Influence of choosing materials on 6/4 switched reluctance motor performance

Influência da escolha de materiais no desempenho do motor de relutância comutada 6/4

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Layachi Chebabhi
PhD in Mechanical Engineering
Institution: Laboratory Applied Automation and Industrial Diagnostics at the Department of Mechanical Engineering in the Faculty of Science and Technology, University of Djelfa
Address: BP 3117, Djelfa, Algeria
E-mail: layachi.chebabhi@univ-djelfa.dz

Toufik Tayeb Naas
PhD in Mechanical Engineering
Institution: Renewable Energy Systems Applications Laboratory (LASER), University of Djelfa
Address: BP 3117, Djelfa, Algeria
E-mail: toufiknaas@gmail.com

Mohamed Zitouni
PhD in Electrical Engineering
Institution: Electrotechnical Research Laboratory, Ecole Nationale Polytechnique (ENP), University of Djelfa
Address: BP 3117, Djelfa, Algeria
E-mail: med.zitouni@univ-djelfa.dz

Ismail Ghibeche
PhD Student in Agronomic Sciences
Institution: Department of hydraulics in the Faculty of Science and Technology, University of Djelfa
Address: BP 3117, Djelfa, Algeria
E-mail: ismail.ghibeche@univ-djelfa.dz

Tahar Benmessaoud
PhD in Mechanical Engineering
Institution: Laboratory Applied Automation and Industrial Diagnostics, University of Djelfa
Address: BP 3117, Djelfa, Algeria
E-mail: t.benmessaoud@gmail.com
ABSTRACT
The Switched Reluctance Motor (SRM) is used in many industrial applications that require high torque due to its ability to achieve high and efficient performance, simplicity, low material costs and ease of design. This motor functions on the principle of generating motion by attracting and repulsing magnetic cores. The SRM is characterized by the efficient use of energy in applications that require rapid changes in speed and has a higher resistance to shocks and vibrations. Among the essential factors that affect the performance of the SRM motors are the embrace of poles stator and rotor, dimensions, the size of the motor, the shapes of rotor geometry and the number of stator and rotor poles. This paper aims to study the effect of material selection on improving the SRM performance. First, we created a basic design of the SRM with appropriate characteristics to obtain the best operation conditions of high speed and torque. Then, we applied different materials and compared the obtained results using the ANSYS RMxp tool. We focused on studying the effect of selecting materials in the rotor and stator parts on the SRM 6/4 performance through the efficiency, total losses, speed and rated torque. After comparing and analyzing the basic results, a two-dimensional model of the SRM was created using the ANSYS Maxwell 2D tool to evaluate the motor’s performance. The analysis includes the curves of torque, speed, current, flux linkages and voltage, in addition to the variation of flux lines and magnetic flux density. The results were analyzed using the finite element method (FEM), which is characterized by speed and accuracy in electromagnetic analysis and various data.

Keywords: switched reluctance motor, materials, finite element method, ANSYS Maxwell, performance.

RESUMO
O Motor de Relutância Comutada (MRC) é utilizado em muitas aplicações industriais que requerem alto torque devido à sua capacidade de alcançar desempenho elevado e eficiente, simplicidade, baixo custo de material e facilidade de design. Este motor funciona com base no princípio de gerar movimento atraindo e repelindo núcleos magnéticos. O MRC é caracterizado pelo uso eficiente de energia em aplicações que requerem mudanças rápidas de velocidade e tem uma maior resistência a choques e vibrações. Entre os fatores essenciais que afetam o desempenho dos motores MRC estão o abraço dos polos do estator e do rotor, dimensões, tamanho do motor, formas da geometria do rotor e o número de polos do estator e do rotor. Este artigo tem como objetivo estudar o efeito da seleção de materiais na melhoria do desempenho do MRC. Primeiramente, criamos um projeto básico do MRC com características apropriadas para obter as melhores condições de operação de alta velocidade e torque. Em seguida, aplicamos diferentes materiais e comparamos os resultados obtidos usando a ferramenta ANSYS RMxp. Focamos em estudar o efeito da seleção de materiais nas partes do rotor e do estator no desempenho do MRC 6/4 através da eficiência, perdas totais, velocidade e torque nominal. Após comparar e analisar os resultados básicos, foi criado um modelo bidimensional do MRC utilizando a ferramenta ANSYS Maxwell 2D para avaliar o desempenho do motor. A análise incluiu as curvas de torque, velocidade, corrente, ligação de fluxo e voltagem, além da variação das linhas de fluxo e densidade de fluxo magnético. Os resultados foram analisados usando o método dos elementos finitos (MEF), que é caracterizado por velocidade e precisão na análise eletromagnética e vários dados.
1 INTRODUCTION

Switched reluctance motors are used in industrial applications such as wind energy systems, pumps, and electric vehicles [1-2]. It is easy to manufacture due to its simple construction and low cost of materials. The SRM has a high efficiency, the ability to withstand harsh conditions and better reliability. It is used in applications that require precise movement control due to its high ability to control torque and speed. The SRM motor is distinguished from other motors by its resistance to high temperatures. Despite the characteristics of the SRM motor, the design has some problems and challenges, including vibration and noise [3]. The control of torque and speed must be precise [4], which makes it more complex, as well as the types of materials, excitation setting, and winding configuration. Among the challenges are evaluating the motor's static and dynamic characteristics and performance, such as flow Magnetic coil, inductance versus rotor position, torque ripple, and estimation of core and winding losses.

Fenercioğlu Ahmet et al. [5] studied the impact of different rotor geometries on performance using the same stator geometry in switched reluctance motors 6/4. Özüpak Yıldırım proposed and studied the design of a switched reluctance motor model to reduce the radial force acting on the rotor poles to obtain a model with high torque and low leakage flux was obtained [6]. Yogesh B. Mandake and Deepak S. Bankar [7] presented mathematical calculations related to the selection of motor size for e-rickshaw application. They proposed a model for optimizing the design and performance of the Switched Reluctance Motor, focusing on the effect of stack length and stacking factor for electric vehicle applications. Abunike Emmanuel C et al. [8] conducted a design model of an SRM motor for high-speed operation, focusing on the effect of critical geometric parameters and adjusting the stator and rotor’s diameters on efficiency and torque. Kumar Avinash et al. [9] investigated and studied the impact of the pole embrace factor of the stator and rotor of an SRM designed for a water pumping application. He found that the pole embrace factors of the stator and rotor have essential effects on the performance. Optimizing the geometric parameters to reduce the torque ripples and average...
total loss and improve the efficiency and average torque was introduced in [10]. The vibration analysis and acoustic noise of the SRM motor have already been presented in several research works [11-12-13-14].

The selection of essential characteristics and dimensions in the machine's design is important. However, it is also crucial to choose the appropriate materials used for the stator and rotor well because they differ in characteristics from one material to another. Therefore, their effect on the efficiency and the performance of the motor varies, as do the losses, electromagnetic analysis and power loss. The objective of this paper is to study the influence of choosing materials on 6/4 switched reluctance motor performance in order to improve the design in terms of efficiency, total losses, speed and rated torque by focusing on the stator and rotor materials based on the finite element method by ANSYS Maxwell.

2 MATERIALS AND METHODS

A basic design for the SRM 4/6 motor was created by ANSYS RMxprt by choosing the geometry with the appropriate dimensions and settings to obtain high speed, torque, and efficiency. The motor was designed under the following operating conditions: speed of 1500 rpm, power of 550 W, and voltage of 220 V. After determining the settings, we applied different materials in the stator and rotor parts to compare their effect in improving the performance and efficiency of the motor and reducing total losses.

Figure 1 – Geometry of 6/4 SRM

Figure 1 shows the geometry of the 6/4 SRM design using the RMxprt tool of ANSYS Maxwell software for 220V, 550W, 1500 rpm motor.
In this study, we relied on the finite element method for analysis due to its accuracy in analyzing the machine’s performance in a short time using ANSYS Maxwell 2D to examine the electromagnetic analysis, which includes analysis of flux density, flux lines, and magnetic field.

Table 1 – Parameters of the 6/4 SRM motor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Stator Poles</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Outer Diameter of Stator</td>
<td>130</td>
<td>mm</td>
</tr>
<tr>
<td>Inner Diameter of Stator</td>
<td>80</td>
<td>mm</td>
</tr>
<tr>
<td>Length of Stator Core</td>
<td>62</td>
<td>mm</td>
</tr>
<tr>
<td>Number of Turns per Pole</td>
<td>142</td>
<td></td>
</tr>
<tr>
<td>Number of Rotor Poles</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Inner Diameter of Rotor</td>
<td>30</td>
<td>mm</td>
</tr>
<tr>
<td>Length of Rotor Core</td>
<td>62</td>
<td>mm</td>
</tr>
<tr>
<td>Stacking Factor</td>
<td>0.98</td>
<td></td>
</tr>
<tr>
<td>Length of Air Gap</td>
<td>0.5</td>
<td>mm</td>
</tr>
<tr>
<td>Rated Output Power</td>
<td>550</td>
<td>W</td>
</tr>
<tr>
<td>Rated Voltage</td>
<td>220</td>
<td>V</td>
</tr>
<tr>
<td>Given Rated Speed</td>
<td>1500</td>
<td>rpm</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>75</td>
<td>C</td>
</tr>
</tbody>
</table>

Source: Authors.

The voltage per phase equation of SRM is:

\[ V = Ri + \frac{d\lambda(\theta, i)}{dt} \]  \hspace{1cm} (1)

flux linkage per phase given is:

\[ \lambda = L(\theta, i)i \]  \hspace{1cm} (2)
\[ V = Ri + \frac{dL(\theta, i)}{dt} \]  

(3)

\[ V = Ri + L(\theta, i) \frac{di}{dt} + i \frac{d\theta}{dt} \cdot \frac{dl(\theta, i)}{d\theta} \]  

(4)

\[ V = Ri + \frac{L(\theta, i) di}{dt} + \frac{dl(\theta, i)}{d\theta} \omega_m i \]  

(5)

\[ L_T(i_{ph}, \theta_{ph}) = \frac{d\lambda_{ph}(i_{ph}, \theta_{ph})}{di_{ph}} \]  

(6)

\[ T_{ph}(i_{ph}, \theta_{ph}) = \int_{i_{ph}}^{i_{ph}} \frac{\lambda_{ph}(i_{ph}, \theta_{ph}) di_{ph}}{\theta_{ph}} \]  

(7)

The equation for motion is given as:

\[ J \frac{d\omega}{dt} = T - T_L - B_m \omega \]  

(8)

the instantaneous torque is:

\[ T = \sum_{j=1}^{3} T_{ph}(j) \]  

(9)

The motor efficiency is defined as:

\[ \eta = \frac{P_{out}}{P_{in}} = \frac{T_m \omega}{V_{dc} i_{dc}} \]  

(10)

\[ \eta = \frac{P_{out}}{P_{out} + P_{loss}} \]  

(11)

\[ P_{loss} = P_{cu} + P_{fe} + P_{mech} \]  

(12)

3 RESULTS AND DISCUSSION

Table 2 shows the results obtained after applying different materials in the rotor and stator using the ANSYS RMxpert tool, where the difference in motor efficiency, torque and total losses appears. We note from the results that choosing Steel 1008 was the best among the materials provided, as we notice an increase
in motor efficiency to 85.044% and a decrease in the total losses of 15 W, becoming 96.65 W. The results were close in terms of torque in most materials. The table results highlight that the selection of materials has a different impact on motor performance. Some materials had more significant losses than others, which explains the difference in motor efficiency.

Table 2 – Effect of materials selection

<table>
<thead>
<tr>
<th>Materials</th>
<th>Efficiency (%)</th>
<th>Total Loss (W)</th>
<th>Rated Speed (rpm)</th>
<th>Rated Torque (N.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M43_20C</td>
<td>83.1273</td>
<td>111.61</td>
<td>2492.85</td>
<td>2.10639</td>
</tr>
<tr>
<td>M235-35A_20</td>
<td>83.5191</td>
<td>108.417</td>
<td>2514.2</td>
<td>2.08676</td>
</tr>
<tr>
<td>DW465_50</td>
<td>83.1267</td>
<td>111.558</td>
<td>2490.03</td>
<td>2.10768</td>
</tr>
<tr>
<td>DW360_50</td>
<td>83.3825</td>
<td>109.698</td>
<td>2496.16</td>
<td>2.10576</td>
</tr>
<tr>
<td>M36_29G</td>
<td>82.8674</td>
<td>113.616</td>
<td>2489.96</td>
<td>2.10756</td>
</tr>
<tr>
<td>D23_50</td>
<td>81.4433</td>
<td>125.374</td>
<td>2495.72</td>
<td>2.10541</td>
</tr>
<tr>
<td>M19-24G</td>
<td>83.3368</td>
<td>109.777</td>
<td>2528.55</td>
<td>2.07342</td>
</tr>
<tr>
<td>M27_29G</td>
<td>83.2581</td>
<td>110.476</td>
<td>2511.79</td>
<td>2.08869</td>
</tr>
<tr>
<td>M350-50A_20C</td>
<td>83.4136</td>
<td>109.232</td>
<td>2503.175</td>
<td>2.09563</td>
</tr>
<tr>
<td>Steel_1008</td>
<td>85.044</td>
<td>96.6538</td>
<td>2493.64</td>
<td>2.10467</td>
</tr>
<tr>
<td>Steel_1010</td>
<td>83.9434</td>
<td>105.025</td>
<td>2489.95</td>
<td>2.10575</td>
</tr>
</tbody>
</table>

Source: Authors.

Figure 3 – Steel 1008 B-H curve used as stator and rotor material

![Figure 3 – Steel 1008 B-H curve used as stator and rotor material](image)

Source: Authors.

Figure 4 – Input DC current vs Speed

![Figure 4 – Input DC current vs Speed](image)

Source: Authors.
Figure 5 – Output power vs Speed

Source: Authors.

Figure 6 – Efficiency vs Speed

Source: Authors.

Figure 7 – Flux linkage vs Current at different positions

Source: Authors.
Figure 8 – Output torque vs Speed

Source: Authors.

Figure 9 – Flux Linkage characteristic

Source: Authors.

Figure 10 – Phase Voltage

Source: Authors.
Figure 11 – Meshed model of 6/4 SRM motor

Source: Authors.

Figure 12 – 6/4 SRM drive circuit

Source: Authors.

Figure 13 – Variation of motor Flux lines

Source: Authors.
The flux lines indicate the direction of the magnetic field in the switched reluctance motor. The flux lines are in the areas aligned with the teeth of the rotor and stator. It is relatively uniform in this region.

Figure 14 – Variation of magnetic flux density

Source: Authors.

Figure 15 – Vectorial distribution of magnetic flux density

Source: Authors.

Figure 14 represents the variation of the SRM 6/4 flux density, as it is high between the teeth of the stator and the rotor. The vectorial magnetic flux distribution is more concentrated in this region. Figure 15 shows the flux density vector rotates and changes directions while the motor moves. The flux density of the SRM is relatively high, which means the SRM can produce high torque.
Figure 16 shows the variation of torque, which changes consistently and smoothly as it increases until it reaches the maximum torque value and decreases slightly with a low ripple, and the torque rated is 2.10467 Nm. Figure 17 shows the speed curve, where it is constant and stable, estimated at 2493.64 rpm. That makes the control of the motor speed easier.
Figure 18 – Graph of SRM currents

Source: Authors.

Figure 19 – Flux Linkages of SRM

Source: Authors.

Figure 20 – Graph of induced voltages

Source: Authors.
4 CONCLUSION

In this study, we conducted detailed modelling and simulation of the 6/4 SRM. First, the characteristics and dimensions of the SRM are selected carefully to obtain appropriate essential characteristics, which showed that the designed machine could be used at high operating conditions of speed and torque. Then, we applied different materials in the stator and rotor parts and analyzed their impact on the performance of the motor using the ANSYS RMxpert tool. After analyzing the results and comparing the effect of the selection material on the SRM performance, it shows that using Steel 1008 was the best among the materials provided regarding motor efficiency. It was estimated at 85.044%, with a rated torque of 2.10467 Nm, reducing the total losses compared to other materials, as it became 96.65 W. It also contributed to improving torque. The results after electromagnetic analysis using the finite element method were better compared to other materials applied in the motor. Through this study, based on the observations of the analysis results, we conclude that the selection of materials has considerable effects on the efficiency and performance of SRM motors and reduces the total losses.

The specific conditions and parameters used in the simulation may not accurately reflect the industry data or a wide range of operating conditions because simulation results often rely on various assumptions and simplifications of the complex systems model, which hinders its applicability and usefulness to society and academia. In future studies, researchers can improve designs by focusing on various other factors, such as choosing appropriate dimensions. Improved models can also be presented more effectively by focusing on the shape of the rotor and developing models to reduce vibrations and noise and improve speed and noise control.
REFERENCES


