# SWITCHED RELUCTANCE MOTOR BASED ON SHORT FLUX PATH CONTROL METHOD

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## ABSTRACT

This paper presents the design and control of a 3-phase 12/10 asymmetrically structured switched reluctance motor (SRM). The nonlinear magnetisation characteristics of the SRM make the motor complex. Finite element analysis (FEA) is therefore model these characteristics. Analysis and verification obtained from simulation and modelling were used to guide the design and production of a prototype SRM. This motor is based on a short flux path control scheme.

Keywords: switched reluctance motor, short flux path, finite element analysis

## I. INTRODUCTION

The switched reluctance motor (SRM) is attracting interest due to its simple construction, low manufacturing cost, reliable operation and high efficiency. It has a high power to weight ratio and robust rotor structure which is capable of operating in harsh environments [1], [7]. Recent advances in power electronics and microelectronics have demonstrated the huge potential of switched reluctance motor drives. The manufacturing and maintenance costs for switched reluctance motor drives will be much cheaper than alternatives such as the brushless DC motor, the induction motor and the AC motor [1].

A prototype 3-phase 12/10 asymmetrical switched reluctance motor has been designed. This motor has irregular stator geometry as shown in Figure 1. The purpose of this paper is to present the design of this motor using a short flux path technique. The magnetic flux of this designed switched reluctance motor flows in a shorter loop in adjacent pole-pairs compared to conventional switched reluctance motors in which the flux flows in a long flux path.

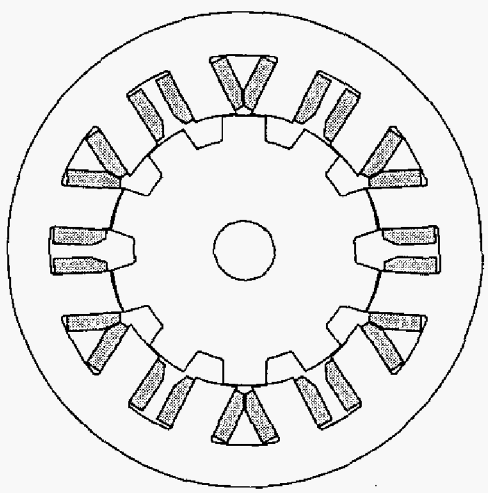

**Figure 1. Cross section of a 3-phase 12/10 SRM with concentrated winding on each stator pole**

## II. ELECTROMAGNETIC ANALYSIS

Finite element analysis (FEA) is used to obtain the nonlinear magnetization data for applying in the simulation [2]. The mathematical model of the SRM is based on the voltage equation which is defined as

$$v = Ri + d\lambda/dt \qquad (1)$$

where $v$ is the phase voltage
$R$ is the phase resistance
$i$ is the phase current
$\lambda$ is the flux linkage of the phase

The static torque of the SRM can be obtained by using the partial derivative of the co-energy with respect to rotor displacement under constant current. Co-energy, $W_{ce}$ is the energy conversion of the nonlinear electromechanical system.

$$T(\theta, i) = \left.\frac{\partial W_{ce}}{\partial \theta}\right|_{i=\text{constant}} \quad (2)$$

where $T$ is the static torque, Nm
$W_{ce}$ is the co-energy, J
$\theta$ is the rotor position, mechanical degree
$i$ is the stator current, A

The FE mesh generated from the FEA software has consisted 18424 nodes and 36660 elements as shown in Figure 2.

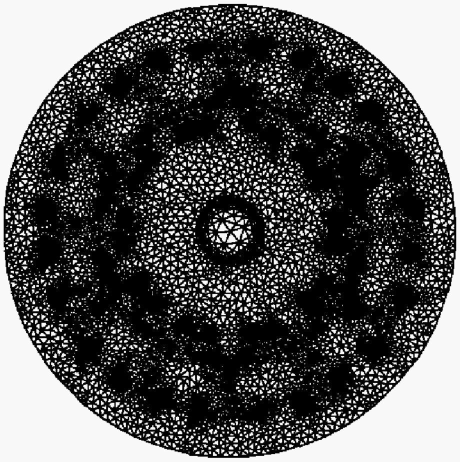

**Figure 2. Finite element mesh for the motor**

## III. SHORT FLUX PATH

The electromagnetic operation for this prototype SRM is different from that of a conventional SRM. Magnetic flux travels in a short flux loop in contrast to conventional SRMs which use a long flux loop. Figure 3 depicts the fully aligned position of the stator and rotor poles. When a stator pole is excited the most adjacent rotor pole-pair is attracted towards the excited stator pole which will achieve alignment between both stator poles and rotor poles. This is caused by the nature of the reluctance path [6].

The advantages of using a short flux path are to reduce the eccentric forces between the stator and rotor poles. In addition, core losses are significantly reduced due to the short distance of the travelling magnetic fields in the short flux path design. Flux reversals in the back iron are also eliminated [1]. The disadvantage arises from the asymmetrical structure of the stator poles structure which limits the space available for the coil windings.

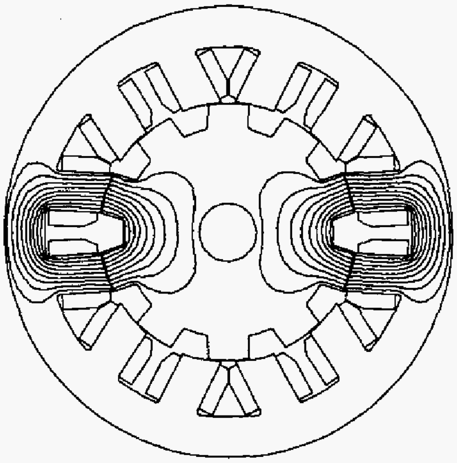

**Figure 3. Aligned flux distribution for Phase 1 with rotor at 0 degrees**

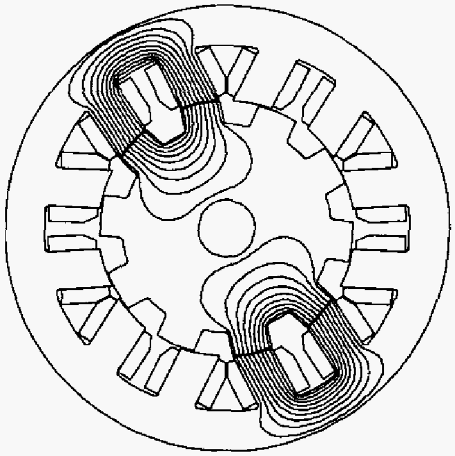

**Figure 4. Aligned flux distribution for Phase 2 with rotor at 12 degrees in anticlockwise direction**

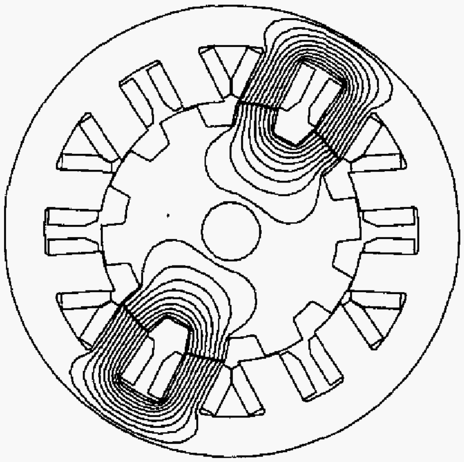

**Figure 5. Aligned flux distribution for Phase 3 with rotor at 24 degrees in anticlockwise direction**

This 12/10 SRM is capable of being turned on a single-phase and a single-double phase operating mode [3], [4]. Single-double phase operating mode will significantly reduce the torque ripples generated compared to single-phase operating mode [5].

### A. Single-Phase Operating Mode

Every phase will turn on and turn off in sequence with 12 mechanical degrees apart with respect to rotor angle or 120 electrical degrees for a single step. Figures 3, 4 and 5 show the magnetic flux distribution of the SRM of each phase in aligned position. Phase 1 is fully aligned at 0 mechanical degrees, Phase 2 is fully aligned at 12 mechanical degrees and Phase 3 is fully aligned at 24 mechanical degrees. Every 12 mechanical degrees will bring an excited pole-pair to full alignment. This means 1 full motor revolution will require 30 switchings from the SRM inverter drive.

*Phase 1 – Phase 2 – Phase 3 - repeat*

### B. Single-Double Phase Operating Mode

One of the phases will turn on then the adjacent phase will turn on without turning off the previous phase. This means that both phases are turned on simultaneously. A flux distribution for double-phase operating mode is shown in Figure 6 where Phase 1 and Phase 2 are both excited in alignment and the rotor has moved 6 degrees in an anticlockwise direction.

*Phase 1 – [Phase 1 & Phase 2] – Phase 2 – [Phase 2 & Phase 3] – Phase 3 - [Phase 3 & Phase 1] - repeat*

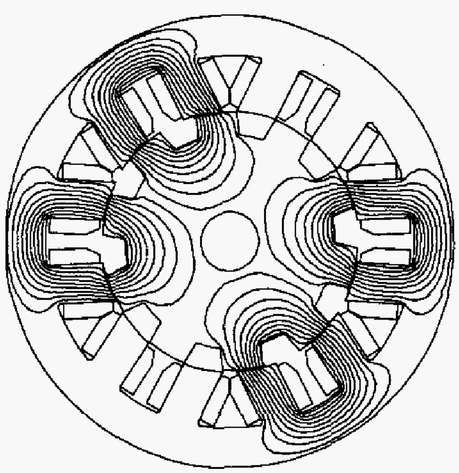

**Figure 6. Aligned flux distribution for double-phase operating mode where Phase 1 & Phase 2 are excited**

## IV. MOTOR DESIGN AND RESULTS

The flux linkage characteristics and static torque of the SRM have been analysed and calculated using CAD, FEA and MATLAB software. These results are important to the simulation and modelling of the SRM. Figure 7 shows the flux linkage characteristics and Figure 8 shows the static torque for the designed SRM. These results have shown the good characteristics prior to production of the SRM.

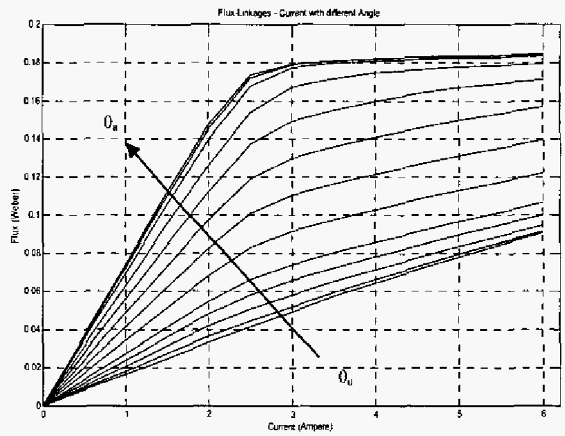


**Figure 7. Flux linkage profile at different current levels and rotor angles**

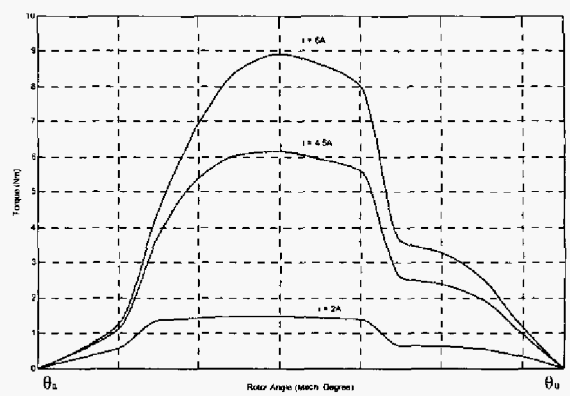


**Figure 8. Static torque in the SRM for single-phase excitation of 2A, 4.5A and 6A**

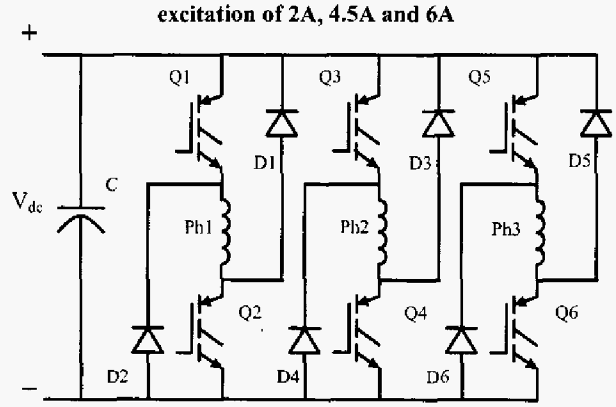


**Figure 9. Asymmetric half-bridge inverter**

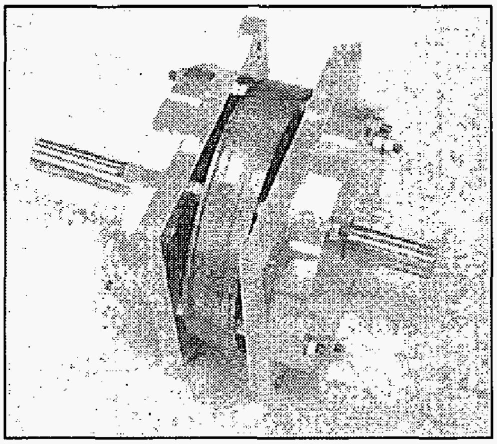

**Figure 10. 3-Phase 12/10 prototype SRM**

## V. CONCLUSIONS AND FURTHER WORK

A prototype SRM has been built based on finite element analysis and analytical studies. FEA has been used to investigate the behaviour and characteristics of the short flux path control of SRM.
A Digital Signal Processor (DSP) will be used to control the whole electric drive with flexible control algorithms. A schematic diagram of the asymmetric half-bridge inverter is shown in Figure 9. This is a conventional SRM inverter which consists of six IGBTs and six free-wheeling diodes for 3-phase operation. This type of inverter is able to control the SRM in soft and hard switching with firing PWM signals from DSP. The photo of the prototype 3-phase 12/10 SRM is shown in Figure 10.
Extensive simulation and modelling of the motor drive system and practical control experiments will be untaken to validate the designed prototype SRM.

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