EFFECT OF STEEL LAMINATION ON CORE LOSSES IN SWITCHED RELUCTANCE MOTORS

J. Kartigeyan and M. Ramaswamy
Member IEEE, Department of Electrical Engineering, Annamalai University, Tamil Nadu, India.

ABSTRACT

The paper orients to investigate the influence of the steel lamination on the occurrence of the core losses in a three phase switched reluctance motor (SRM). The study attempts to compare the core losses in terms of its magnitude for the different types of core laminations on the motor with the same structure, operating under the same conditions. The effort involves the use of 2D finite-element method (FEM) to obtain the core loss characteristics for a range of lamination thickness. The method allows a dynamic simulation procedure to evaluate the extent of loss reduction and suggest the choice of the appropriate size of the lamination for high speed applications.

Key words: Electrical Steels, FEM, Laminated Iron Core, Loss Reduction, SRM.


1. INTRODUCTION

The focus emerges to develop electronic motors for many high speed and industrial applications that require operation in extreme environments [1]–[3]. The switched reluctance motor (SRM) belongs to the category of a typical permanent magnet free motor, potentially attractive due to its simplicity in construction, cooling, geometric versatility, durability, and higher permissible rotor temperature [4]–[7].

The SRM occupies a pre-eminant place in high-speed applications such as the aero-engine starter generators[8],[9], fault-tolerant multiphase power generation [10], centrifuges [11] and electrically assisted turbochargers [12] in addition to many other low- and high-speed industrial applications.

The theory of loss reduction in electrical machines augurs to be an important consideration for environmental conservation and enforces measures on the minimization of the core losses and the enhancement of efficiency of SRM. The efforts centre on the optimization of mechanical design parameters, development of novel mechanical/electromagnetic designs [13], [14], the selection of appropriate core material [15]–[19], and the choice of the appropriate control strategy [8], [15], [20] and [21].

The rationale of this paper owes to investigate the minimization of the core loss in a SRM using different core laminations and arrive at the suitable choice of the lamination thickness for target high speed applications. The exercise engages core loss measurement of non-oriented electrical steel using single
sheet tester and also involves the application of 2D finite-element method (FEM) base simulation analysis to extract the core loss characteristics of the stator and rotor of SRM and provide interpretative results.

2. SWITCHED RELUCTANCE MOTOR

2.1. Basic Operation Philosophy
Both the stator and rotor of a SRM inherit a salient-pole structure and serve to produce a high output torque by the alignment tendency of poles. The rotor, basically a piece of steel (and laminations) forms salient poles with no windings or permanent magnets on it. It shifts to a position with minimum reluctance and corresponds to the position of maximum inductance of the magnetic path of the excited stator phase winding. It lends to an inherent simplicity in geometry for SRM as evidenced from the 2D finite element model shown in Fig. 1 and includes its specification in Table 1.

![Finite element mesh for the SRM](image)

**Figure 1** Finite element mesh for the SRM

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (Kw)</td>
<td>1.5</td>
<td>Stator yoke thickness (mm)</td>
<td>11</td>
</tr>
<tr>
<td>Speed (rpm)</td>
<td>5100</td>
<td>Stator-rotor gap (mm)</td>
<td>0.3</td>
</tr>
<tr>
<td>Torque (N-m)</td>
<td>2.8</td>
<td>Rotor outer diameter (mm)</td>
<td>70</td>
</tr>
<tr>
<td>No. of phases</td>
<td>3</td>
<td>Rotor yoke thickness (mm)</td>
<td>08</td>
</tr>
<tr>
<td>No. of stator/rotor poles</td>
<td>12/8</td>
<td>Shaft diameter (mm)</td>
<td>30</td>
</tr>
<tr>
<td>Stator outer diameter (mm)</td>
<td>120</td>
<td>Voltage (V)</td>
<td>72</td>
</tr>
</tbody>
</table>

2.2. Topology
A variation in the number of phases, the number of stator and rotor poles enables to realize many different geometries of the SRM. The combinations range over \( N_s=4, N_r=2; N_s=6, N_r=4; N_s=8, N_r=6; N_s=12 \) and \( N_s=8 \) and ensure that the rotor does not align in a position where the summation of the electromagnetic torque generated by each phase turns out to be zero [22]. The single phase SRM falls into the simplest category with the advantage of the fewest connections between the machine and power electronic
interface. However the higher torque ripple and the inability to start at the angular positions assuage to be a drawback [23] and enumerate to be suitable for very high-speed applications.

The use of a stepping the air-gap can avoid the starting problems in a two phase SRM and the higher torque ripple forays to be an important drawback [24]. The most popular topology of a three-phase SRM represents a good compromise between starting and torque ripple problems and the number of phases. Besides alternative three-phase machines with doubled-up pole numbers can offer a better solution for high speed applications.

The four-phase motor known for reducing the torque ripple finds the large number of power electronic devices and connections to be a major drawback, limiting it to a specific application field. However a practical limitation leads to consider the larger phase numbers in the measure of the increase of the converter phase units and hence the total cost [25].

2.3. Topology Selection
The choice of the three phase topology arises because of the unique features and advantages and the comparative study of 6/4 and 12/8 machines driving a compressor [26] shows that the 6/4 topology edges to be better in efficiency due to the lower commutation frequency compared to that of 12/8. The 12/8 topology offers a lower torque ripple than the 6/4 and the issues relating to the noise and vibration [27], reveal that the radial force of 6/4 SRM becomes more than two times as that one of 12/8 SRM at the same output power. The $3\phi$, 12/8 SRM targeting a high speed application therefore evinces an extensive scope primarily due to its higher level of performance.

3. CORE LOSS TESTER AND LAMINATION MATERIAL

3.1. Single Sheet Tester

The tests performed using single sheet tester DW-21 as seen in Fig. 2 at 50 Hz and high flux densities on the material of a 12/8 SRM serve to predict the accuracy of the core loss of the magnetic materials listed in Table 2. The tester measures through a two way approach one by weight method and the other using thickness. The digitally programmable arrangement involves the use of separate setting keys for three standard induction input. It allows testing the specimen from 35Hz to 125Hz and avails the role of a microcontroller to engage the measurement in Watt/kg. It follows a single strip testing procedure and can be expressed as economic alternate of Epstein tester.

![Figure 2 Single sheet tester DW-21](image-url)
3.2. Lamination Material
In non-oriented electrical steel, with silicon content ranging from about 2.7% to about 3.0% and typically including about 0.003 % carbon, 0.15 % manganese, 0.01 % phosphorus, 0.001 % sulphur to increase their resistivity and thus reduce core losses, and are processed to provide for uniform magnetic properties both longitudinally (with the grain) and transversely (across the grain of the steel). For rotating machinery, non-oriented silicon steels provide good to very good values for all key attributes. Of moderate silicon content, they allow for reasonably long tool life and ease of processing. Used in a wide variety of motor [28]-[31] and generator applications, including servo motors for motion control systems, aerospace accessories, hybrid and other electric vehicle traction motors[32], [33] and industrial and public service motors and generators where long-term energy efficiency is of concern.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
<th>W15/50Hz (W/kg)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M400-65A</td>
<td>0.65</td>
<td>4.20</td>
<td>7700</td>
</tr>
<tr>
<td>M400-50A</td>
<td>0.50</td>
<td>3.89</td>
<td>7700</td>
</tr>
<tr>
<td>DI MAX-M19</td>
<td>0.47</td>
<td>2.78</td>
<td>7650</td>
</tr>
<tr>
<td>DI MAX-M19</td>
<td>0.35</td>
<td>2.56</td>
<td>7650</td>
</tr>
<tr>
<td>DI MAX-M15</td>
<td>0.47</td>
<td>2.59</td>
<td>7650</td>
</tr>
<tr>
<td>DI MAX-M15</td>
<td>0.35</td>
<td>2.34</td>
<td>7650</td>
</tr>
</tbody>
</table>

Figure 3 Core loss curves of M400-65A-0.65 mm and M400-50A-0.50 mm at 50 Hz

Figure 4 Core loss curves of DI MAX-M19-0.47 mm and DI MAX-M19-0.35 mm at 50 Hz
The Figure 3-5 shows the core loss curves of various non-oriented steels at 50 Hz with lamination thickness ranges from 0.35 mm to 0.65 mm. It evinces from the loss curves that thinner lamination contribute to reduced losses than the thicker ones. The eddy current losses as observed from Table 3 cannot be eliminated completely, but can be greatly reduced and controlled by reducing the thickness of the steel.

4. CORE LOSS FORMULATION

The loss separation is widely used with problems involving magnetic laminations. The loss separates the total core loss into hysteresis loss $W_h$, eddy current loss $W_e$, and excess loss $W_{ex}[34]$

$$W_c = K_h f (B_m)^2 + K_e (f B_m)^2 + K_{ex} (f B_m)^{1.5}$$

(1)

Where $B_m$ is the amplitude of flux component, $f$ is the frequency, $K_h$ is the hysteresis core loss coefficient, $K_e$ is the eddy-current core loss coefficient, and $K_{ex}$ is the excess core loss coefficient.

The equation (1) can be written as

$$W_c = K_1 B_m^2 + K_2 B_m^{1.5}$$

(2)

From equation (1) and (2) $K_1$ and $K_2$ can be

$$K_1 = K_h f + K_e f^2 \text{ and } K_2 = K_{ex} f^{1.5}$$

(3)

The eddy current loss coefficient is calculated directly as

$$K_e = \pi^2 \sigma \frac{d^2}{6}$$

(4)

Where $\sigma$ the conductivity and $d$ is the thickness of lamination.

Minimizing the quadratic form to obtain $K_1$ and $K_2$

$$f(K_1, K_2) = \sum [W_{ci} - (K_1 B_{m1}^2 + K_2 B_{m1}^{1.5})]^2 = \text{min}$$

(5)

Where $W_{ci}, B_{m1}$ is the $i^{th}$ point of the data on the measured loss characteristics curve.

The other two loss coefficients are obtained as
Effect of Steel Lamination on Core Losses in Switched Reluctance Motors

\[ K_h = \frac{(K_I - K_e f_0^2)}{f_0} \] \quad and \quad \[ K_{ex} = \frac{(K_z)}{f_0^{1.5}} \] \hspace{1cm} (6)

Where \( f_0 \) is the testing frequency for loss curve. The coefficients \( K_h \) and \( K_{ex} \) are determined using curve fitting of the core loss data. The loss coefficients of the selected laminations are obtained as seen in Table 3.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (mm)</th>
<th>( K_h )</th>
<th>( K_e )</th>
<th>( K_{ex} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>M400-65A</td>
<td>0.65</td>
<td>2.69 \times 10^{-2}</td>
<td>1.5 \times 10^{-4}</td>
<td>5.19 \times 10^{-4}</td>
</tr>
<tr>
<td>M400-50A</td>
<td>0.50</td>
<td>2.69 \times 10^{-2}</td>
<td>1.17 \times 10^{-4}</td>
<td>3.24 \times 10^{-4}</td>
</tr>
<tr>
<td>DI MAX-M19</td>
<td>0.47</td>
<td>2.01 \times 10^{-2}</td>
<td>8.07 \times 10^{-5}</td>
<td>1.07 \times 10^{-4}</td>
</tr>
<tr>
<td>DI MAX-M19</td>
<td>0.35</td>
<td>2.01 \times 10^{-2}</td>
<td>5.34 \times 10^{-5}</td>
<td>-</td>
</tr>
<tr>
<td>DI MAX-M15</td>
<td>0.47</td>
<td>1.82 \times 10^{-2}</td>
<td>8.07 \times 10^{-5}</td>
<td>1.59 \times 10^{-4}</td>
</tr>
<tr>
<td>DI MAX-M15</td>
<td>0.35</td>
<td>1.82 \times 10^{-2}</td>
<td>5.34 \times 10^{-5}</td>
<td>-</td>
</tr>
</tbody>
</table>

The comparison of the computed core losses with those evaluated by using a 2D time-stepping finite element modelling show that the maximum core loss employing M400-65A-0.65 mm, M400-50A-0.50 mm, DI MAX-M19-0.47 mm, DI MAX-M19-0.35 mm, DI MAX-M15-0.47 mm and DI MAX-M15-0.35 mm are found to be 3.22\times10^{-14} \text{W/m}^3 (4.18 \text{ W/kg}), 2.98\times10^{-14} \text{W/m}^3 (3.87 \text{ W/kg}), 2.11\times10^{-14} \text{W/m}^3 (2.75 \text{ W/kg}), 1.94\times10^{-14} \text{W/m}^3 (2.53 \text{ W/kg}), 1.97\times10^{-14} \text{W/m}^3 (2.57 \text{ W/kg}) and 1.78\times10^{-14} \text{W/m}^3 (2.32 \text{ W/kg}) respectively.

Figure 6 Core loss distribution of SRM using M400-65A-0.65 mm at 50 Hz
Figure 7 Core loss distribution of SRM using M400-50A-0.50 mm at 50 Hz

Figure 8 Core loss distribution of SRM using DI MAX-M19-0.47 mm at 50 Hz

Figure 9 Core loss distribution of SRM using DI MAX-M19-0.35 mm at 50 Hz
Effect of Steel Lamination on Core Losses in Switched Reluctance Motors

The Figure. 6-11 brings out the influence of lamination thickness on decrease in motor core loss using various non-oriented steels at the operating flux density of 1.5T. From Table 3, the thinner laminations offer lower eddy current loss coefficient and enables a larger reduction of the motor core loss. The core loss as observe from Figs. 6-11 reduces by 45% with 0.35 mm compared with 0.65mm thickness.

5. CONCLUSION

The effort has been epitomized to relate the effects of the lamination thickness on the core loss of the material used in the 12/8 SRM. The DW-21 tester has been sought to measure the loss and the approach validated using 2D-transient FEM analysis. The results have been projected to show that a decrement lamination of steel sheet enables to reduce the eddy current loss. The magnetic core loss has been seen to be reduced by using thinner lamination in the magnetic structure. The investigative study has been accomplished to show that the rotor and stator frame using 0.35 mm thickness of non-oriented steel sheets forays to be the best choice for constructing the SRM.
REFERENCE


Effect of Steel Lamination on Core Losses in Switched Reluctance Motors


J. Fang, and S. Xu, Effects of eddy current in electrical connection surface of laminated cores on high-speed PM motor supported by active magnetic bearings, IEEE Trans. Magn., 51(11), 2015.
