Improved Torque Performance of Switched Reluctance Machines by Reducing the Mutual Saturation Effect

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***Abstract*—Switched reluctance machines (SRMs) are normally designed to operate in the saturated region, and phase currents have some overlap to achieve better output torque performance. This results in mutual saturation effects. These effects are analyzed in detail in this paper. The experimental results show the influence of both the magnitude and direction of the leading phase current and the influence of the trailing phase current on the flux linkage of the working phase. In addition, the effect of the mutual saturation on the output torque is also demonstrated. It shows that a change of the phase winding connections can increase the output torque.**

***Index Terms*—Saturation, switched reluctance motor, torque, winding.**

I. INTRODUCTION

THE switched reluctance motor (SRM) is attracting attention from both academia and industry due to its simple and robust structure, high-fault tolerance, and high-speed potential [1]–[6]. However, one of the disadvantages of the SRM drive is that it has higher torque ripple due to the doubly salient structure, the commutation principle, and the saturated flux. Numerous methods have been studied for constant torque control of SRM drives [9]. As saturation is involved, finite element methods (FEMs) are often used to calculate flux-linkage, inductance, current, static, and instantaneous torque of the SRM [10]. To achieve lower torque ripple, some overlap of the phase conduction is desirable. In this overlap region, some interaction between the phases is inevitable. Normally, the phase flux linkage and the torque of a SRM are treated independently (i.e., the mutual effects between the phases are ignored, except for the fully-pitched SRM [7]). Usually, the results have sufficient accuracy. But when high-grade control is needed, the mutual effects should be considered.

The interaction between phases can be classified into two categories: mutual coupling effects and mutual saturation effects. Mutual coupling is due to some of the flux of one phase linking another phase. Mutual saturation is the influence of the second phase excitation on the saturation level of the first phase. The saturation level affects the flux linkage and output torque.

In most cases, the SRM (except the fully pitched winding SRM) is designed so that the mutual coupling is small; therefore, the control of phases can be treated independently. However, since the SRM is designed to operate in the saturation region even with only one phase excitation, the excitation of another phase, which shares part of the flux path, will change the saturation level of the first phase. This effect is caused by the back core saturation, which is shared between the phases.

Some previous work has considered the mutual coupling effects, but most previous work has ignored the mutual saturation effects between the phases. In [8], the ideas of mutual saturation effects were presented, mostly from the motor-design point of view. The authors point out that the stator back core width has a considerable influence on the torque ripple when two phases are excited, and they present a design guide for a low torque ripple SR motor with multiphase excitation.

The mutual saturation effect is studied in detail in this paper, including the influence of the leading phase on the flux linkage of the working phase, the influence of trailing phase on the flux linkage of the working phase, and the mutual saturation effect on output torque. As the phase number increases, there is a larger overlap between phases in operation. So the mutual influence is larger in a four- or five-phase motor than in a three-phase motor. Experimental results on the 8/6 four-phase SRM in the laboratory validate the analysis in this paper.

II. MUTUAL SATURATION ANALYSIS

An 8–6 SRM is shown in Fig. 1. The two extreme positions of unalignment [Fig. 1(a)] and alignment [Fig. 1(b)] are shown. Fig. 2 illustrates the leading phase influence. In Fig. 2(a), only one phase is conducting, labeled as phase 2 and referred to as the “working phase.” The rotor is rotating anticlockwise.

Phase 3 is called the “leading phase,” while phase 1 is called the “trailing phase.” The stroke angle for the 8/6 SRM is 15° and the positive torque production region for a phase is 30°. If the conduction angle for each phase is less than 15°, then there is no overlap of current between phases; hence, no influence between phases. However, to achieve low torque ripple, usually there is an overlap of current between phases. In the overlapping region, both phases contribute flux to the machine, with flux paths shown in Fig. 2(b). Except for the back of core between the two phases, where the flux contribution from each phase opposes each other, the individual phase fluxes add in the rest of the back of core. In a conventional machine, the back of core experiences some saturation at certain rotor angles even with just one phase conducting, particularly in the aligned position. It is therefore clear from Fig. 2(b) that multiphase operation in such a machine will enhance the saturation effects if the same levels

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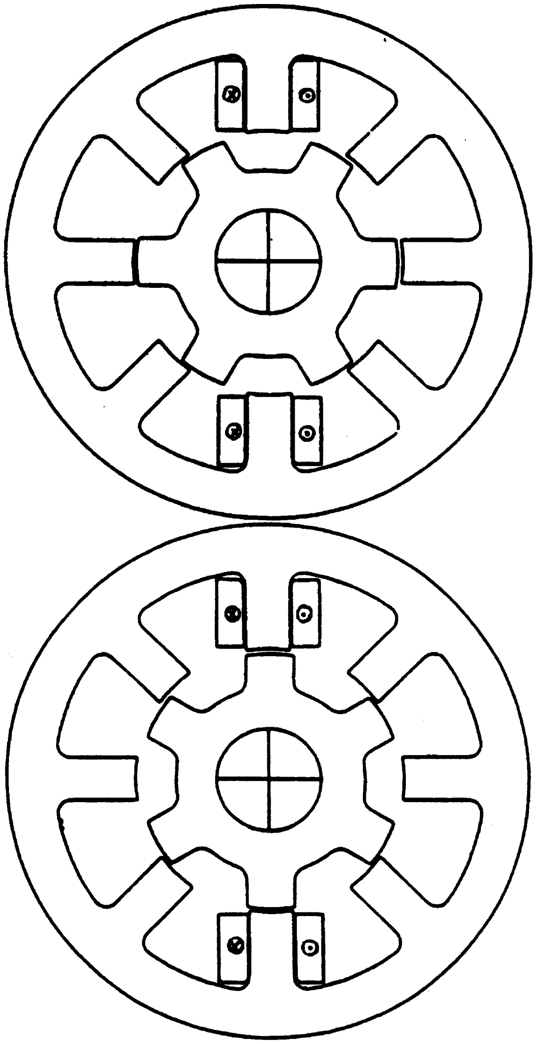

Fig. 1. (a) Unaligned position ($\theta = 0°$) for the verticle phase. (b) Aligned position ($\theta = 30°$) for the verticle phase.

of excitation are used. A finite-element plot of the flux during single-phase excitation is given in Fig. 3(a) for a 15° position of the working phase. Both halves of the back of core, which is symmetrical about the working phase, experience similar levels of flux density during single-phase excitation. However, a finite-element plot of multiphase excitation reveals the enhanced saturation in the back of core as shown in Fig. 3(b). In Fig. 3(b), the leading phase is at the aligned position, while the working phase is at the 15° position. This corresponds to the point of turn-off. A different current excitation in the leading phase has a different influence on the flux distribution, which is shown in Fig. 2(c). The flux contribution of each phase is additive only in the section of the back of core between the excited poles. The resultant flux in the back of core in the rest of the machine is actually reduced. A finite-element plot shown in Fig. 3(c) confirms this result, where saturation is high only in that section of the core between the two excited poles. In essence, the machine is forced to adopt short flux paths. The net effect tends to reduce saturation effects and core losses in the majority of the back core, when compared with multiphase excitation with the same polarity. In Section III, it will be shown that there is an extra benefit of this excitation on the output torque.

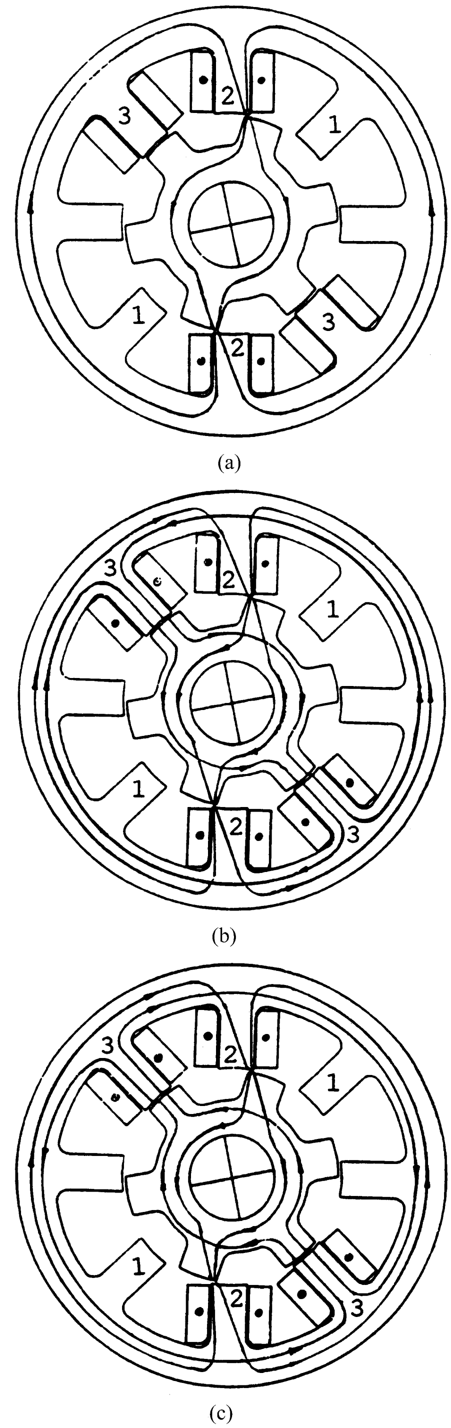

Fig. 2. Leading phase influence on flux. (a) Single phase conducting. (b) Positive current in the leading phase 3. (c) Negative current in the leading phase 3.

In normal operation, from 0° to 15° of the working phase, the leading phase is still in its positive torque production region, so the leading phase current can be used to enhance output torque. From 15° to 30° of the working phase, the trailing phase is in its positive torque production region, so the trailing phase current can be used to enhance output torque. 0° represents the unaligned position of the working phase and 30° represents the aligned position of the working phase.

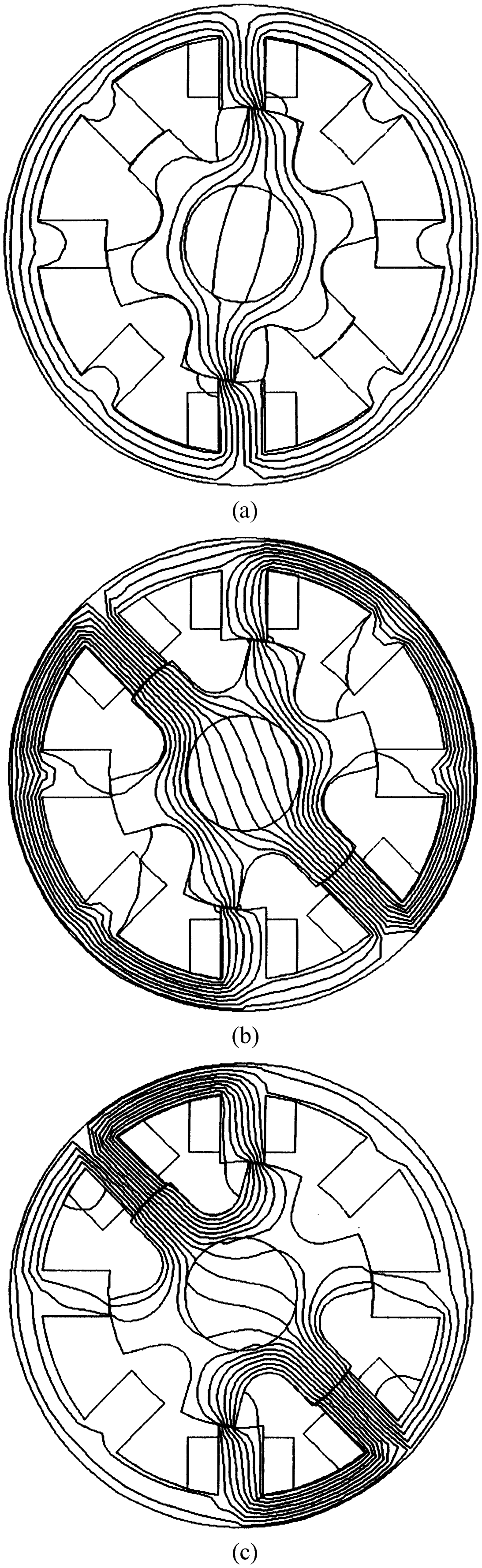

Fig. 3. Finite-element plots for the excitation patterns in Fig. 2.

In Fig. 2, if phase 3 is considered the working phase, then phase 2 is the trailing phase. So the flux distribution with the trailing phase influence is the same as the leading phase influence.

III. Mutual Saturation Effect on the Phase Flux Linkage

The experiment is carried out on a 5.5-hp four-phase 8/6 SRM. The process is as follows: The electrical equation representing one phase is given as

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

where $v(t)$ is the instantaneous voltage, R is the phase resistance, $i(t)$ is the instantaneous current, and $\psi(t)$ is the instantaneous flux linkage. Equation (1) is integrated with respect to time to yield the equation for flux linkage

$$\psi(t) = \psi(0) + \int_0^t (v(t) - Ri(t))dt. \tag{2}$$

To evaluate the integration, a step voltage is applied and the instantaneous current is recorded, with the rotor locked at a specific position. When the rotor is locked at incremental positions from unaligned to the aligned position, voltage and current can be measured and used to calculate the flux linkage, which is then formed into a table $\psi(i, \theta)$. The incremental data were obtained by attaching a protractor to the motor base/frame so that it is aligned with the center of the shaft. A pointer is attached to the shaft and aligned with the center in order to read rotor position on the protractor. One phase of the SRM is excited with the rotor unblocked, allowing the rotor to align with that phase. The pointer position is read on the protractor and recorded as the rotor position reference point. With the reference position noted, the rotor is locked at an incremental position, while a step voltage is applied until the current reaches a steady-state value. Once steady state is reached, the voltage is switched off at time $t = 0$, allowing the current to decay. From the time $t = 0$, the current data are collected until it reaches zero. The data are measured with electronic test equipment and loaded into a computer with a data-acquisition system. The stored data are processed with (2) and entered into a table along with the current and rotor position. The stored current, flux linkage, and rotor position data are then processed with a cubic spline method to fit a curve to the data points. The data from the spline fitted flux linkage table $\psi(i, \theta)$ are used along with

$$W' = \int_0^t \psi di \tag{3}$$

to calculate the coenergy table $W'(i, \theta)$. The cubic spline is again used to fit a curve to the coenergy data. The data from the spline fitted coenergy table $W'(i, \theta)$ are used with

$$T = \left[\frac{\partial W'}{\partial \theta}\right]_{i=\text{constant}} \tag{4}$$

to calculate the torque table $T(i, \theta)$, which gives the instantaneous torque value for any given current and rotor position. To study the effect of multiple phases, the leading phase (or trailing

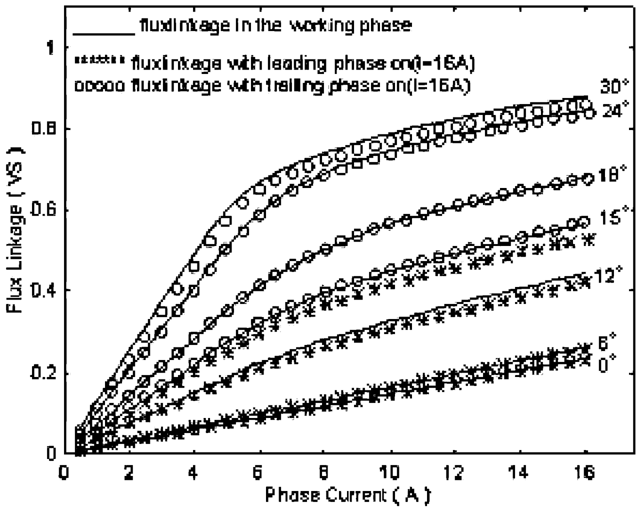

Fig. 4. Flux linkage *versus* current.

phase) is excited with a constant current while the transient of the working phase is recorded to calculate the flux linkage. In Fig. 4, the solid lines show the flux linkage versus current curve of the SRM under single excitation. Also shown are the effects of a constant (16 A) current flowing in the leading phase on the flux-linkage of the working phase. This effect is illustrated from the unaligned position of the working phase to its 15° position. When the working phase is in the unaligned position, its flux linkage is low. At the same time, the leading phase flux linkage is not at its peak value, since it is not aligned. Thus the effect of the leading phase on the working phase in the unaligned position is small. However, at the 15° position of the working phase, its flux is higher than its value at the unaligned position; in addition, the leading phase is in its aligned position so that it is experiencing its maximum flux linkage. The mutual saturation effect on the flux linkage of the working phase is therefore large at this point; this is also the region at which maximum torque is produced by the working phase.

From the position of 15° to 30°, when the working phase reaches alignment, it is under the influence of the trailing phase. When the trailing phase is first excited, it is in its unaligned position and the leading phase, which was in its aligned position, is turned off. The effect on the back of core is to produce a transition in the flux from the large contribution by the leading phase to the much smaller contribution by the trailing phase.

This is shown in Fig. 4 where the effects of the trailing phase at 15° are negligible compared to the effects of the leading phase. The effects of the trailing phase on the working phase are enhanced as the latter approaches alignment and the trailing phase approaches its peak torque production, since the flux linkage of both phases is increasing. Overall, there is a noticeable impact on the flux linkage results of the working phase.

From Fig. 4, it is also evident that at 15°, when the leading phase is turned off and the trailing phase is turned on, there is a jump in the flux linkage. This occurs because the leading phase at this angle is fully aligned and experiencing its maximum flux linkage. Subsequently, the leading phase is switched off and the trailing phase is switched on. At this time, the trailing phase is

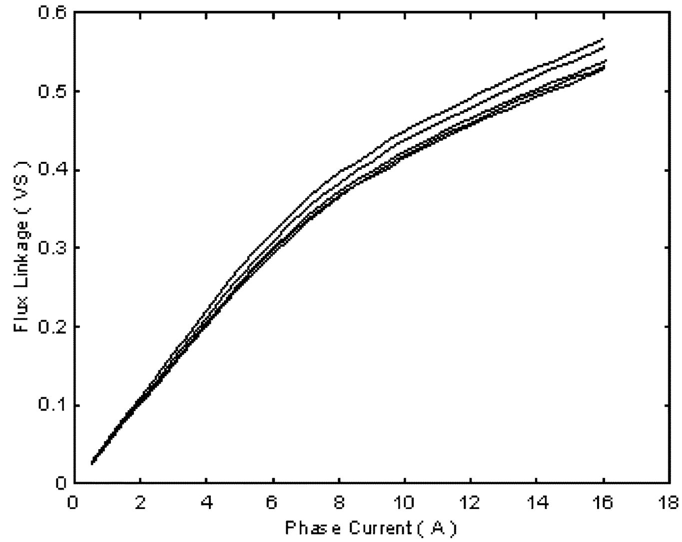

Fig. 5. Flux linkage in the working phase with 0, 4, 8, 12, 16 A flowing in the leading phase (0 A is the top curve and 16 A is the bottom curve).

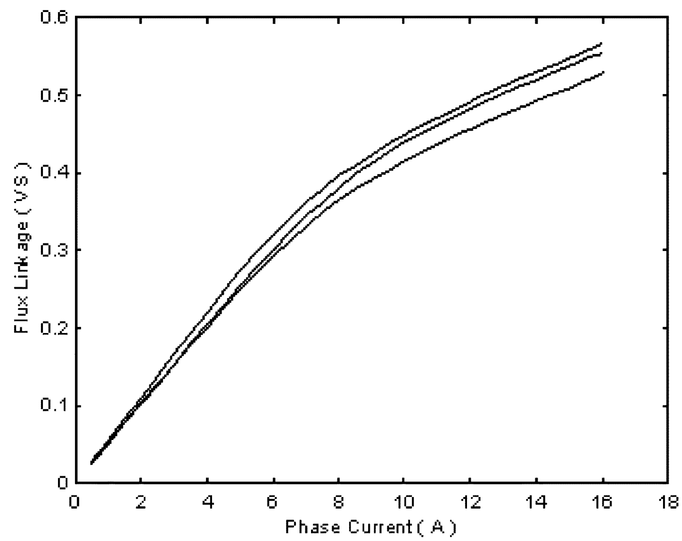

Fig. 6. Flux linkage *versus* current in the working phase with 0 A (top), -16 A (middle) and $+16$ A (bottom) in the leading phase.

experiencing its minimum flux linkage because it is in the unaligned position. Thus, the flux linkage jumps from a maximum effect on the working phase (when the leading phase is on) to essentially no effect when the trailing phase is on at this position.

The results in Fig. 4 show the effect of a constant 16-A current in the leading or trailing phase. Fig. 5 demonstrates the effects of different current magnitudes in the leading phase on the flux linkage of the working phase at the particular angle of 15°. A substantial reduction in the working phase flux linkage occurs with increasing current in the leading phase.

The effect of the direction of the current in the leading phase is shown in Fig. 6. It is clear that an opposite current to that flowing in the working phase causes a smaller effect on the overall saturation, than a current flowing in the same direction as that in the working phase. However, in this particular machine, the overall saturation is still higher with two phases excited than with only

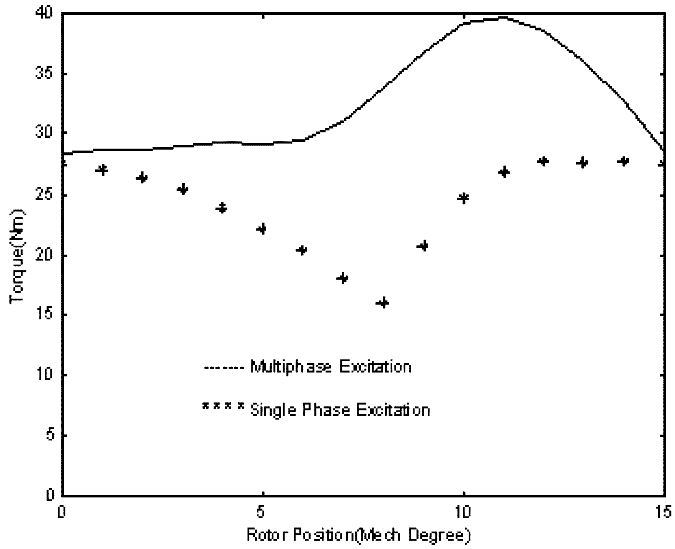

Fig. 7. Measured output torque difference between single phase excitation and multiphase excitation.

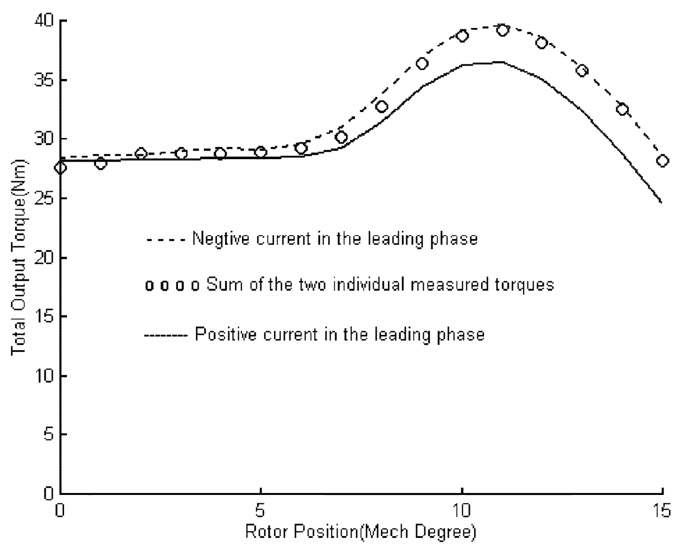

Fig. 8. Measured output torque of the SRM.

one excited (regardless of current polarity). The fact that certain portions of the back of core are under heavy saturation at the 15° angle accounts for this phenomenon.

IV. Mutual Saturation Effect on the Torque

For the 8/6 SRM, the positive torque region for each phase is 30 mechanical degrees, while the stroke angle is 15°. Thus, it allows the current to have some overlap between the adjacent phases. This will enhance the overall output torque. Fig. 7 shows the difference of the measured output torque between single-phase excitation where the conduction angle is 15° and the multiphase excitation where the conduction angle is 30°.

Due to the mutual saturation effect, in multiphase operation, the total output torque of the SRM is not simply the sum of the two-phase torques when they are excited individually. The experimental measurement of the output torque is shown in Fig. 8.

TABLE I
Output Torque With Two-Phase Excitation

Position	T+	T-	Difference	Difference%
0	28.1	28.4	0.3	1.0676
1	28.1	28.5919	0.4919	1.7506
2	28.2289	28.6361	0.4072	1.4426
3	28.2356	28.9809	0.7453	2.6397
4	28.3286	29.2	0.8714	3.076
5	28.4	29.0733	0.6733	2.3707
6	28.4641	29.5647	1.1006	3.8666
7	29.2576	30.9373	1.6797	5.7411
8	31.4508	33.7276	2.2768	7.2393
9	34.358	36.9565	2.5985	7.563
10	36.2433	39.1599	2.9165	8.0471
11	36.4839	39.7001	3.2162	8.8154
12	35.1295	38.5749	3.4454	9.8076
13	32.4257	36.0064	3.5807	11.0428
14	28.7779	32.7804	4.0025	13.9083
15	24.5692	28.487	3.9178	15.9458

The experiment is done only for 15 mechanical degrees, since the stroke angle for an 8/6 SRM is 15°. Normally a SRM is assumed symmetrical, resulting in the output torque curve repeating itself every 15°.

The solid line shows the total output torque with both the working phase and leading phase excited at 16 A. The leading phase current is conducting in the same direction as the working phase, as shown in Fig. 2(b). The dash line shows the total output torque with both the working phase and leading phase excited at 16 A, but with the leading phase current conducting in the opposite direction to the working phase, as shown in Fig. 2(c). The line of the small circles is the sum of the two individual phase torques measured separately. It can be seen that the same direction excitation of two phases has a significant decrease in the output torque, compared to opposite direction excitation. This is due to the higher saturation in the back of the core with same polarity excitation. The output torque with opposite direction excitation is similar to the sum of the two individual phase torques. The result of the output torque with two-phase excitation is shown in Table I. Column 1 is the rotor position in mechanical degrees. $T+$ is the output torque with both phases conducting in the same direction. $T-$ is the output torque with both phases conducting in the opposite direction; column 4 is the difference between $T+$ and $T-$, and column 5 is column 4 divided by $T+$ in percentage. The torque is in Nm. A maximum of 15% difference of the output torque can be seen for different current excitation directions.

The average value for $T+$ is 30.4 Nm and the average value for $T-$ is 32.4 Nm. Therefore, the change of the current direction in this operation mode can increase the output torque by 6.6%.

A natural question would be how to take advantage of this effect. Usually, a SRM drive converter can provide only unidirectional current. Special converters at the expense of additional active switches and a higher cost can achieve bidirectional current. Another way to achieve opposite direction excitation is to rearrange the phase winding connections, so that the adjacent phases would have opposite flux with the same direction current excitation, which is shown in Fig. 9.

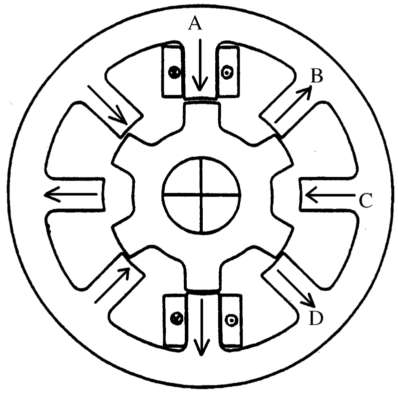

Fig. 9. Phase winding connections for highest output torque. Note that the other half of the phase is diametrically opposite.

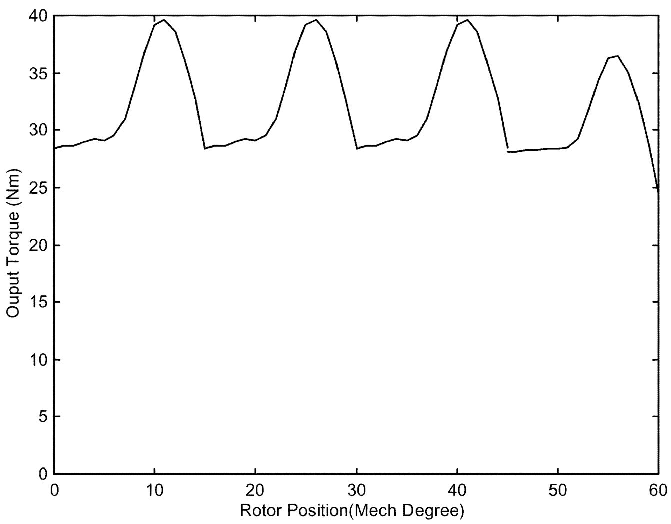

Fig. 10. Output torque with the winding arrangement in Fig. 9.

Unfortunately, after one sequence of excitations of phases A, B, C, D, with each phase excited with opposite polarity of the previous phase, when the excitation goes back to the A phase, D and A will have the same direction for excitation. This is unavoidable for an even phase machine. The output torque in one cycle is shown in Fig. 10, which is calculated based on the experimental data [11]. Because of the same direction excitation in the commutation from D back to A, a lower pulsating torque is produced, because of the higher saturation. Thus, three of the four torque pulsations will be equal in magnitude and higher in value than the 4th pulsation. The average torque in this way is 31.9 Nm. The average torque for this connection is 30.9 Nm. There is a 3.2% increase of output torque by the new winding connection. If all four phases were excited with the same polarity, then three of the four torque pulses will be the same and equal to the fourth pulse in Fig. 10, as shown in Fig. 11.

V. Conclusion

The mutual saturation effect is analyzed in detail in this paper. The experimental results show the influence of the magnitude and direction of the leading phase current on the flux linkage of the working phase, and the influence of the trailing phase current on the flux linkage of the working phase. In addition, the effect of the mutual saturation on the output torque was also

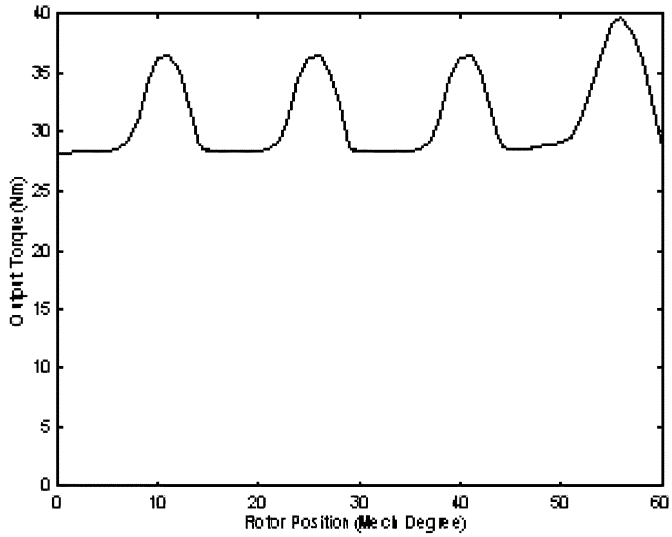

Fig. 11. Output torque with same polarity winding arrangement.

demonstrated. It is shown that a change of the phase winding connections can increase the output torque.

Appendix
Nameplate Data

4 phases, 5.5 hp, 380/415 V, 9 A, 50/60 Hz, 1500 r/min.

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