Optimal Design of SRM for EV Application

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Abstract. Electric vehicles (EVs) need a wide speed and torque range for their reliable operation and working. Switched reluctance motors (SRMs) offer several advantages like high life cycle, meager cost, simple construction, robustness, good speed characteristics, and fault-tolerance, making it a suitable motor drive for EV application. The selection of independent variables like dimensions, winding turns, make materials, the number of slots, and the shape of rotor and stator teeth is a cumbersome task as SRM performance is mainly dependent on these parameters. This paper describes the methodology for selecting these independent variables by evaluating the SRM performance for different shapes of rotor and stator teeth, with the different stator and rotor materials, by taking all the design constraints like winding resistance, turns, and the number of slots. The EV drive performance is evaluated for the chosen independent variables and analyzed using JMAG software for determining the efficiency, Torque, and speed responses for comparison and analysis to get the optimal design constraints of the independent variables of SRM.

Index Terms — Rotor tooth shape, switched reluctance motor, slots

1.  INTRODUCTION

The utilization of conventional sources for transportation has an adverse effect on the environment, and their economic viability resulted in the significant growth of EVs. EVs are environment friendly as they have less CO2 emissions and good fuel efficiency, which results in the reduction of transportation charges among individuals [1-2]. The Electric vehicle motor drive must possess uncompromising.

Characteristics for driving requirements. A permanent magnet synchronous motor is extensive as a drive for EV applications [3]. These drives make use of rare earth materials for their work, making the drive costlier as rare earth materials are limited. SRM gave a promising solution as a high-performance drive without using these rare earth elements. It grasped the eyes of researchers as the best alternative to permanent magnet synchronous motors [4].
With the advent of power electronic devices, SRM usage and application is increased remarkably. SRM offers several advantages due to its rigid and simple construction, like low manufacturing cost, high reliability, good efficiency, high life cycle, and Fault tolerance. Over a wide speed range, the power density and output torque are very high [5]. Unlike the conventional motors for propulsion, SRM does not have windings on the rotor. The SRM’s high nonlinearity makes it study complex [6]. The main drawbacks of SRM are that the Torque ripple is higher in SRM compared to other motors, which results in increased acoustic noise and vibration. Windage losses in salient pole rotor shape are higher than in the equivalent cylindrical rotor of the same diameter. The torque ripples are reduced by employing advanced torque control strategies [7]. The proper optimal geometrical tuning of stator and rotor will reduce the torque ripple and copper losses [8-9].

The SRM has a lot of constructional design parameters. SRM is a double salient machine; it has salient poles in both rotor and stator, so a wide variant of combinations is available for a particular design application. So, selecting the best design is a big task. Hence it is necessary to get the design parameters to get optimal performance of the SRM for the required objective functions like maximum torque, efficiency, and size [10]. The core selection of the core material of SRM plays a crucial role as the motor drive's weight depends on the nature of the core material. The core losses and torque are also affected by the nature of the core material [11]. The pole number selection has a significant impact on the Torque ripples of the SRM drive. Selecting the optimal pole number will greatly enhance EV performance by reducing Torque ripples [12].

2. METHODOLOGY
The size of the motor is determined by considering the initial specifications of the required drive (i). JMAG software Selection of optimal teeth shape of stator and rotor is carried out (ii). The proper core material is selected based on efficiency with minimal core losses (iii). Optimal pole configuration is determined, which gives less torque ripples and good efficiency (iv).

3. SRM MODELLING
The SRM working principle is related with law of conservation of energy and electromagnetic induction.

Voltage equation for the $n_{th}$ phase of SRM:

$$V_n = I_n R_n + \frac{d\psi_n}{dt}$$  \hspace{1cm} (1)

Where, $V_n$ represents the $n_{th}$ phase voltage, $I_n$ presents phase current, $R_n$ represents the phase winding resistance, $\psi_n$ represents the flux linkage of the phase winding.

The flux linkage of the $n$ phases is obtained by neglecting the mutual inductance of each phase of SRM:

$$\psi_n = L_n(\theta_n, i_n) i_n$$  \hspace{1cm} (2)

Where, $\theta$ is the rotor position angle.

By assuming that the core material is linear and by neglecting resistance in the ideal case and when the SRM rotates with angular-speed of $\omega$, then the voltage (1) is replaced by

$$V = L(\theta) \frac{di}{dt} + i \frac{dL(\theta)}{dt} \omega$$  \hspace{1cm} (3)

Where, $L$ is the inductance, $\omega$ is the angular speed, and $\theta$ is the rotor position.
From (3), electromechanical energy conversion in SRM is obtained by

\[ V_i = \frac{d}{dt} \left( \frac{1}{2} L(\theta) i^2 \right) + \frac{i^2 dL(\theta)}{2} \omega \]  

(4)

From (4) the left part is the supplied input power, is converted to electromechanical energy. The 1\textsuperscript{st} term on the right side is the

Stored magnetic energy and the 2\textsuperscript{nd} term is the mechanical energy.

The torque equation is obtained as

\[ T = \frac{1}{2} L(\theta) i^2 \]  

(5)

It shows that the torque is dependent on the rotor position, square of the current and slope of the inductance.

The power developed by SRM in terms of diameter is given by

\[ P = k_e k_d k_3 A_s D^2 L B N_r \]  

(6)

Where \( k_e \) is the efficiency, \( k_d \) is the duty cycle, \( k_3 = \frac{\pi}{4} \).

\begin{table}[h]
\centering
| Initial considerations | \\
|------------------------|---|
| \( P_d \) | Rated power | 75kW |
| \( N_r \) | Rated revolution speed | 3000rpm |
| \( N \) | Maximum revolution speed | 6000rpm |
| \( V_{dc} \) | Input voltage | 600V |
| \( D \) | Outer diameter of stator | 290.4 |
| \( l_g \) | Air gap length | 2mm |
\end{table}

Table 1. SRM design variables

The above table 1. Shows the motor drive power requirements which are considered as initial parameters for calculating the motor dimensions.

4. SELECTION OF ROTOR AND STATOR TEETH SHAPES

The SRM performance is validated using JMAG software for the following different pole shapes for both stator and rotor: Round tooth bottom (RTB), straight tooth bottom (STB), taper tooth round bottom (TTRB), taper tooth straight bottom (TTSB).
Fig 1: RTB stator and RTB rotor

Fig 2: RTB stator and STB rotor

Fig 3: RTB stator and TTRB rotor

Fig 4: RTB stator and TTSB rotor

Fig 5: RTB stator with different rotor configurations

Fig 6: RTB stator with different rotor configuration
Fig 7: RTB stator with different rotor configurations

Fig 8: RTB stator with different rotor configurations

Fig 9: STB stator and RTB rotor

Fig 10: STB stator and STB rotor

Fig 11: STB stator and TTRB rotor

Fig 12: STB stator and TTSB rotor
Fig 13: Torque of STB stator with different rotor configurations

Fig 14: Efficiency of STB stator with different rotor configurations

Fig 15: Iron losses of STB stator with different rotor configurations
Fig 16. Copper losses of STB stator with different rotor configuration

Fig 17. TTRB stator and RTB rotor

Fig 18. TTRB stator and STB rotor

Fig 19. TTRB stator and TTRB rotor

Fig 20. TTRB stator and TTSB rotor

Fig 21. Torque of TTRB stator with different rotor configurations
Fig 22. Efficiency of TTRB stator with different rotor configurations

Fig 23. Iron Loss of TTRB stator with different rotor configurations

Fig 24. Copper loss of TTRB stator with different rotor configurations
Fig 25. TTSB stator and RTB rotor

Fig 26. TTSB stator and STB rotor

Fig 27. TTSB stator and TTRB rotor

Fig 28. TTSB stator and TTSB rotor

Fig 29. Torque of TTSB stator with different rotor configurations

Fig 30. Efficiency of TTSB stator with different rotor configurations
Various rotor configurations that are possible with RTB with are shown in figure 1, -figure 4. Similarly, different rotor configurations for STB stator, TTRB stator and TTSB stator are shown in figure 10, -figure 13, figure 18, -figure 21, figure 25, -figure 28. And the torque, efficiency and iron loss characteristics of them are shown in figure 5, -figure 7, figure 13, -figure 15, figure 20, -figure 22 and figure 23, -figure 24. From figure 8. The copper loss doesn’t have a remarkable value with respect to the shape changing of rotor and stator poles. There is a significant change in the iron losses with the shape of the poles. By comparing all the configurations of pole shapes of stator and rotor. From figure 14. STB stator and TTSB rotor gives maximum efficiency on an average of around 85% with an average Torque of 144 Nm which is optimal compared to all configurations and also Torque profile also increased slightly because this construction offers minimal iron losses as the construction of TTSB offers less mass and there is a significant decrease of rotor mass.

### 5. SELECTION OF ROTOR AND STATOR MATERIAL

The selection of material for stator and rotor plays a curial role in the motor performance in the aspects of efficiency as well as thermal endurance and mechanical strength. The performance of SRM for with materials like china steel, diado steel, HosanAB, JFE steel-JNEX and Jsol sheets for stator and rotor are visualized below.
Fig 33: China steel stator with different rotor materials Torque characteristics

Fig 34: China steel stator with different rotor materials Efficiency

Fig 35: China steel stator with different rotor materials Iron Loss
**Fig 36:** Diado steel stator with different rotor materials Torque

**Fig 37:** Diado steel stator with different rotor materials Efficiency

**Fig 38:** Diado steel stator with different rotor materials Iron Loss
Fig 39: HoganasAB steel stator with different rotor materials Torque

Fig 40: HoganasAB with different rotor materials Efficiency

Fig 41: HoganasAB with different rotor materials Iron Loss
Fig 42: JFE steel JNEX stator with different rotor materials Torque

Fig 43: JFE steel JNEX stator with different rotor materials Efficiency

Fig 44: JFE steel JNEX stator with different rotor materials Iron Loss
Fig 45: JSOL sheets stator with different rotor materials Torque

Fig 46: JSOL sheets stator with different rotor materials Efficiency

Fig 48: JSOL sheets stator with different rotor materials Iron Loss

The optimal teeth design is taken to evaluate the SRM performance for the manufacturing material. SRM performance of is evaluated with different make materials of both stator and rotor. figure 33. –
figure 47. indicates the Torque, Efficiency and iron loss profiles of SRM with and different rotor and stator combinations make configurations using the materials chinasteel, Diado steel, HoganasAB, JFE steel JNEX, and JSOL sheets.

Table 2. The magnetic flux density variability of make materials.

| Material         | Flux density (Wb/m2) |
|------------------|----------------------|
| China steel      | 1.5-1.8              |
| Diado steel      | 0.8-0.9              |
| HoganasAB        | 1.8-2                |
| JFEsteel JNEX    | 1.8-1.85             |
| JSOL             | 1.8-2                |

The maximum efficiency attained is around 89% for china steel stator and JFE steel JNEX rotor, Jsol rotor also gave similar performance around 88% efficiency is achieved.

figure 36., figure 37., and figure 38., indicates the Torque, Efficiency and iron loss profiles of SRM with Diado steel stator and different rotor make configurations the maximum efficiency on an average attained is around 85% for Diado steel stator and JFE steel JNEX rotor, Jsol rotor also gave similar performance around 84% efficiency is achieved.

figure 39., figure 40., and figure 41., indicates the Torque, Efficiency and iron loss profiles of SRM with HosanAB stator and different rotor make configurations the maximum efficiency on an average attained is around 81% for HosanAB stator and JFE steel JNEX rotor, Jsol rotor also gave similar performance around 80% efficiency is achieved.

figure 42., figure 43., and figure 44., indicates the Torque, Efficiency and iron loss profiles of SRM with JFE steel JNEX stator and different rotor make configurations the maximum efficiency on an average attained is around 92.4% for JFE steel JNEX stator and JFE steel JNEX rotor.

figure 45., figure 46., and figure 47., indicates the Torque, Efficiency and iron loss profiles of SRM with Jsol stator and different rotor make configurations the maximum efficiency on an average attained is around 89% for Jsol stator and JFE steel JNEX rotor.

6. SELECTION OF POLE NUMBER

The pole number plays a major role in the performance of SRM as an electric drive with proper pole selection major iron and core losses can be reduced.
Fig 48: Efficiency characteristics of SRM with different pole numbers

Fig 49: Torque characteristics of SRM with different pole numbers

Fig 50: Peak current characteristics of SRM with different pole numbers

The efficiency, Torque and peak current characteristics of SRM for 12/8, 6/4 and 18/12 configurations are shown in the figure 48-50. The 12/8 configuration SRM gives the optimal performance for the high powered 75kW motor.
7. CONCLUSION

SRM efficiency plays a crucial role for its wide usage. For application of EV the SRM must have high starting torque and wide speed range. The 75kW motor drive performance is analyzed with independent variables and summarized as follows. In order to achieve good efficiency various constructional constraints are chosen in a way to achieve optimal performance of srm drive. The straight tooth bottom stator and taper tooth straight bottom rotor provides optimal efficiency and material JFE steel Jnex offers efficiencies upto 93% with best thermal endurance and mechanical strength. The pole configuration of 12/8 gives optimal functionality of the specified electric motor drive.

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