Super Core Magnetic Material based Switched Reluctance Motor for Electric Vehicle Applications

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Abstract. In recent days, the proliferation of environmental effect from the industries like electric vehicles, automation become more popular. Compared to induction and permanent magnet motors, the Switched reluctance motor have rugged construction, less torque ripple and acoustic noise. So, the motivation of this research is to design Switched reluctance motor (SRM) for Electric vehicle applications using super core magnetic material. The design has been carried out on the SRM machine configuration of 8/6, 0.55kW and 1500RPM. The designed parameters are validated through the Finite Element analysis (FEM) using the Ansys Maxwell Software. The flux has distributed uniformly to reduce the losses. In order to get the accurate results, the Electromagnetics 17.2 software is used to analyse the desirable characteristics of Switched reluctance motor such as flux linkage, losses and efficiency.

Keywords: Ansys; switched reluctance motor; super core material

Introduction

The electric motor plays vital role in electric vehicle [1]. Presently the motor which is used for the electric vehicle applications are brushless DC motor, synchronous motor with permanent magnet and induction motor. Even though brushless DC motor and synchronous motor with permanent magnet have higher efficiency and power density, high cost magnetic material is required for Electric vehicle.[2] It is necessary to select the machine with low cost material and high-power density. So Switched reluctance motor is most suitable to overcome the above said drawbacks. It works on the principle of variable reluctance. It is a doubly excited machine. The salient pole structure is on both stator and rotor. The winding is accommodated only in the stator which is excited by DC supply. This makes to align the stator poles with rotor poles which in turn torque is developed. SRM have many advantages over other type of machines such as high temperature withstanding capability, less cost, simple and rugged construction. Even though it has many advantages, it has some issues such as more torque ripple and high noise due to its double saliency. But for electric vehicle application torque ripple should be reduced. So, the switched reluctance motor has been designed to overcome the above issue. The simulation results using Ansys Maxwell software is discussed and
1. Methodology

The initial considerations are needed to design switched reluctance motor.[2] Selection of magnetic material is important for making the electrical machines [3]. The SRM modelling and finite element analysis is done for this configuration. By using ANSYS maxwell software, analytical data is validated.

2. Super Core Magnetic Material

Super core magnetic material is used to achieve the maximum value of flux density in the airgap and less core loss. It can be used for reactors which is operated at high frequency range, high-frequency transformers, magnetic shields, motors, etc. Core loss vs magnetic flux density of different super core material is shown in Figure 1. Among all these material, grain oriented electrical steel sheets have been proposed in this paper to make SRM.

![Characteristics of different core material](image)

**Figure 1.** Characteristics of different core material

**Table 1 Characteristics of different super core material**

| Material          | Thickness (mm) | Saturation magnetization (T) | Magnetic flux density B8 (T) | Magnetic flux density B25 (T) | W10/50 | W10/400 | W10/1k | W5/2k |
|-------------------|----------------|-------------------------------|----------------------------|------------------------------|--------|---------|--------|--------|
| JNHF- Core        | 0.15 to 0.25   | 1.89 to 1.93                 | 1.17 to 1.07               | 1.41 to 1.45                | 11.1   | 30.0    | 19.2   |
| JNEX-core Grain Oriented silicon steel | 0.12 | 1.82 | 1.32 | 1.38 | 0.4 | 4.7 | 18.7 | 12.7 |
|                   | 0.12           | 2.02                         | 1.81                       | 1.84                        | 0.6    | 4.0     | 22.7   | 21.0   |
| Grain Oriented silicon steel | 0.37 | 1.95 | 1.42 | 1.52 | 0.6 | 14.4 | 60.0 | 49.2 |
| Non-oriented silicon steel | 0.02 | 1.52 | -    | -    | 0.2 | 1.5   | 4.5   | 9.1    |
| Amporphous        | 0.02 to 0.06   | 1.52                         | -                          | -                           | 0.2    | 1.5     | 4.5    | 9.1    |
Table 1 shows characteristics different super core material. From this it is concluded that grain-oriented silicon steel material produces the higher value of magnetic flux density compared to other type of materials.

3. Design Procedure

The design procedure of SRM is similar to three phase induction motor.[4] The stator outer diameter and rotor outer diameter is 120 mm and 74 mm respectively. The stack length of the machine is 65mm. The torque ripple in the SRM is reduced by increasing the number of phases. But no of switch requirement is more. Based on the greater number of switches and pulsation in torque value the optimum value of number of phases has been selected as four. The number of poles on stator and rotor are assumed as 8 and 6. The winding turns decides the shape of torque-speed characteristics. If the no of turns is large, machine produces the high torque with less speed while lesser number of turns in machines develops the less torque with high speed range. Figure 2 shows the torque vs speed for various number of turns.

![Figure 2. Torque vs speed Characteristics](image)

3.1 SRM Modelling

The SRM has been designed with best optimized designed parameters. The modelling equations has been developed based on the working principle and existing research. The equations are described below

![Figure 3.SRM configuration](image)

Voltage equation of SRM is given in equation (1)

\[
V_{dc} = R_a I_a + L \frac{dt}{dt} + Eb
\]  

The equation 2 gives the interlinking the supply voltage, flux linkage and position of rotor angle (\(\theta\))
\[ V_{dc} = R_a I_a + L_a \frac{dI_a}{dt} + \frac{\partial \psi_a}{\partial \theta} \frac{d\theta}{dt} \]  

(2)

Since \( \psi_a = L_a I_a \)

\[ V_{dc} = R_a I_a + L_a \frac{dI_a}{dt} + \frac{\partial L_a}{\partial \theta} \frac{d\theta}{dt} \]  

(3)

The torque developed by switched reluctance motor is given in equation (4) and (5)

\[ T = \frac{1}{2} i^2 \frac{\partial L_a}{\partial \theta} \]  

(4)

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

(5)

3.2 Sizing Equation

The torque developed by SRM in terms of diameter is given in expression (6) [5]

\[ \tau_d = k_e \ast k_d \ast k_0 \ast \frac{\pi}{4} \ast B \ast A_x \ast D^2 \ast L \]  

(6)

Stator pole width and Rotor pole width is expressed in equation (7) and (8) respectively

\[ \omega_{sp} = D \ast \sin(\beta_s / 2) \]  

(7)

\[ \omega_{rp} = D \ast \sin(\beta_r / 2) \]  

(8)

Stator yoke height and Rotor yoke height is given in equation (9) and (10) respectively

\[ b_{sy} = 0.6 \ast \omega_{sp} \]  

(9)

\[ b_{ry} = 0.6 \ast \omega_{rp} \]  

(10)

The stator pole height can be calculated using the below expression

\[ D_0 = D + 2 \ast b_{sy} + 2 \ast h_{sp} \]  

(11)

| Table 2. Calculated SRM design variables |
|-----------------------------------------|
| Stator design Parameter | value |
|-------------------------|--------|
| D_0 | Outer diameter of stator | 120mm |
| P_s | No of stator phase | 8 |
| \( \omega_{sp} \) | Stator pole width | 20mm |
| b_{sy} | Stator yoke height | 12mm |
| l_g | Airgap length | 0.5 mm |

| Rotor Design parameter |
|-------------------------|
| D | Outer diameter of rotor | 74mm |
| P_r | No of stator phase | 6 |
| \( \omega_{rp} \) | Rotor pole width | 30mm |
| b_{sy} | Rotor yoke height | 12mm |

| Rated capacity of SRM |
|------------------------|
| P_0 | Power | 0.55kW |
| N | speed | 1500rpm |
The Table 2 shows the calculated design parameter using the Sizing equation. Finite Element Analysis (FEM) can be done through this calculated design parameters.

4. Finite Element Analysis of SRM

The stator and rotor is made up of steel laminations which makes SRM less cost and manufacturing. Since the absence of winding on the rotor, there will be no heat generated and cooling is done on the stator side only which makes simpler to make the motor. SRM creates a flux path i.e resistance will be minimum when the stator and rotor is aligned position. Figure 1 shows the mesh plot of SRM which is used to get accurate results. [6-7] ANSYS Maxwell Electromagnetic suit software is used for finite element analysis (FEM) of machine. The most important parameter in SRM are flux distribution and flux density. Figure 1 shows the magnetic flux which will pass through the stator and rotor. For various range of flux density has been analysed by using FEM. [8] The core losses have been reduced by using super core magnetic material for stack laminations.

![Figure 4. Mesh plot of SRM](image1.png)

Since the magnetic flux is not flowing in one direction, grain oriented steel is not favourable to make stator and rotor. So the non-grain oriented steel is used to make the uniform flux direction. Even though the grain oriented silicon steel gives higher efficiency and torque compared to non-grain oriented steel, it’s decreased as the motor speed increases. In this design non-grain oriented steel is investigated and flux analysis can be done. Figure 4 shows the flux lines which interlinks between the stator and rotor with unaligned position in 2D model which is obtained from Rmxprt. The flux density value has been taken at a rated speed of 1500 rpm at rated load condition. It achieves the maximum flux density when the stator phase winding is energized. [9-10]

![Figure 5. SRM with unaligned position](image2.png)

Airgap influences the major role in electrical machines. When the stator and rotor is in aligned position, the reluctance of the machine will be lower which in turn increases the torque value due to lower airgap between stator and rotor. The optimum value of airgap is around 0.3mm-0.8mm. Figure 6 show the flux linkage waveform in airgap with respect to time. The average value of flux density is obtained as 0.32wb [11-12]
Figure 6. Flux linkage

Figure 7 shows the current vs time of SRM. Maximum value of current value is approximately equal to 7A from the graphical results. [13]. The torque developed by the motor is dependent on current. The torque value is decreased because of the low value of current when the motor speed increases the rated speed.

Figure 7. Current at rated load condition

Figure 8 shows the torque characteristics of SRM with respect to time. From the simulation results the torque obtained as 4 Nm. [14-15]. Torque value is increased up to 3000 rpm beyond that torque is decreased even though the speed is increases as mentioned in the Fig.7.

Figure 8. Torque at rated load condition

Conclusion

The switched reluctance motor provides great reductions in volume and weight compared to the other types of motor. It is 10.6-15.8 % weight and 8.2 - 12.6 % volume of the other types of the motor. It shows the 15% reduction in weight and 8% reduction in volume. The average torque and efficiency of switched reluctance motor is calculated as 4Nm and 90 % respectively for high-speed applications and Oscillations in speed and torque can be nullified using this proposed methodology. The super core material has been proposed to reduce the core losses. The analytical data has been verified using Ansys Maxwell software. From the above results, it is concluded that the torque and efficiency of the proposed machine has been improved so that SRM is preferred instead of induction motor for Electric vehicle applications.
References

[1] Zabihi, Nima & Gouws, Rupert. (2016) “A Review on Switched Reluctance Machines for Electric Vehicles” in 25th IEEE International Symposium on Industrial Electronics (ISIE), June 2016, 10.1109/ISIE.2016.7744992.

[2] S. R. Patel, N. Gandhi, N. Chaitanya, B. N. Chaudhari and A. Nirgude, "Design and development of Switched Reluctance Motor for electric vehicle application," 2016 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Trivandrum, Dec 2016, pp. 1-6, doi: 10.1109/PEDES.2016.7914356.

[3] S. Kachapornkul, P. Jitkreeyarn, P. Somsiri, K. Tungpimolrut, Akira Chiba and Tadashi Fukao, “A design of 15 kW switched reluctance motor for electric vehicle applications,” International Conference on Electrical Machines and Systems (ICEMS), Seoul, Oct 2007, pp. 1690-1693.

[4] Prem, P. & Pandarinathan, Sivaraman & J S, Sakthi & Mohamed Ali, Jagabar S. & Almakhles, Dhafer. “Fast charging converter and control algorithm for solar PV battery and electrical grid integrated electric vehicle charging station” Automatika. October 2020 61. 614-625. 10.1080/00051144.2020.1810506

[5] J S, Sakthi & Pandarinathan, Sivaraman & Prem, P. & Matheswaran, Alagu. (2020). Wide Band Gap semiconductor material for electric vehicle charger. Materials Today: Proceedings. April 2020 10.1016/j.matpr.2020.02.916

[6] Mingyao Ma Rui Wang Fei Li Jianing Wang Shuying Yang “A fault-tolerant control strategy for switched reluctance motor drive for electric vehicles under short-fault condition” Microelectronics Reliability Volumes 88–90, September 2018, Pages 1221-1225

[7] Muhammad Usman Jamil, Waree Kongprawechnon, Nattapon Chayopitak, “Average Torque Control of a Switched Reluctance Motor Drive for Light Electric Vehicle Applications” IFAC-Papers On Line Volume 50, Issue 1, July 2017, Pages 11535-11540

[8] A. Chiba, K. Kiyota, N. Hoshi, M. Takemoto and S. Ogasawara, "Development of a Rare-Earth-Free SR Motor With High Torque Density for Hybrid Vehicles," in IEEE Transactions on Energy Conversion, vol. 30, no. 1, pp. 175-182, March 2015, doi: 10.1109/TEC.2014.2343962.

[9] J. Zhu, K. W. E. Cheng, X. Xue and Y. Zou, "Design of a New Enhanced Torque In-Wheel Switched Reluctance Motor With Divided Teeth for Electric Vehicles," in IEEE Transactions on Magnetics, vol. 53, no. 11, pp. 1-4, Nov. 2017, Art no. 2501504, doi: 10.1109/TMAG.2017.2703849.

[10] W. Wu, H.C. Lovatt, J.B. Dunlop, “Optimisation of switched reluctance motors for hybrid electric vehicles,” in International Conference on Power Electronics, Machines and Drives, June 2002, https://doi.org/10.1049/cp:20020110.

[11] Zheng Liu and Miaoshan Lin, “The Control of Switched Reluctance Motor in Electric Vehicle”, in Sensors & Transducers, Vol. 171, Issue 5, May 2014, pp. 15-19.

[12] Gao, Xudong Risha Na Jia,Chengyu, Wang,Xudong and Zhou,Yongqiu, “Multi- objective optimization of switched reluctance motor drive in electric vehicles" in Computers and Electrical Engineering, volume 70,August 2018,Pages914-930 https://doi.org/10.1016/j.compeleceng.2017.12.016

[13] Wei Sun, Yinong Li, Jingying Huang and Nong Zhang, “Vibration effect and control of In-Wheel Switched Reluctance Motor for electric vehicle” in Journal of Sound and Vibration,Volume 338, 3 March 2015, Pages 105-120, https://doi.org/10.1016/j.jsv.2014.10.036
[14] Xinxin Shao, Fazel Naghdy, Haiping Du and Yechen Qin, “Coupling effect between road excitation and an in-wheel switched reluctance motor on vehicle ride comfort and active suspension control”, Volume 443, 17 March 2019, Pages 683-702, https://doi.org/10.1016/j.jsv.2018.12.012

[15] Sun, Xiaodong, Diao, Kaikai, and Yang, Zebin, “Performance improvement of a switched reluctance machine with segmental rotors for hybrid electric vehicles”, in Computers and Electrical Engineering, Volume 77, July 2019, Pages 244-259, https://doi.org/10.1016/j.compeleceng.2019.06.002.