Conducting screen utilisation in switched reluctance motors

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Abstract: The torque production of the switched reluctance motor is a function of the ratio of the unaligned inductance to the aligned inductance and decreasing this ratio will result in increased torque development. In this paper, non-magnetic electrical conducting screens on the rotor are used to achieve a reduction in the effective unaligned ac inductance due to the eddy currents produced in these screens. Non-magnetic electrical conducting end laminations on both the rotor and stator stacks are used to minimise end flux leakage. Experimental and analytical methods of evaluating the effects of conducting screens and copper stack end laminations are detailed.

Keywords: Switched Reluctance Motor, flux barriers

I. INTRODUCTION

Recent interest in doubly salient switched-reluctance motor (SRM) drives has involved many researches because of the drives cost advantages and ruggedness, which make it suitable for variable speed applications like pumps, fans and even traction. The emphasis of the research has been on motor principles and operation [1], motor design [2], converter topologies [3] and control [4]. In this paper, non-magnetic electrical conducting screens on the rotor and stator of a 500W four-phase switched reluctance motor have been used to produce eddy currents in the screens which decrease the unaligned ac inductance. Decreased unaligned inductance increases torque output at a given speed and also extends the base speed range since higher di/dt's are possible for a given supply voltage. The screens have been evaluated analytically using finite element analysis and experimentally by static measurement using ac bridge techniques and by measuring the performance on-load. Non-magnetic copper laminations are used on the ends of the rotor and stator stacks to minimise ac end flux leakage. Motor performance is compared, with and without these laminations.

II. CONDUCTING SCREEN THEORY

The positive torque in a switched reluctance motor is composed of torque pulses produced when current flows in a phase winding whose inductance rate of change is positive. Fig. 1 shows the typical shape of the flux linkage-current characteristics per phase.

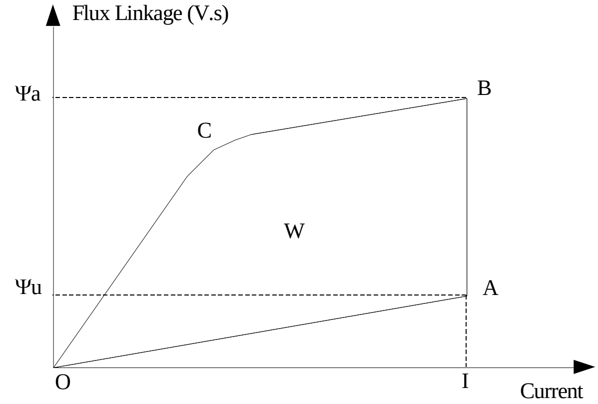
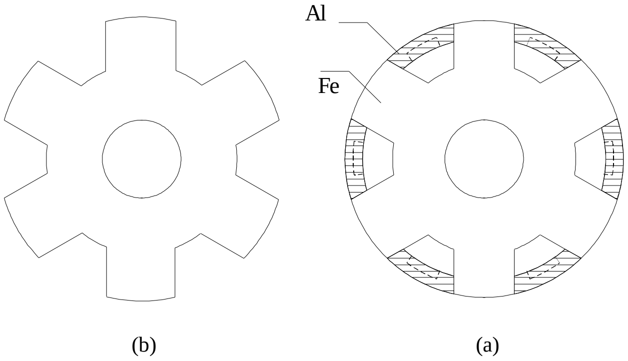


Fig. 1. Typical shape of the flux linkage/current characteristics per phase

The straight line OA shows the unaligned position characteristics where the stator poles of a phase winding are midway between two rotor poles. This is a linear characteristic since the magnetic circuit is dominated by large interpole air gaps. The slope is the minimum inductance (L_u). The curved characteristic section OCB represents the minimum reluctance aligned position characteristics where the stator and rotor poles overlap and the maximum inductance (L_a) of the phase winding is dependent on current magnitude. The electrical energy converted to mechanical energy per phase during one step of the rotor is equal to the conversion area (W) enclosed by the trajectory OABCO. The average electro-mechanical torque is given by:

$$T = W \frac{N_S N_r}{2\pi \left(N_S - N_r\right)} \qquad \text{(Nm)} \qquad (1)$$

where N_s and N_r are the number of stator and rotor poles, respectively. The conversion area (W) and subsequently the average torque can be increased by reducing the unaligned inductance (L_u) or by increasing the aligned inductance (L_a). To these ends, non-magnetic, electrical conducting screens made of aluminium (or copper) are inserted to fill the space between rotor poles as shown in Fig. 2.



(b) (a)

Fig. 2. The 6-pole rotor (a) without and (b) with conducting screens

Each screen bar is electrically insulated from the rotor and there is no electrical connection between adjacent bars. This is to prevent the bars from creating a squirrel cage rotor. Aluminium is used because it is cheaper and lighter than copper but it does have a higher resistivity. Anodising the aluminium bars simplifies the electrical isolation arrangement, Al_2O_3 being an insulator. A simple explanation for the operating principle of the conducting screens is as follows. The induced emf in the aluminium screens due to a portion of the principle flux is given by :

(2) (V)

$$V = \frac{d\psi}{dt}$$

This voltage produces eddy currents in the screen bars. These currents in turn produce an opposing flux ($i \alpha H$). That is, if the product of the instantaneous inductance and current is not constant then the flux linkage is changing, as given by :

(3) (V)

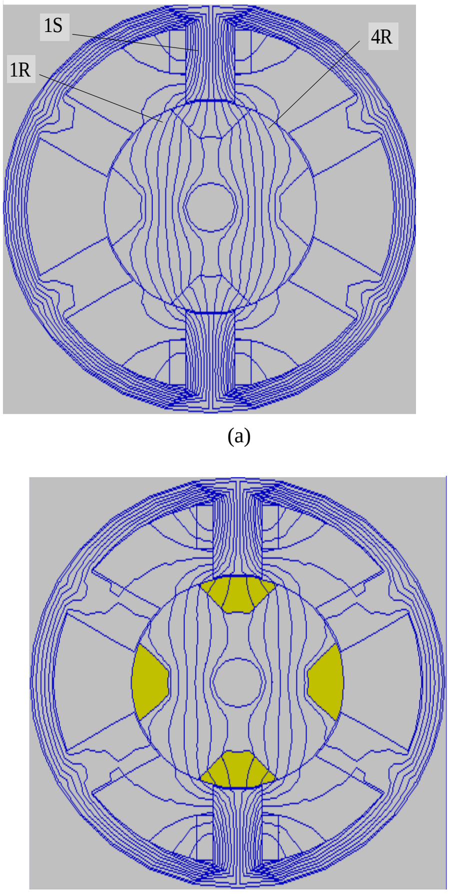
$$\frac{d\psi}{dt} = \frac{dLi}{dt}$$

As a result eddy currents will be produced in the screens so as to set up an opposing flux, hence reducing their driving flux. Therefore the effective ac inductance of the phase winding (L_e) will be reduced according to the equation :

(4) (H)

$$L_e = L\left(1-k^2\right)$$

where L is the unscreened inductance and k is the coupling coefficient between the winding and the screens, which results in flux paths dominated by long lengths. Since the reluctance path is longer, the non positive torque producing fluxes will be of lower magnitude. The screens, shown in Fig. 2b, can be hollow in order to minimise inertia and cost, as well as windage reduction, due to their use in the first instance. Several configurations of copper flux screens have previously been used in a 50W three-phase SRM [5]. The earlier researchers concluded that the benefits from rotor or stator screens are negative. The present researchers attribute the negative results to the fact that the inherent negative torque production by a three-phase SR motor is significantly increased when screens are used. In the unaligned position (Fig. 3a) assuming the rotor rotates in clockwise direction, the flux in stator tooth 1 and rotor tooth 1 produces positive torque while that flux in stator tooth 1 and rotor tooth 4 produces negative torque. Asymmetry is accentuated away from the unaligned position. When the screens are inserted (Fig. 3b) the flux associated with negative torque is increased and therefore the performance with screens is worse. For the four phase motor (whose number of phases is even), the negative torque is not dominant because the fluxes in the stator quadrature poles tend to cancel due to the flux symmetry, independent of the presence of screens and rotor angle. Flux barrier bars have been used to form a more rigid rotor structure [6].



(a)

(b)

Fig. 3. Flux distribution (a) without and (b) with conducting screens in a 3-ph SRM

III. ANALYTICAL EVALUATION OF CONDUCTING SCREENS ON THE ROTOR

To evaluate the screens analytically, finite element analysis was used to predict the aligned and unaligned inductances at different current values (to include saturation effects) in a 4 phase SR machine, with dimensions as given in Table 1.

TABLE 1. SRM DETAILS

Pole arc/pole ratio stator = 0.45	Air gap length = 0.25 mm

Pole arc/pole ratio of rotor = 0.5
Outside frame diameter = 125 mm
Bore diameter = 65 mm
Rotor inner diameter = 42.5 mm
Shaft diameter = 15 mm
Back iron width = 7 mm
Stack length = 47 mm
no. on turns / coil = 355 turns
Inductance ratio (L_u/L_a) = 0.333
Resistance/Phase = 9.6 Ω

As in [5], the conducting screens were modelled as an impermeable boundary condition, (μ_r<1) over the entire surface of the screen. The flux linkage/current characteristics for both screened and unscreened rotors are shown in Fig. 4, from which it is seen that the conducting screens increase the conversion area (W). Fig. 5 shows a finite element flux-plot used in the calculations for Fig. 4. It should be noted that this model does not accurately simulate the behaviour of the conducting screens. The result is different if the permeability is not uniformly zero, but the model still predicts approximate values for the inductance reduction.

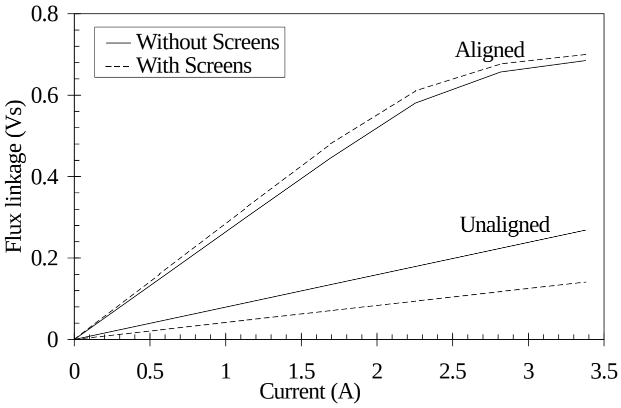


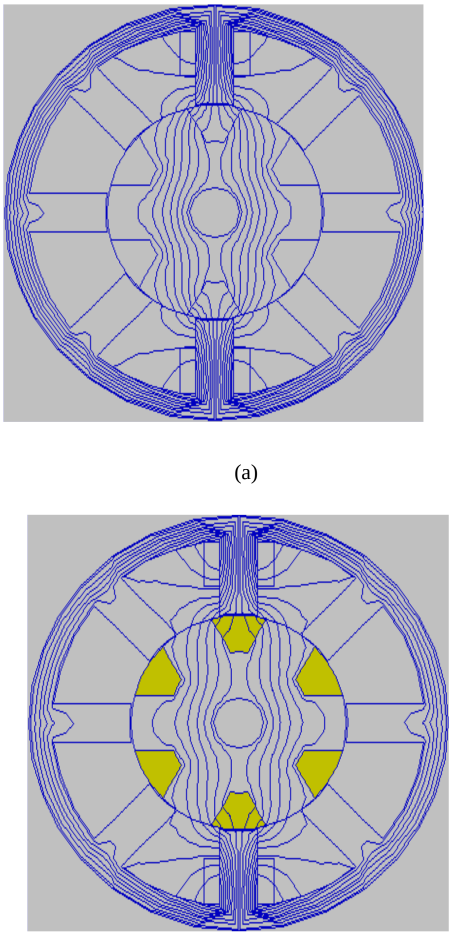
Fig. 4. Calculated flux linkage/current characteristics for screened and non-screened rotors of a 4-ph SRM

IV. PRACTICAL EVALUATION OF CONDUCTING SCREENS ON THE ROTOR

Two practical methods were applied to evaluate the presence of conducting screens.

A. Static inductance test

The aligned and unaligned inductances per phase are measured with and without conducting screens on the rotor using a sensitive ac bridge, at different test frequencies. The beneficial relationship between inductance and frequency with screens is shown in Fig 6. It is seen that the higher the frequency, the more effective the screens. The minimum inductance, which is significantly reduced, by 34% at 1kHz, is minimally affected by current magnitude since it is air dominated and usually the stator current is low in this rotor position. The maximum inductance is only marginally increased, by 1% at 1kHz. The air paths hence leakage and fringing are minimal hence the screens only have a minimal effect in reducing these two flux components. The inductance per phase for the reluctance motor is a function of position and changes from a minimum value at the unaligned or the reference position and reaches its maximum value at the aligned position. To study the effect of the conducting screens on this profile, the inductance at different rotor positions is measured using an ac bridge at 1kHz, with and without the conducting screens. Results are plotted in Fig. 7. The profile of the unsaturated inductance for this motor approximates a co-sinusoidal waveform.



(a)

(b)

Fig. 5. Flux distribution (a) without and (b) with conducting screens in a 4-ph SRM

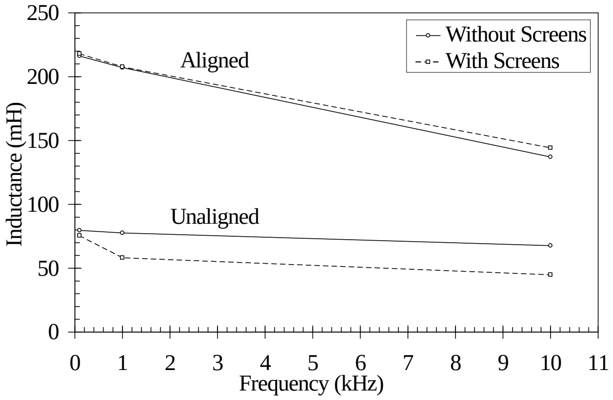


Fig. 6. The relationship between aligned and unaligned inductances versus frequency for screened and non-screened 4-ph SRM rotors

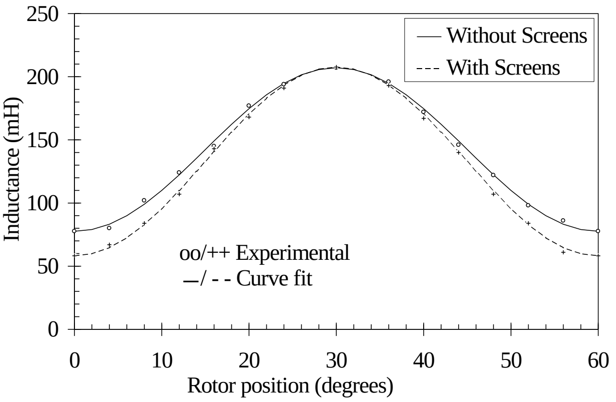


Fig. 7. The relationship between inductance and rotor position for screened and non-screened 4-ph SRM rotors

B. Dynamic inductance test

The dynamic effect of flux screens can be assessed by on-load tests. Load torque was measured from spring balance measurements. The same phase current shape is used for each case, as shown in Fig. 8, using a PWM controller. This gives constant copper losses. Thus at a given speed and current any performance difference is due solely to the screens and not any coil I^2R, windage or friction differences. The performance improvement will include the losses due to the eddy current I^2R losses in the screens. Fig. 9 shows the torque-speed characteristics with screened and unscreened rotors for different current magnitudes. It is clear that the screens enhance performance and that the screens are more effective at high speeds, that is, they produce an ac phenomena.

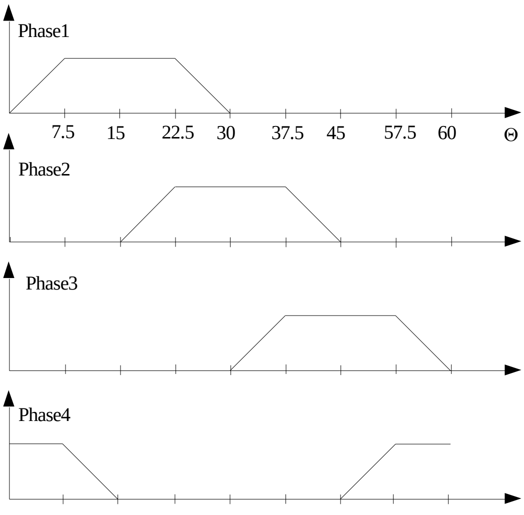


Fig. 8. Four-phase current waveforms

V. CONDUCTING SCREENS ON THE STATOR

Insulated copper foil conducting screens were inserted into the stator slots, as shown in Fig. 10.

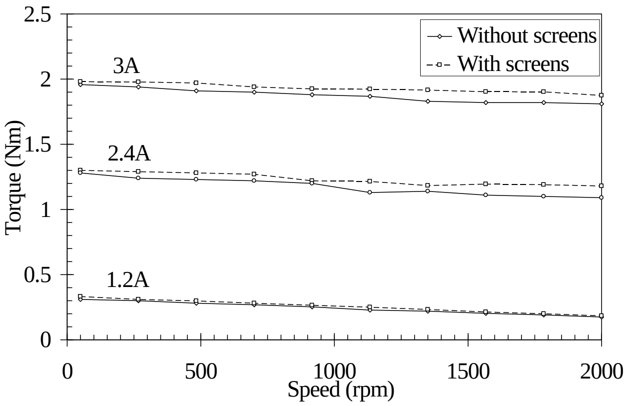


Fig. 9. Torque/Speed characteristics at different current levels for screened and non-screened 4-ph SRM rotors

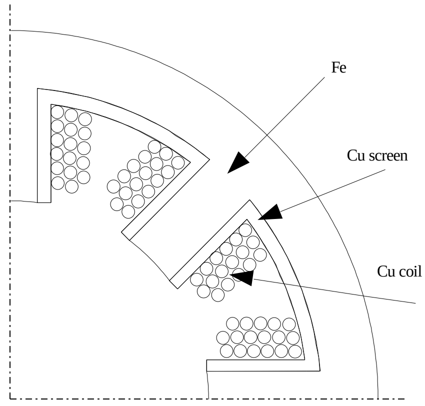
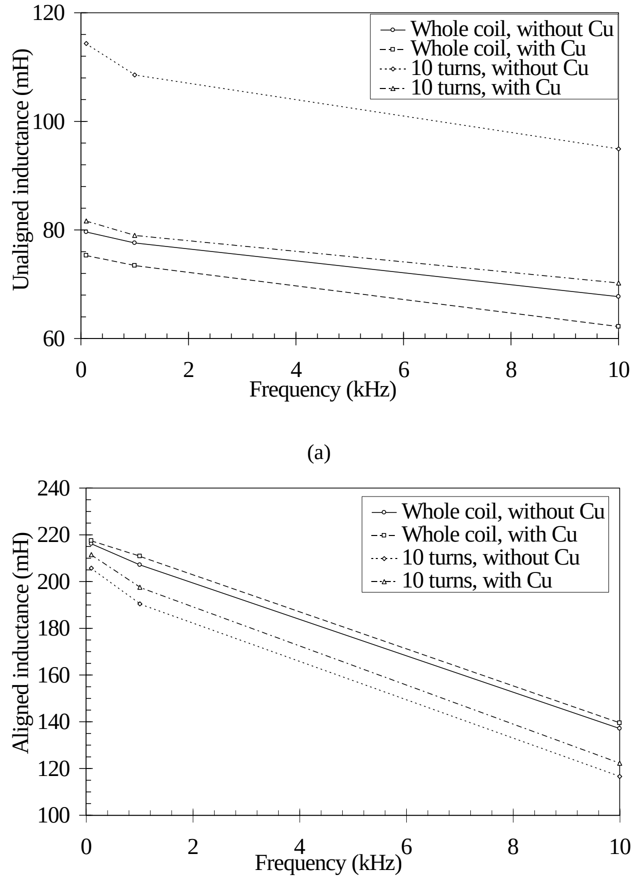


Fig. 10. Cross section of the 4-ph SRM stator with Cu screens

Using static motor measurements, the screens did not produce any inductance reduction. This is independent of the foil thickness. This is because the windings on the stator act as screens themselves and therefore inserting conducting screens does not significantly improve inductance values. To prove this experimentally, a coil of ten turns and of very small cross sectional area was wound on the stator. Fig. 11 shows that the inductance for 10 turns scaled to 355 turns (squared relationship), with copper foil is similar in performance to 355 turns without copper screens. That is, a copper filled slot behaves like a slot with a copper foil screen. Therefore, the conducting screens on the stator do not significantly reduce the unaligned inductance because the coils act as screens, at least at low leakage flux change levels. At higher flux level changes the coil effective shorting resistance may not be low enough to be highly effective. Leakage for the 10 turn coil is also increased due to the small coil geometry relative to the pole size and poor winding distribution. Fig. 11b shows that stator screens are only marginally effective in the aligned position, because leakage is minimal due to minimal air gaps in the principle flux path.

VI. EFFECT OF LAMINATION SCREENS ON THE ROTOR AND STATOR STACK ENDS

In electric machines, the end flux leakage can be high, especially in short stack length machines. To limit the stack end ac leakage paths, non-magnetic laminations made of copper were used on the stator and rotor stack ends [7]. The performance curves on load, without and with copper laminations on the rotor and stator and on the rotor only, are shown in the parts of Fig. 12. It can be concluded that the end laminations on the rotor enhance the performance while those on the stator do not, for the same reason why the conducting screens are not effective on the stator (see section V). From Fig. 12a, at 2000rpm, 300V and 3A phase current, the output torque is increased by 3%. At higher currents the torque improvement is increased because the leakage fluxes tend to increase at higher flux levels. Because of the decrease in unaligned inductance the speed limit of the machine is increased, hence power output is increased, since a higher current level can be forced into the motor for a given supply voltage.



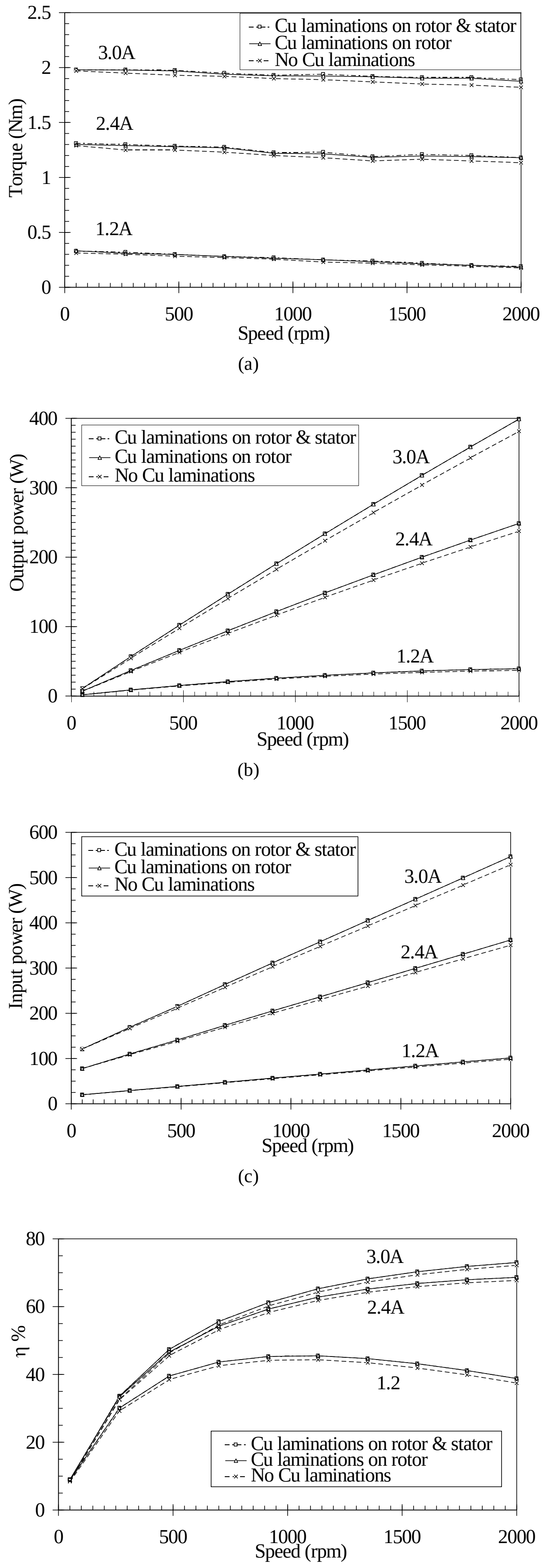
(a)

(b)

Fig. 11. Relationship between (a) unaligned and (b) aligned inductances versus frequency

VII. CONCLUSION

Non-magnetic, insulated, electrical conducting screens made of aluminium have been inserted on the SRM rotor to fill the space between each pair of rotor poles. The eddy currents produced in the screens reduce the unaligned inductance by 34% at 1kHz and consequently the dynamic torque is increased. A 3% increase in rated torque and 1% improvement in efficiency are obtained at 2000rpm.



(a)

(b)

(c)

(d)

Fig. 12. The relationship of (a) torque, (b) output power, (c) input power and (d) efficiency against speed at different current levels

The screens effects have been evaluated analytically using finite element analysis and experimentally using static measurements and motor load tests. Rotor screens, rather than stator screens, are more effective and dominate at high speeds and currents. Conducting screens on the stator do not give any significant improvement because the copper phase coils themselves act as flux screens. Rotor stack copper end laminations enhance the performance of the machine on load while copper end laminations on the stator stack yield minimal benefit.

VIII. REFERENCES

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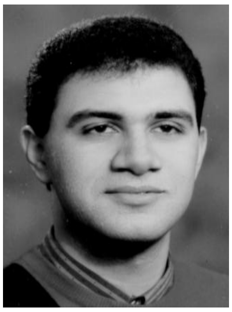
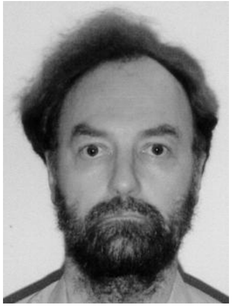
IX. BIOGRAPHIES



Yasser Gaber Dessouky was born in Alexandria, Egypt, 1969. He got his B.Sc. and M.Sc. in Electrical and Control Engineering from Alexandria University, Egypt in 1991 and 1993 respectively. Since 1991 he has been employed in the Department of Control and Electrical Engineering of the Arab Academy of Science and Technology, Alexandria, Egypt. He is currently completing a Ph.D. degree at Heriot-Watt University, UK. His research interest includes Machine Drives and Microprocessor applications.



Barry W. Williams received the M.Eng.Sc. degree from the University of Adelaide, Adelaide, Australia, in 1978 and the Ph.D. degree from Cambridge University, Cambridge, UK, in 1980. After seven years as a Lecturer at imperial College, University of London, UK, he was appointed to as Chair of Electrical Engineering at Heriot-Watt University, Edinburgh, UK, in 1986. His teaching covers power electronics (in which he has a text published) and drive systems. His research activities include power semiconductor modelling and protection, converter topologies and soft-switching techniques, and application of ASIC’s and microprocessors to industrial electronics.

John Edward Fletcher, born in 1970, graduated from Heriot-Watt University, Edinburgh with a B. Eng. in Electrical and Electronic Engineering in 1991, receiving the Watt Club Medal for academic excellence. A study into the design and control of synchronous reluctance machines led to the award of the Ph.D. degree in 1995 also from Heriot-Watt university. His current research activities include design and control of electrical machines and associated controller IC’s. He has acted as visiting Professor to the Universiti Malaya and is the author of four patent applications.