FINITE-ELEMENT STUDY ON A TWO PHASE SWITCHED RELUCTANCE MOTOR WITH SLITTED ROTOR POLES

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***Abstract* --- The magnetic saturation characteristic of the switched-reluctance (SR) motor has a very strong influence on its current, torque and power. The best power per weight ratio of SR motor can be achieved by employing equal cross-section area in every part of its magnetic core. However, in some designs a non-uniform or larger stator-core cross-sectional area is required to achieve acceptable rigidity and acoustic noise levels, and as a consequence these motors do not achieve optimum power density. Adding parallel slits to motor poles may modify the saturation characteristic and air-gap flux distribution of SR motor. This paper investigates the effect of rotor-pole slits on the performance of a small two-phase 4/6-pole SR motor using finite element and time-stepping simulation. It is found that adding suitably sized parallel slits to the rotor poles can enhance the performance of the SR motor.**

Keywords - switched-reluctance motor (SRM), switched-reluctance motor design, finite-element analysis (FEA)

I. INTRODUCTION

SR motor is generally believed to demonstrate good potential in power density, torque/inertia ratio, speed range, efficiency, manufacturing cost, and reliability, even though these advantages are often offset by some design compromises such as levels of acoustic noises and torque ripples. More advantages of SR motor have been discussed in [1-3]. The difficulties of the SRM design are mainly attributed to the following reasons: 1) high magnetic and control nonlinearities; 2) many flexible design parameters, including those that affect vibrations and acoustic noises; 3) interdependence on the design of the converter and control parameters; 4) variable speed operations; 5) thermal management bottleneck due to the concentrated coils; 6) difficulty of thermal rating prediction; and 7) possible high sensitivity of design to manufacturing tolerance [5]. The fundamental of the SRM electrical design was described in [1], [4], [5], [6] and [7]. References [9] and [10] presented time-stepping electrical simulations. The magnetic finite element analysis (FEA) of the SR motors had been reported in [12]-[14]. The analysis of SR motor noise reduction was reported in [15]-[17].

The SR motor is a variable speed machine. Controlling the excitation time or modulating the excitation may control its torque and speed. Although SR motor is the simplest motor in terms of construction, its analysis and design however is complicated due to its highly saturated magnetic core. Finite element technique of analysis is appropriate in SR motor modeling. Most common electric motors are based on the principle that force is created by interaction between magnetic fields. However, the SR motor uses another principle such that a piece of iron placed in a magnetic field will always align in the minimum reluctance position where the magnetic field meets the lowest resistance.

II. SRM THEORETICAL BACKGROUND

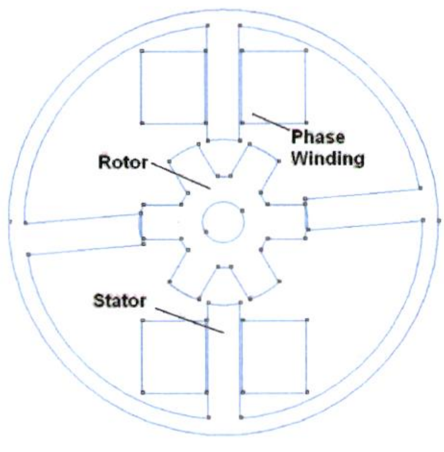

Figure 1.0: Cross Section View of 4/6 SRM

Figure 1.0 shows a cross section view of 4/6 SR motor. Both the rotor and the stator have iron

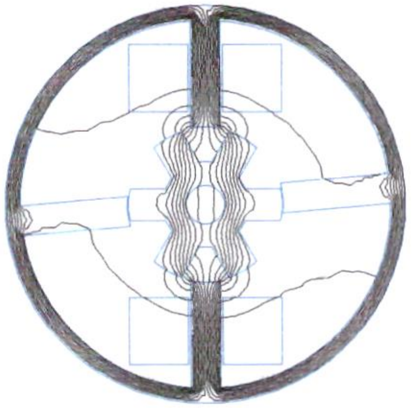

Figure 2.0: Rising current condition

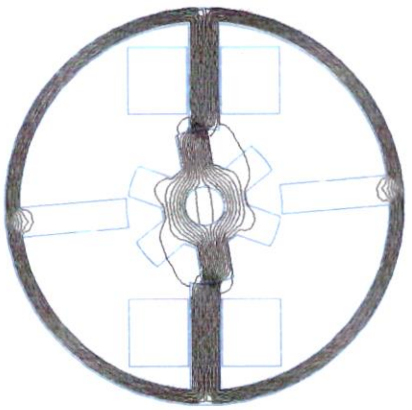

Figure 2.1: Torque Production condition

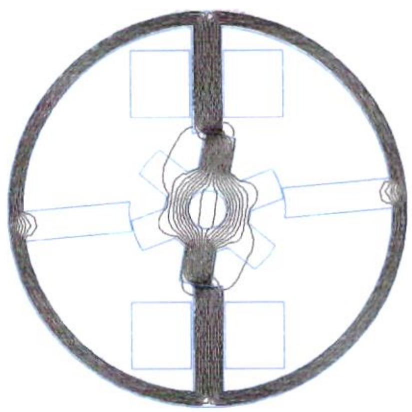

Figure 2.2: Current commutation condition

To improve the motor performance, the slit pattern should reduce the rotor pole cross-sectional area sufficiently to provide adequate saturation. Slit length and width should be adequate to provide adequate increase of reluctance (decrease of inductance). The slitting has caused rotor saturation to be rotor orientation dependent. Such effect on rotor flux distribution could not be achieved by other methods of magnetic constriction.

IV. METHODOLOGY

Since the relationship between current and torque in a particular SR motor is non-linear, it is difficult to study the characteristic of the motor. To solve this, advance Finite Element Analysis (FEA) programs are performed in order to analyze and simulate the SR motors. The SR motor without any slit is used as the based model. Then, the designed SR motor with different slit lengths and positions are analyzed using the 2D Finite Element Method Magnetic program (FEMM) developed by David Meeker (dmeeker@ieee.org) to generate the static flux-linkage/current Ψ-i-θ and torque/position T-θ-i model for the SR motor. The FEMM provide time stepping simulations that used to solve the flux linkage in each time step and the current and torque are obtained by interpolating the static flux-linkage and torque data. The FE solutions will provide detailed flux pattern of each configuration. The user's manual of FEMM is provided in [8].

FEMM torque computation is based on the weighted stress tensor volume integral of FEMM. The Weighted Stress Tensor block integrals compute a weighting function over the finite element mesh that allows all possible air elements to contribute to the stress tensor integration. Only one finite element analysis is required for the torque computation. The approach has better accuracy than other techniques and is essentially identical to the weighted stress tensor approach described in [9]. Figure 3.0 shows the finite element mesh or triangulation that used in the torque calculation.

The best configuration is then selected for the performance analysis, which evaluated using Matlab software. The resulted analysis of the designed and the model based SR motor are then compared and the trend of the output power with respect to the parameter variations (slit patterns) is presented to indicate the effect to the motor performance.

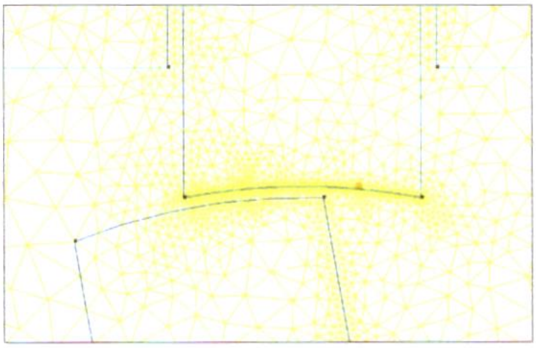

Figure 3.0: Finite element mesh (triangulation) created by FEMM

V. OPTIMUM SLIT PATTERNS AND RESULT

A small 4/6-pole SR motor is being used in this paper investigation. The non-slit model SR motor (base model) and the SR motor with 5 slits on the rotor part are named as motor A and B respectively. The slits positions are symmetrically arranged in parallel to ensure that the motor has the same operation and performance in either direction. Figure 4.0 and figure 4.1 are the resulted flux distribution of motor A and B respectively.

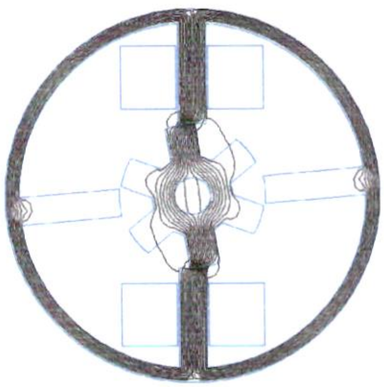

Figure 4.0: Flux distribution of motor A

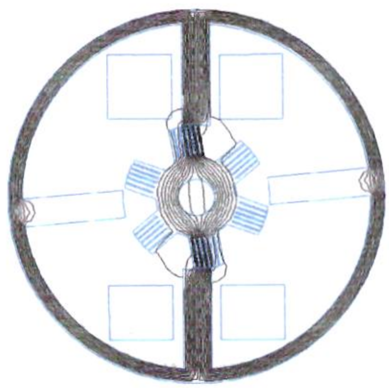

Figure 4.1: Flux distribution of motor B

The boundary condition of the outer boundary is set as zero vectors potential. The standard Ψ-i-θ and T-θ-i characteristics are computed for the full range of rotor positions (60 degrees) as the introduction of slits may have destroyed the symmetry of static flux-linkage curves. The voltage, current and torque waveforms of motor A and B are given in figure 4.2 and 4.3 respectively. These waveforms are computed by the performance analysis using the Matlab software after the Ψ-i-θ and T-θ-i models have been obtained from the FEA.

The base model of SR motor produces a standard torque and current output waveforms. However, the proposed SR motor with an introduction of slits on its rotor poles achieved an improvement on its current waveform such that a flattop shape current is obtained. This scenario can be explained by knowing the relation of the magnetic-saturation of SR motor.

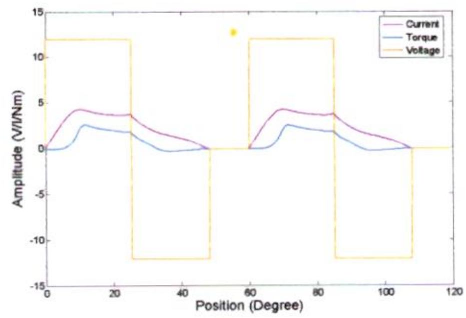

Figure 4.2: Voltage, current and torque waveform of motor A

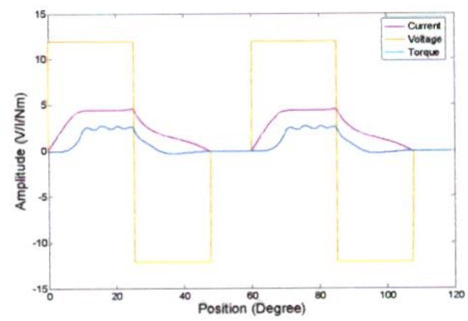

Figure 4.3: Voltage, current and torque waveform of motor B

Magnetic saturation (increase in reluctance but decease in inductance) causes current to increase. Motor A does not have a flat-top current because heavy saturation does not occur. Figure 4.4(a) shows the flux distribution of motor A while figure 4.4(b) shows its normal flux density along XX'.

Figure 4.5(a) and figure 4.5(b) shows the flux distribution of motor B and its normal flux density along XX' respectively. (Both cases; base and 5-slit model are simulated at excitation current of 5A and 10° degrees of aligned axis). It is observed that the flux is forced to flow along the narrow slits of the rotor core. The flattop current achieved mainly due to the enhancement in saturation level where the rms current increases while the peak current remains almost constant. This action will enhance and allows control of the motor magnetic saturation. The output power of motor B is increased by about 15% without any increase of current peak magnitude.

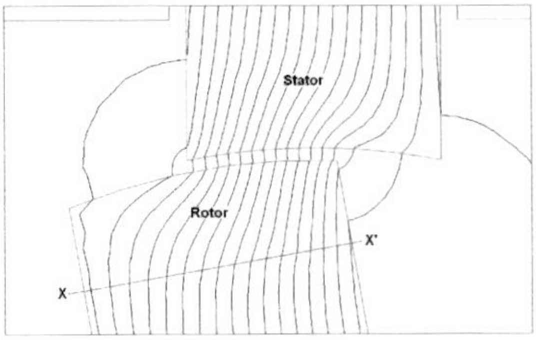

Figure 4.4(a): Rotor pole flux distribution of motor A

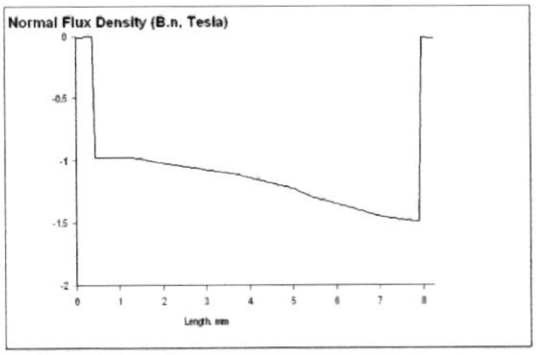

Figure 4.4 (b): Normal flux density along XX' of motor A

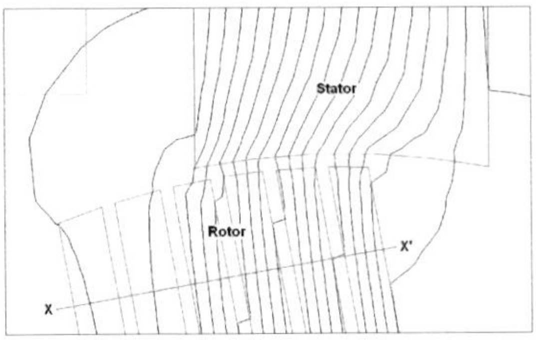

Figure 4.5 (a): Rotor pole flux distribution of motor B

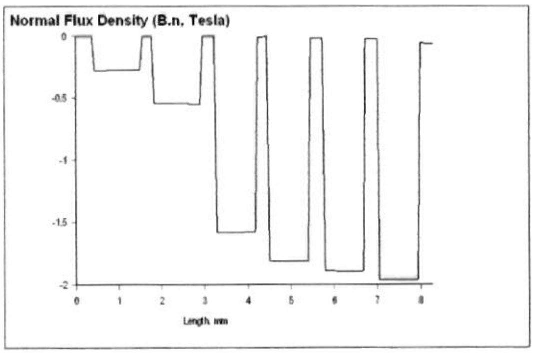

Figure 4.5 (b): Normal flux density along XX' of motor B

It is found that the rotor slits will force the magnetic flux to flow through it. The reluctance of the rotor pole can be controlled by varying the number, width and length of the slits. It is important to know the effect of these parameters to the motor performance. Slit patterns may make the rotor pole saturation position dependent. The optimum slit patterns for a motor depends on parameter such as size of the motor, length of the stator pole, production possibility etc.

To investigate the effect of the slit width and length to the motor performance, the trend of output power with respect to the parameters variations are obtained. A fix width of 0.3mm and length of 7.5mm are being used as the optimum slit pattern in this paper investigation. The width and the length of the slit pattern are then increased gradually and the resulted trend of output power is illustrated in figure 4.6 and figure 4.7.

It has been observed that as the slit width and length increase, the resulted output power will also increase. This is because increasing width and length increases the reluctance. As a consequence, current will increase and hence greater output power will be produce.

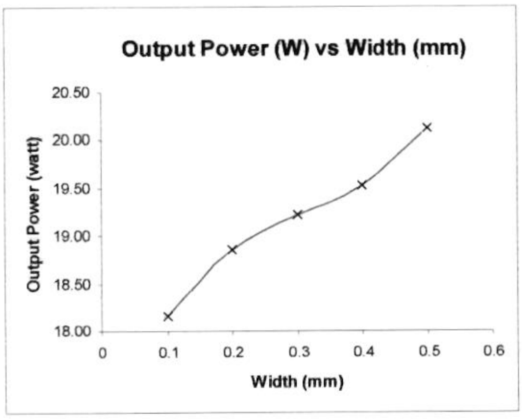

Figure 4.6: Graph output power vs. slit width

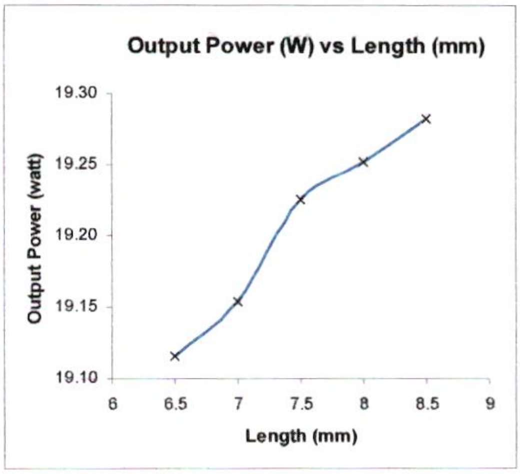

Figure 4.7: Graph output power vs. slit length

Another factor that has significant effect to the motor performance is the number of slits. For a large number of slits such as five, it had been found that fairly good saturation control such that a flat top current can be obtained. Having a small number of slits such as three on the other hand will provide less output power compared to 5 slits. This scenario happened since three slits produce large step change of reluctance as a new strip of material enters the stator-rotor overlap. This will cause saturation to be hard to control thus the enhancement in output power will be minimal. A three-slit rotor with same width and length as motor B are illustrated in figure 4.8 and its voltage, current and torque waveforms are indicated in figure 4.9.

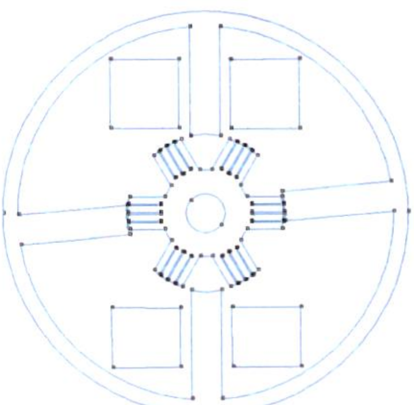

Figure 4.8: SR motor with three slits on rotor poles

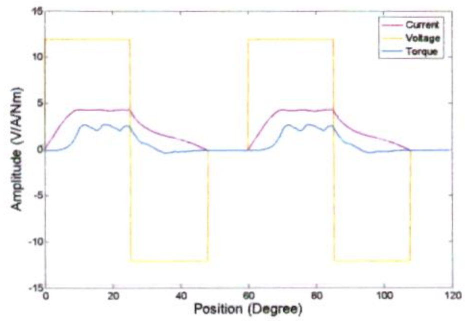

Figure 4.9: Voltage, current and torque waveforms of three-slit SR motor

From analysis that had been done, the three-slit SR motor operates in a lower current and produced higher ripple in the output torque compared to the five-slit SR motor. These scenarios can be observed by looking at its waveforms illustrated in figure 4.9. It has been found that the performance of the motor had increase about 11%

In selecting a slit pattern, requirement of production (stamping) must be taken into consideration. For big motor, the number of slits can be large as the slit width will not be too small for stamping but for small motor (like the motor that being investigate in this paper) increase the number of slits simply means that the production of the motor will be complicated such that the manufacturer have to cut very narrow slits for the motor production.

VI. CONCLUSION

The effect of rotor slits on the performance of a small two-phase 4/6 pole SR motor was investigated using finite element and time-stepping simulation. Results had indicated that a flattop current waveform and higher power could be achieved without an increase in peak current magnitude. It is found that adding suitable sized parallel slits to the rotor poles may enhance the performance of the SR motor.

VII. FUTURE DEVELOPMENT

There is no doubt that SR motor featuring high capability on its power, torque and inertia per weight ratio. However, these advantages are restricted by its acoustic noises and torque ripples.

Research had shown that the acoustic noise produced by the SR motor can be eliminated by providing rigid and oversize stator core [16], but these designs tends to lower the power density of the motor since large size of stator core will be less saturated. The proposed SR motor structure in this project offers solution to this problem. By providing slits at the rotor pole for the design of low-noise SR motor, the power density of the SR motor can be enhance and at the same time, a high performance low-noise SR motor can be produced.

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cores with salient poles. The windings around the poles of the stator are diametrically connected, two and two, as phase windings. Due to the salient poles in the rotor and stator, each phase circuit has a reluctance that varies with the rotor position. When a phase winding is energized, the rotor tries to position itself to achieve the minimum reluctance for that phase just as the rotor approaches equilibrium, current is switched to the next phase winding so that rotation is maintained. It is necessary to switch the current between the various phases at exact rotor positions. The controlling electronics ensure that the current and voltage are switched in sequence between the phases of the motor so that they follow the rotor.

The SRM mathematical model was discussed in [6]. The phase voltage equation in a SRM can be written as:

$$v(t) = Ri(t) + \frac{d\psi}{dt} \qquad (1)$$

where, V is the dc bus voltage, 'i' is the instantaneous phase current, R is the phase winding resistance and Ψ is the flux linking the phase coil. Ignoring stator resistance, Equation (1) can also be written as:

$$V = L(\theta)\frac{di}{dt} + i\frac{dl(\theta)\omega}{d\theta} \qquad (2)$$

where, ω is the rotor speed, θ is the rotor angular position, and L (θ) is the instantaneous phase inductance. The rate of flow of energy can be obtained by multiplying the voltage with current and can be written as:

$$Vi = Li\frac{di}{dt} + i^2\frac{dl}{d\theta}\omega \qquad (3)$$

or

$$P = \frac{1}{2}\frac{d}{dt}(Li^2) + \frac{1}{2}i^2\frac{dl}{d\theta}\omega \qquad (4)$$

The first term of the above equation represents the rate of increase in the stored magnetic field energy while the second term is the mechanical output. Thus, the instantaneous torque can be written as:

$$T(\theta,i) = \frac{1}{2}i^2\frac{dl}{d\theta} \qquad (5)$$

This paper investigates the application of magnetic constrictions to enhance the output power of SR motor. The proposed motor structure involves cutting a number of parallel slits on the rotor poles (not necessary equal portions). Such slits increase the reluctance of tangential flux paths and force the flux to flow along narrow strips of the core material. These slits re-distribute the air gap flux and enhance local saturation.

The depth of the slit with respect to the rotor pole high, the position of slit, and the slit width with respect to the aligned air-gap are important parameters in this design. The focus of this project is to investigate the effect of these parameters on the performance of a two-phase SR motor using finite element approach and finally searches for an optimum slit pattern that enhance the two-phase motor operation. The laboratory testing of this modified motor is not included in the scope of this project.

III. ROTOR SLITTING AND MOTOR MAGNETIC SATURATION

The proposed modification to the rotor pole will not have significant effect on the initial current build up due to unsaturated magnetic condition and on the main torque production region as the stator and rotor pole pair is almost aligned. However, the slit increases the reluctance during a large portion of the current commutation duration and hence improves the commutation process. The above stated conditions are illustrated in figure 2.0 – 2.2.

SR motor performance is usually being measured by its ability to produce high torque and output power. The higher the torque and the output power, the better the SR motor will be. An increase in current in the SR motor operation could give result to a higher torque production. In SR motor design, parameters such as, current, inductance and reluctance could give a significant effect to the motor performance. It is observed that the current of SR motor start to decrease as the stator and rotor pole overlap. This is due to the increase of inductance caused by the poles alignment. It is possible to control the magnetic saturation in such a way that the increase of inductance due to alignment is partly compensated by the decrease of inductance due to saturation.