

DESIGN OF A SWITCHED RELUCTANCE MOTOR FOR AN ELECTRIC VEHICLE

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Abstract

Switched reluctance motors (SRMs) have recently been gaining attention as contenders in the drives industry. The recent advances in power electronics technology have made SRMs an attractive candidate for electric vehicle (EV) applications. This paper presents the design of a low power, 3-phase SRM that will be used to verify the design procedure and process for an EV application. A 2D model of the SRM is created using the results obtained from the design calculation. Finite element analysis (FEA) shows the expected characteristics of the designed SRM. The designed SRM is constructed and results from FEA match the performance of the experimental motor. The design procedure and FEA is then used to predict the performance of a 4-phase, 22kW SRM designed for an EV.

1. INTRODUCTION

The maturing of environmental awareness worldwide has led to the development of a market for transportation with reduced environmental impact. Although there are variety of technological options being developed, the electric vehicle (EV) has been the most commercially successful to date.

The Electrical and Computer Engineering Department at the University of Canterbury has been involved in the research and development of electric vehicles since the oil crisis of 1974. The first two cars use standard induction motors, which have been rewound to operate at frequencies up to 150Hz, and therefore have a high power to weight ratio. EV3, a Toyota MR2 sports car, is the latest electric vehicle in the department which is currently being converted into an electric car. The induction motor used for the new car has been selected so as to operate with a high nominal frequency. To make the electric vehicle more competitive against the internal combustion engine, the EVs must provide not only the driving range but also the attractive driving performance for general users. Therefore the induction motor must be able to generate high torque at low speeds.

An important consideration in the selection of the motor for electric vehicles is its cost, weight and efficiency. A heavy motor will increase the overall weight of the vehicle resulting in lower acceleration and reduced overall performance. A motor that is specifically designed for the EV is a better choice than purchasing a standard motor. Switched reluctance motors (SRMs) are a good choice for an EV motor as

they are relatively cheap and robust, and can be designed to have minimum weight [1]. The recent advances in power electronics technology have made SRMs an attractive candidate for EV applications. Because of its desirable features such as simple and rugged motor construction, SRM technology offers an impressive list of advantages that is making industrial users seriously looking at switched reluctance motor drives.

SRMs have been considered the simplest of all electric machines to understand, however their behaviour is probably the most difficult to analyse and the performance is the most difficult to calculate. SRMs are difficult to analyse, therefore we need a design process and methods that will accurately model their performance.

This paper presents the design of a SRM that is suitable for an EV application, in particular for the EV3. Results from the simulation are discussed and compared to see how closely the design process predicts the performance of a real low power motor. These results are then used to propose the design of a four phase SRM that is suitable for the MR2.

2. DESIGN OF A LOW POWER SRM

The design process combines design calculations and finite element analysis (FEA) to predict the performance of the candidate designs. Design refinements are evaluated using more exact magnetisation curves, which are characteristics of flux-linkage versus rotor position, and parameterised with winding currents.

The dimensions of the low power SRM is selected using the design procedure proposed by Miller [2][3]. The chosen design motor is a three-phase 6-4 SRM, which has 6 stator poles and 4 rotor poles. The 6-4 is selected due to its simple structure and low cost of electronics required for the controller. The specification of the SRM is given below

Operating speed:	1500RPM
Output power:	200W
DC Voltage:	24V
Maximum torque:	1.2Nm

The output power and operating speed is based on the test rigs available in the laboratory. This means it will be easy to test and the 24V is provided from a bench top power supply in the laboratory. This specification is used to build a simple motor for prototype testing and then used to propose the design of an EV SRM.

The main dimensions of the design SRM are:

Number of Stator Poles	6
Number of Rotor Poles	4
Number of Turns	38
Stator Diameter	97mm
Rotor Diameter	48.5mm
Stator Pole Arc	30
Rotor Pole Arc	32
Air Gap Length	0.4mm
Stack Length	48.5mm

3. FINITE ELEMENT ANALYSIS

MagNet software [4] is then used to create a 2D model of the actual motor from the design calculations for simulations. The design of the SRM prototype is verified from the flux-linkages versus current characteristics for both the aligned and unaligned positions

The dimensions of the designed SRM are used to create a 2D model of the actual motor for performance analysis. The stator and rotor are drawn in AutoCad before exported to the wire cutting machine. Figure 1 shows a typical flux distribution. A flux density of 2.05T in the pole tips is saturating the lamination material, which has a B_{sat} of approx 1.7T. The flux lines of the stator poles are spreading outward back to the stator yoke, through the adjacent stator poles, the rotor yoke and also the rotor poles. A zoom view of the spreading flux lines is shown in Figure 2. The flux-linkage and torque for different orientations of the rotor and stator poles and different values of the winding current are obtained by using FEA [4].

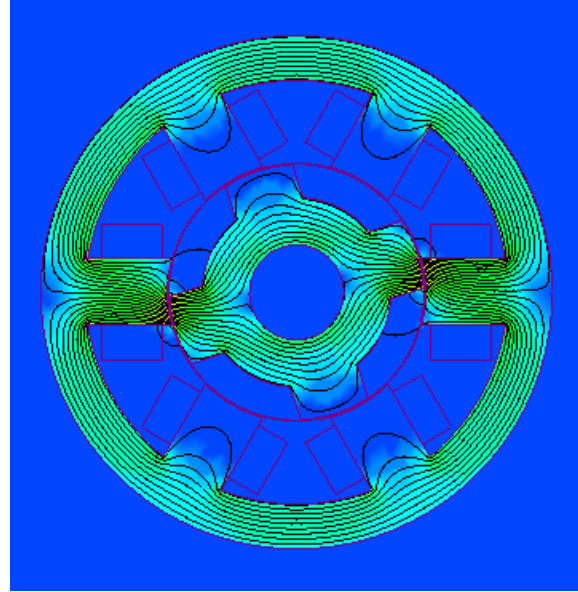


Figure 1: Flux distribution at 15 degree rotor position with the energised phase carries a current of 10A. These results were obtained using the commercially available FEA software MagNet 6.6.2 [4].

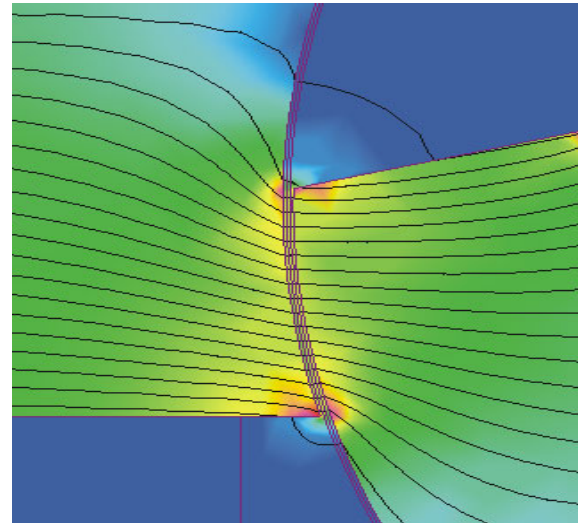


Figure 2: Zoom flux distribution at 15 degree rotor position.

Figure 3 shows the static torque versus rotor position for various currents. This is the result for 50RM400 non-oriented silicon steel as the material of the motor stack. In the case of the 6-4 SRM a rotor position of 0 degrees is the aligned position, where the rotor poles align with the stator poles of the phase winding of interest. A rotor position of 45 degrees is the unaligned position, where the alignment of the rotor and stator poles is a minimum. This results shows that the peak torque is 0.9Nm for a phase current of 10.5A. Figure 3 also shows the non-linear relationship between the phase current and the torque produced [2].

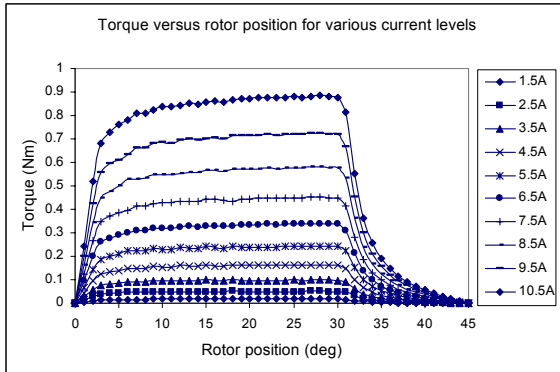


Figure 3: Static torque versus rotor position from the winding current of 10.5A (top curve) to that of 1.5A (bottom curve) by increments of 1.5A.

Figure 4 shows the flux-linkage characteristics of the experimental motor. At a current of 10.5A, the SRM produces a flux-linkage of 0.106Wb.

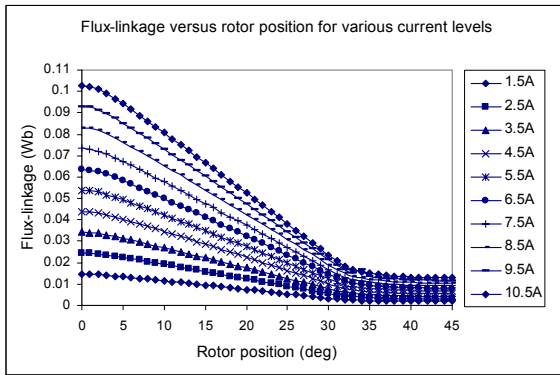


Figure 4: Flux-linkage versus rotor position from the winding current of 10.5A (top curve) to that of 1.5A (bottom curve) by increments of 1.5A.

4. MOTOR CONSTRUCTION

The first step in the construction of the SRM is to find an appropriate method to support the stator and rotor. For this motor an old inductor motor frame is used to house the SRM and provide the bearings for the rotor. Figure 5 shows the final designed SRM in the old motor frame. Spark erosion wire cutting is used to cut out the stator and rotor stacks from non grain oriented silicon sheet steel. The accuracy of the cutting is within 0.04mm. The stator stack is held together by two aluminium cups that aligned and centred the stator stack in the middle of the motor casing. Figure 6 shows the fully completed stator and stator housing and the aluminium cups are visible within the motor frame. The rotor stack was clamped over the non-magnetic stainless steel shaft by a stainless steel nut at one side, and a flange on the other. Figure 7 shows a photograph of the rotor and shaft. The flange that clamps the rotor stack over the shaft is visible and it has a larger size compared to the bearings internal

diameter. The coils were pre-formed and then slipped over the poles without interfering with each other (Figure 5 and 6). The stator coil windings with insulation tape have been taken off to enable a closer look at the windings. All leads are then brought out to the terminals on the side.



Figure 5: Experimental SRM.

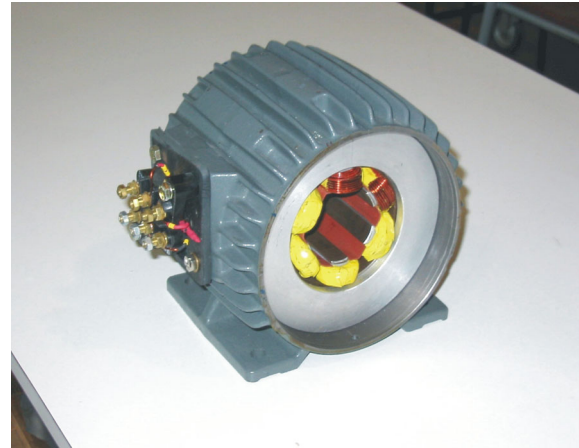


Figure 6: Stator and stator housing.



Figure 7: Rotor and shaft.

The location of the bearings in this design depends on the end housing of the motor case. Figure 7 shows the motor end cap on the far end and how one bearing is housed. The rotor position is determined by using an optical encoder disk that is placed on the outer of the end housing. Only the wires from the sensor can be seen in Figure 7.

5. SRM PERFORMANCE

To fully test the SRM, both static and dynamic tests are carried out. To do this, the SRM is mounted on to a JJ Lloyd instruments test frame that is able to provide a load of up to 2Nm. The test setup consists of the designed SRM being mechanically coupled to a d.c dynamometer, which has a load inertia that is similar to the designed SRM.

The motor performance can be determined by the magnetisation curves of the SRM. The measurement of magnetisation curves is an important step in validating the performance of simulation tools and for determining optimised control strategies, such as current profiling to achieve smooth torque. To measure these curves a pulse of current is injected into the motor winding with the rotor clamped to a fixed position. The oscilloscope captures the motor phase voltage and current. From these measurements it is possible to calculate and then plot the magnetisation characteristics. Figure 8 shows the magnetisation characteristics of the low power SRM in 5 degree steps from the aligned position (0 degrees) to unaligned position (45 degrees).

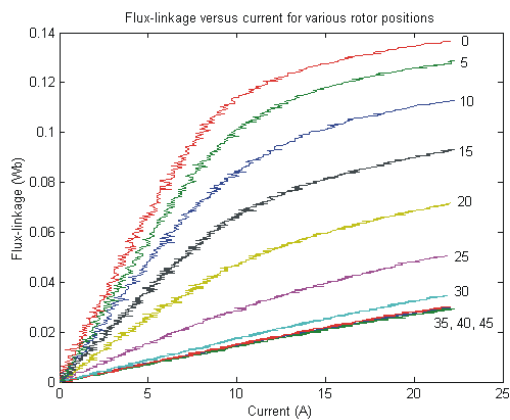


Figure 8: Magnetic characteristics of the design SRM (0 degrees aligned, 45 degrees unaligned).

From the measurements, a flux-linkage of 0.11Wb is obtained from a current of 10.5A. This closely matches the 0.106Wb from the FEA simulation at the same current level. The next test conducted is the measurement of the static torque when the rotor is

rotated 5 degree steps from the aligned to unaligned position. The static torque is measured using a digital force meter placed perpendicular at distance 6.2cm from the shaft centre and on the opposite side to the direction of rotation. This counter-balances the force that acts on the rotor when the phase winding is energised. The rotor position at which the torque is exerted is measured using a protractor attached to the rotor shaft. Figure 9 shows the comparison between the measured static torque (M) and the FEA result at 5.5A. From the measured static torque, the SRM produced a torque of 0.24Nm at 5.5A. This matches the 0.24Nm obtained from the simulation (see Figure 4) at the same current level.

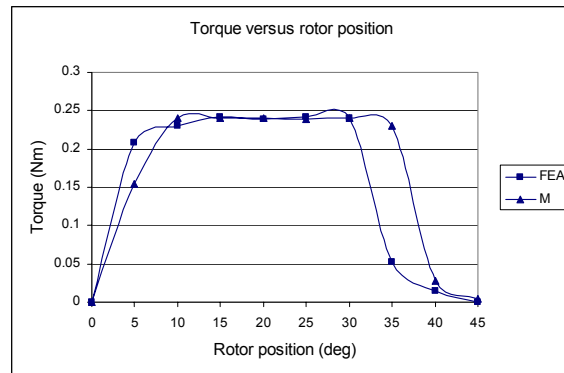


Figure 9: Torque at different rotor position calculated from the FEA and measurement (M).

6. DESIGN OF AN EV SRM

The FEA results closely match the experimental results; therefore FEA can be used to predict the performance of a new EV motor. The proposed motor specifications for the EV3 Toyota MR2 are required to be:

Maximum Operating Speed	8000RPM
Continuous Output Power	22kW
DC Voltage	312V
Maximum Torque	150N
Motor Weight	less than 50kg

These requirements provide the driving performance which is currently available with the internal combustion engine. To accelerate at rate equal to the original MR2 petrol engine then the SRM is required to produce a minimum torque of 150Nm at low speed. To drive at 120km/h, the MR2 requires the motor to produce a continuous power of 21kW. The proposed SRM is designed using the same design procedure [2] used for the low power SRM.

The proposed SRM is a four-phase. A four-phase SRM is selected due to the four-phase SRM producing less acoustic noise and torque ripple compared to a

three-phase SRM [1][2]. The torque ripple especially at low speed is undesirable for EV application. Another benefit of selecting a four phase SRM over a five-phase SRM, which has lower torque ripple, is that less power devices and current sensors are required.

The stator diameter and stack length are optimised to achieve high specific power and torque. The main dimensions of the proposed SRM are:

Number of Stator Poles	8
Number of Rotor Poles	6
Number of Turns	13
Stator Diameter	300.4mm
Rotor Diameter	159.2mm
Stator Pole Arc	19
Rotor Pole Arc	21
Air Gap Length	0.7mm
Stack Length	111.4mm

Figures 10 and 11 show the flux-linkage and torque versus rotor positions for various current levels. These are the results for the same lamination material used for the prototype motor as the material for the motor stack. Linear characteristics from a rotor position of 3 to 20 degrees, torque producing regions, of the proposed SRM is shown in both figures. At a stator current of 200A, the SRM produces a flux-linkage of 0.51Wb in the aligned position. From Figure 11, the SRM produces a peak torque of 320Nm at a current of 300A. The small variation of the torque waveform between 11 to 20 degrees, especially at 300A, is due to the meshing of the 2D model. The mesh in this region is not fine enough and it would take significantly more computation time if it is refined.

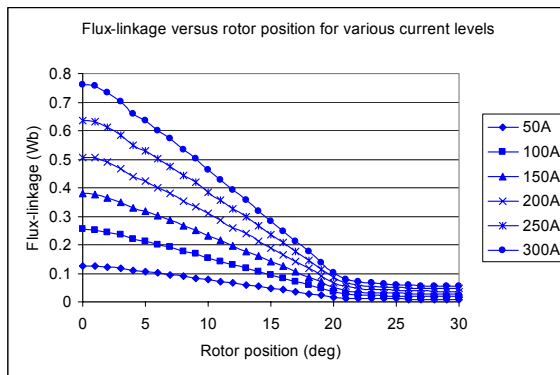


Figure 10: Flux-linkage versus rotor position from the winding current of 300A (top curve) to that of 50A (bottom curve) by increments of 50A.

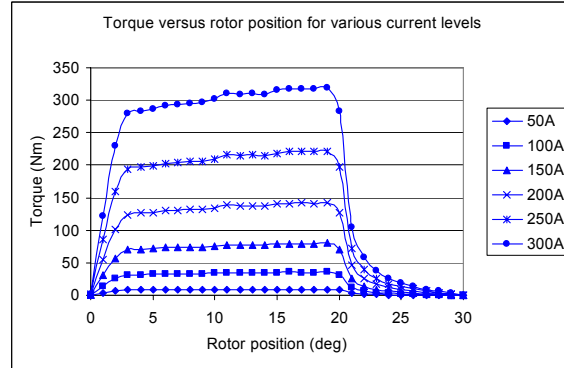


Figure 11: Static torque versus rotor position from the winding current of 300A (top curve) to that of 50A (bottom curve) by increments of 50A.

The motor current torque level that generates torque would be limited by the controller. It is expected that for a normal operation of the car at 60km/h, it would require 8kW or 40 to 50 Nm. From Figure 11 a current level of 100A is required. To accelerate between 0km/h to 60km/h the car requires 150Nm of torque and therefore a current of greater than 200A is needed to give good performance.

7. CONCLUSION

This paper presents the design and construction of a low power, 3-phase SRM that verifies the design procedure process for an EV application. Finite element analysis simulations show the expected characteristics of the design SRM match the design specifications. Flux-linkage and torque measurements both match the FEA simulations.

A proposed 4-phase, 22kW SRM for a Toyota MR2 is presented that has a peak torque of 150Nm at a current of 210A. This motor should accelerate the MR2 with good performance between 0 to 60km/h. The motor diameter and stack length are optimised to achieve high specific power and high specific torque.

8. REFERENCES

- [1] T. Uematsu, R. S. Wallace "Design of a 100kW Switched Reluctance Motor for Electric Vehicle" IEEE Transactions on Industrial Electronics, vol. 49, no 1, pp 160-170, Feb 2002
- [2] T.J.E. Miller, Switched Reluctance Motor and Their Control, Magna Physics and Clarendon Press, Oxford, 1993.
- [3] T.J.E. Miller, "Optimal Design of Switched Reluctance Motors" IEEE Transactions on Industrial Electronics, vol. 49, no 1, pp 160-170, Feb 2002.
- [4] MagNet 6.2.2 (2001), Finite-element package for electromagnetic analysis, Infolytica Corporation, Montreal.