A New Variable Reluctance Motor Utilizing An Auxiliary Commutation Winding

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***Abstract*— A new concept for solving the current commutation and energy circulation problems in conventional variable reluctance motors (VRMs) is presented. The concept enables the energy stored in the magnetic field to be retained and utilized within the motor instead of being returned to the source. A new VRM and two companion converters are proposed and described in this paper. The operating principles of the motor and the converters are presented. Simulation results based on a linear model are presented to verify the operating principles. A prototype motor is built and tested to demonstrate the degree of improvement that can be realized with the new motor. The experimental results show that by eliminating these two problems, this new motor has important performance advantages over conventional VRMs.**

I. Introduction

It is well known that the short pitch concentrated windings and doubly salient structure of conventional variable reluctance motors (VRMs) provide these motors with performance advantages such as simple and robust motor and converter structures, high efficiency, good reliability, high speed capability, good thermal characteristics and low cost. However, these features also give rise to undesired characteristics such as relatively high torque ripple, high nonlinearity, current commutation difficulty and excessive energy circulation [1–5]. The difficulties in solving these problems have resulted in slow acceptance of such machines in most applications. In this paper a solution for two of the most perplexing problems concerning VRMs, namely current commutation and energy circulation, is proposed [6].

A. Current Commutation

It is important that the phase currents of a VRM be increased to its desired value or be decreased to zero as quickly as possible in order to achieve best utilization of the torque-producing capacity of this type of motor. Unfortunately, the presence of the motor phase inductance prevents the current from changing instantaneously. The situation becomes worst when the rotor is in the aligned position since the inductance reaches its maximum value whereas the phase must be turned off (motoring) or turned on (generating) at that moment. Because of this high inductance, each phase of a VRM in motoring mode has to be turned off considerably before the alignment position is achieved. This, however, leads to poor utilization of the torque-producing capability of the motor. It has been reported for a 10 HP VRM that if there were no voltage limitation on the semiconductor devices then the currents would approach the ideal waveform and the output would be 65% higher than its rated output [7]. For the same reason, the output power of a VRM in the generating mode is much less than that of the ideal case because the phase current can not increase as rapidly as desired. Obviously, power output of motor structures can be substantially increased or, conversely, motor size can be considerably reduced for a given power rating if this problem can be overcome.

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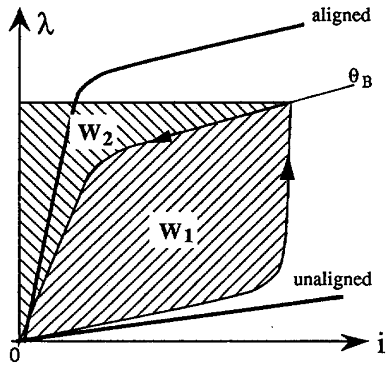

Fig. 1. Energy conversion in one stroke of a VRM.

B. Energy Circulation

It is well known that not all of the input energy can be converted to mechanical form in a conventional VRM. As shown in Fig. 1, the energy converted to mechanical form, represented by the area W_1, is only a part of the total input energy, which is represented by the areas W_1 and W_2. The energy represented by the area W_2 is returned back to the source after each "stroke" or current pulse. For a VRM operated as a generator, there also exists the same portion of energy flowing back and forth between the source and motor. This problem is sometimes called the "excitation penalty" [8] and it becomes more severe as the motor size decreases. Since the energy circulation between the motor and converter causes extra losses and creates a need for a larger DC bus capacitor and converter switch rating, it is clear that solving this problem can result in a motor having a higher system efficiency as well as a lower cost converter.

Thus far, numerous converters have been proposed to accomplish necessary current commutation of VRMs [9, 10]. However, none of these converters can avoid the inherent tradeoff between semiconductor device VA ratings and motor specific output. That is, the higher the motor specific output, the higher the device VA rating.

The method commonly used to tackle the second problem is to increase the saturation level. However, a higher saturation level leads to higher r.m.s. current per unit torque and therefore higher losses [11]. As a means to increase the energy conversion ratio, a so-called premagnetization concept has been applied for use with a VRM structure [12, 13]. However, while the energy conversion ratio can be somewhat improved by means of premagnetization, these two problems have, by no means, been completely solved.

II. Proposed Motor Configuration

Even though there are two problems to be solved there is, in reality, only one cause: the trapped energy is dealt with improperly in conventional VRMs. First, extracting the trapped energy from the motor and returning it to the source causes the energy circulation problem directly. Secondly, attempts to extract the trapped energy out of the machine as fast as possible leads to a trade-off between the converter VA rating and the motor specific output. Obviously, a better method to deal with trapped energy is the key to the solution to these problems.

Since the field energy is inevitably needed for the motor operation, and physical laws do not allow the field energy to change instantaneously, it can be expected that the two problems can only be eliminated if the trapped energy can be retained and utilized within the motor.

On one hand the short pitch windings in a conventional VRM can not, by themselves, perform the function of utilizing the trapped energy. On the other hand the motor structure of conventional VRMs has several advantages which would be useful to retain. To implement a means of storing the magnetic field energy, an auxiliary winding is introduced into a conventional VRM to form, in effect, a commutation winding. With this commutation winding in place, an alternative switching concept can be implemented in two steps. In the first step the energy in the short pitch winding being turned off can be transferred to the commutation winding. In the second step the trapped energy is utilized in the commutation winding to produce torque. To perform this desired function, the commutation winding should satisfy the following conditions:

1) It should have good coupling with the short pitch winding to be turned off in order to rapidly absorb the trapped energy;
2) Its self inductance should be independent of the rotor position in order to avoid the possibility of negative torque;
3) It should retain a mechanism for converting the trapped energy to mechanical energy and/or transferring this energy to the field of next conducting phase.

Careful study of the stator and rotor structures of VRMs leads to the finding that a full pitch winding in a 6/4 VRM (six stator poles and 4 rotor poles) whose stator pole arc is thirty degrees and rotor pole arc equal to or greater than thirty degrees, can satisfy the above conditions. Based on this finding, the motor configuration shown in Fig. 2 is proposed. The idealized winding inductances of this motor are shown in Fig. 3.

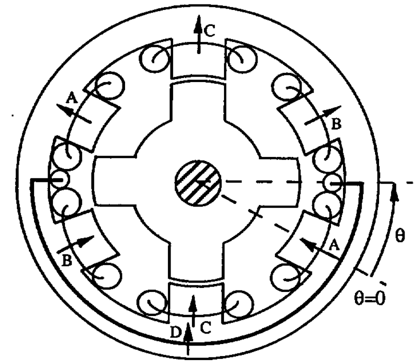

Fig. 2. Structure of the proposed motor.

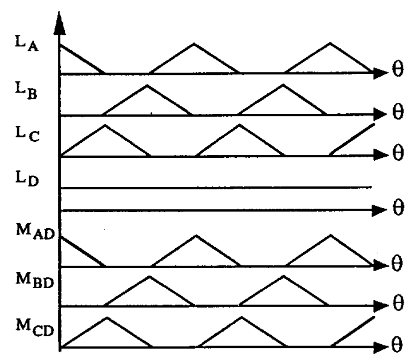

Fig. 3. Idealized inductance waveforms.

From Fig. 2 it can be seen that the full pitch winding (i.e. phase D) has good coupling with phase B which is to be turned off. This satisfies the first condition. Also from Fig. 2 it can be seen that the reluctance of the flux path of phase D is constant because the total overlapped area between the stator and rotor poles is unchanged. This satisfies the second condition. As discussed later, the trapped energy can partially transferred to the field of next phase and partially converted to mechanical energy through the interaction between the currents in phase D and next phase to be turned on. This feature satisfies the third condition.

III. Operating Principles of the New Motor

A. Excitation of the Short Pitch Windings

The excitation of the short pitch windings is the same as that of conventional VRMs except the current in the winding can be turned off closer to the point of stator/rotor pole alignment for better utilization of the torque-producing capability of the motor.

B. Turn-Off of the Short Pitch Windings

In this section the turn-off process is analyzed first and then, based on the analysis three means to turn off a short pitch winding are proposed. To simplify the analysis two assumptions are made:

1) The inductance of a short pitch winding is constant during its turn-off period.
2) The effect of the current of the next phase in the turn-off process is negligible.

The first assumption is valid when the rotor pole arc is greater than the stator pole arc. When the rotor and stator pole arcs are equal to each other, the first assumption is still a good approximation because the inductance changes little around the aligned position because of saturation. The second assumption is a good approximation because the coupling between phase D and next conducting phase is weak at this instant.

Assuming phase B is being turned off, the equations of the system are

$$V_B = R_B i_B + \frac{d\lambda_B}{dt} \tag{1}$$

$$V_D = R_D i_D + \frac{d\lambda_D}{dt} \tag{2}$$

$$\lambda_B = L_B i_B + M_{BD} i_D \tag{3}$$

$$\lambda_D = L_D i_D + M_{BD} i_B \tag{4}$$

$$L_B = K * M_{BD} + L_{lB} \tag{5}$$

$$L_D = M_{BD}/K + L_{lD} \tag{6}$$

where K is the turns ratio $\frac{N_B}{N_D}$, M_{BD} is the mutual inductance, and L_{lB} and L_{lD} are leakage inductances.

From (1) to (6), neglecting the resistance of phase D, one obtains

$$V_B - K * V_D = R_B i_B + \left(\frac{M_{BD}(L_{lD}K + L_{lB}/K) + L_{lD}L_{lB}}{M_{BD}/K + L_{lD}} \right) \frac{di_B}{dt} \tag{7}$$

Neglecting the smaller terms $L_{lD}L_{lB}$ in numerator and L_{lD} in denominator, (7) can be simplified to the form,

$$V_B - K * V_D = R_B i_B + (L_{lD}K^2 + L_{lB}) \frac{di_B}{dt} \tag{8}$$

It can be seen from (8) that the effective inductance faced by current i_B is on the order of the leakage inductance. This observation suggests that the current i_B can decay to zero in the ACVRM much more rapidly than it does in a conventional VRM. In fact, the current (i.e. energy) in phase B is transferred to phase D because of the flux conservation principle. From (8) it can be seen that one can turn off phase B by

1) applying a negative voltages to phase B and short circuiting phase D; or
2) applying a positive voltage to phase D and short circuiting phase B; or
3) applying a negative voltage to phase B and a positive voltage to phase D.

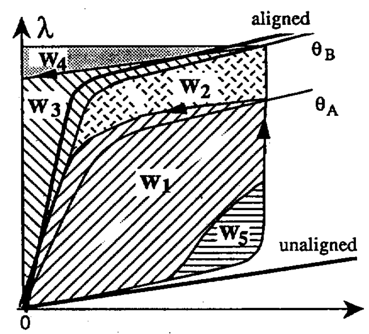

Fig. 4. Energy conversion in the new VRM.

In terms of performance, the third approach is the best because current i_B decays most rapidly in this case.

After current i_B reaches zero, phase B must be open circuited and phase D is short circuited. After the current in phase D decays to zero, phase D is then open circuited.

C. Utilization of the Trapped Energy

As pointed out above, the current in the short pitch winding is transferred to the full pitch winding during the turn-off process. As a result, the main flux remains in the motor and the energy associated with the main flux is transferred from phase B to phase D. It can be seen in Fig. 2 that as the rotor rotates, the overlapped area under the stator poles of next phase (e.g. phase A) is increasing while the overlapped area under the stator poles of phase B is decreasing. As a result, part of the flux, which links winding B and D originally, is shifted from the area under stator poles of phase B to the area under stator poles of phase A. Consequently, the field energy associated with this part of the flux is transferred to the field in the region under the stator poles of phase A. This means part of the field energy stored in phase D is directly transferred to the field of next phase.

It can been noticed from Fig. 3 that in the period when the self inductance of phase A is increasing the mutual inductance between phase D and phase A increases as well. As a result, a back EMF is induced in winding A by the current in winding D. If phase A is energized in such a manner that the flux produced by its current is in the same direction as the flux produced by the current in phase D, then the induced back EMF in phase A will interact with the current i_A. As a result, a positive torque is developed and part of the field energy stored in phase D is converted to mechanical energy. If the motor is not saturated the corresponding torque is given by

$$T = i_D i_A \frac{dM_{AD}}{dt} \tag{9}$$

As the energy stored in phase D transfers partially to the field of next phase, partially to the output and partially to losses, the current in phase D decreases and finally decays to zero.

Fig. 4 illustrates the energy conversion process in both a conventional VRM and the new auxiliary commutated VRM. The area $W_1 + W_5$ represents the energy converted to mechanical form during one stroke of the conventional VRM. The area

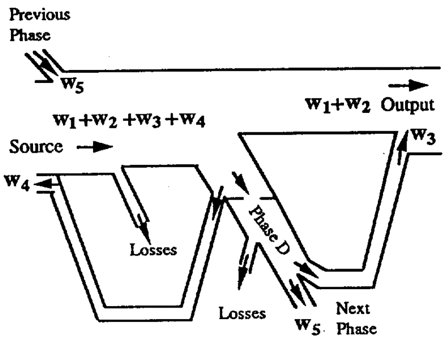

Fig. 5. Energy flow in the new VRM system.

$W_1 + W_2 + W_3$ represents the energy converted in the new motor. The area W_2 represents the increase in output due to the fact the current in the short pitch winding can be turned off closer to the point at which stator/rotor pole alignment is reached. The area W_3 represents the energy converted from the field energy trapped within the motor to mechanical form. The area W_4 represents the energy stored in the leakage field, which is returned to the source. The area W_5 represents the field energy transferred from the field energy of the previously conducting phase. It is clear from Fig. 4 that the new motor can have significantly higher output torque than a conventional VRM.

Fig. 5 shows the energy flow in the new auxiliary commutated VRM. It can be seen that only a small amount of energy, which is stored in the leakage field, needs be returned to the source. This means the energy circulation problem is virtually solved in the new motor drive.

IV. Converter Configurations

Since the new motors have a great deal of similarities with the conventional VRMs in terms of electromechanical energy conversion, it is not a surprise to observe that most of the converter circuits for the conventional VRMs can be employed for the new motors with only minor modifications made for the full pitch winding. Also it is also possible to develop new converter topologies for the new motors because they provide a new means to deal with the trapped energy and consequently a new means to turn on and turn off the phase windings as required.

Fig. 6 shows two basic converters for the new motor. Converter A of Fig. 6 can be used to implement any of the three switching strategies previously mentioned because any one of the four windings can be connected to either positive or negative voltage or be short circuited (zero voltage). To have the best performance, the short pitch winding to be turned off should be connected to a negative voltage through two freewheeling diodes and the full pitch winding should be connected to a positive voltage through two switches during the turn-off process. This converter functions better in terms of performance but has a drawback that it requires more devices. Converter B is simpler and cheaper, but it can not give the system as good performance as converter A since a

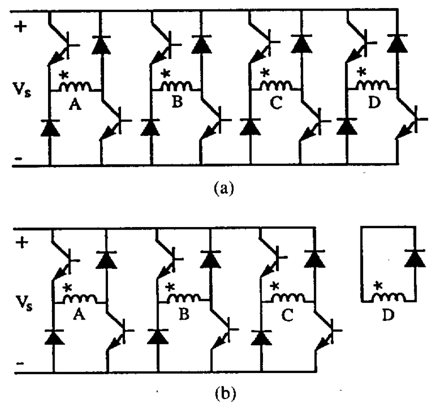

Fig. 6. Basic converters for the new motor.

positive voltage can not be applied to the full pitch winding to speed up the turn-off process. To provide more options for different tradeoff between the performance and the cost, the authors have proposed several other converter circuits [6]. A comparison of the performance and cost of these new converters will be presented in a future paper.

V. Simulation Results

Even though VRMs have a simple structure and their operating principles appear to be straightforward, it is generally not easy to obtain an accurate prediction of their performance because such machines are usually highly saturated. Since a mutual coupling is introduced between the full pitch winding and the other short pitch windings, it can be expected that the modeling of the ACVRM will be challenging. While nonlinear modeling and accurate performance prediction for the new motor are presently being developed, the operating principles can be verified and some quantitative ideas about the performance of this motor can be obtained by doing simulation based on a simple linear model. In this simulation the following assumptions are made:

1) There is no saturation or fringing.
2) The speed is constant.
3) There is no mutual coupling between the short pitch windings.

A conventional and an ACVRM have been simulated for comparison purposes. Both of the motors are identical except the new motor has a full pitch winding.

The equations of the system are as follows

$$V_A = R_A i_A + \frac{d\lambda_A}{dt} \tag{10}$$

$$V_B = R_B i_B + \frac{d\lambda_B}{dt} \tag{11}$$

$$V_C = R_C i_C + \frac{d\lambda_C}{dt} \tag{12}$$

$$V_D = R_D i_D + \frac{d\lambda_D}{dt} \tag{13}$$

$$\lambda_A = L_A i_A + M_{AD} i_D \tag{14}$$

$$\lambda_B = L_B i_B + M_{BD} i_D \tag{15}$$

$$\lambda_C = L_C i_C + M_{CD} i_D \tag{16}$$

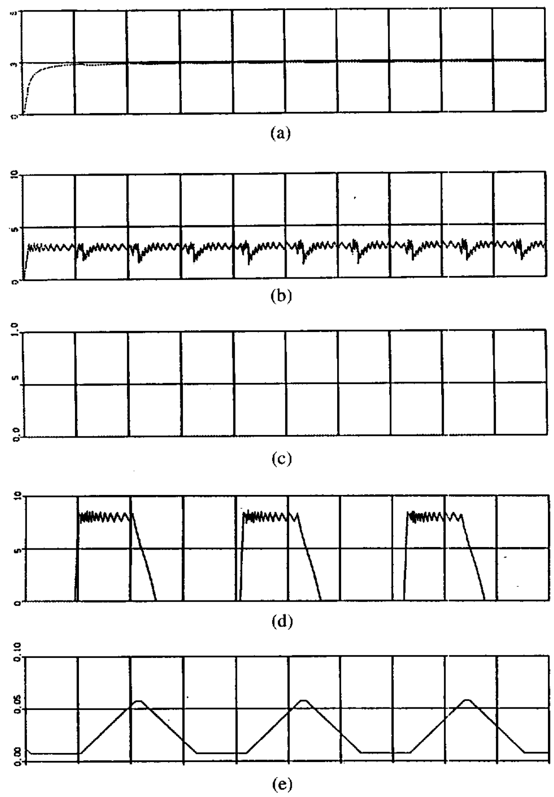

Fig. 7. Simulation results of a conventional VRM in low speed operation ($\omega = 0.4$ p.u.) (a) Average Torque (10 ms/div., 3 Nm/div.) (b) Instantaneous Torque (10 ms/div., 5 Nm/div.) (c) Current in the Full Pitch Winding (10 ms/div., 5 A/div.) (d) Current in the Short Pitch Winding (10 ms/div., 5 A/div.) (e) Phase Inductance (10 ms/div., 50 mH/div.).

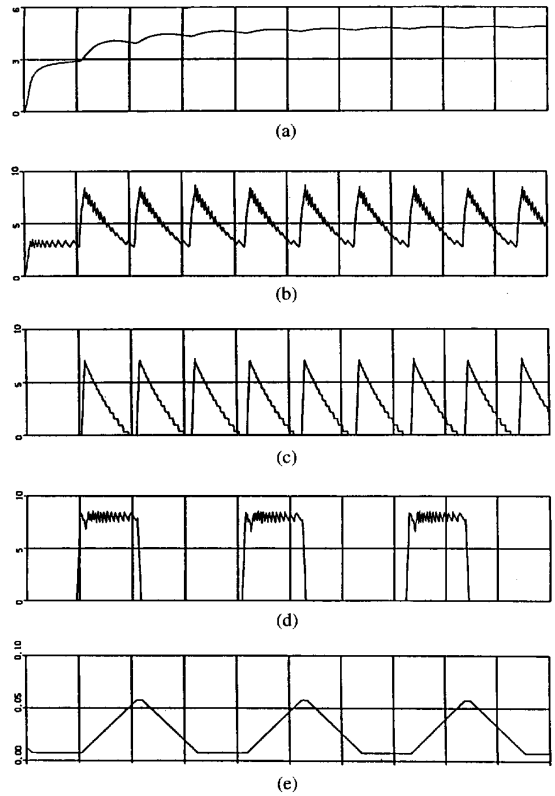

Fig. 8. Simulation results of a new VRM in low speed operation ($\omega = 0.4$ p.u.) (a) Average Torque (10 ms/div., 3 Nm/div.) (b) Instantaneous Torque(10 ms/div., 5 Nm/div.) (c) Current in the Full Pitch Winding (10 ms/div., 5 A/div.) (d) Current in the Short Pitch Winding (10 ms/div., 5 A/div.) (e) Phase Inductance (10 ms/div., 50 mH/div.).

$$\lambda_D = L_D i_D + M_{AD} i_A + M_{BD} i_B + M_{CD} i_C \quad (17)$$

$$T = \frac{1}{2}(i_A^2 \frac{dL_A}{d\theta} + i_B^2 \frac{dL_B}{d\theta} + i_C^2 \frac{dL_C}{d\theta} + i_D(i_A \frac{dM_{AD}}{d\theta} + i_B \frac{dM_{BD}}{d\theta} + i_C \frac{dM_{CD}}{d\theta} \quad (18)$$

In the simulation, the currents are solved from (10) to (17) after the voltages are determined according to the switching pattern and the rotor position. Torque is calculated from (18) once the currents have been calculated. For the purpose of modeling the conventional motor, the current i_D and flux λ_D are set to zero.

The turn-on angle is chosen to ensure that a phase current can reach the current limit at the point when the phase inductance begins to increase. The turn-off angle is chosen to realize the highest possible torque. For the conventional motor, a phase is connected to a negative voltage during its turn-off period. For the new motor, converter A shown in Fig. 6 is used and the third turn-off switching strategy mentioned above is employed. That is, a negative voltage is applied to the off-going phase while a positive voltage is impressed on phase D in the turn-off period.

Two operating modes are simulated. One mode concerns low speed operation (chopping operation) and the other concerns high speed operation (single pulse operation). Figs. 7 and 8 show the simulation results for the two motors operated in the chopping mode, while Figs. 9 and 10 show the simulation results of the two motors operated in the high speed mode.

The following observations can be made concerning the simulation results illustrated:

1) The currents in the short pitch windings of the ACVRM clearly decay to zero much more rapidly than they do in the conventional motor. This means the new motor does not suffer from the current commutation problem to the same degree as the conventional VRM.
2) The ACVRM has a higher output torque than the conventional motor for the same bus voltage and current limit.
3) Both of the motors clearly have torque spikes which can be interpreted as a disadvantage. It should be pointed out, however, the torque spikes are due to the fact that saturation and fringing are not taken into account in the simulation. It can be expected that the torque will be smoothed out to a great extent in an actual motor.
4) The ACVRM has higher torque ripple. The reason for this behavior and the possible means to reduce the torque

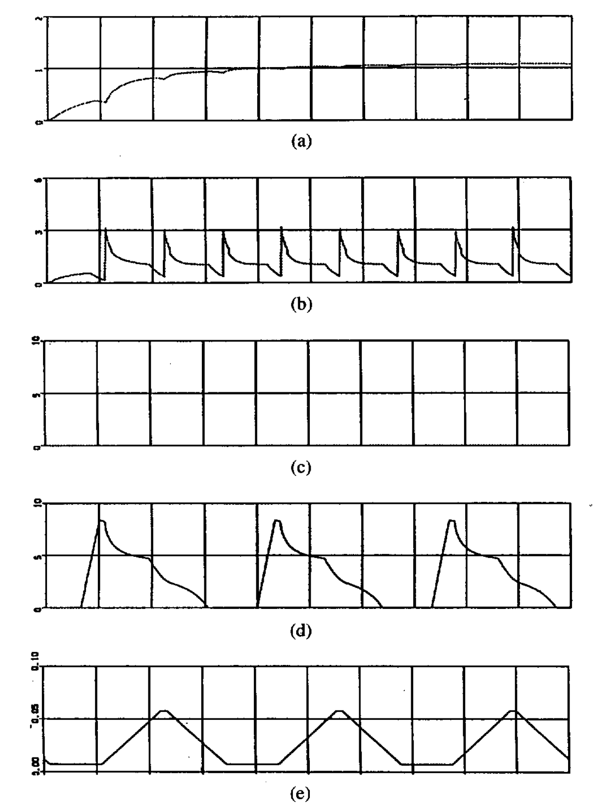

Fig. 9. Simulation results of a conventional VRM in high speed operation (ω = 2.0 p.u.) (a) Average Torque (2 ms/div., 1 Nm/div.) (b) Instantaneous Torque (2 ms/div., 3 Nm/div.) (c) Current in the Full Pitch Winding (2 ms/div., 5 A/div.) (d) Current in the Short Pitch Winding (2 ms/div., 5 A/div.) (e) Phase Inductance (2 ms/div., 50 mH/div.).

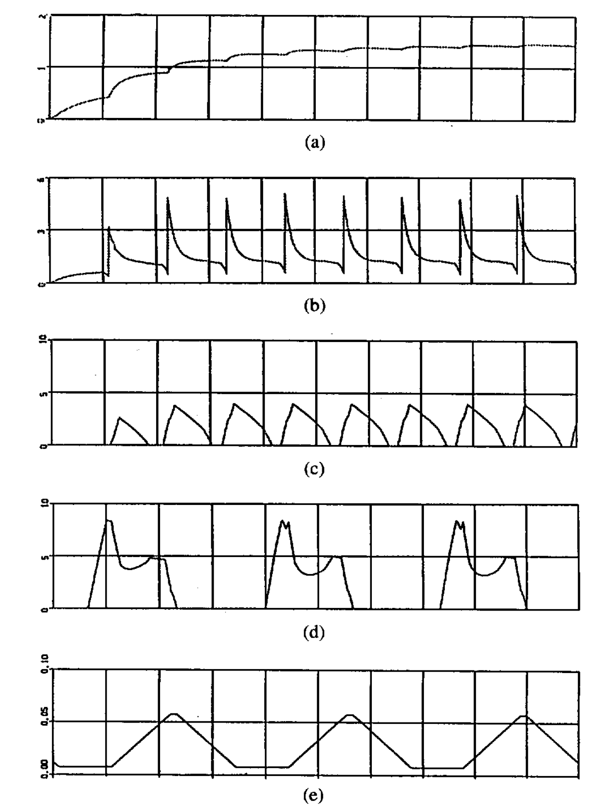

Fig. 10. Simulation results of new VRM in high speed operation (ω = 2.0 p.u.) (a) Average Torque (2 ms/div., 1 Nm/div.) (b) Instantaneous Torque (2 ms/div., 3 Nm/div.) (c) Current in the Full Pitch Winding (2 ms/div., 5 A/div.) (d) Current in the Short Pitch Winding (2 ms/div., 5 A/div.) (e) Phase Inductance (2 ms/div., 50 mH/div.).

ripple itself or its effect on the speed are discussed in next section.

VI. Experimental Results

To verify the operating principles of the new motor proposed in this paper and to show the performance improvement that the new motor can achieve, a drive system employing the new VRM has been built and investigated experimentally in the Wisconsin Electric Machines and Power Electronics Consortium (WEMFEC) lab.

A. Description of the Drive System

Motor: In this study, the emphasis is on proof-of-concept rather than on the optimization of the new motor. Therefore, an existing conventional VRM is modified and changed into the motor used in the experimental drive system by inserting a full pitch winding into the motor. The parameters and dimensions of the motor are listed below:

Stator pole number:	6	
Rotor pole number:	4	
Stator pole arc:	28	degrees
Rotor pole arc:	32	degrees
Stator OD:	4.79	inch
Stator ID:	2.40	inch
Rotor OD:	2.38	inch
Air gap:	0.01	inch
Stack length:	2.75	inch
Turns per phase (Short Pitch Windings)	232	
Turns per phase (Full Pitch Winding)	116	

The motor was operated either as a conventional or a new motor in the experiments. When the motor was operated as conventional motor the full pitch winding was disconnected.

Converter and Controller: To investigate the performance improvement that the new motor can achieve with the simplest converter and therefore, the simplest control and lowest cost, the converter shown in Fig. 6(b) was built and used in the experimental drive. IGBTs are used as switching devices in the converter.

The timing of the excitation of the three windings is determined by the rotor position, and the current is regulated by hysteresis control at low speeds and by changing the turn-on and turn-off angle at high speeds. To implement the current control a controller based on the Motorola DSP56000 was built. The input commands to the controller are phase current limit, turn-on angle, and turn-off angle and the feedback

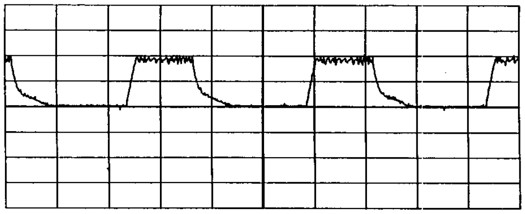

Fig. 11. Current waveform of the conventional motor at 850 rpm (5 ms/div., 5 A/div.).

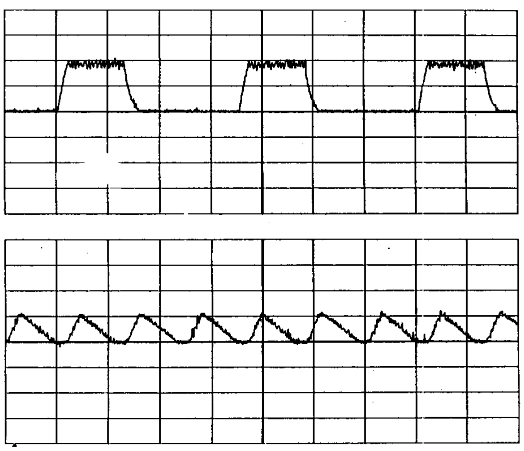

Fig. 12. Current waveforms of the new motor at 850 rpm (5 ms/div., 5 A/div.). Top trace: Current in the short pitch winding. Bottom trace: Current in the commutation winding.

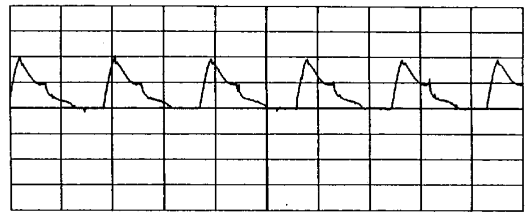

Fig. 13. Current waveform of the conventional motor at 1600 rpm (5 ms/div., 5 A/div.).

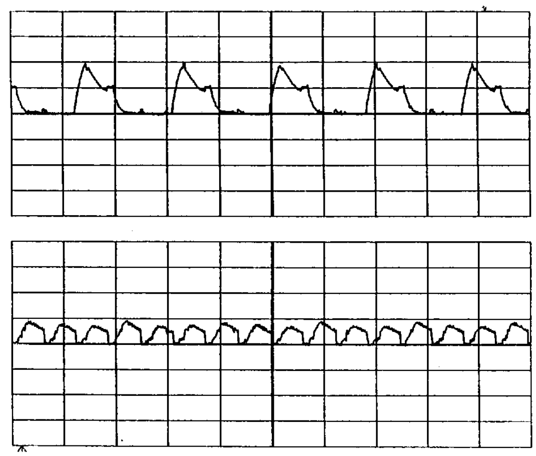

Fig. 14. Current waveforms of the new motor at 1600 rpm (5 ms/div., 5 A/div.). Top trace: Current in the short pitch winding. Bottom trace: Current in the commutation winding.

signals are the phase currents and the rotor position. Based on the three control commands and the current and position information the controller generates gating signals, which are transmitted to the gate drivers of the converter.

Load: The load of the tested motor is provided by a DC generator. The operating point of the tested motor can be changed by changing the field current of the DC generator or/and the resistance of the resistive load bank.

B. Experimental Results

Test of the experimental motors was carried out under different speeds and torque levels. For each set of operating conditions, the stator current command was set at a fixed value which was chosen to make the motors highly saturated. The turn-on and turn-off angles were then adjusted to the optimal values in terms of torque output and efficiency.

Turn-off Performance Comparison: According to the analytical study the new motor can have better turn-off performance because of the utilization of a commutation winding. The experimental results support this conclusion.

Figs. 11 to 14 show the current waveforms of the conventional and new motors operated at two different speeds. As can be seen in Figs. 11 and 13 the phase current of the conventional motor has a tail after the phase is turned off. Compared with the current waveforms of the conventional motor it can be seen that the current can decrease to zero faster in the new motor than it does in the conventional motor. The current in the commutation winding increases as the current in the short pitch winding decreases. After the current in the short pitch winding decreases to zero the current in the commutation winding decreases as the energy stored in the field is transferred to the field of next phase and converted to mechanical energy.

As shown in Fig. 11 to Fig. 14, the new motor has better turn-off performance as predicted by the analytical study. It should be pointed out that the turn-off performance can be improved even more if the converter topology shown in Fig. 6(a) is used.

Output Torque and Power Comparison: The output torque and power comparison is made based on such constraint that the efficiency of the new motor is not lower than that of the conventional motor. The torque/speed characteristics of the two motors are shown in Fig. 15, and the output power/speed curves are shown in Fig. 16. Several important observations can be made by the output comparison of the two motors:

1) Compared with the conventional motor, the output power of the new motor can be increased by about 11 percent in the constant torque operation region and from 14 percent to 20 percent in the constant power operation region.
2) The increase in the output power of the new motor is achieved without a marked reduction in the efficiency of the motor.

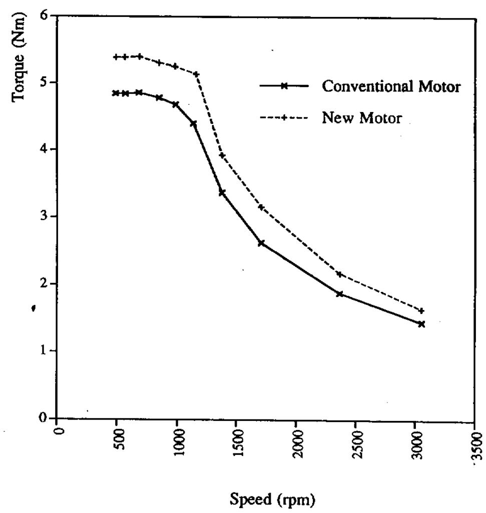

Fig. 15. Torque/speed characteristics of conventional and the new motor with the same efficiency.

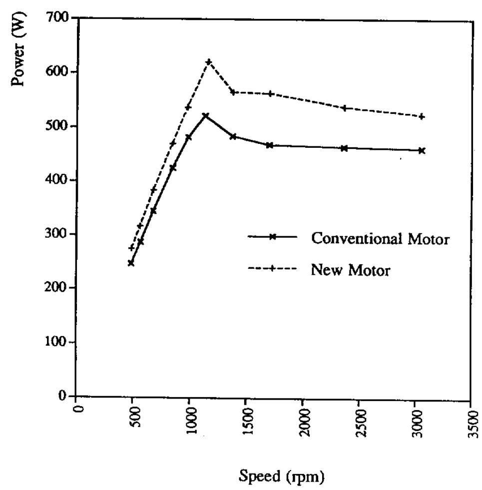

Fig. 16. Power/speed characteristics of conventional and the new motor with the same efficiency.

3) The increase in the output power of the new motor is achieved with the same bus voltage and current limit. That means a drive system employing the new motor can have higher output with the same converter rating or conversely, can have the same output with a smaller converter. This is an important advantage, which is a direct result of the improvement of the energy conversion ratio.
4) The new motor could have had even higher output if the converter topology shown in Fig. 6(a) had been used. In such a case, a positive voltage can be applied to the commutation winding in the turn-off periods of the short pitch windings and as a result, the turn-off performance can be improved even better and a greater part of the energy stored in the field can be converted to mechanical energy.
5) The new motor could have had even higher output if it were built from ground up. The reason is that the stator pole arc of the particular conventional motor, which was modified and converted to the new motor, is 28 degrees rather than the desired 30 degrees. Due to this fact, there is a "gap" of 2 degrees during which the mutual inductance between the commutation winding and next short pitch winding has little change after the ending point of the inductance increase (torque production) region of each phase. Hence, in this region the current transferred to the commutation winding induces basically no back emf in the next short pitch winding and therefore the current in the commutation winding can not produce torque but only causes copper loss in this region. Based on the above analysis, it can be expected a new motor with the desired stator and rotor pole arcs can have better performance than the motor tested in this experimental study. In other words the output increase achieved by the motor tested should not be regarded as the best that this type of new motor can achieve.

Efficiency Comparison: For some applications efficiency is more important than the output or the converter rating. In such cases the output increase of the new motor can be traded for efficiency by either lowering the current limit or reducing the phase conduction angle. To show how much the efficiency can be improved with the tested motor, the new motor was operated in the experiments under such a constraint that its output power was not less than that of the corresponding conventional motor. Fig. 17 shows the efficiency/speed curves of the two motors and Fig. 18 shows the corresponding output power of the two motors.

It can be seen from Fig. 17 and Fig. 18 that the new motor can have higher efficiency than the conventional motor with the same output. Even though more copper is used in the new motor because there is an auxiliary commutation winding, the new motor still has an important advantage that its higher efficiency is obtained without sacrificing the power density because the commutation winding is inserted into the slot space region,which usually cannot be utilized by the short pitch windings if theyb are bobbin wound.

Torque Ripple Comparison: Fig. 19 shows the torque ripples of the two motors at a speed of 1370 rpm. As can be seen the new motor has higher torque ripple than the conventional motor. Even though the variation the self-inductance of the commutation winding due to the undesired stator and rotor pole arc of the tested motor has some contribution to the higher torque ripple, it is expected that a new motor with the desired pole arcs still has higher torque ripple because the current in the commutation winding has a pulse-like nature. Theoretically the torque ripple can be reduced to some extent by controlling the current in the short pitch winding based on the information about the current in the commutation winding. However, the implementation of such a control will increase the system cost and reduce the output improvement. Another compromise can also be made: The commutation winding can be disabled at low speeds

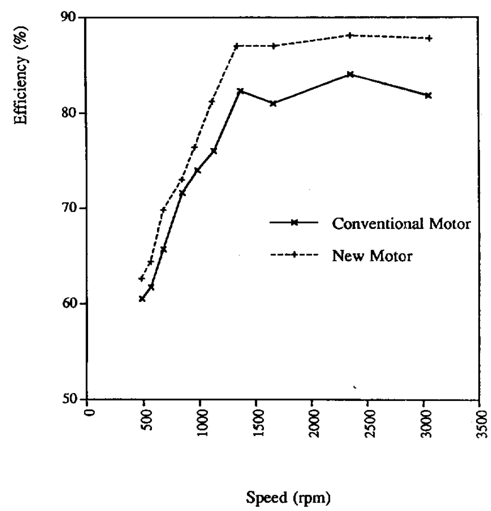

Fig. 17. Efficiency/speed curves of conventional and the new motor with the same output power.

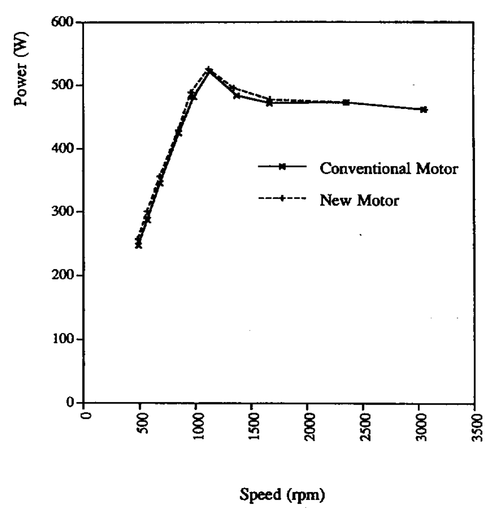

Fig. 18. Power/speed curves of conventional and the new motor in the operational regime corresponding to Fig. 17.

and put into operation only at high speeds. Because at low speeds the torque ripple has more significant effect on the speed while the current commutation problem is less severe, disabling the commutation winding at low speeds may give better overall performance. At high speeds (constant power operation) the high frequency of the torque ripple will reduce its effect on the speed while the current commutation problem becomes more serious. Therefore putting the commutation winding into operation at high speeds can yield the advantages listed above but without causing speed ripple. Having higher torque ripple is clearly the main disadvantage of the new motor and more research needs to be done to develop a control to reduce the torque ripple itself or its effect on the speed.

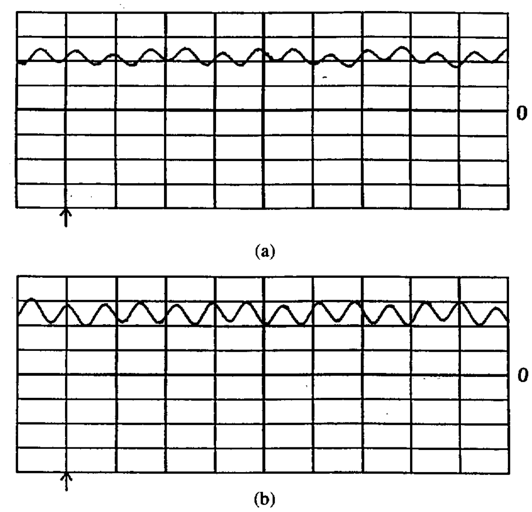

Fig. 19. Torque waveforms of conventional and the new motor at 1370 rpm (2 Nm/div.). (a) Conventional motor. (b) New motor.

VII. Future Research

The authors believe that research on this type of motor drives described in this paper is just beginning. For example, as an extension of the concept proposed in this paper the authors have proposed another motor which have two full pitch windings and two short pitch windings, as shown in Fig. 20. The operating principles are similar to those of the motor shown in Fig. 2. The advantage of the second motor over the ACVRM described in this paper is that the slot utilization is increased. The authors are conducting research on the motor shown Fig. 20 and the results will also be presented in a future paper.

In addition to the research mentioned above, the authors are engaged in research in the following areas:

1) Additional converter topologies, including soft switching converters.
2) Torque ripple control.
3) Elimination of the position sensor.

VIII. Conclusion

Two of the perplexing problems concerning VRMs, namely current commutation and energy circulation, are the target problems of this paper. The cause of these two problems has been identified and a new concept for solving the problems is proposed in this paper. Based on the concept a new motor utilizing an auxiliary commutation winding is proposed. By utilizing the commutation winding to retain and utilize the field energy within the motor, the new motor is basically free from the current commutation and energy circulation problems. Consequently, compared with the conventional VRMs the new motor can have higher output with the same converter rating; higher speed with the same bus voltage; higher efficiency with the same output while they retain those advantages of conventional VRMs due to the simple structure, such as low cost, robustness and high torque-to-inertia ratio.

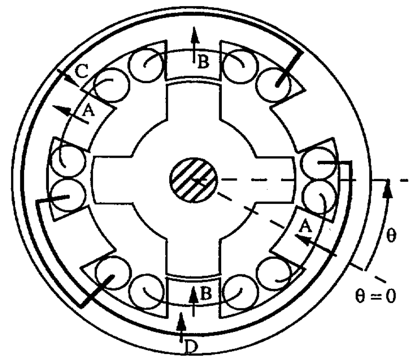

Fig. 20. Variable reluctance motor with two full pitch windings.

It should be mentioned in closing that Murphy's Law has yet to be repealed. The penalties paid for these advantages are: (1) more active copper is used; (2) torque ripple is higher; (3) reliability is decreased because there now exists a mutual coupling between the short pitch windings and the full pitch winding.

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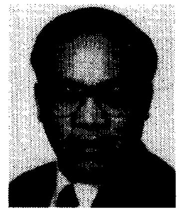

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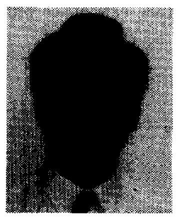

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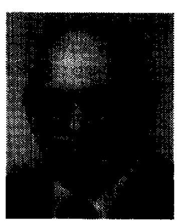

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