Design & Simulation of Switched Reluctance Motor for E-Vehicle

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Abstract: It is predicted that the energy consumed by transport system could be doubled by 2050. In the meantime, the total CO2 emissions are expected to reduce to half. In order to meet this challenge, significant use of electrified vehicles is needed to replace conventional internal combustion engine-based vehicles. In Automobile Industry, Permanent Magnet Synchronous motor is widely used. The objective is to design and simulate a Switched Reluctance motor in Magnet Software. The flux linkage of SRM with different materials is analyzed and an efficient material will be selected. The Challenges faced in the motor design are High Torque Density, High rotational speed with maximum efficiency. It is difficult to work in the high-temperature harsh environment due to permanent magnets demagnetization features. Alternatively, SRM can provide similar output characteristics and a wider speed. Thus, SRM is considered to be more fault-tolerant and more reliable.

IndexTerms - Switched Reluctance Motor, Electric Vehicle, High Starting Torque, Low Cost, Maximum Efficiency.

I. INTRODUCTION

In India, Air Pollution is major serious health issue. Air gets polluted due to the contamination of some harmful gases that are present in the environment. Mainly, Greenhouse gases are that are present in the atmosphere are harmful to the health of humans and it affects Global warming. These greenhouse gases such as Nitrous oxide, Carbon monoxide, Carbon dioxide etc., are exposed to the environment by means of Industries and energy supply, Automobiles, Agricultural practices, Household energy etc. In recent studies, it states that 70% of greenhouse gases are exposed to the environment by means of Automobiles [1]. Due to this issue, several countries are planning to reduce the usage of Internal combustion engine based vehicles and preferring us to use Electric vehicles. By using electric vehicles, we can reduce the usage of fuel and we can prevent the environment from being affected. At present, in Industries they have been using Permanent Magnet Synchronous Motor as engines for Electric vehicles. As Permanent Magnet Synchronous Motor has many advantages it has some of the disadvantages like it does not have high starting torque and high rotational speed, it is not suitable to work at high temperature environment due to its demagnetizing features. Hence, we are preferring that by using Switched Reluctance Motor these disadvantages can be rectified. Although, Switched Reluctance Motor has some disadvantages like Acoustic noise and Torque ripple these can be rectified by selecting a perfect material for motor by using simulation [10].

II. PROPOSED SYSTEM

2.1 Design of SRM

SR motor is electromagnetic and electrodynamics equipment that converts the electrical energy into mechanical energy. The SR motor drives for industrial applications are of recent origin. The origin of this kind of motor can be traced back to 1842, but the “reinvention” has been possible due to inexpensiveness, high power switching devices. Even though this SR motor is similar to a synchronous machine, it has certain novel features

2.2 Principle

As we know that magnetic flux tends to flow through the lowest reluctance path, therefore rotor always tends to align along the minimum reluctance path. This is the basic working principle of Switched or Variable Reluctance Motor.

2.3 Types of Construction

The Switched Reluctance motor is divided into two types based on the construction of the stator and rotor.

2.4 Single Salient Construction

A singly salient construction of SRM comprises a non-salient stator and a salient two-pole rotor. The rotor does not have any winding wound over it but the stator has two-phase winding as shown in the fig.1.

![Fig.1 Single Salient Construction of SRM](Image)
It should be noted that in actual SRM the number of the phase winding on stator may be more than two. Since the rotor is of salient construction, the inductance of the stator phase winding varies with the rotor position. The inductance is minimum when the rotor axis and stator phase winding axis coincides whereas it is maximum when both the axis is in quadrature.

2.5 Doubly Salient Construction

Doubly salient switched reluctance motor is in salient construction which has four poles which is shown in fig. The rotor does not carry any winding and is of salient construction but has two poles. Thus this type of SRM is a heteropolar motor where the numbers of stator and rotor poles are not the same.

The stator phase windings are concentrated winding. These concentrated windings on radially opposite poles are either connected in series or parallel to result into two-phase winding on the stator.

A doubly salient type Switched Reluctance Motor or variable Reluctance Motor produces more torque as compared to a singly salient type for the same size. Therefore a doubly salient type SRM is more common and widely used.

![Fig.2 Doubly Salient Construction of SRM](image)

2.6 Construction of SRM

Fig. 3 & 4 shows the front view design and 3D view of switched reluctance motor.

![Fig. 3. Front View of SRM](image)

<table>
<thead>
<tr>
<th>TABLE I</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DESIGN VALUES OF 6/4 SWITCHED RELUCTANCE MOTOR</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shaft radius</td>
<td>10 mm</td>
</tr>
<tr>
<td>Rotor pole width radius</td>
<td>18.2 mm</td>
</tr>
<tr>
<td>Rotor outer radius</td>
<td>26.3 mm</td>
</tr>
<tr>
<td>Air gap</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Stator pole root radius</td>
<td>41.6 mm</td>
</tr>
<tr>
<td>Stator outer radius</td>
<td>53.25 mm</td>
</tr>
<tr>
<td>Stacked length of Rotor</td>
<td>60 mm</td>
</tr>
<tr>
<td>Stator pole arc</td>
<td>30.8 deg</td>
</tr>
</tbody>
</table>

The design parameter values are given in the Table. I.
The power developed by Switched Reluctance motor is

\[ P_d = K_d K_1 K_2 B A_s D_2 L N_r \]

Where,
\[ K_d = \text{Efficiency} \]
\[ K_d = \text{Duty Cycle} \]
\[ B = \text{Specific Magnetic Loading} \]
\[ A_s = \text{Specific Electric Loading} \]
\[ D_2 = \text{Inner Core Diameter} \]
\[ L = \text{Length of Core} \]
\[ N_r = \text{Speed of Rotor} \]
\[ K_1, K_2 = \text{Constant} \]

\[ K_d = \theta q r_{p_{s}} \]
\[ K_1 = \frac{\pi}{120} \]
\[ 0.65 < K_2 < 0.75 \]

2.7 Stator Construction
Construction details of switched reluctance motor with six stator poles and four rotor poles are explained below:

1. The stator is made up of silicon steel stampings with inwardly projected poles.
2. The number of poles of the stator can be either an even number or an odd number. Most of the SR motors available have even number of stator poles (6 or 8).
3. All these poles carry field coils. The field coils of opposite poles of the stator are connected in series so that their MMF is additive. This is known as phase windings.
4. Individual coil or a group of coils constitute phase windings. Each of the phase winding is connected to the terminal of the motor.
5. These terminals are suitably connected to the output terminals of a power semiconductor switching circuitry, whose input is a dc supply.

2.8 Rotor Construction

1. Silicon steel stampings are used in the rotor with outward projected poles.
2. The Number of poles of the rotor is different from the number of poles of the stator. Most of the SR motors available in the market where the number of poles of the rotor is four or six depending upon the number of stator poles six or eight.
3. The rotor shaft carries a position sensor. The turning ON and OFF operation of the various devices of the power semiconductor circuitry (Asymmetric Bridge Rectifier) are influenced by the signals obtained from the rotor position sensor.

III. Simulation of SRM

The Motor is designed in Magnet Software and the operating modes are shown in the figure 5 to 7. To start with stator pole axis AA’ and rotor pole axis aa’ are in alignment. They are in the minimum reluctance position so far as phase windings are concerned. Then \( dL_a/d\theta = 0 \). At this position inductance of B, windings are neither maximum nor minimum.
Now if the b phase is energized, then the rotor develops a torque due to variable reluctance and existence of variation in inductance. The torque developed is adequate to \((1/2)ib(d(lb)/d\theta)\). This direction is specified bb' and bb' attempt to get aligned. If this torque is over than the opposing load torque and frictional torque the rotor starts rotating. When the shaft occupies the position specified bb' and bb' are in alignment (i.e., \(\theta=30^\circ\), no torque is developed as during this position \(d(lb)/d\theta=0\).

Now phase winding B is switched off and phase winding C is turned on to DC supply. Then the rotor experiences a torque as \((d(LC)/d\theta)\) exists. The rotor continues to rotate. When the rotor rotates further 30°, the torque developed due to winding C is zero. Then the phase winding C is switched off and phase winding A is energized. Then the rotor experiences a torque and rotates further step 30°. This is a continuous and cyclic process. Thus the rotor starts. It is a self-starting motor.

As the speed increases, the load torque requirement also changes. When the average developed torque is more than the load torque the rotor accelerates. When the torques balance the rotor attains a dynamic equilibrium position. Thus the motor attains a steady speed. At this steady-state condition power drawn from the mains is equal to the time rate of change of stored energy in the magnetic circuit and the mechanical power developed.
When the load torque is increased, the speed of the motor tends to fall, so that the power balance is maintained. If the speed is to be developed at the same value, the develop torque is to be increased by increasing the current. Thus more power is drawn from the mains. Vice-versa takes place when the load is reduced. Thus electrical to mechanical power conversion takes place.

The designed motor is simulated with different materials and their field strengths are observed.

**Fig. 8 Crio Cold Rolled 1010 Steel**

Figure 8 shows the flow of flux linkage in a switched reluctance motor. The material used is CRIQ Cold Rolled 1010 Steel. Flux Linkage of coils are given,

a. Coil - A: 0.3906 Weber
b. Coil – B: 0.0481 Weber
c. Coil – C: 0.0509 Weber

Torque obtained by the rotor is 0.2325 Newton meter.

**Fig. 9 M19 Silicon Steel**

Figure 9. Shows the flow of flux linkage in the switched reluctance motor. The material used is M19 Silicon Steel. Flux Linkage of coils are given,

a. Coil - A: 0.4488 Weber
b. Coil – B: 0.0505 Weber
c. Coil – C: 0.0524 Weber

Torque obtained by the rotor is 0.3081 Newton meter.
Figure 10. shows the flow of flux linkage in the switched reluctance motor. The material used is Samarium Cobalt. Flux linkage of coils are given, a. Coil - A: 0.0049 Weber b. Coil – B: 0.0004 Weber c. Coil – C: 0.0003 Weber Torque obtained by the rotor is 1.5828 Newton meter.

Switched Reluctance motor is analyzed based on the flux linkage and Torque characteristics using three different types of material namely Cold-rolled Steel, M19 Silicon Steel, and Samarium Cobalt. Table II and III gives the comparison of SRM with different materials. While comparing the three material M19 Silicon Steel and Cobalt have similar characteristics. But comparing in terms of cost, Cobalt is high cost and M19 Silicon Steel is comparatively low, thus M19 Silicon Steel is preferred.

<table>
<thead>
<tr>
<th>Material</th>
<th>Torque</th>
<th>CRIO Cold Rolled 1010 Steel</th>
<th>M19 26 GA Silicon Steel</th>
<th>Samarium Cobalt 18/30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil A</td>
<td>0.247 Nm</td>
<td>0.3081 Nm</td>
<td>1.5828 Nm</td>
<td></td>
</tr>
</tbody>
</table>

**TABLE II**

**TORQUE COMPARISON OF DIFFERENT MATERIALS**

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CRIO Cold Rolled 1010 Steel</td>
<td>0 Watts</td>
<td>0 Watts</td>
<td>0 Watts</td>
<td>0 Watts</td>
</tr>
<tr>
<td>M19 26 GA Silicon Steel</td>
<td>2.2042 Watts</td>
<td>0.8925 Watts</td>
<td>0.7974 Watts</td>
<td>0.1858 Watts</td>
</tr>
<tr>
<td>Samarium Cobalt 18/30</td>
<td>0 Watts</td>
<td>0 Watts</td>
<td>0 Watts</td>
<td>0 Watts</td>
</tr>
</tbody>
</table>

**TABLE III**

**IRON LOSS COMPARISON WITH DIFFERENT MATERIALS**

IV. CONCLUSION

Thus the design and simulation for Switched Reluctance Motor has been done in Magnet software. By comparing the flux linkage property of materials like cold rolled steel, M19 silicon steel and Samarium Cobalt, M19 Silicon Steel is preferred because it is economic. The proposed work is simple for implementation and execution. Due to the features of switched reluctance motor, this is preferred for an electric vehicle applications.

REFERENCES