A NOVEL LOW COST VARIABLE RELUCTANCE MOTOR DRIVE

UN NOUVEL ENTRAINEMENT ELECTRIQUE A BAS PRIX PAR MOTEUR A RELUCTANCE VARIABLE

A. Ometto
Department of Electrical Engineering
University of L'Aquila
67040 Poggio di Roio, L'Aquila, Italy

A. Julian and T.A. Lipo
University of Wisconsin - Madison
1415 Johnson Drive
Madison, WI 53706-1691

Abstract
This paper describes a new type of low cost converter for variable reluctance motor (VRM) drives. The major advantage of this converter is that it requires only one fully controllable switch per motor phase while driving the machine at rated speed. The converter prototype has been tested to supply a VRM with different mechanical loads. Experimental results are reported and the converter is contrasted with other converter topologies.

Keywords
- electrical drives
- single-rail converter
- variable reluctance motor

Introduction

The VRM has a doubly salient structure with different numbers of stator and rotor poles. Since there is no winding in the rotor the torque is only produced by the reluctance variations and it does not depend on the polarity of the stator winding currents. In fact, with the assumption that there is no mutual coupling between the stator phases, the torque produced by the n-th phase can be expressed as:

$$T_n = \frac{1}{2} i_n^2 \frac{dL_n}{d\beta_r} \qquad (1)$$

where i_n is the current in the n-th phase, L_n is the inductance of the n-th phase and β_r is the electrical rotor angle.
In Fig. 1 the idealized waveforms of the phase inductance and its derivative function are shown. Based on eq. 1 and these waveforms it is possible to draw the theoretical waveform of the current in the n-th phase (see Fig. 2) to produce motoring torque. For β_r between $(\beta_1 + 2k\pi)$ and $(\beta_2 + 2k\pi)$ current is not needed because the torque would be null even with current flow. Furthermore for β_r between $(2k\pi)$ and $(\beta_1 + 2k\pi)$ the current produces generating torque. In both cases the machine efficiency would be negatively affected.
Unfortunately it is not possible to have infinite values of di / dt as required and there will be two finite time intervals to magnetize and demagnetize the phase winding. Of course two rotor electrical angles correspond to the finite time intervals by means of the motor speed. For a fixed time interval needed to build up the current, as the speed increases, the corresponding angle becomes higher, making the theoretical current waveform more difficult to achieve.
Neglecting the winding resistance, the di / dt depends on the applied voltage. phase inductance and back e.m.f. Of course the voltage should be as high as possible (rated voltage of the machine) and should be applied across the winding in either polarity to minimize the magnetizing and demagnetizing time interval. Because the back e.m.f. mainly depends on the speed it can be neglected at low speed but as the speed increases, the e.m.f. becomes more and more important and it dominates the behaviour of the machine at rated speed. Thus, as the speed increases, the di / dt decreases and the phase winding has to be energized in advance with respect to the angle β_2 in order to achieve almost the full current when the inductance starts increasing. The same technique can be used for the demagnetization period to avoid the current when the derivative function of L_n is negative. Given the finite di / dt, the currents of adjacent phases overlap regardless of the speed range.

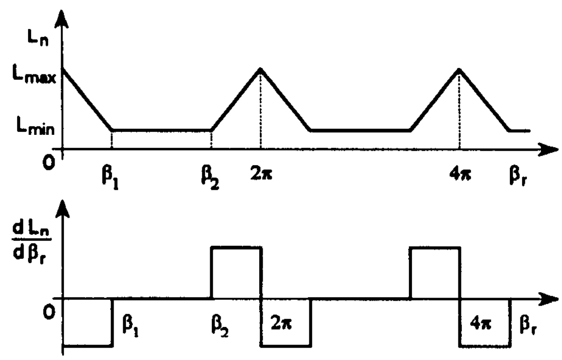

Fig. 1 - Idealized waveforms of phase inductance

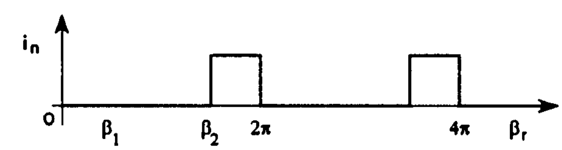

Fig. 2 - Theoretical current waveform

To summarize, it can be said that to achieve good performance of the VRM drive, the converter must be able
- to apply the machine rated voltage with either polarity;
- to allow the current overlap in adjacent phases.

The purpose of this project is to investigate the performance of a novel low cost converter when used to control a low speed, four phase, VRM. Four converter topologies are contrasted here to emphasis the capabilities of the novel converter being presented. Only the single-rail converters are considered because all dual-rail converters need devices rated at twice the motor supply voltage and which is a disadvantage mainly for high voltage machines.

Converter topologies

The traditional converter, shown in Fig. 3, uses one asymmetric bridge per motor phase realizing several necessary functions for robust control of a VRM. First, the motor phase currents can be independently controlled, allowing phase currents to overlap, because each phase is supplied by its own devices. Second, the full dc supply voltage is also available for demagnetization of each motor phase minimizing the time to switch the current off. However, the scheme is expensive because of the high switch/phase ratio (two fully controllable switches per phase). The switches are rated at rated voltage and current of the motor.

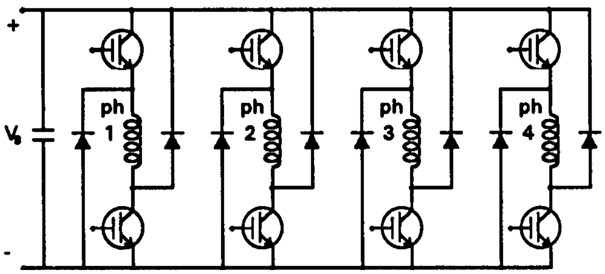

Fig. 3 - Traditional converter

Numerous alternatives to the traditional converter exist [1], [2]; the primary motivation of these alternatives is to reduce the cost of the converter. However many low cost converters sacrifice some functional control of the VRM in order to reduce the circuit topology.

Fig. 4 shows a minimum switch topology that can control a four phase VRM [2]. This circuit topology utilizes four asymmetrical switches (each rated at twice the phase current). The main disadvantage in this case is that the demagnetization voltage is only a fraction of the supply voltage. The voltage available to turn the current off in one phase depends on the voltage used to turn on the next phase, namely the supply voltage is shared by the two phases. As the speed and the back e.m.f. increase this problem becomes more severe and, due to the duration of the tail current, the torque of the VRM is limited. The motor cannot be operated at rated current and speed, under-utilizing the capabilities of the VRM. The minimum switch topology converter might be utilized to supply a VRM with a larger number of stator poles, providing a machine derating, to keep down the cost of the drive.

Finally the six switch converter (see Fig. 5) has been reported which is functionally equivalent to the novel converter described in the following paragraphs.

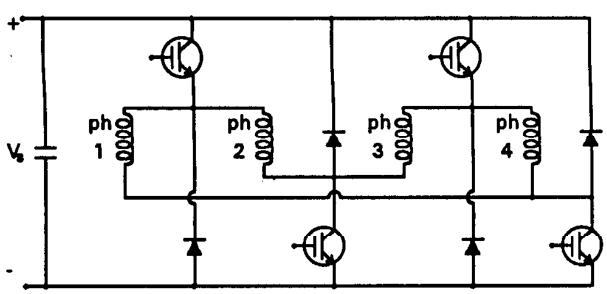

Fig. 4 - Minimum switch topology

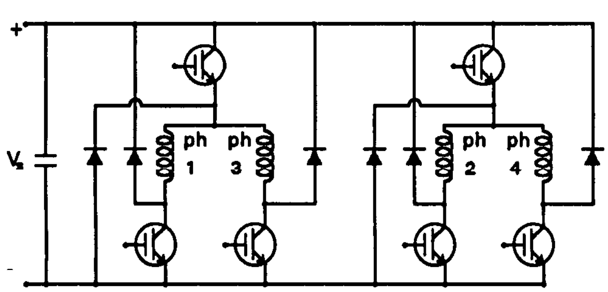

Fig. 5 - Four phase converter with six switches

Novel low cost converter operation

Fig. 6 shows the novel low cost converter proposed in this paper. It requires only one fully controllable switch and one SCR per phase and can match the performance of the traditional converter. This topology can be realized with simpler gate drive circuits for the SCRs, reducing the cost. The voltage and current ratings required of the switches are the supply voltage and the phase current, respectively.

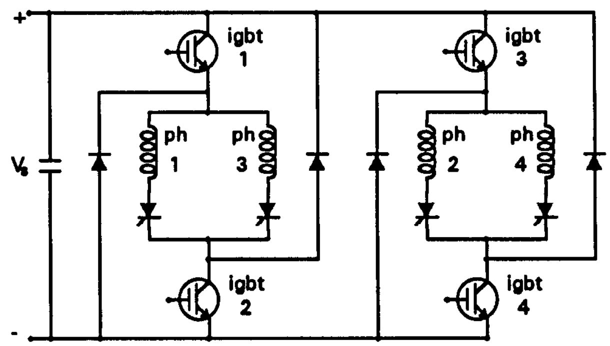

Fig. 6 - Novel low cost converter

In contrast to the circuit topology of Fig. 5, the novel converter replaces two fully controllable switches, requiring more complex gate drive circuits, and two diodes with four SCRs.

Comparing this converter topology with the traditional converter one, it is easily seen that only half of the number of asymmetric bridges is required utilizing only one SCR per phase. In fact each asymmetric bridge can supply two non-adjacent phases of the VRM whereas the SCRs control which phase is on. After the phase has been selected, its current is controlled in the same manner as for the traditional converter. Specifically there are three possible states: magnetization, freewheeling and demagnetization. In the first state both switches are on and the supply voltage is applied across the phase. This state is utilized to build up the current and during the chopping period. In the second one, utilized only in the chopping period, the winding is in short circuit through one switch and one diode. Either switch for each pair of phases can be used to regulate the current during the chopping period. Finally, when both switches are off the supply voltage (negative) is applied across the phase to switch the current off.

The new converter topology is based on the assumption that there is no need for currents of non adjacent phase to overlap. In effect this is the only limit of this converter because it is essential that the SCR for one phase is off before it is time to energize the other phase corresponding to the same pair of switches. Moreover the thyristor turn-off time t_q must elapse before trying to energize the other phase. Full supply voltage is used for demagnetization at turn-off time, minimizing this limitation. It is shown in the next section that the VRM used in this investigation can reach rated current and speed; the converter can fully utilize the capabilities of the motor.

Testing and Measurements

A prototype of the novel converter that utilizes IGBTs as switches has been built and utilized to supply a VRM whose parameters are reported in Table 1. A Motorola DSP56000 digital signal processing development system is used to control the inverter and an absolute encoder is used as rotor position transducer.

Table 1 - VR Motor Parameters

stator poles	rotor poles	rated power	rated voltage	rated current	rated speed
8	6	0.4 Hp	150 V	3 A	750 rpm

Three different operating conditions have been considered to show the performance of the drive. Figs. 7-9 show current wave forms in IGBT 1 and IGBT 3 where IGBT 2 and IGBT 4 are used to control the currents. Hysteresis control is utilized to regulate the currents during the chopping period. The supply voltage is used to increase the current during regulation. When the current amplitude exceeds the hysteresis band the modulating switch is turned off; the current free wheels through a diode. Because the (negative) supply voltage is not used to decrease the current during regulation, the hysteresis switching frequency is lower, reducing the switching losses. Fig. 7 reflects the advantage of this method of hysteresis control; the regulated current decays slower since the demagnetization voltage (back emf) is less than the supply voltage. Fig. 8 is included to demonstrate the performance of the current regulator below rated speed.

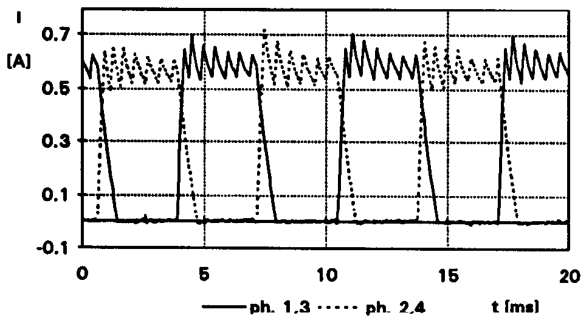

Fig. 7 - Experimental results showing light load current at rated speed (757 rpm)

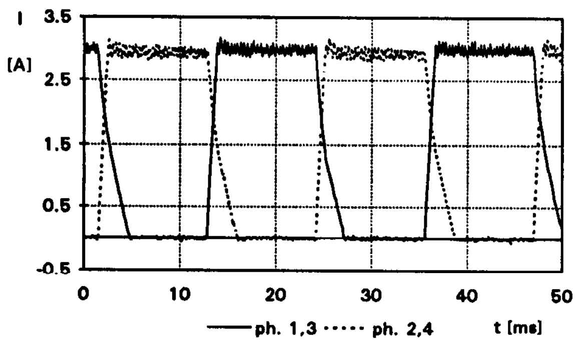

Fig. 8 - Experimental results showing rated current at low speed (215 rpm)

As discussed in the previous section, demagnetization of non-adjacent phases is the only potential performance limitation of the novel converter. Fig. 9 demonstrates that at rated current and speed demagnetization is completed well ahead of the magnetization of the next non-adjacent phase. Transient over-torque and over-speed conditions are possible with the novel converter, enhancing its performance as a VRM controller.

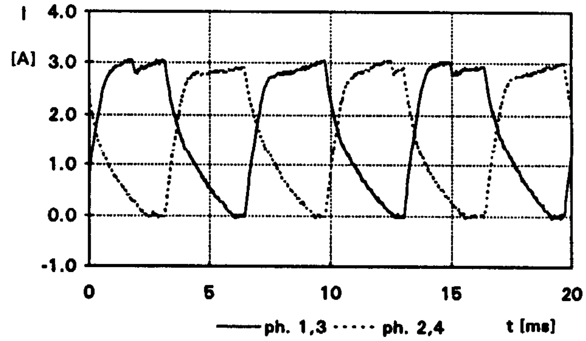

Fig. 9 - Experimental results showing rated current at rated speed (755 rpm)

Conclusion

Designing the converter and VRM as an integrated system increases the utilization of all components in the system. The novel low cost converter presented in this paper represents a reduced topology converter capable of robust control of the VRM studied here. Significant cost factors have been reduced with respect to the other functionally equivalent topologies, namely the gate drive circuits and the number of fully controllable switches required.

References

[1] S. Vukosavic, V. R. Stefanovic, 'VRM Inverter Topologies: a Comparative Evaluation'. IEEE Trans. Ind. Appl., vol. 27, no. 6, Nov./Dec. 1991.

[2] C. Pollack, B. W. Williams, 'An Integrated Approach to Switched Reluctance Motor Design', in Proceeding of the Conference EPE, 1983, Grenoble, France.

[3] P. J. Lawrenson et al., 'Variable-speed switched reluctance motors', IEEE Proceeding, Vol.127, Pt. B, No. 4, July 1980.