A Doubly Salient Doubly Excited Variable Reluctance Motor

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***Abstract*— A new variable reluctance motor is introduced to help solve the energy circulation problems which exist during commutation in conventional variable reluctance motors (VRM's). The new motor design enables the energy stored in the magnetic field to be retained and utilized within the motor, instead of being returned to the source. The operating principles of the motor and associated converters are presented. The analysis shows that by employing both short pitch and full pitch windings, this new motor can eliminate the two problems without extra conductors in the slots. As a result, the new motor has the following important performance advantages over conventional VRM's: (1) It allows a significant improvement in the turn-off process and therefore allows higher speed capacity; (2) it has higher output with the same or higher efficiency with the same output because of the improvement on the turn-off performance and due to the utilization of the trapped energy; (3) the machine can have a higher output with the same power converter because of the improvement of the energy conversion ratio.**

I. Introduction

IT IS well-known that the short pitch concentrated windings and doubly salient structure of conventional variable reluctance motors (VRM's) provide these motors with certain performance advantages. These advantages include simple and robust motor and converter structures, good efficiency, excellent reliability, high-speed capability, and good thermal characteristics. However, these machines also have their own disadvantages, such as relatively high torque ripple, high nonlinearity, current commutation difficulties during high speed, and excessive energy circulation between the machine and the converter [1]–[5]. The difficulties in solving these problems have resulted in slow acceptance of such machines in most applications. A potential answer for two of the most perplexing problems concerning VRM's, namely current commutation and energy circulation, is the objective of this research.

II. New Concept

For proper operation of conventional VRM's it is necessary to decrease the current in each phase to zero quickly after the phase is turned off in order to develop the maximum torque possible and avoid negative torque intervals. In terms of energy, it is therefore necessary to extract the energy trapped in the magnetic field as rapidly as possible. The strategy employed by all conventional VRM's is to extract the energy out of the motor by applying a negative voltage to the winding. Unfortunately, the trapped energy cannot change instantaneously. It can be expected that the outcome of the "tug of war" between the trapped energy and the outside force, i.e., the applied negative voltage, will be a trade-off between the utilization of the torque production capacity and the switch voltage rating. Such give-first-and-take-back-later manipulation of the magnetic energy results in another undesired outcome, that is a large back-and-forth energy flow between the motor and source which causes extra motor and converter losses and creates a need for a large dc bus capacitor.

A better means to deal with the trapped energy would be to retain the energy within the motor, converting, if possible, part of this energy into useful output mechanical energy and transferring the remainder of the field energy to the next phase. In this case the trapped energy becomes a beneficial rather than a detrimental effect and there is neither the energy circulation problem nor the same trade-off issues to deal with as with the conventional VRM.

In order to implement the concept proposed above, a new variable reluctance motor utilizing an additional commutation winding has been proposed by several of the authors [6]. Since an extra winding was introduced, however, the motor configuration may not retain sufficient slot space for the extra winding, although for typical VRM designs there always is some "spare" slot space which cannot be utilized by the short pitch windings. To solve this potential slot space problem another motor configuration also was proposed briefly in [6], as shown in Fig. 1. The motor again has a doubly salient structure and utilizes both full pitch windings and short pitch windings to form the three phases of the machine. As can be seen in Fig. 1, the conductor number of each slot is the same for all the six slots and as a result, this motor does not have the slot space allocation problem. In this paper, the analysis of this motor employing two full pitch windings is considered in detail.

III. Operating Principles of the New Motor

It can be noted from Fig. 1 that the new machine is equipped with both conventional short pitch as well as full pitch windings. The excitation of the short pitch windings of the new motor is the same as that of conventional VRM's except that the current in these windings of the new motor can

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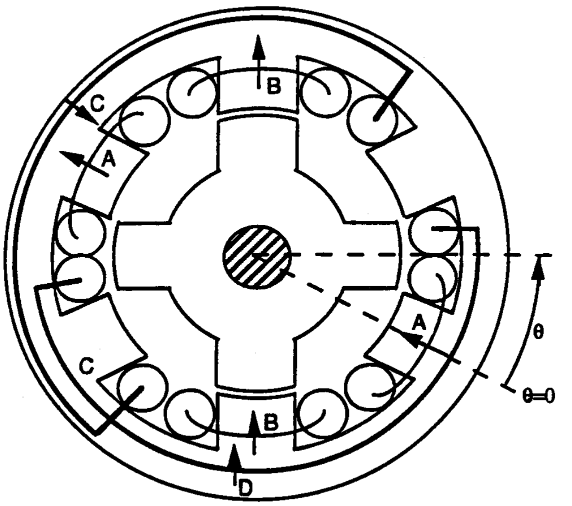

Fig. 1. VRM with two full pitch windings.

be turned off closer to the point of stator/rotor pole alignment for better utilization of the torque-producing capability of the motor. One of the two full pitch windings (denoted as phase D in Fig. 1) is used as a commutation winding to assist in the turn-off of phases A, B, and C. The approaches used to manipulate this winding during the turn-off process of the short pitch windings are the same as those of the motor with a single full pitch winding, which were presented in [6].

As was the case for the motor with a single full pitch winding, the current in full pitch winding D is allowed to interact with the currents in the short pitch windings or the current in the other full pitch winding as a result of mutual coupling. Hence, the energy stored in phase D is partially transferred to the field of the next phase, partially converted to the output and partially dissipated in the winding. The mechanism is the same as previously described for the motor with a single full pitch winding [6].

As indicated by its name, both of the short and full pitch windings in the new motor are energized in turn to produce continuous torque. The unique feature of this motor is that one of the two full pitch windings (denoted as phase D on Fig. 1) is used both as commutation winding and as a torque-producing winding while the other full pitch winding (denoted as phase C) is only used as a torque-producing winding. (Alternatively, full pitched windings C and D could be "time shared" to implement the commutation function). The self inductances and the mutual inductances between the short and full pitch windings as a function of the rotor position, are shown in Fig. 2.

The following equations which are based on a linear model show the principle of operation of the new motor. If phase C and D are energized, the coenergy in the motor is given by

$$\begin{aligned} W_{\mathrm{C}} &= \frac{1}{2}(\lambda_{\mathrm{C}} i_{\mathrm{C}} + \lambda_{\mathrm{D}} i_{\mathrm{D}}) \\ &= \frac{1}{2}(L_{\mathrm{C}} i_{\mathrm{C}}^2 + L_{\mathrm{D}} i_{\mathrm{D}}^2) + i_{\mathrm{C}} i_{\mathrm{D}} M_{\mathrm{CD}}. \end{aligned} \tag{1}$$

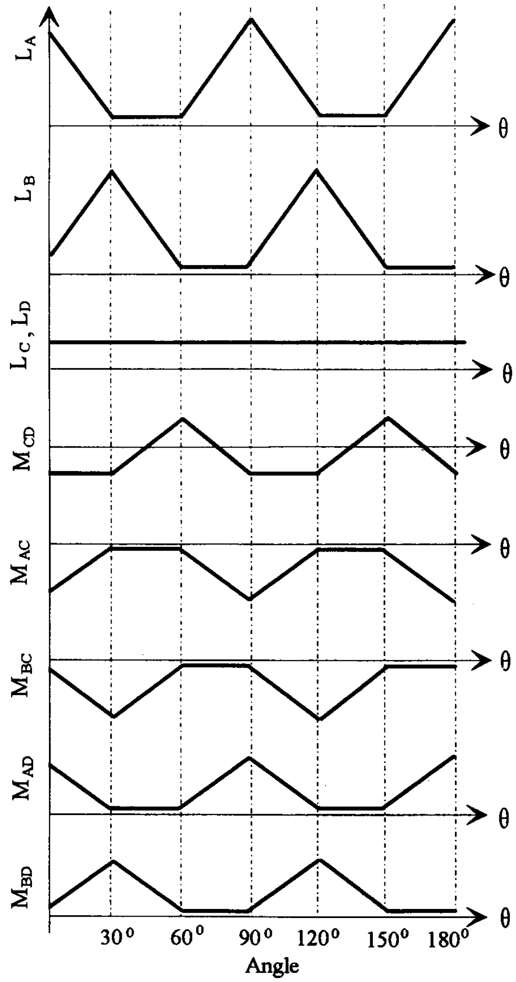

Fig. 2. Inductance profiles of motor with two full pitch windings. From the top L_{A}, L_{B}, L_{C}: Self inductances of phases A, B, and C, M_{CD}, M_{BC}, M_{AD}, and M_{BD}: mutual inductances between phases A, B, C, and D.

Hence, the torque produced by the two full pitch windings is given as

$$\begin{aligned} T = \left.\frac{\partial W_{\mathrm{C}}}{\partial \theta}\right|_{i=\mathrm{constant}} &= \frac{1}{2}\left(\frac{\partial L_{\mathrm{C}}}{\partial \theta} i_{\mathrm{C}}^2 + \frac{\partial L_{\mathrm{D}}}{\partial \theta} i_{\mathrm{D}}^2\right) \\ &+ i_{\mathrm{C}} i_{\mathrm{D}} \frac{\partial M_{\mathrm{CD}}}{\partial \theta}. \end{aligned} \tag{2}$$

Because the self inductances of the full pitch windings are constant, the torque produced by winding C and D is

$$T = i_{\mathrm{C}} i_{\mathrm{D}} \frac{\partial M_{\mathrm{CD}}}{\partial \theta}. \tag{3}$$

The above equation shows that if phases C and D are energized while the mutual inductance between the two windings is increasing, a positive torque indeed can be developed. If the number of turns is the same for both the short and full pitch coils, we have then, approximately

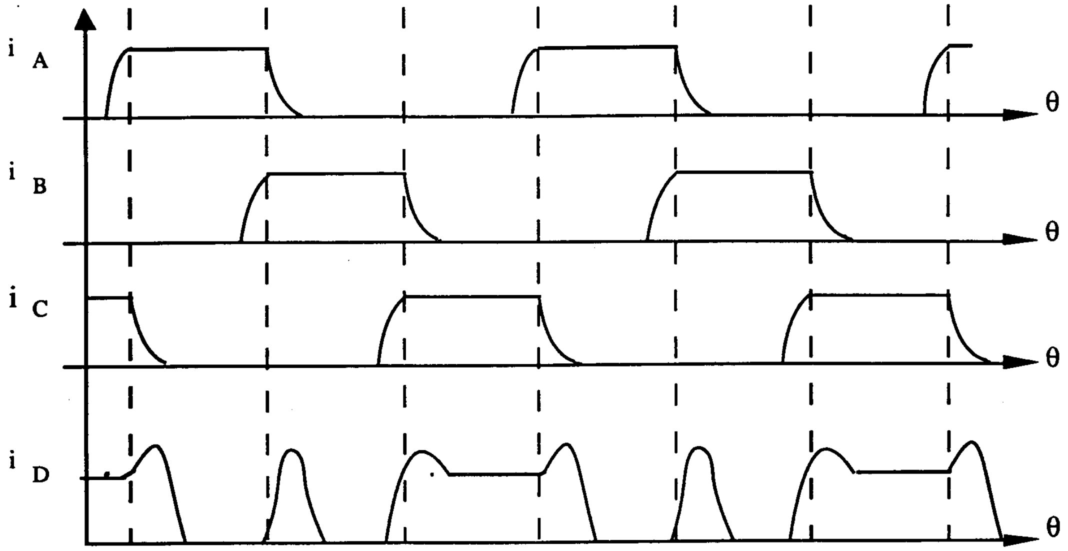

Fig. 3. Schematic current waveforms of a VRM with two full pitch windings.

$$\frac{\partial M_{\mathrm{CD}}}{\partial \theta} = \frac{1}{2}\frac{\partial L_{\mathrm{A}}}{\partial \theta} \tag{4}$$

then

$$T = \frac{1}{2} i_{\mathrm{C}} i_{\mathrm{D}} \frac{\partial L_{\mathrm{A}}}{\partial \theta}. \tag{5}$$

It can be seen that if the short pitch and full pitch windings have the same current, the developed torque is effectively the same.

When winding C is turned off, its current is transferred to winding D through the mutual inductance in the same manner as when the current in the short pitch windings are transferred to winding D. A sketch of the current waveforms of the motor with two full pitch windings is shown in Fig. 3.

IV. CONVERTER CONFIGURATIONS

Two converter configurations can be considered for the new motor, and are shown in Fig. 4. Fig. 4(a) shows a converter circuit with winding D connected to the source. The switching pattern is straightforward for this converter. To turn off phase A, switch S_{A2} is turned off first and the winding of phase A is short circuited automatically through the freewheeling diode D_{A}. Switch S_{D} is then turned on to supply a positive voltage to the full pitch winding D. After the current in phase A reaches zero, switch S_{D} and S_{A1} are turned off and the winding D is short circuited by the diode D_{D}.

To obtain improved performance, a half bridge converter with winding D connected to the source can be used. The converter circuit is shown in Fig. 4(b). Compared with the converter in Fig. 4(a), this converter has several advantages as described below. Winding A is assumed to be turned off in the following description.

1. The turn-off process is the faster. If switches S_{A1} and S_{A2} are turned off and switches S_{D1} and S_{D2} are turned on in the turn-off period, a negative voltage is applied to winding A while a positive voltage is applied to winding D. The current in phase A will decrease at the fastest possible rate.
2. Efficiency can be higher since the chopping frequency is lower due to the fact that in this case the full pitch winding D is not involved in the chopping period. A negative voltage is applied to the short pitch winding only when this phase is to be turned off.

In terms of performance, the converter shown in Fig. 4(b) is the superior because it provides the most effective control of the motor. The disadvantage is that more semiconductor devices are needed for this converter.

V. SIMULATION AND EXPERIMENTAL RESULTS

A simulation based on a linear model has been implemented to verify the operating principles of this new motor. In this simulation, the following assumptions have been incorporated.

1. Saturation and fringing is neglected.
2. The speed is constant.
3. No mutual coupling exists between the short pitch windings.

Both a conventional and the new VRM have been simulated for the purpose of comparison. Both of the motors are identical except the new motor has two full pitch windings which are wound with the same conductors as the short pitch windings. The main parameters chosen for the two motors are as follows:

DC bus voltage: 100 V
Peak Current: 8 A
Rated Speed: 1200 RPM
Rated Output: 300 W
Turns Ratio Between Short & Full Pitch Wdgs.: 1
Stator Pole Arc: 30°

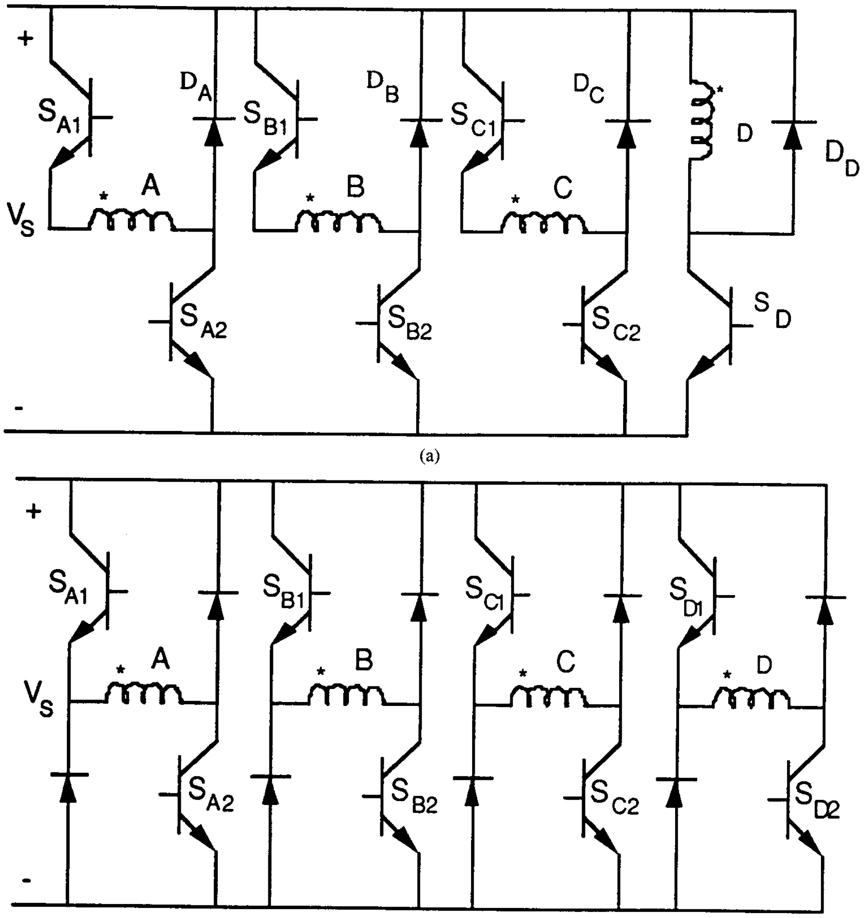

Fig. 4. (a) Power converter with winding D connected to the source. (b) Half bridge converter with winding D connected to the source.

Rotor Pole Arc: 32°
Short pitch winding resistance: 0.54 Ω
Full pitch winding resistance: 0.91 Ω
Maximum Inductance per phase: 62 mH
Minimum Inductance per phase: 7.0 mH.

The equations of the system are as follows:

$$V_{\mathrm{A}} = R_{\mathrm{A}} i_{\mathrm{A}} + \frac{d\lambda_{\mathrm{A}}}{dt} \tag{6}$$

$$V_{\mathrm{B}} = R_{\mathrm{B}} i_{\mathrm{B}} + \frac{d\lambda_{\mathrm{B}}}{dt} \tag{7}$$

$$V_{\mathrm{C}} = R_{\mathrm{C}} i_{\mathrm{C}} + \frac{d\lambda_{\mathrm{C}}}{dt} \tag{8}$$

$$V_{\mathrm{D}} = R_{\mathrm{D}} i_{\mathrm{D}} + \frac{d\lambda_{\mathrm{D}}}{dt} \tag{9}$$

$$\lambda_{\mathrm{A}} = L_{\mathrm{A}} i_{\mathrm{A}} + M_{\mathrm{AC}} i_{\mathrm{C}} + M_{\mathrm{AD}} i_{\mathrm{D}} \tag{10}$$

$$\lambda_{\mathrm{B}} = L_{\mathrm{B}} i_{\mathrm{B}} + M_{\mathrm{BC}} i_{\mathrm{C}} + M_{\mathrm{BD}} i_{\mathrm{D}} \tag{11}$$

$$\lambda_{\mathrm{C}} = L_{\mathrm{C}} i_{\mathrm{C}} + M_{\mathrm{AC}} i_{\mathrm{A}} + M_{\mathrm{BC}} i_{\mathrm{B}} + M_{\mathrm{CD}} i_{\mathrm{D}} \tag{12}$$

$$\lambda_{\mathrm{D}} = L_{\mathrm{D}} i_{\mathrm{D}} + M_{\mathrm{AD}} i_{\mathrm{A}} + M_{\mathrm{BD}} i_{\mathrm{B}} + M_{\mathrm{CD}} i_{\mathrm{C}}. \tag{13}$$

From (7) through (13), one can solve for the quantities $\frac{di_{\mathrm{A}}}{dt}$, $\frac{di_{\mathrm{B}}}{dt}$, $\frac{di_{\mathrm{C}}}{dt}$, $\frac{di_{\mathrm{D}}}{dt}$, as

$$\begin{bmatrix} V_{\mathrm{A}} \\ V_{\mathrm{B}} \\ V_{\mathrm{C}} \\ V_{\mathrm{D}} \end{bmatrix} = \begin{bmatrix} L_{\mathrm{A}} & 0 & M_{\mathrm{AC}} & M_{\mathrm{AD}} \\ 0 & L_{\mathrm{B}} & M_{\mathrm{BC}} & M_{\mathrm{BD}} \\ M_{\mathrm{AC}} & M_{\mathrm{BC}} & L_{\mathrm{C}} & M_{\mathrm{CD}} \\ M_{\mathrm{AD}} & M_{\mathrm{BD}} & M_{\mathrm{CD}} & L_{\mathrm{D}} \end{bmatrix} \begin{bmatrix} \frac{di_{\mathrm{A}}}{dt} \\ \frac{di_{\mathrm{B}}}{dt} \\ \frac{di_{\mathrm{C}}}{dt} \\ \frac{di_{\mathrm{D}}}{dt} \end{bmatrix} + \begin{bmatrix} R_{\mathrm{A}} + \frac{dL_{\mathrm{A}}}{dt} & 0 & \frac{dM_{\mathrm{AC}}}{dt} & \frac{dM_{\mathrm{AD}}}{dt} \\ 0 & R_{\mathrm{B}} + \frac{dL_{\mathrm{B}}}{dt} & \frac{dM_{\mathrm{BC}}}{dt} & \frac{dM_{\mathrm{BD}}}{dt} \\ \frac{dM_{\mathrm{AC}}}{dt} & \frac{dM_{\mathrm{BC}}}{dt} & R_{\mathrm{C}} & \frac{dM_{\mathrm{CD}}}{dt} \\ \frac{dM_{\mathrm{AD}}}{dt} & \frac{dM_{\mathrm{BD}}}{dt} & \frac{dM_{\mathrm{CD}}}{dt} & R_{\mathrm{D}} \end{bmatrix} \begin{bmatrix} i_{\mathrm{A}} \\ i_{\mathrm{B}} \\ i_{\mathrm{C}} \\ i_{\mathrm{D}} \end{bmatrix}. \tag{14}$$

Once the currents are determined by solving the state equations, the torque can be calculated by

$$T = \frac{1}{2}\left(i_{\mathrm{A}}^2 \frac{dL_{\mathrm{A}}}{d\theta} + i_{\mathrm{B}}^2 \frac{dL_{\mathrm{B}}}{d\theta}\right) + i_{\mathrm{C}}\left(i_{\mathrm{A}} \frac{dM_{\mathrm{AC}}}{d\theta} + i_{\mathrm{B}} \frac{dM_{\mathrm{BC}}}{d\theta}\right) + i_{\mathrm{D}}\left(i_{\mathrm{A}} \frac{dM_{\mathrm{AD}}}{d\theta} + i_{\mathrm{B}} \frac{dM_{\mathrm{BD}}}{d\theta} + i_{\mathrm{C}} \frac{dM_{\mathrm{CD}}}{d\theta}\right). \tag{15}$$

In the simulation traces shown, the turn-on angle is chosen to ensure that each phase current can reach the peak desired current at the point when the phase inductance begins to increase. The turn-off angle is chosen to realize the highest possible torque.

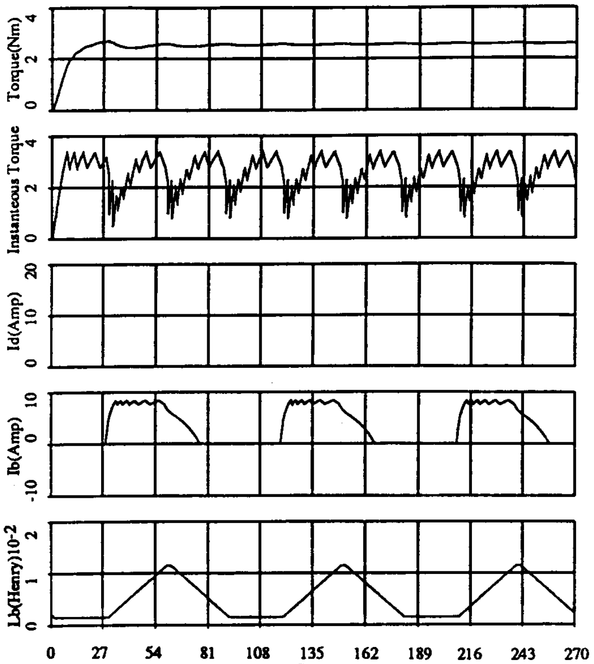

Fig. 5. Simulation results of a conventional VRM in chopping mode.

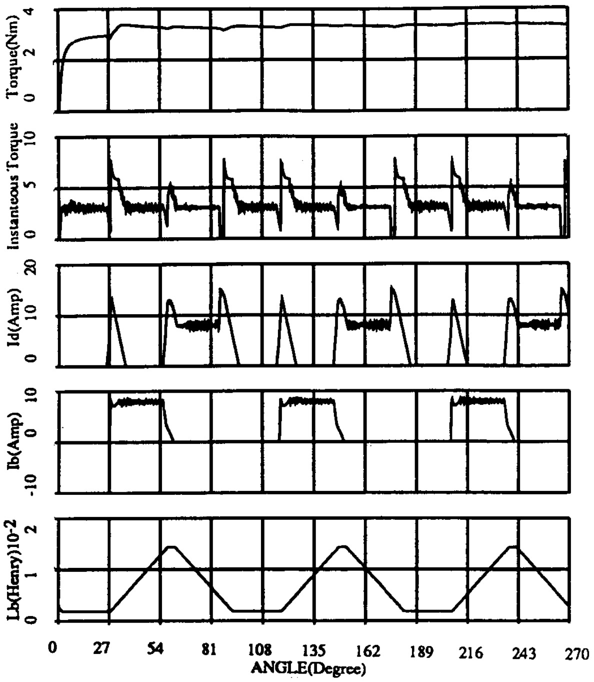

Fig. 6. Simulation results of a two full pitch windings VRM in chopping mode.

Two operating modes are simulated and shown for both conventional and two full pitch windings motors. One mode concerns low-speed operation (chopping operation) and the other concerns high-speed operation (single-pulse operation). Figs. 5 and 6 show the simulation results for the two motors operated in the chopping mode, while Figs. 7 and 8 show the simulation results of the two motors operated in the single pulse mode.

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

1. The currents in the short pitch windings of the new motor clearly decay to zero much more rapidly than they do in the conventional motor. This means the new motor does not suffer from the commutation problem to the same degree as the conventional VRM.
2. The new motor has a higher output torque than the conventional motor for the same input current limit and at the same speed. This result suggests that the new motor can have higher output with the same converter rating and higher speed capability with the same bus voltage. This is a direct result of the improvement in the energy conversion ratio and turn-off performance.
3. Both motors clearly have torque spikes which can be interpreted as a disadvantage. It should be pointed out, however, that the relatively higher torque "spikes" in the new machine 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 the actual motor.
4. The new motor has higher torque ripple. The reason for this behavior is that in there is an extra torque component due to the interaction between the currents in the short pitch windings and the full pitch winding. Because the current in the full pitch winding does not

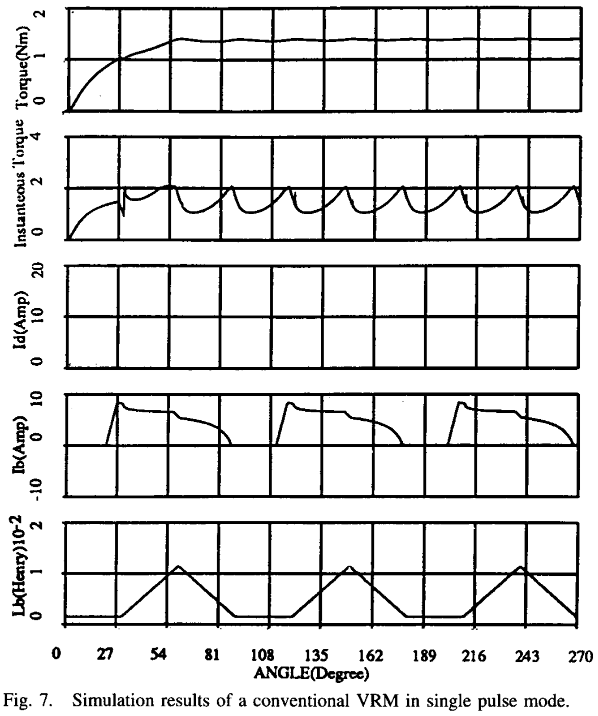

Fig. 7. Simulation results of a conventional VRM in single pulse mode.

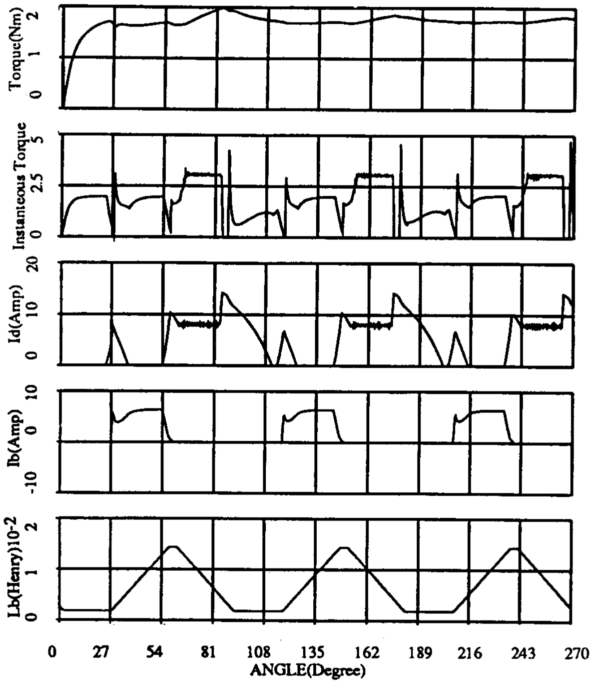

Fig. 8. Simulation results of a two full pitch winding VRM in single pulse mode.

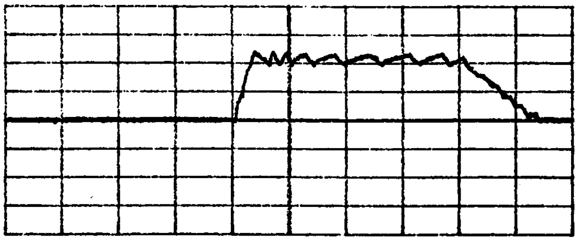

Fig. 9. Experimental current waveform of conventional VRM, scale: (2 A/div; 10 ms/div).

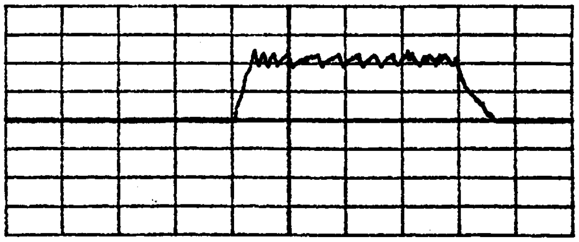

Fig. 10. Experimental current waveform of two full pitch windings VRM, scale: (2 A/div; 10 ms/div).

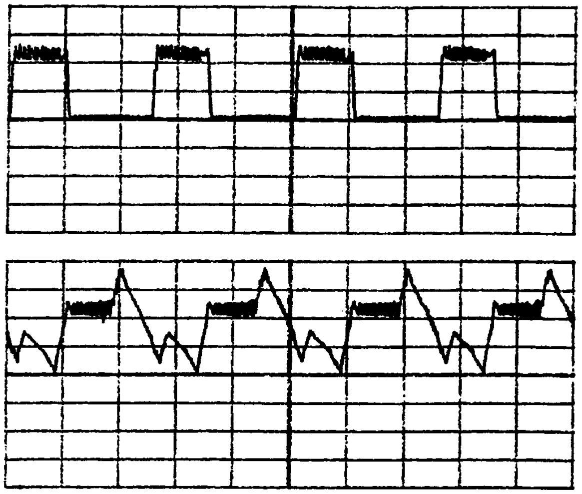

Fig. 11. Currents in short pitch winding (trace 1) and in full pitch winding (trace 2), scale: 2 A/div; 10 ms/div.

maintain constant, its corresponding torque component changes as i_D changes. In terms of energy conversion, the trapped energy is converted to mechanical energy at different rate in the conversion process. As a result, the additional torque due to the full pitch winding in the new motor varies and therefore, the total torque has higher torque ripple. It should be pointed out that the torque ripple of the new motor can be manipulated further if desired by controlling the currents in the short pitch winding as a function of the current in the full pitch winding.

The new motor and its associated converter (shown in Fig. 4(b)) have also been constructed and tested. Experiments have been carried out to show the feasibility of the new motor. According to the experimental study, the new motor again has better turn-off performance because of the utilization of a commutation winding. In particular, Fig. 9 shows the current waveform of the conventional VR motor. As can be seen, the current has a tail after the phase is turned off. Fig. 10 shows the corresponding waveforms of the current in a short pitch winding of a two full pitch windings motor. Compared with the current waveform shown in Fig. 9, it can be seen that after the phase is turned off, the current decreases to zero faster than with the conventional motor. Fig. 11 shows the currents in the short pitch winding and in the commutation winding of the new motor.

Nowadays, in some industrial applications, the efficiency is more important than the output power or the rating of the converters used for the machines. In order to show how much the efficiency can be improved with the two full pitch winding VRM, performance experiments have been done. Fig. 12 shows the efficiency/speed curves of the two full pitch winding and conventional VRM's. Fig. 13 shows the corresponding output power of the two motors. The two full pitch winding VRM can have a higher efficiency than the conventional VRM under the same output power constraint.

As shown in Figs. 5–13, the new motor has substantially better turn-off performance as predicted by both simulation and the experimental study.

It should be emphasized that the performance of the new motor tested in this experimental study should not be considered as the best achievable result. Better performance can be achieved with a new motor suitably optimized and/or with sophisticated control.

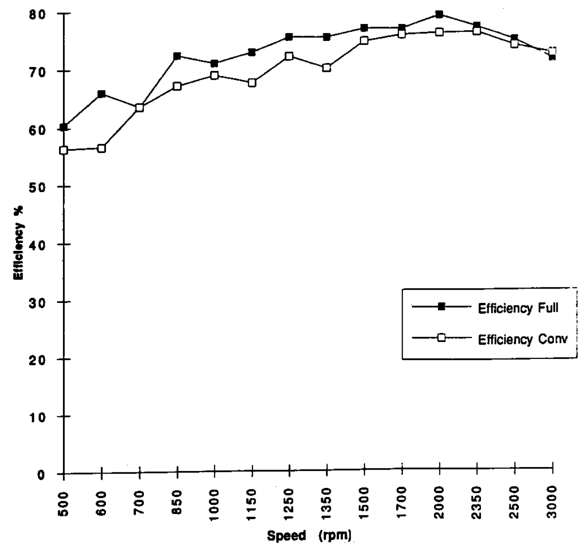

Fig. 12. Power ouput comparsion of a two full pitch winding VRM and a conventional VRM.

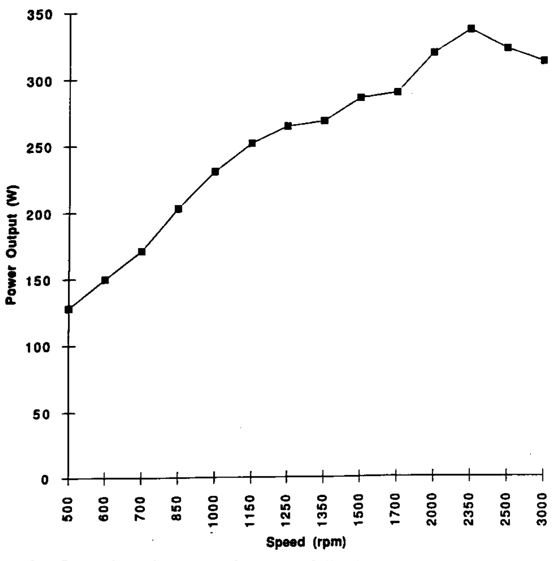

Fig. 13. Power/speed curve of a two full pitch winding VRM and a conventional VRM in the operation corresponding to Fig. 12.

VI. CONCLUSION

A solution to two of the perplexing problems concerning variable reluctance motors, namely current commutation and energy circulation, have been targeted in this paper. For this purpose, a new motor with two full pitch windings has been proposed. The operating principles of the new motor were presented and a linear model of the new motor was developed to verify its operating principles. A simulation study was done to illustrate the improvement of the motor performance.

The new motor has the following advantages over conventional VRM's: (1) The configuration allows a significant improvement in the turn-off process and therefore allows higher speed capacity than conventional VRM's; (2) the machine has higher output because of the improvement in the turn-off performance and due to the utilization of the trapped energy; (3) the new machine can have higher output with the same converter or the same output but with smaller converter capacity because of the improvement in the energy conversion ratio. There are, inevitably, penalties to be paid for the above advantages. (1) The new motor uses more copper than a conventional VRM. (2) The new motor has lower reliability than a conventional motor since the three phase windings are coupled with each other through the two full pitch windings. This feature becomes an issue when the full pitch windings are short circuited. (3) The new motor has higher torque ripple without implementing control efforts to minimize this effect.

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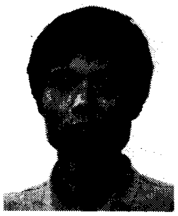

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Dr. Lipo has received 18 IEEE prize paper awards for his work, including being co-recipient of a Best Paper Award in the IEEE Industry Applications Society Transactions for 1984 and 1993. In 1986, he received the Outstanding Achievement Award from the IEEE Industry Applications Society for his contributions to the field of ac drives. In 1990, he received the William E. Newell Award of the IEEE Power Electronics Society for contributions to the field of power electronics. He currently serves as the President of the IEEE Industry Applications Society.