Investigation of Torque Development in SRM Under Single phase Excitation.

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***Abstract* — This paper presents the results of an investigation of torque development in the air gap of a 6/4 and 8/6 switched reluctance machines (SRM). Due to the force components acting on the rotor enables us to provide more accurate picture of the torque generation and vibration in this family of electric machines. 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 switched reluctance motor (SRM) drives for industrial applications are of recent origin. Key to an understanding of any machine is its torque expression, which is derived from principles. The implications of machine operation and its salient features are inferred from the torque expression. The torque expression requires a relationship between machine flux linkages or inductance and the rotor position. The machine operation in all of its four quadrants of torque vs. speed is derived from the inductance vs. rotor position characteristic of the machine. Its use may be limited in design but it has a larger impact on the high-performance controller derivations and understanding.

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 [1-8].

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 [1-14].

II. DESIGN OPTIMIZATION FOR SR MOTOR & FEM ANALYSIS

To achieve SR motor optimization 2 methods have been investigated; first by changing the size of the rotor and the second method by dimensional variations for stator and rotor poles and yoke size. The first investigated method has been performed by chosen four different cross sections of the SR motor. Fig.1a shows 6/4, 3 phase reference switched reluctance motor. Fig. 1b shows the rotor size, which contains approximately 76% iron. Fig. 1c shows the rotor size, which contains approximately 91% iron. Fig. 1d shows the rotor of the SR motor, which has a different size and shape in comparison with the reference SR motor.

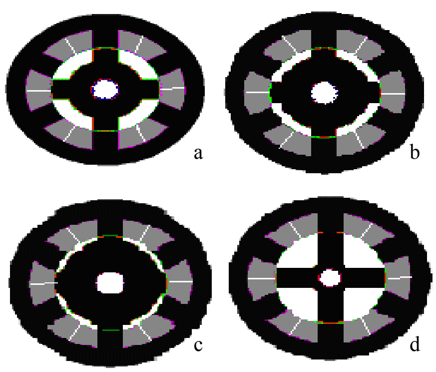

Fig. 1: a) Reference model, b) second model, c) third model, d) fourth model

Fig. 2 shows the graphical results for the above four SRM models, starting to analyse the developed torque when rotating the rotor from 0º to 30º for all the models. The highest developed torque is generated in the base (reference) model.

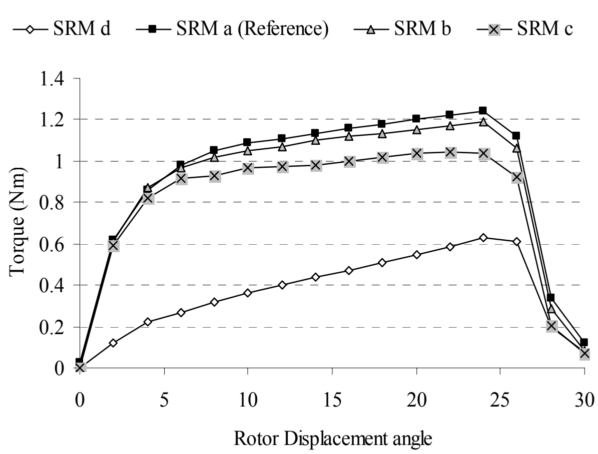

Fig. 2: Torque versus rotor position for four SR motors

The second method shows the approach for the torque optimization by the dimensional variations of the stator, rotor poles and yoke sizes. Fig. 3 shows the cross sections of three models of the SR motors, Fig.3a shows the reference model, rotor pole arc/pole pitch ratio (γ) is equal to 0.443, Fig.3b shows the second cross section model after changing the dimension of the rotor pole, in this model the rotor pole arc/pole pitch ratio (γ) is equal to 0.246. The third rotor pole arc/pole pitch ratio (γ) for the third cross section model is equal to 0.384 as shown in Fig.3c.

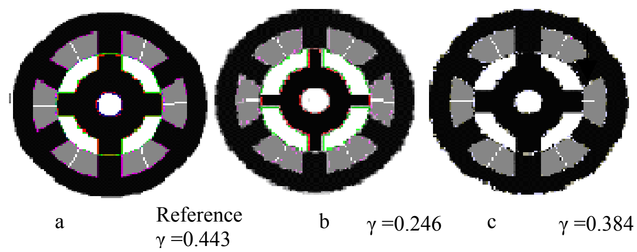

Fig. 3: a) Reference model, b) second model with γ =0.246, c) third model with γ =0.384.

Fig. 4 shows the graphical results for the above three SRM models, starting to analyse the developed torque when rotating the rotor from 0º to 30º for the three models. The highest developed torque is generated when the rotor pole arc/pole pitch ratio (γ) is equal to 0.384.

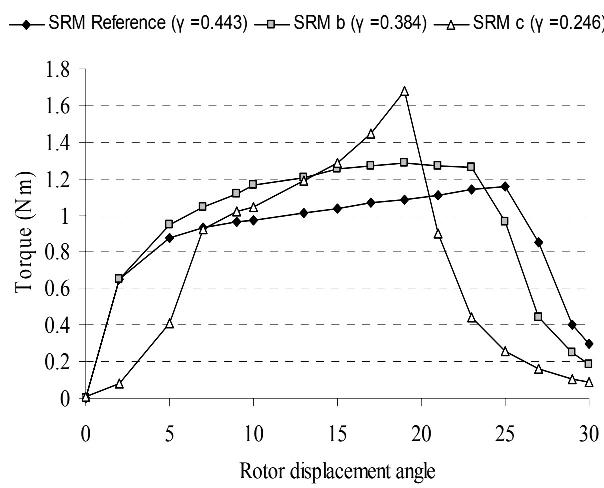

Fig. 4: Torque versus rotor position for three models by changing the rotor pole arc/pole pitch ratio

Fig. 5 shows the cross sections of three models. The first model is the reference or base model with stator pole arc/pole pitch ratio is equal to 0.443 as shown in Fig 5a, Fig. 5b shows the second model with stator pole arc/pole pitch ratio is equal to 0.25, Fig. 5c shows the third model with stator pole arc/pole pitch ratio is equal to 0.5.

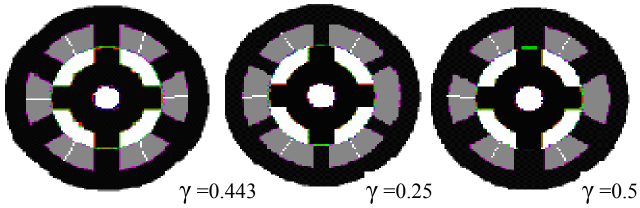

Fig. 5: a) Reference model, b) second model with γ =0.25, c) third model with γ =0.5.

Fig. 6 shows the graphical results for the above three SRM models. The highest developed torque is generated when γ (stator pole arc/pole pitch) is equal to 0.5. The rotor was rotated from 0º to 30º. The worst developed torque is generated when γ (stator pole arc/pole pitch) is equal to 0.25. The ampere-turn for each model of SR motor is 150 AT.

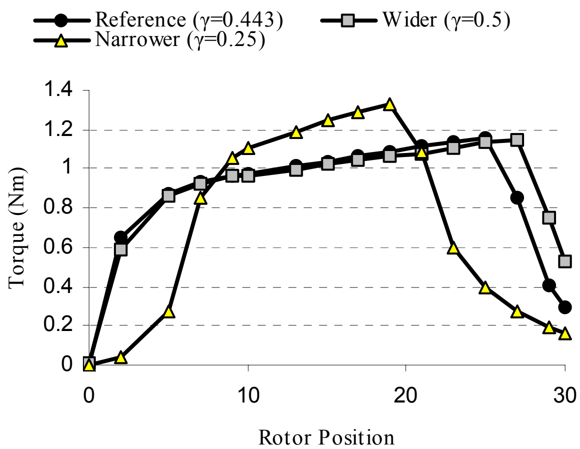

Fig.6: Torque versus rotor position for three models by changing the stator pole arc/pole pitch ratio.

Fig. 7 shows the cross sections of three models by changing the yoke thickness. The first model is the reference or base model as shown in Fig 7a, Fig. 7b shows the second model with yoke thickness is equal to 3mm; Fig. 7c shows the third model with yoke thickness is equal to 10 mm.

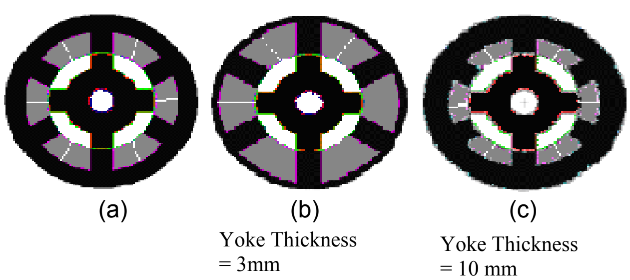

Fig. 7: a) Two cross sections for stator poles, b) Two cross sections for rotor poles, c) Two cross sections for Yoke.

Fig. 8 shows the graphical results for three SRM models with different yoke dimensions. The highest developed torque is generated when the yoke thickness is equal to 10 mm; the worst developed torque is generated when yoke thickness is equal to 3 mm.

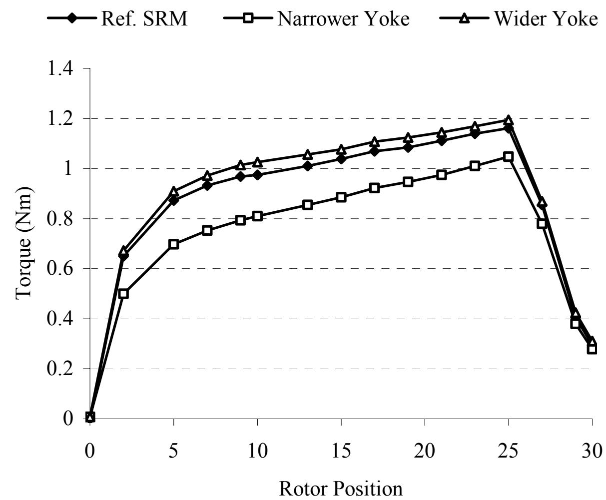

Fig. 8: a) Reference model, b) second model yoke thickness = 3mm, c) third model yoke thickness =10mm.

Fig. 9a shows the reference switched reluctance motor, Fig. 9b shows the final optimised design for the switched reluctance motor after dimensional variations are applied to the rotor, stator poles and yoke thickness.

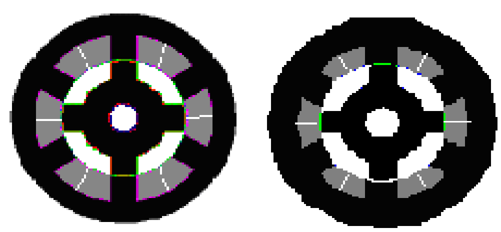

Fig. 9: a) Reference model, b) ooptimized model

Fig. 10 shows the graphical results for torque development of the reference SR motor and the optimised SR motor; starting to analyse the developed torque when rotating the rotor from 0º to 30º for the optimised and reference models. The torque developed in the optimised model is less than the torque developed in the reference model when rotor rotates from 0º to 5º; the torque developed for optimised model is higher than the developed torque for the reference model when the rotor rotates from 5º to 30º.

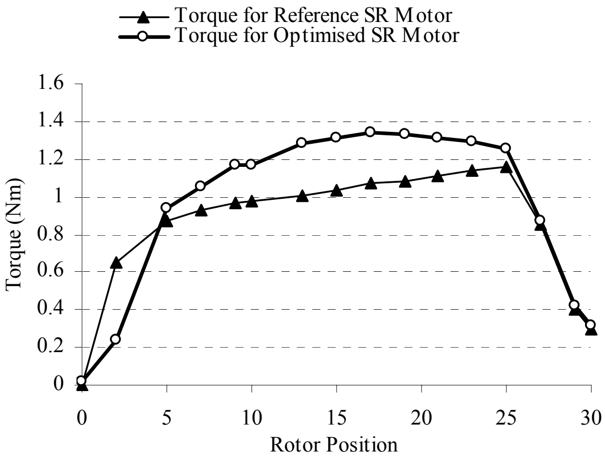

Fig. 10: Torque versus rotor position for two SR motors.

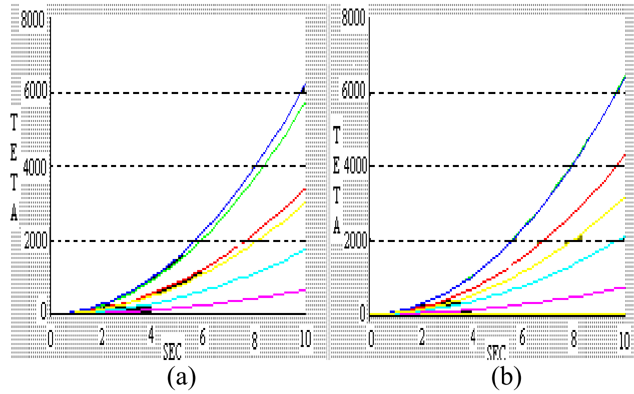

Fig. 12: a) The mechanical speed of the reference b) the mechanical speed of the optimized SRM

III. MOTOR SIMULATION

Matlab simulink package was used to simulate the SR motor; this software has a good performance and satisfies all features required. This simulation was based on equations 1, and the table of torque in function of rotor angle and current T (θ, I), which was extracted from the numeric data of the motor design by a finite elements method. Used lock up table from simulink library to generate the developed torque in the optimised SR motor, as the displacement angles was considered as row parameters, which vary between (0°→30°), and the mmf was considered as column parameters, which vary between (30→210) AT as shown in Fig. 11. Where T is the torque, T_e is the electromechanical torque, T_l is the load torque, ω is the electrical speed, Teta is the mechanical speed, J momentum of inertia. Multiplying the developed torque table by momentum of inertia (1/J), then single and double integration, the electrical and mechanical speeds have been obtained. It is obvious that the speed obtained from optimised SR motor, is higher than the speed obtained from the reference SR motor as shown in Fig. 12a and Fig. 12b.

$$T = T_e - T_l = J\,(d\omega/dt) \quad (1)$$

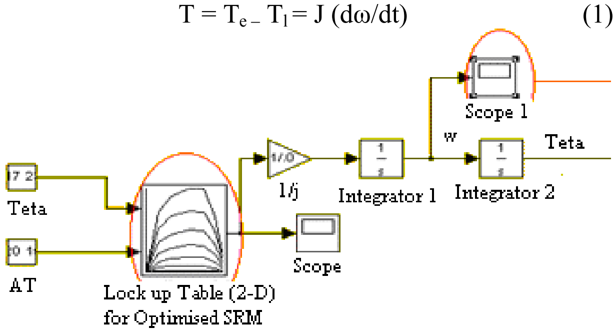

Fig. 11: Block diagram of the simulation for SR motor

IV. FUZZY LOGIC CONTROLLER AND SRM

As inputs are received by the system, the rule base is evaluated. The antecedent (IF X AND Y) blocks test the inputs and produce conclusions. The consequent (THEN Z) blocks of some rules are satisfied while others are not. The conclusions are combined to form logical sums. These conclusions feed into the inference process where each response output member function's firing strength (0 to 1) is determined [15]. The FLC generates current reference changes (ΔI_{ref}) based on speed error eω and its changes ceω.

$$e\omega = \omega_{ref} - \omega_{actual} \quad (2)$$

$$ce\omega = e\omega(k+1) - e\omega(k). \quad (3)$$

Substituting equation 2 and 3 into equation 1, the initial limits for the universes after some manual changes of the antecedents (eω, ceω) and consequent (ΔI_{ref}) were; eω = -850, 850 rad/s; ceω = -20, 20 rad/s/s; ΔI_{ref} = -1.5, 1.5 A. Table 1 shows the rule data base for both antecedents and consequent linguistic variables. Fig. 13 shows the antecedents linguistic variables are represented by seven triangular membership functions. Fig. 14 shows (ΔI_{ref}) generation by FLC, as soon as any variable changes or both (eω, ceω, and both) during the process, then the output (ΔI_{ref}) changes accordingly.

Table 1: Rule data base

ew/cew	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

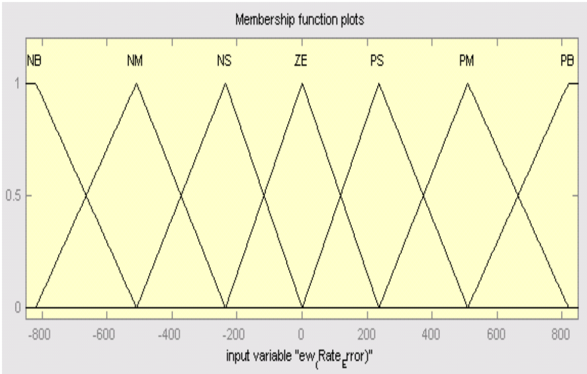

Fig. 13: Linguistic rules for speed error

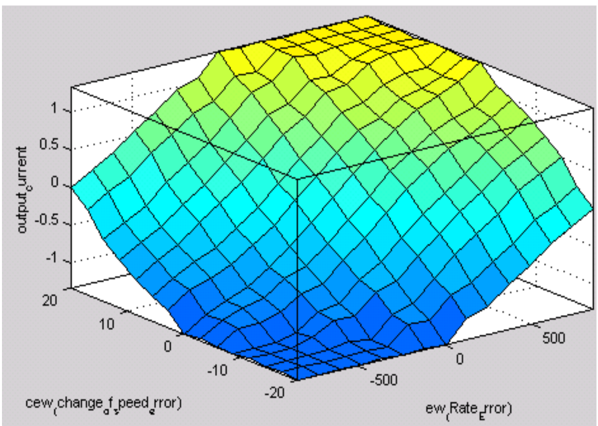

Fig. 14: current reference changes generated by FLC

V. CONCLUSION

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 size for the reference switched reluctance, the torque is increased by 11.5 % when mmf varies between 30→210 AT. Implemented matlab, simulink, and fuzzy logic controller to achieve this study.

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