Evaluation of Mutual Coupling in Four-Phase SR Motors

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Abstract:- To evaluate the Switched Reluctance (SR) motor design and performance properly, an accurate magnetic model is required. However the SR motor has significant mutual inductances between adjacent phases, which are normally ignored in present design. In this paper the mutual coupling between phases especially of an off phase has been obtained from a 4-phase 8/6 SR motor. The coupling between phases of the 4-phase SR motor is examined by exciting only two phases from the power converter and observing the voltages on the terminals of the remaining two phases which are open circuited. The approach to the problem is initially experimental aimed at recording the mutually induced voltage waveform for a variety of torques and speeds. This is followed by a more theoretical consideration of mutual effects, to find a theoretical basis for the observed voltages.

Key-Words: - Switched reluctance motor, mutual inductance.

1 Introduction

The development of switched reluctance (SR) technology has progressed rapidly and successfully without any detailed knowledge of inter-phase mutual inductances. It was established early in the development of SR drives that the mutual inductances between phases were small and could be safely neglected in terms of basic motor design [1]-[3]. Even in more recent works on the design optimization of SR motor, such as [4-6], the magnetic coupling between adjacent phases has not been investigated.

However, such knowledge of mutual coupling assumes considerable importance when motor windings are to be used for indirect rotor position measurement [7]-[9]. Signals injected for indirect position measurement are distorted by mutually induced voltages which are difficult to compensate for unless their creation is properly understood. The paper examines experimentally the mutually induced voltages in SR motor windings and provides a theoretical explanation for their shapes based on a lumped reluctance model for the motor.

A schematic diagram of the 4-phasc 8/6 switched reluctance motor used in this research is shown in Fig. 1. For one direction of rotation the phases are energised in the sequence 1,2,3,4 and, when each pair of stator poles is excited, the nearer pair of rotor poles is pulled towards alignment (i.e. increasing overlap) according to the well known principle of minimisation of reluctance. The rotor therefore rotates in the opposite direction of that of the stator pole excitation.

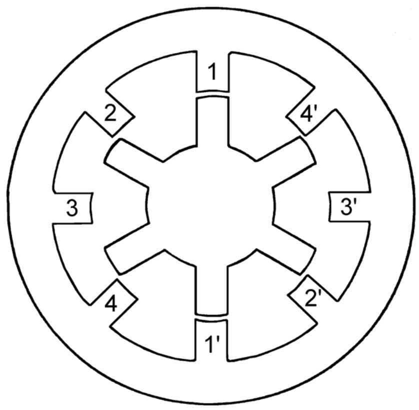

Fig.1. Schematic diagram of a 4-phase SR motor with 8/6-pole configuration.

The paper focuses on the mutually induced voltages in phases adjacent to the one(s) producing torque. This is only possible if the adjacent phases are not themselves used for torque production, but are temporarily disconnected from the power converter for the purpose. Since torque production in an SR motor is contributed individually by each phase in turn, it is feasible to use less than the total number of phases for torque production and use the remainder for exploring mutually induced voltages. This partial excitation of an SR motor is possible, provided the operation of the power converter is not in some way unbalanced by the removal of some phases. In the case of the 4-phase SR motors and converters which are commercially available, the disconnection of two phases is possible, as shown in Fig 2. The disconnection of phases was achieved with a manually operated switch once the motor was running at the desired speed.

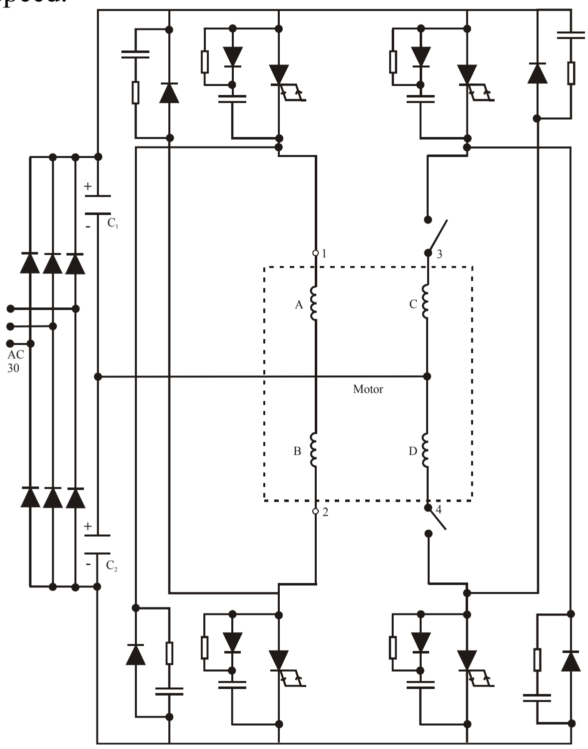

Fig. 2. Converter circuit for 4-phase SR motor, showing switches for disconnecting phases C and D (3&4).

The approach to the problem was initially experimental aimed at recording the mutually induced voltage waveform for a variety of torques and speeds. Clearly the torque had to be scaled in proportion to the smaller number of active phases. This was followed by a more theoretical consideration of mutual effects, to find a theoretical basis for the observed voltages.

2 Experimental Setup

2.1 Drive Details

Fig. 2 shows the 4-phase circuit used. The dc link filter capacitor is split to produce a dual direct voltage source for the converter. The current in phase 1 is drawn from the top half supply when the GTO is on, and returned to the bottom half supply when the GTO is off, but always flows into the capacitor mid-junction. For phase 2 the reverse applies. This ensures that the currents drawn from Cl and C2 are balanced, and the mid-point voltage remains at the mid-point.

2.2 Phase Disconnection

Mutual coupling between adjacent phases is examined by powering the motor with only two phases (1 & 2) and disconnecting phase 3 and 4 by means of a switch as shown in Fig 2. This permits the observation of the voltages on the terminals of phases 3 and 4. Disconnection could have been achieved by disabling the drive to the semiconductor switches powering phases 3 and 4 but this would have left the snubber circuits connected, which would mask or distort the waveforms being observed [10].

The drive was started and run up to the speed which applies to single-pulse operation with all four phases connected. Phases 3 and 4 were then disconnected so that the mutually induced voltages V_3 and V_4 could be observed. The load torque applied to the motor with only two phases operating was half that used for 4-phase operation. This is a valid assumption, since the concern is the overall average torque and not the instantaneous torque. Similar current pulses were produced for the two cases. This similarity is clearly visible in Figures 7 and 8.

2.3 Measurement Equipment

Torque was inferred by measuring the power generated by the DC load machine and making an assumption of load machine efficiency (80%). It must be pointed out this is only an approximate assumption. However it was good enough for this experiment, since the main objective is to observe and record the induced voltage waveforms at different loading conditions and not necessarily at accurate output torques.

The SR drive was rated at 7.5 kW and 1500 r/min, i.e. a torque represented by 47.8 Nm. To allow for generator efficiency, a generated output of 6 kW at 1500 r/min was assumed to represent rated toque on the SR motor. Table 1 shows the generated powers and speeds used for the tests.

3 Test Findings

The experimental results of these tests were obtained for two cases, firstly when the snubbers across the switches remain connected to phases 3 and 4, secondly where there are no snubber circuits connected to the windings across which mutually induced voltages are examined. With snubbers connected, however, the induced voltages were masked by snubber resonances, and results presented are therefore for no snubbers connected, and for the speeds and torques as shown in Table 1.

Table 1. Tests conducted for 4-phase and 2-phase operation at different speed and load.

Torque (Nm & %)		Generated power at 1500rpm	Generated power at 1000rpm
100%	47.8 with 4-phase 23.9 with 2-phase	6 kW 3 kW	4 kW 2 kW
50%	23.9 with 4-phase 11.9 with 2-phase	3 kW 1.5 kW	2 kW 1 kW
25%	11.9 with 4-phase 5.95 with 2-phase	1.5 kW 0.75 kW	1 kW 0.5 kW

Figures 7 and 8 show the voltage waveforms across the disconnected phases, V_4, together with the current in phase 1 which appears at the top of all figures as a reference.

The remarkable consistency of the nature and shape of V_4 will be discussed in detail in section V. The sharp ringing which appears in the waveforms sometimes but is absent on other recordings, is the consequence of sampling the waveforms using a digital storage oscilloscope. These effects are ignored in the discussion.

4 Magnetic Circuit Modelling

Although some researches on the electromagnetic modelling of the SR motor, [11]-[13], have addressed the mutual coupling issue, however some details were still lacking. The initial aim of this paper is to evaluate the mutual coupling between adjacent phases experimentally. Then a thorough theoretical consideration followed to find a detailed theoretical basis for the observed mutually induced voltages. It must be stated that a previous research work reported in [11] provided the background for this work.

Based on this experimental and theoretical investigation, a comprehensive model for the magnetic equivalent circuit of a 4-phase SR motor has been produced; see Fig. 3, more explanation on this is following. The stator pole can be considered as having two reluctances, R_{pb}, and R_{pt}, where R_{pb} is constant and R_{pt} varies with effective change of pole area depending on rotor position and with saturation. The rotor can be considered as having two reluctances R_{rc} and R_{rp}, where R_{rc} is the rotor core reluctance which is constant and R_{rp}, is the reluctance of the rotor pole, which varies with effective pole area depending on rotor position. Each section of the stator back-iron has been assigned a reluctance R_{sc} which is constant.

The stator pole MMF has been subdivided into two portions, one associated with the reluctance R_{pb} and the other part associated with the reluctance R_{pt}. A slot body leakage R_{sl} which is constant has been introduced to represent the flux which crosses the slot and thereby links part of the adjacent coils. The leakage reluctance R_l between two stator pole tips has been introduced to represent more accurately leakage flux which spans pole tips or which passes between stator pole tips via the rotor, this feature was not introduced in [11].

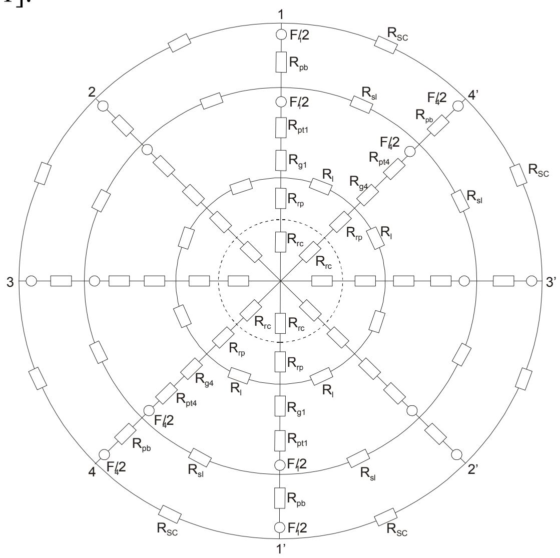

Fig. 3. Magnetic circuit model for 4-phase SR motor.

This paper has been centred on evaluating the effect of R_{s1}, which represents the flux ϕ_{l1} crossing the slot, and the effect of R_l which represents the flux ϕ_{l2} crossing between pole tips as shown in Fig. 4 for phase 1 and 4 where phase 1 is on and phase 4 is off; however there is also a leakage flux ϕ_{l3} resulting from the difference in magnetic potential between phase 1 and 4 developed across the reluctance R_{sc}. Based on the magnetic circuit of Fig. 4 a qualitative estimation of the flux distribution was produced in Fig. 5. Where Fig. 5 shows the flux distribution of the phase 1 and the leakage fluxes ϕ_{l1}, ϕ_{l2} and ϕ_{l3} to the phase 4.

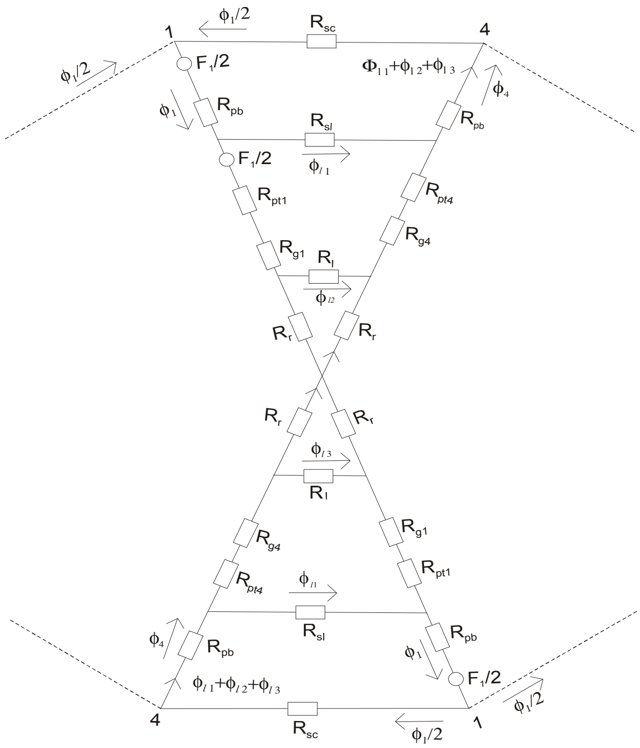

Fig. 4. Magnetic equivalent circuit with phase 1 excited and phase 4 off.

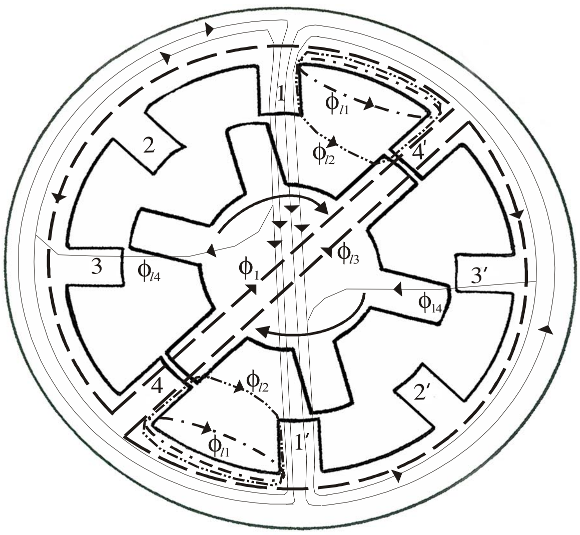

Fig. 5. Flux distribution of phase 1.

5 Analysis of Mutual Voltages

From the experimental results, the voltage V_4 across phase 4 with the phase disconnected is shown in Fig. 6d while phase 1 is on. The nature and shape of V_4 is remarkably consistent throughout the tests of Table 1.

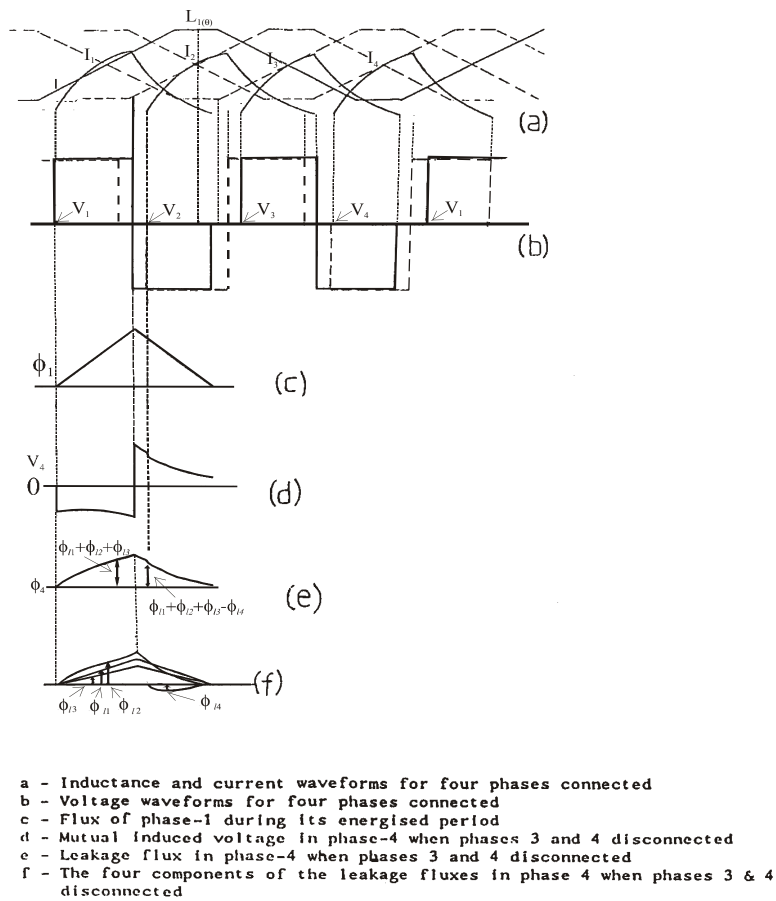

Fig. 6. Schematics waveforms based on experimental observation.

The flux, ϕ_1, at any instant is related to the voltage, V_1, applied to the winding 1 with N turns;

$$V_1 = i_1 r + N\frac{d\phi_1}{dt} \tag{1}$$

If the resistance voltage drop, $i_1 r$, is neglected, then the relationship becomes:

$$V_1 = N\frac{d\phi_1}{dt} \tag{2}$$

By integrating the square wave voltage V_1, ϕ_1 can be obtained as shown in Fig 6c (neglecting saturation)

$$\phi_1 = \frac{1}{N}\int V_1\, dt \tag{3}$$

While phase 1 is on and phase 4 off the voltage across phase 4 has been observed as shown in Fig. 6d. Since there is no current in phase 4, this voltage relates only to the changing of leakage flux. By taking the integral of voltage V_4, the leakage flux from phase 1 to phase 4 is shown in Fig. 6e.

$$\phi_4 = \frac{1}{N}\int V_4\, dt \tag{4}$$

This flux ϕ_4 can be represented by three components: leakage flux ϕ_{l1} through R_{sl}, leakage flux ϕ_{12} through R_1, where ϕ_{l1} is depending on flux in phase 1, and ϕ_{l2} is depending on the flux of phase 1 and on the rotor position, and the third component is ϕ_{l3} produced by the magnetic potential across R_{sc} which depends on the flux in phase 1.

Thus the mutual inductances between adjacent phases can be considered as having three components, one related with leakage flux ϕ_{l1};

$$L_{m1} = (N/2)^2 / R_{s1} \tag{5}$$

The second mutual inductance component L_{m2} which is related to leakage flux ϕ_{l2};

$$L_{m2} = N^2 / R_1 \tag{6}$$

The third mutual inductance component L_{m3} which is related to leakage flux ϕ_{l3};

$$L_{m3} = N^2 / R_{sc} \tag{7}$$

Note for ideal $(\mu_r = \infty)$ iron, $\phi_{l3} = 0$.

It should be noticed that the leakage flux ϕ_{l2} goes to zero after alignment between the rotor and the excited stator pole as shown in Fig 6f. From this position of pole alignment and thereafter, there will be no tendency for flux to cross the stator slot at the airgap radius, since the airgap to the rotor represents a much lower reluctance path.

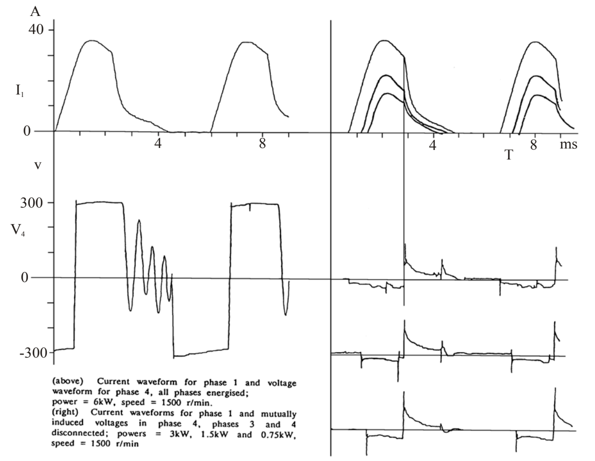

Fig. 7 Experimental waveforms at 1500 rpm with mutually induced voltages in phase 4.

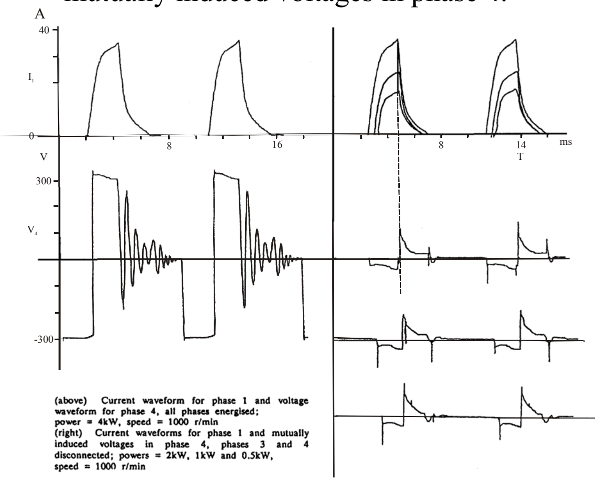

Fig. 8 Experimental waveforms at 1000 rpm with mutually induced voltages in phase 4.

6 Conclusion

The paper investigated experimentally the mutually induced voltages in a 4-phase 8/6 SR motor. The paper focused on the mutually induced voltages in phases adjacent to the one(s) producing torque. This was only possible if the adjacent phases are not themselves used for torque production, but are temporarily disconnected from the power converter for the purpose. Initial experimental tests have been carried out aimed at recording the mutually induced voltage waveform for a variety of torques and speeds. These tests were followed by a more theoretical consideration of mutual effects. The experimental results have shown a remarkably consistent shape and nature for the induced voltages in the disconnected phases: they also support the explanations based on the lumped-circuit reluctance model of the motor.

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