Analysis and Torque Optimisation of Switched Reluctance Motor

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***Abstract* — This paper shows the developed torque of a 4 phase 8/6 poles switched reluctance motor by simulation tests. The analysis for the torque is computed by finite element method. The torque optimisation is investigated by changing the pole arc/pole pitch ratio (γ) of the stator, rotor and yoke dimensions.**

***Index Terms* — Reluctance motors, Simulation**

I. INTRODUCTION

The concept of the switched reluctance motor was established by 1838, but the motor could not realize its full potential until the modern era of power electronics and computer-aided electromagnetic design. Since the mid-1960s, these developments have given the SR motor a fresh start and have raised its performance to levels competitive with DC. and AC drives and brushless DC drives. The SRM is a relatively newcomer to the family of electric motors and is unusual for having salient poles on both rotor and stator and for its complete dependence on its power electronic controls. It is however remarkably versatile. The design problem is that the switched reluctance motor does not conform to the established design techniques used for classic DC and AC motors.

The practical design engineer is confronted with a machine that has no steady state, has extreme localized saturation and requires an unfamiliar power-electronic converter to make it work at all. The geometry is rather simple and everything about the motor and its control seems at first sight to be a gift to the production engineer. But the attainment of good designs and satisfactory performance is practically impossible by traditional design methods. Although SRM motors have been well known for a long time, only today's industry is paying attention to these kinds of electrical machines [1-7].

The motor is doubly salient with phase coils mounted around diametrically opposite stator poles. The energisation of a phase will lead to the rotor moving into alignment with the stator poles, so minimising the reluctance of the magnetic path. This is the same principle of operation as the VR stepper motor. As a high performance variable speed drive, the motor's magnetics are optimised for closed-loop operation. The rotor position information is used to control phase energisation in an optimal way to achieve smooth, continuous torque and high efficiency. The maximum inductance corresponds to the minimum reluctance pole-aligned position. The positive torque is only produced at angles when the inductance gradient is positive.

At low speeds, the phase current has to be constrained to protect the electronics because of the high available volt-seconds. At higher speeds, the current is naturally constrained, and single-pulse voltage control is normally employed with angle advance prior to the unaligned position to optimise performance. The energy conversion mechanism is illustrated by the co-energy trajectory. Fig. 1 shows the W_{con} area, the energy converted into mechanical energy (or converted from in the case of a generator). W_{ret} is the surplus energy returned to the power supply rails. Minimising W_{ret} by good magnetic design and optimal phase energisation control are the key features of an SR system. SR machines can offer a wide variety of aspect ratios and salient pole topologies. This means that each application is likely to be better suited to a specific SR topology [7-13].

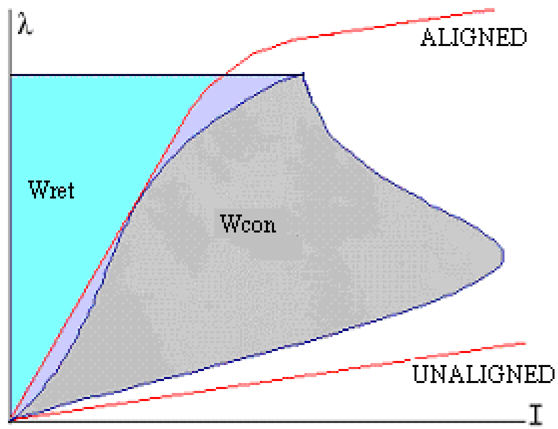

Fig. 1: Flux linkage versus current for SRM

II. MATHEMATICAL MODEL of SRM

A four-phase motor may be popular for reducing torque ripple further, but the large number of power devices and connections will probably limit four phases to a limited application field. Five and six-phase motors can offer better torque ripple reduction compared with four-phase and three-phase. Single-ended converters can be used but the favourite is the two-transistor forward converter topology (asymmetric half-bridge) which has two power switches connected to either end of the power rails and in series with a winding for fluxing the machine and two diodes forming a return path. In the past there has been some debate about VA ratings when comparing other motor topologies but with modern majority carrier devices such as IGBTs, this argument is largely irrelevant especially when compromises are made with respect to torque ripple and acoustic noise. Similar rated drive electronics will more than likely have the same size devices. There is a cost disadvantage over a MOSFET inverter since the inherent MOSFET anti-parallel diodes cannot be used [1-13].

The rotor position feedback is required in some form and traditionally this is done with a rotor-mounted sensor. Not only do they introduce cost to the motor, but they can also be a major source of poor performance and unreliability. SR machines have a significant torque ripple, especially when operated in single-pulse voltage control mode. This is the price to pay for high efficiency. For many applications where the machine is operating at fairly high speeds, this is not a problem since the mechanical time-constant is far longer than the fast rates of change of instantaneous torque produced by the motor. There are applications where the torque ripple is a major concern [7]. Optimising the individual phase torque-angle characteristic by salient pole shape profiling, longitudinal skewing of the rotor and angular phase current profiling can all help to minimise the inherent torque ripples [7]. If the mutual inductance between non-adjacent phases is neglected, the voltage and flux linkage equations for four-phase SRM can be expressed in terms of both phase currents and flux linkages as below:

$$V_a = R_s I_a + (d\lambda_a/dt) \tag{1}$$

$$V_b = R_s I_b + (d\lambda_b/dt) \tag{2}$$

$$V_c = R_s I_c + (d\lambda_c/dt) \tag{3}$$

$$V_d = R_s I_d + (d\lambda_d/dt) \tag{4}$$

Where V_a, V_b, V_c, V_d are the voltages applied to the stator windings, R_s is the stator winding resistance, I_a, I_b, I_c, I_d are the stator current passing through phase a, b, c and d. $d\lambda_a/dt$, $d\lambda_b/dt$, $d\lambda_c/dt$ and $d\lambda_d/dt$ are the rates of flux linkages for phases a, b, c and d.

It is fairly easy to show that under constant current, the torque developed (T) can be written as follows:

$$T = \frac{\partial Wc}{\partial \theta}, i = \text{Constant} \tag{5}$$

Where θ = rotor position, W_c is the co energy, and i is the stator winding current

III. FINITE ELEMENT ANALYSIS

Fig. 2a shows a sample 4 phases, 8/6 poles 1.1 kw SRM, the cross section for the reference 4 phases 8/6 poles SR motor is shown in Fig. 2b, The first motor SRM #1 is the reference 4 phases SR motor, with α = stator pole arc β_s / rotor pole arc βr equal to 1. Fig. 2c shows the torque developed in the reference SR motor versus displacement angles, while varying the mmf (Ampere turns), ATs from 200 → 4000. It is found that the torque is increasing with increasing ampere - turns. Fig. 2-d shows the torque developed in the reference SR motor versus different mmfs. For each mmf, the rotor position displacement is changed from aligned to unaligned positions. The lowest developed torque are obtained at rotor position equal to (0°) and rotor position equal to (30°); because both torque values are too low nearly zero it appears as a single curve as shown in Fig 2d, while in the intermediate positions, the developed torque is higher than the torque values in aligned and unaligned positions.

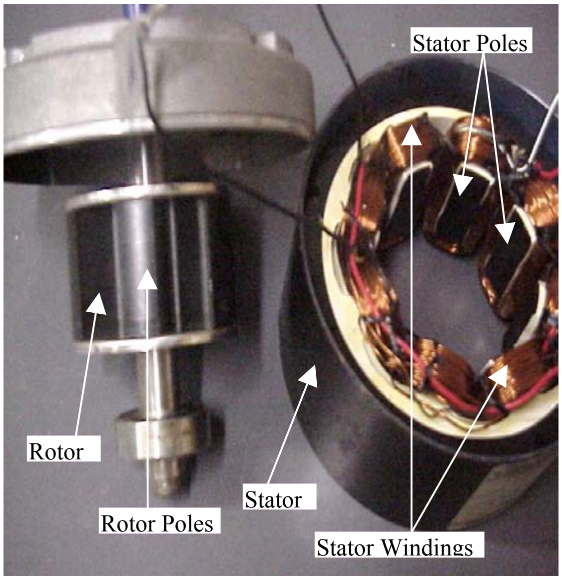

Fig.2a: 4 phase, 8/6 SRM

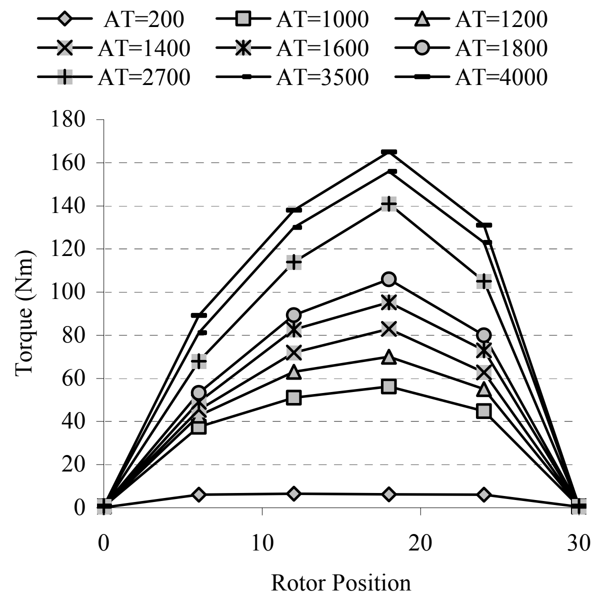

Fig. 2c: Torque versus rotor position at different MMFs

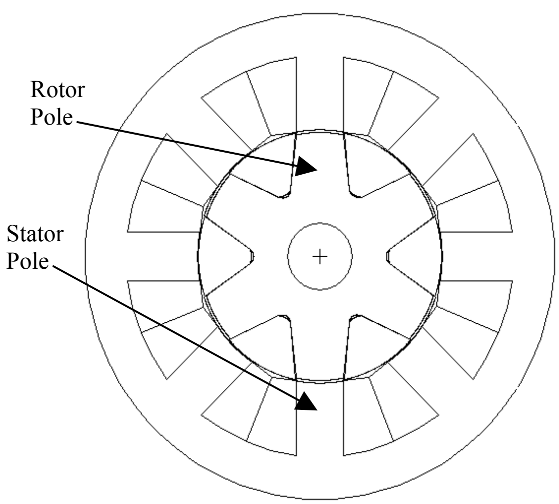

Fig. 2b: Cross section for 4 phase, 8/6 poles reference SR motor.

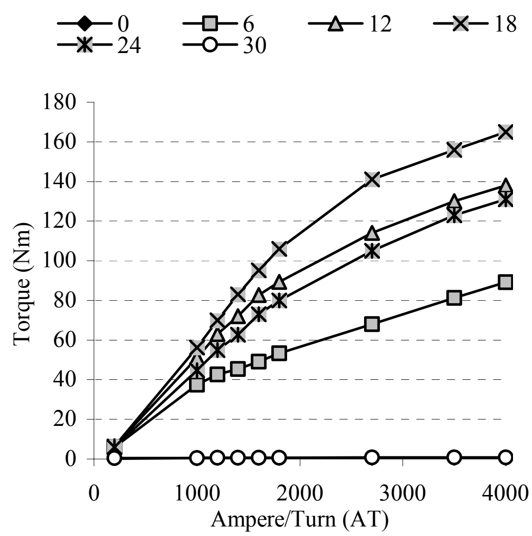

Fig. 2d: Torque versus MMFs at different rotor positions.

Fig. 3a shows optimised switched reluctance motor after dimensional variations are applied to the rotor, stator and yoke of the reference switched reluctance motor, with γ = (stator pole arc β_{s} / rotor pole arc βr) = 0.76. Fig. 3-b shows the torque developed in the optimised SR motor versus displacement angles. Varying the mmf from 200 → 4000 AT, found the torque is increasing as soon as the ampere - turn increases. It is obvious that the developed torque, obtained from optimised SR motor, is higher than the developed torque values obtained from the reference SR motor. Fig. 3-c shows the torque developed in the optimised SR motor versus different mmf. For each mmf, the rotor position displacement is changed from aligned to unaligned positions. The lowest developed torque is obtained at aligned and unaligned positions, while in the intermediate positions, the developed torque is higher than the torque in aligned and unaligned positions. The results for the optimised SR motor are higher than the reference SR motor

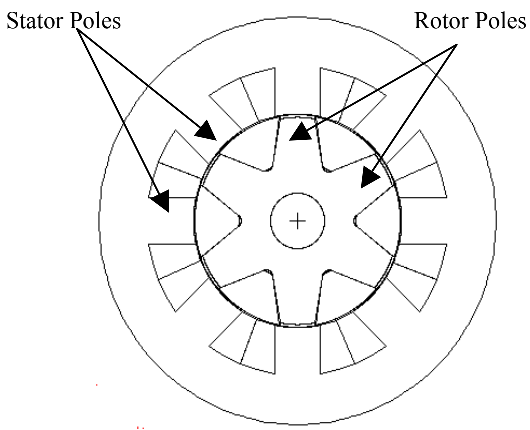

Fig. 3a: Optimised SR motor configuration

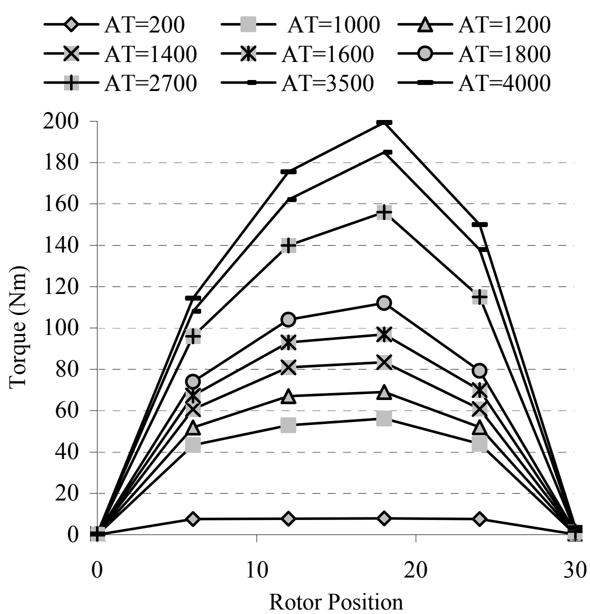

Fig. 3b: Torque versus rotor position at different MMFs

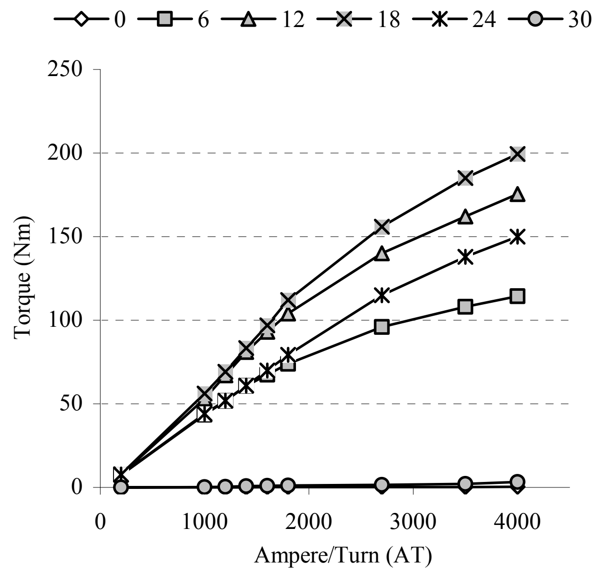

Fig. 3c: Torque versus MMFs at different rotor angles

IV. SIMULATION RESULTS and DISCUSSION

Since start up searching the torque optimisation for the SRM, the concern for the dimensional variations of the stator, rotor poles and yoke size of 3 phase 6/4 SRM are considered. Reducing and increasing the value of γ randomly by 0.4 each step. Since the value of γ equal one for the reference SRM, then the values of γ for the proposed design are varying between 0.4 → 1.8 as mentioned randomly, in each random value of γ. The developed torque is recorded and so on for all suggested steps. it has been found that the best developed torque is when the value of γ is equal to 0.76. So by implement the same value of γ on 4 phase 8/6 reference SRM; it has been found that the best developed torque is recorded when the γ is equal to 0.76. Fig. 4 shows the comparative SR motor with base motor (γ=1) and optimised design with (γ=0.76). As soon the mmf varies from 200→1000 AT, the developed torque for optimised SRM is higher slightly than the developed torque of reference SRM. The developed torque of the optimised SRM increases rapidly compares with the developed torque of the reference SRM between 1000→ 4000 AT. The incremental torque percentage for the optimised SRM between 200→4000 AT is 12.9%. The number of turns for the reference SRM is 280 turn and current equal to 5A, then ampere/turn equal 1400 AT. At this value the incremental torque percentage for the optimised SRM is 8%. Since the focus is to optimise the developed torque of the optimised design for SRM so the controller scheme will be published in the future.

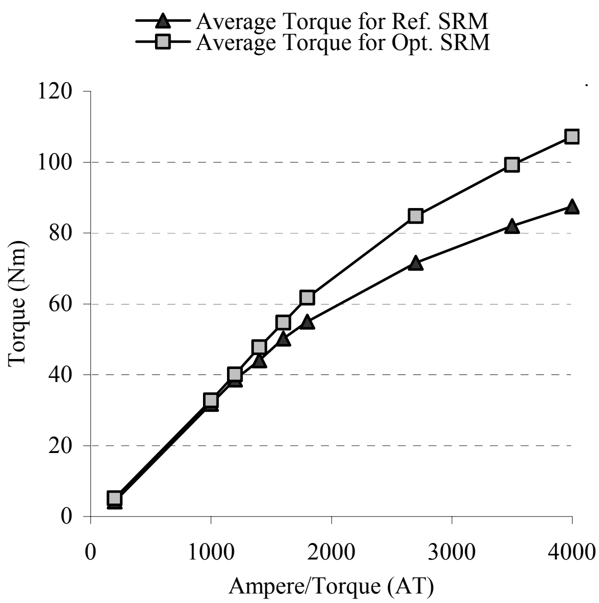

Fig. 4: Average torque versus ampere/turn for 4 phase, 8/6 poles reference and optimised SRM

V. CONCLUSIONS

This paper outlined the design optimisation of SR motor with torque as objective function. By varying the pole arc/pole pitch ratio (γ) of the stator, rotor and yoke for the reference switched reluctance, the torque is increased by 12.9% when mmf varies between 200→4000AT, and torque for optimised SRM is increased by 8% when mmf equal to 1400 AT (nominal value). These results are obtained by simulation using finite element method. Further study is being carried out to improve the torque by control strategies. This paper is showing the simulation results for the developed torque of the reference and optimised SRM. These results are achieved by finite element method for the reference and proposed design of SRM. All the concern was on the developed torque, the future work is to add the mathematical representation, motor current and motor efficiency of the proposed design for SRM.

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