machine (PMSM). The improved efficiency is on account, of absence in windings on the rotor as compared to conventional machines, while reduction in cost is on account of the absence of permanent magnets as compared to PMSM. The advance designs offer improved power factor as compared to ordinary synchronous reluctance machines. The lower torque ripple, vibration, and noise compared to the switched reluctance motor. Therefore they can be considered as an alternative solution to induction and PMSM in various applications, such as pumping, vehicle traction machines etc [2].

In addition to above mentioned advantages the SynRM suffer from the draw backs which cannot be overlooked. Synchronous reluctance machines are normally operated in saturation to achieve high torque density. Additionally, there is a significantly high cross-saturation of the inductances. Therefore it requires model analysis under saturation for several applications, such as sensorless speed control and efficiency optimization [3].

Fig. 1. (a) Axially and (b) Transversally Laminated Rotor for SynRM

The initial models of reluctance machines appeared in 20th century. Several designs were proposed by the researchers since then, however they become obsolete with time due to their inferior performance as compared to their counterpart conventional machines. The modern SynRM designs normally use axially and transversally laminated rotors as depicted in Figs. (1a) and (1b) respectively. An axially laminated rotor can present a high anisotropy and provides a very high unsaturated saliency ratio on optimizing pole span and insulation ratio [4,5,6]. However, from the mechanical design consideration, this rotor also exhibits some drawbacks as compared to the transversally laminated rotor core. The performance of transversally laminated rotors can be improved by using flux barriers with proper positions, shape and the number. A reasonably good magnetic design can be obtained by using numerical techniques [8]. However, the analysis by using FEM considers the nonlinear magnetic behaviours of the materials which play a key role for performance under saturation and overload condition [9].

This paper aims at optimizing the design of a SynRM’s by FEM analysis on axially and transversally laminated synchronous reluctance motors. In this procedure, different rotor parameters and their relative effects on the motor performance in terms of torque output and torque ripple are studied. The impact of several rotor
design parameters on the performance for SynRM is investigated in [10,11,12]. It is evident that the flux-barrier widths and position have a key influence on the SynRM output torque and torque ripple, respectively. Therefore the main objective is to find parameters value to get a best compromise between output torque and torque ripple.

II. DESIGN PROCEDURE

The design is carried out using the 2D/3D-FEM, in Ansys Maxwell software. The FEM solver is used to analyze the different SynRM rotor designs in a nonlinear, two dimensional, magneto-static solver. Therefore in this case, the effect of the end windings and flux scatterings at the both sides of the stator are ignored.

The SynRM stator design is based on a 24-slot stator with 3 phase, 4-pole full pitched distributed winding and 80 mm inner diameter. Basically, the stator is same for both axially and transversally laminated SynRM. The SynRM rotors with air gap of 0.3 mm designed in such a way that it is possible to optimize its performance by varying parameters in feasible ranges. The calculation method used to evaluate the torque takes into account the effect of cross saturation between the d and q axes inductances, but the effect of the core losses on torque production is ignored. In all of the digital computer simulations, the amount of the ampere per turn (AT) in stator windings is kept constant but the rotor angle is changed to determine the torque at different rotor angles.

Axially Laminated Rotor:

(A). Design Strategy:

The axially laminated rotor design consists of steel laminations interleaved with plastic insulation sheets. The rotor has been designed for four poles configuration. The lamination and insulation layers are clamped tightly together between the Bakelite pole holders and shaft. The Fig. 2 shows the schematic design configuration of axially laminated rotor.

Fig. 2. Schematic Figure of Axially laminated rotor

(B). Effect of Pole Span:

The rotor is made up of 25 layers of silicon steel sandwiched between layers plastic sheet insulation. Fig. (3a) and (3b) shows the rotors with 0.2 and 0.4 mm silicon steel laminations and with same thickness plastic sheet insulation respectively. So the insulation ratio is 0.5 for both cases.

Fig. 3. Shows Axially Laminated Rotors with Different Pole Spans

The Fig. 4 shows the Torque developed at different rotor angles for rotor designs with 0.2, 0.4, 0.6 and 0.8 mm combined thickness of silicon steel and plastic insulation layer with insulation ratio equals to 0.5. The maximum developed torque increases with increase in pole span and peaks at 0.7 mm.

Fig. 4. Variation of Torque vs Rotor Angle at Different Pole Spans

(C). Effect of Insulation Ratio:

The Fig. 5 shows the variation of torque with respect to rotor angles at different insulation ratios. Initially with increase in insulation ratio the maximum torque increases but later obtaining the highest maximum Torque for 2/7 Insulation Ratio it decreases further. The curve is close to sinusoidal pattern.

Fig. 5. Variation of Torque Vs Rotor Angle at Different Insulation Ratios

On optimizing rotor by considering the effect of pole span and Insulation ratio the maximum torque value
reached is 17.56 Nm at torque ripple equals to 11.29 over a slot pitch. The optimized rotor design obtained with 25 layers of 0.7 mm combined thickness of silicon steel and plastic sheet insulation having insulation ratio of 2/7.

Transversally Laminated Rotor:

(A). Design Strategy:

The Fig. 6 shows specifications of a single flux barrier in the rotor design. In case of a single flux barrier b1 represents the flux barrier position angle on the rotor outer surface perimeter with respect to axis transverse to axis of symmetry and w1 is the width of flux barrier. While in case of multiple flux barriers the position angles are b1, b2, b3 and b4 with flux barrier width w1, w2, w3 and w4 respectively for first, second, third and fourth flux barrier.

It is possible to investigate the effect of the flux barrier numbers as well as their position angles and widths on the maximum torque and torque ripple. In the transversally laminated rotor, usually the width of the tangential and radial ribs is not zero due to mechanical reasons. These parameters have adverse effect on the torque and efficiency of SynRM.

In order to achieve a low q-axis inductance, the ribs of the transversally laminated type rotor should be as thin as mechanically possible. Usually due to punching of the lamination, the rib width should not be less than the thickness of the laminations. Here the thickness of lamination is considered equal to 0.5 mm so the width of tangential ribs cannot be less than 0.5 mm [13].

The slot pitch is 15 mechanical degrees. In the following investigations, the effects of different parameters on the torque are studied by sweeping variables in steps for calculations in FEM analysis with a constant ampere turn. The machine simulation is analysed for torque ripple over pole pitch range by considering suitable angular steps. By movement of the rotor over one pole pitch, all the torque ripples caused by inductance variations are taken into account. Torque developed vs. rotor angle characteristic provides torque ripple and maximum torque variation with respective rotor parameters.

(B). Effect of the Flux Barrier Position:

The effect of a single flux barrier with constant width (2mm) is investigated by changing barrier position angles from 48.75° to 80°. The flux barrier angle changed in steps such that the flux barrier moves away from rotor centre as shown in Fig. 7.

![Fig. 7. Rotor with Different Flux Barrier Position Angles](image_url)

Fig. 8 shows the variation of torque with respect to rotor angle at various flux barrier position angles. The maximum torque initially increases with increase in flux barrier position angle and later decreases with further increase in it.

![Fig. 8. Shows Variation of Torque vs Rotor Angle Curves at Different Flux Barrier Positions](image_url)

Fig. 9 shows the variation of maximum, average and minimum torque of a single flux barrier rotor as a function of the barrier location.
Fig. 9. Shows Variation of Maximum, Minimum and Average Torque with Respect to Flux Barrier Position Angle.

Fig. 10 shows the variation of maximum torque and torque ripple of a single flux barrier rotor as a function of the barrier location over a pole pitch.

The torque attains its maximum values corresponding to flux barrier positions (45° to 75°) are in multiple of half slot pitch and minimum values at intermittent flux barrier positions. The reason for lower torque ripple at these flux barrier positions is the cancellation of the cogging torques at both ends of the flux barrier. The torque ripple is low and high corresponding to flux barrier positions having lower and higher maximum torque respectively. Therefore we can say that lower torque ripple and higher maximum torque are contradictory to each other. Beyond 75° flux barrier position the torque ripple increases sharply due to sharp increase in cogging torque.

(C). Effect of the Single Flux Barrier Width:

The effect of a single flux barrier width has been investigated by changing the width of the barrier as it is presented in Fig. 11.

Fig. 11. Modification of Flux Barrier Width

Fig. 12 shows torque as functions of the rotor angle at different flux barrier widths at rotor position angle 56.25°. At each step the flux barrier width is increased by 2 mm.

Fig. 12. Modification of Torque vs Rotor Angle at Different Flux Barrier Width at Flux Barrier Position Angle 56.25°

The Fig. 13 shows that by increasing the flux barrier width the maximum torque increases non-linearly and peaks at 8mm. The reason could be that the d-axis flux path reluctance does not change while the q-axis flux path reluctance increases rapidly but not linearly due to slot effects. Of course after a certain value of flux barrier width, torque starts decreasing instead the flux barrier width increases. This is due to increase in d-axis flux path reluctance now.

Fig. 13. Modification of Maximum Torque vs Flux Barrier Position Angle at Different Flux Barrier Widths

As it can be seen in Fig. 14 and Fig. 15, the contour plot shows the region of maximum torque and Ripple with respect to variation of flux barrier width and position angle respectively.

Fig. 14. The Contour Plot Shows Maximum Torque Vs Flux Barrier Width and Position Angle
The maximum torque initially increases as a function of the barrier width; however, at the same time the torque ripple also increases, because a constant amper-turn has been used. The air-gap flux varies due to the saturation effect in the stator teeth and ribs. Therefore, it reduces the smoothness of the flux distribution in the air gap. The distribution of the air gap flux and its smoothness depends upon winding. Therefore the lower the Ampere-turns mean the lower the saturation levels in the stator teeth and ribs. Consequently the lower the torque ripple.

The contour plots show the regions of maximum torque and maximum torque ripple coincides. Therefore we can say maximum torque is available with high torque ripple. In order to reduce torque ripple, we have to compromise with maximum torque.

(D). Effect of Ribs:

In the transversally laminated rotor to have more rigidity in the rotor structure the wider tangential and the radial ribs are suitable from mechanical design viewpoint. But the wider tangential and radial ribs have negative impact on output torque and performance of the SynRM. These ribs are shown in Fig. (1b).

The effect of the width of the radial ribs and tangential ribs on the average torque and torque ripple is presented in Fig.-12. The enlargement of the ribs increases the q-axis inductance and decreases the torque. The increase of the q-axis inductance decreases the saliency ratio and increases the effect of the cross saturation.

(E). Optimization Process:

None of the flux barrier positions produce completely smooth torque. This means that in order to optimize rotor design when using several flux barriers the positions of the flux barriers should be selected such that the ratio of torque ripple to maximum torque is minimized. Thus a compromise between torque ripple and maximum torque should be achieved. The rotor designs with multiple flux barriers are analysed for maximum torque and minimum torque ripple by changing variable parameters in steps over possible ranges to obtain optimum design.

The optimized rotor design considering the balance between torque ripple and maximum torque is achieved by using parametric sweep approach using FEM software. So that the nonlinear effect of magnetic core and effect of cross saturation is considered. Table-1 shows the details of the optimized transversally laminated rotor.

<table>
<thead>
<tr>
<th>Barrier Number</th>
<th>Barrier positions (Degree)</th>
<th>Barrier Width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>48.75</td>
<td>4</td>
</tr>
<tr>
<td>Second</td>
<td>56.25</td>
<td>4</td>
</tr>
<tr>
<td>Third</td>
<td>71</td>
<td>2</td>
</tr>
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III. CONCLUSIONS

In this paper, a FEM approach was performed to analyze the effects of rotor design variables such as (a) Pole span and insulation ratio on axially laminated SynRM, (b) Flux barrier width, flux barrier position, width of ribs on transversally laminated SynRM performance. Effects of each variable were shown in the case of a four-pole transversally laminated SynRM. A systematic procedure was applied to obtain the optimized design of SynRM’s. Minimum air-gap length is limited by the mechanical manufacturing limits.

The transversally and axially laminated rotor SynRM having same ampere turns are compared for torque ripple and maximum torque as shown in Table 2.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Transversally Laminated</th>
<th>Axially Laminated</th>
</tr>
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<tbody>
<tr>
<td>1. Max Torque (Nm)</td>
<td>17.35</td>
<td>17.56</td>
</tr>
<tr>
<td>2. Torque Ripple %</td>
<td>14.09</td>
<td>11.29</td>
</tr>
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</table>
The maximum torque in case of axially laminated rotor is higher as compared to transversally laminated rotor. The torque ripple is lower in axially laminated than transversally laminated rotor design, which is due to effect of ribs in case of transversally laminated rotor.

The transversally laminated rotors are more economical for industrial production as compared to axially laminated due to easier fabrication. The performance of transversally laminated SynRM can be further improved by introducing low intensity magnets in flux barriers. This reduces the effect of ribs and improves performance.

IV. REFERENCES


