Investigation of the Mechanical Constraints on the Design of a Super-high-speed Switched Reluctance Motor for Automotive Traction

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Abstract

This paper presents a novel Switched Reluctance Motor (SRM) for automotive traction applications. The electromagnetic and mechanical simulation results of the proposed motor are presented for operation at 50,000 rpm. The SRM is designed to withstand the rotor stresses due to the centrifugal force whilst producing an output power of 60kW. The simulation results confirm that the stresses forced on the rotor in the proposed topology are below the yield strength of the material with a safety factor of 1.2. Fatigue life may be an issue and will be investigated in the future. The high speed operation allows for a smaller overall size, which in turn leads to lower manufacturing costs. This combined with high output power makes this design a good candidate for use in mass production hybrid electric vehicles.

1 Introduction

Since the 1980s, permanent magnet synchronous motors (PMSM) have been a primary research area in electrical machines due to their high efficiency, high torque density and inverter utilisation [1]. The PMSM has been employed in many automotive traction drives, including the Toyota Prius and Nissan Leaf [2]. In recent years (2009-12) the price of rare earth materials increased. Although the price has reduced since, it has prompted research into alternative technologies. As a result, switched reluctance motors (SRM) have become an area of interest and an attractive solution for future automotive traction [3].

The SRM is simple to construct, robust and cost effective as it contains no PM material [4]. The concentrated winding used in these machines reduces the copper loss by virtue of having short end-windings. Furthermore, the rugged structure of the rotor makes it suitable for very high speed operation [5]. Increased torque ripple, increased acoustic noise and vibration are a characteristic of the SRM as is poor inverter utilisation, due to the requirement for a non-standard converter. These shortcomings have been extensively discussed and investigated [6, 7].

The bestselling hybrid electric vehicle is Toyota Prius which uses an Interior Permanent Magnet Synchronous Motor (IPMSM) [8]. Extensive research has been carried out to design an SRM motor with the same frame size as an Interior Permanent Magnet Synchronous Motor (IPMSM) which can produce similar torque and output power [9]. In order to achieve such a design, different factors such as the electrical steel used in the iron core lamination, stator and rotor teeth number, fill factor, tapered stator poles, stator core back thickness and rotor size were investigated and adjusted in order to achieve the same torque as IPMSM [8,9]. The results of this research prove that SRMs are competitive with IPMSMs and by using the correct specifications; they can take the place of Permanent Magnet Motors in manufacturing Electric Vehicles (EV) and Hybrid Electric Vehicles (HEV).

This paper presents a novel design for an SRM to operate at a speed of 40-50krpm. As a result, the required torque is considerably smaller than an equivalent motor with the same output power running at lower speed, and hence this approach allows for much smaller frame sizes. This feature of SRMs, alongside other advantages such as robustness and low copper loss, make them a suitable research area for future automotive applications, as the simple structure of the rotor makes a perfect candidate for high speed operations and the control of SRMs using the pulse width waveforms, provides simple control methods [10]. However, the design of this type of motors, especially in mechanical aspects, requires careful consideration in order to minimise the high mechanical stresses acting upon the rotor. These forces are due to the high radial forces caused by the centripetal force at high speed and the normal electromagnetic forces [11, 12].

The centripetal forces generated in rotating objects, results in radial and tangential stresses being imposed on the object. The higher the rotational speed, the higher the stresses. The stresses concentrate around any sharp corners on the object. Also, the tangential stress is the highest around the shaft. In running at high speeds, the vibrations and natural frequencies of the motor need precise attention as they affect acoustic noise, bearing loss and risk of failure. As the natural frequency is in direct relation with length of the rotor, short shafts are preferable in high speed operations.

As mentioned above, a novel design for an SRM to run at high speeds (40,000-50,000rpm) is proposed here. This motor is competitive to the interior permanent magnet synchronous motor (IPMSM) used in the third generation of Toyota Prius in terms of torque at the wheel and output power. It is shown that making the rotor small is not enough in running at very high speeds and certain mechanical considerations should be taken into account. The simulations presented in this paper are used to evaluate both the electromagnetic and mechanical aspects of the design. Electromagnetic analysis and mechanical analyses are carried out using finite element software.

In the next step, the acoustic noises and vibrations, heat dissipation and losses on the motor will be considered as they can affect the air gap length.

2 Design

As mentioned earlier, there have been several attempts to replace the PM motors with other types of electric motors. The specifications of the SRM proposed by other researches to replace the IPMSM of Toyota Prius [13] are displayed in Table 1.

However, the purpose of this work is to design an SRM to run at a speed range of 40-50krpm. In order to maintain the maximum output power at 60kw, while running the motor at 50krpm, according to Equation 1, the specifications in Table 1 should be scaled down by the ratio of 3.7:1.

$$P = \omega T. \qquad (1)$$

Where P is the output power in $Watts$, ω is the rotational velocity in rad/s, and T is the torque in Nm [15]. A schematic of torque-speed characteristic of the proposed motor is shown in Figure 1 to give an insight on the operating points of the motor.

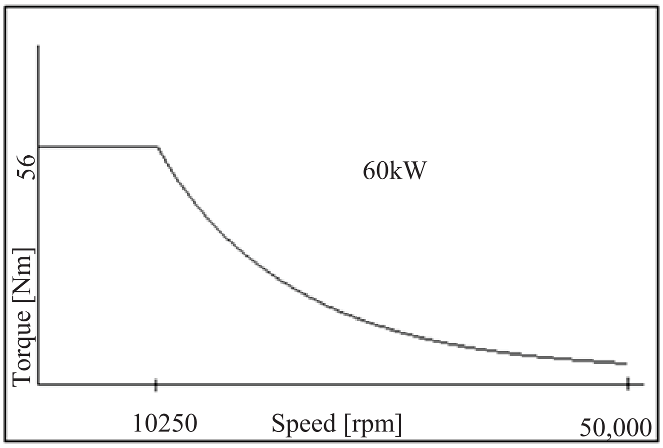

Figure 1. The schematic of torque-speed characteristics of the proposed motor

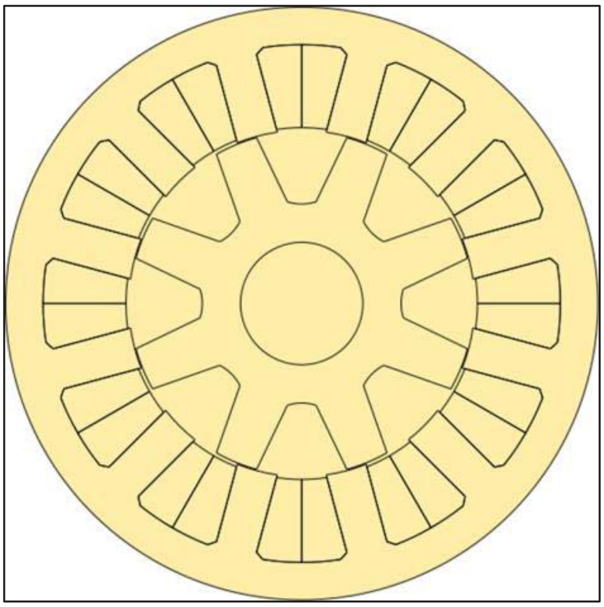

Figure 2. The design schematic of the proposed motor

As it can be seen from Figure 2 the proposed motor is a conventional SRM with 12 stator teeth and 8 rotor teeth (12/8). The reason for this combination is that although the original SRM was an 18/12 type, the new scaled down motor is smaller, hence fewer rotor teeth are used. Furthermore, the higher rotor pole number will require a higher switching frequency and therefore higher iron losses will result.

In order to design a radial SRM motor, a certain procedure should be followed [16].The rotor outer diameter should be about 60% of the stator outer diameter.

$$Rotor_{OD} = 0.6 * Stator_{OD}. \qquad (2)$$

The rotor pole pitch can be obtained from the following equation.

$$\lambda = \frac{\pi * Rotor_{OD}}{Rotor\ tooth\ No.}. \qquad (3)$$

Having the rotor pole pitch, the rotor tooth width can be calculated from Equation 4.

$$Rotor_t = (0.3 \sim 0.4) * \lambda. \qquad (4)$$

It should be mentioned that rotor and stator can have equal tooth width.

As only about half of flux in each tooth passes through the stator yoke, stator yoke does not need to be wider than 60% of tooth width [15].

$$t_y = 0.6 * Rotor_t. \qquad (5)$$

Figure 3 shows the motor at fully aligned position where it enters the saturation mode.

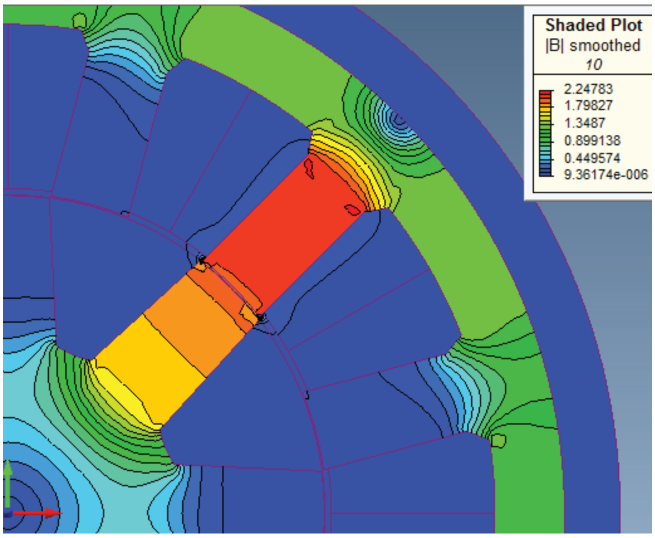

Figure 3. The saturation mode at aligned position

3 Electromagnetic Analysis

From an electromagnetic aspect, the output torque of the proposed motor is the major concern of this analysis. In SRMs torque in non-saturated regions can be calculated using equation 6 [5];

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta}. \qquad (6)$$

Torque is directly depended on current and the rate of change of the inductance with respect to the rotor position.

The initial simulations showed that the obtained torque was lower than expected, as the rotor tooth number was decreased from 12 to 8. To compensate the stator and rotor outer diameters are increased in order to obtain a starting torque of 56Nm. Tapering the rotor poles will also lead to an increase in the torque by smoothing the flux linkage [13]. Advancing the switching angle can also be applied to further increase torque. A range of different angles were tried, 30° advance was found to maximise torque output. Figure 4 shows the torque output at 10,000rpm, in this case the average torque is 55.6Nm.

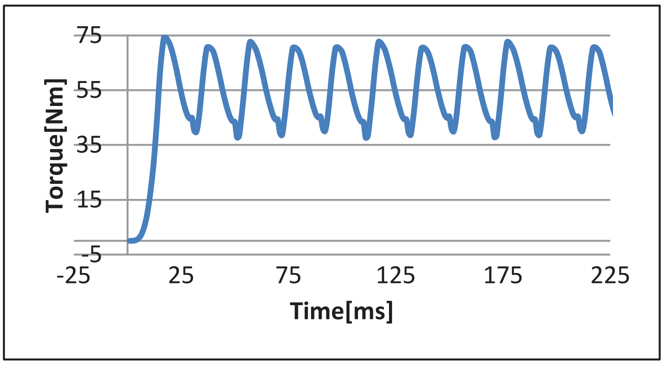

Figure 4, The output torque of the proposed motor

4 Mechanical Analysis

At increasing speed, the centripetal force increases and as a result the stresses induced on the rotating parts will also increase. Calculating the induced stresses is crucial as exceeding the yield strength of the material of the rotating object leads to permanent deformation or failure. The yield stress is a property of the material, and is the maximum stress that the material can withstand. The yield strength of the material is provided by the steel manufacturer. Usually the maximum allowable stress is lower than the yield stress and this can be set by specifying a safety factor or by fatigue analysis which requires knowledge of the duty cycle. The first has been adopted in this case as a first step.

An FEA software (ANSYS) is used to investigate the mechanical stresses on the rotor. ANSYS can simulate the Von Mises stress. In a case where an elastic body is subject to different loads in 3 dimensions, this will result in a 3 dimensional system of stresses. Which means any single point within the object is subjected to stresses acting in different directions, but the direction and the level of stresses change from point to point.

Even if none of the principal stresses that act on any point in the object in three principle directions of x,y and z, exceeds the yield stress of the material, it is possible that the combination of stresses does. The Von Mises criteria is a formula (Equation 3) to calculate the equivalent stress of these 3 stresses, which then can be compared to the maximum allowable stress for the material.

$$(S_1 - S_2)^2 + (S_2 - S_3)^2 + (S_3 - S_1)^2 = 2S_e^2. \qquad (3)$$

where S_1, S_2 and S_3 are the principal stresses and S_e is the equivalent stress, or Von Mises Stress. As it can be seen the Von Mises stress is not a real stress but a number used to indicate the equivalent stress at any point.

Since this motor is designed for automotive applications, the motor should be able to run over a wide range of speed, therefore, 20% over speed is considered and the stresses are investigated at 60,000rpm. The laminated electrical steel used in the rotor is grade M250-35HS manufactured by Cogent steel. This grade is suitable for high speed applications, with guaranteed yield strength of 400MPa [17]. Figure 5 shows the result of stress analysis at 60,000rpm. It can be seen that the stress reaches 750MPa in some areas, significantly higher than the yield. At the base of the rotor teeth, the notch effect is the main reason for excessive stress [12]. Notch effect is the increase in the stress near the sharp corners. Although adding fillets can address this issue, it will also increase the number of sharp angles at the base of the rotor tooth. However, using a tangential curve to connect the bases of each two adjacent teeth creates a smooth path and eliminates the sharp corners. Using this technique, as shown in Figure 6, the stress is reduced by 15% at the base of the rotor teeth. However, 642MPa is still greater than the yield strength of the material and failure is certain.

The main reason for this excessive stress is the hoop stress. The hoop stress is the force applied circumferentially on every point within a rotating cylindrical body. One method to reduce hoop stress is to remove the shaft bore. In this procedure (Figure 7), two plates that each have a shaft extending outwards along the rotating axis will be used to sandwich the laminations. The two plates are then bolted together [18]. The location and shape of the bolts are important as nearer to the outer diameter of the rotor they are in the vicinity of varying magnetic fields and susceptible to eddy current induction and subsequent heating and loss. Conversely removed from this region, toward the centre of the rotor the mechanical stresses increase. Finally, the shape of the holes should be designed to minimise the stress. Figure 8 shows the final proposed topology for the rotor. Stress analysis simulations for this rotor (Figure 9) shows that the maximum stress will not exceed 335MPa, which is 16% below the guaranteed yield strength of the laminations.

Using this new topology will not have any significant influence on the output torque of the motor. The maximum stress at 60,000rpm (120% maximum speed) is lower than the yield strength, with a safety factor of 1.2. Table 1 compares the proposed motor with the original SRM to replace the PM motor of Toyota Prius.

	Original SRM	Proposed SRM
Stator Outer Diameter [mm]	264	176
Rotor Outer Diameter [mm]	182	121
Stack Length [mm]	87	58
Maximum Power [kW]	60	60
Maximum Speed [rpm]	13,500	50,000
Torque [Nm]	207	56
DC Link Voltage [V]	650	400
Fill Factor	0.54	0.5
Stator/rotor teeth combination	18/12	12/8

Table 1. The comparison of the original SRM and the proposed SRM.

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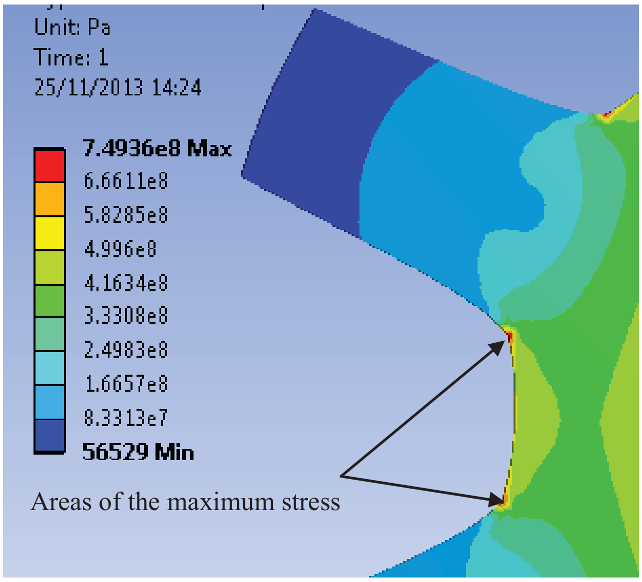

Figure 5, The equivalent stress on the rotor

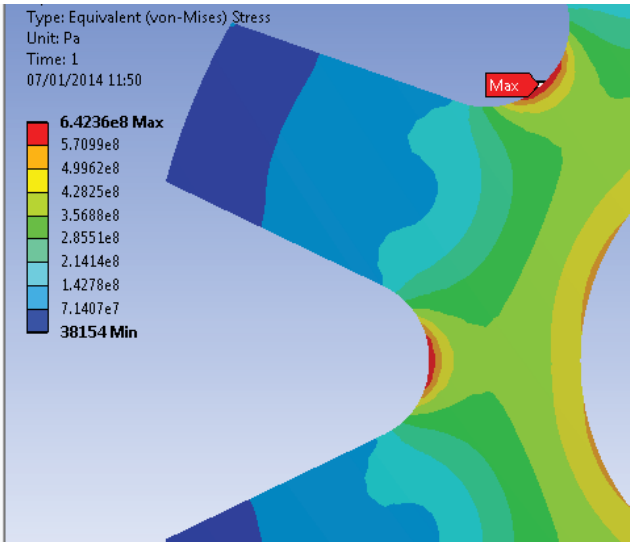

Figure 6. The equivalent stress using tangential curves

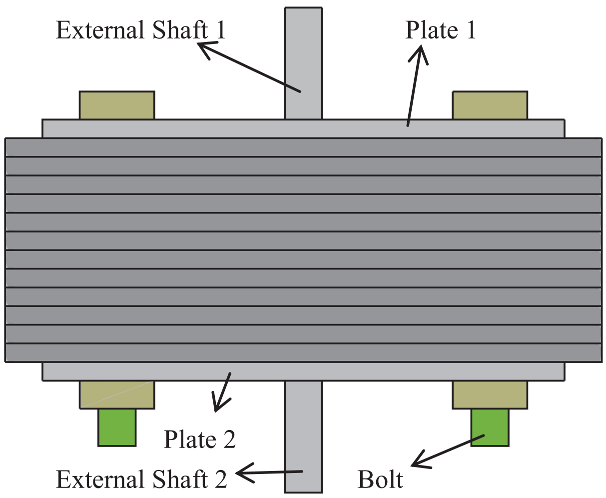

Figure 7. Schematic of the new topology [17]

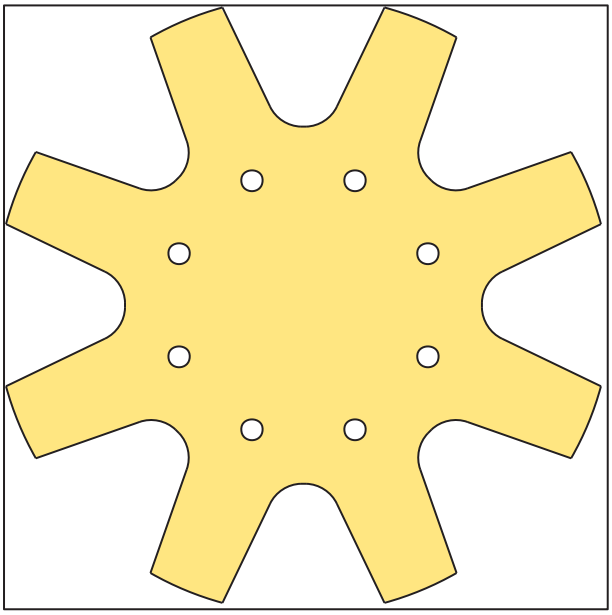

Figure 8. The proposed topology for the rotor

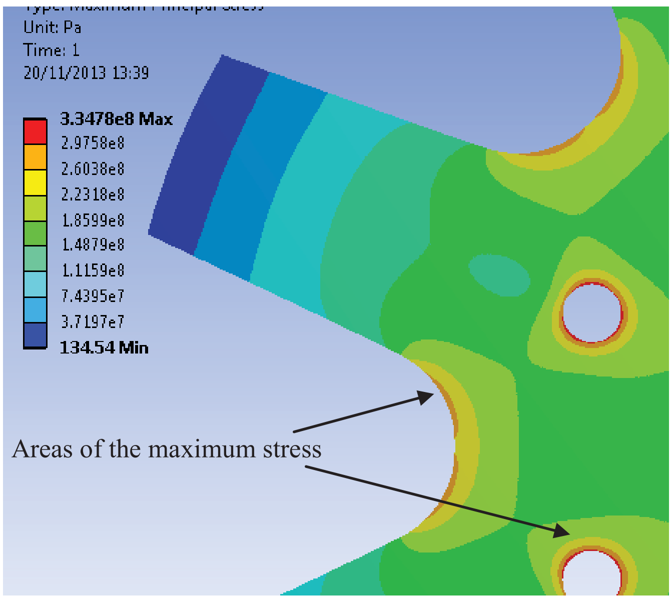

Figure 9. Stress analysis of the proposed topology

5 Conclusion

It can be seen from the results that the proposed motor is capable of running at a speed of 50,000rpm and even in 20% over-speed. The motor can produce the required torque of 56Nm. As a result the target output power of 60kW can be achieved. The results show a promising electric motor for automotive applications which will be further developed for prototyping.

The thermal analysis of the rotor, which plays an important role on the expansion of the rotor into air gap and also on choosing a proper cooling system, will be carried out. The choice of cooling systems depends on estimating the losses, which is the next step in the process. Alongside these, the choice of bearings and the balancing of the rotor are among the main challenges in order to build a prototype

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