MULTILEVEL ASYMMETRIC POWER CONVERTERS FOR SWITCHED RELUCTANCE MACHINES

S.J. Watkins, J. Čorda and L. Zhang

University of Leeds, UK

ABSTRACT

This paper presents a new family of multilevel asymmetric power converters which are suitable for unipolar current loads such as a switched reluctance motor drive. The fundamental operation of each topology is reviewed and some simulation results are presented showing the potential system performance improvements that can be realised by operating with intermediary voltages rather than the full dc-link.

INTRODUCTION

Since Lawrenson et al's work (1) in the 1970s, interest in switched reluctance machines (SRM) has steadily grown with a rising number of publications each year. Throughout this period, one of the main application focuses for researchers and developers has been on low power drives for the automotive and white goods industrial sectors. This has been primarily due to the simple machine construction with no windings or permanent magnets on the rotor leading to potentially low manufacturing costs in high volume. However, one of the first major commercial SRM products to appear was the 'Oulton' drive in the early 1980s, developed by Fulton el al (2). This range of industrial drives using a four-phase machine and thyristor power converter, demonstrated that the SRM can offer excellent performance even in larger sized drives.

Besides the simple machine construction, an SRM drive also has inherent fault-tolerance, high starting torque and high efficiency over a very wide operating speed. These features make it potentially attractive for future higher power variable speed applications such as traction, pumps and compressors, wind-turbines and mining applications. The power levels for these drive applications extend up to several megawatts. To achieve the full potential of a multi-megawatt SRM drive system, the operating voltage needs to be at several kilovolts. The conventional asymmetric half-bridge power converter, Figure 1, can be realised using the latest high-voltage GTO modules, but the increased switching losses can impose limitations on performance. Although there are now commercially available IGBTs with voltage ratings of 6.5 kV, these devices have relatively slow switching characteristics and may not be applicable to all operating voltages and drive speed ranges. Therefore, there is a requirement for alternative power converter topologies suitable for use in a high-power switched reluctance drive system.

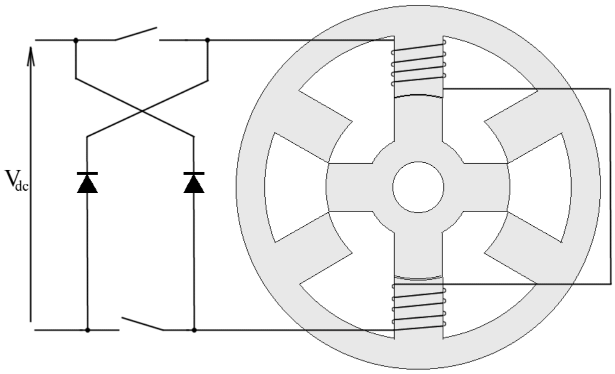

Figure 1: Asymmetric half-bridge SRM topology

SRM power converters generally operate by feeding only unipolar currents to each machine phase winding. The most popular topology, the asymmetric half-bridge, offers fluxing, de-fluxing and freewheeling modes of operation and has no inherent shoot-through behaviour. To achieve operation at higher dc-link voltages, a multiple voltage level approach needs to be adopted where a power converter can be realised using lower voltage rated power switches. This approach will also allow operation at higher switching frequencies than would otherwise be possible with much high voltage power switches. There are three main types of multilevel power converter, which maintain the asymmetric features of conventional power converter and are suitable for driving the SRM with unipolar currents. They are as follows:

1) Diode-clamped multilevel power converter
2) Capacitor-clamped multilevel power converter
3) Cascaded-cell multilevel power converter

Each topology is typified by using more than two power switches in each phase with the maximum voltage across each switch limited to levels less than the maximum applied phase voltage. They are also scalable in terms of the number of voltage levels and switching combinations that can be used to apply intermediate voltage levels and zero voltage (freewheeling) across the phase winding. The following sections describe the circuit topology and operating features of each asymmetric power converter.

DIODE-CLAMPED MULTILEVEL CONVERTER

The extension of an inverter circuit to multiple voltage levels with diodes used to constrain the maximum voltage across the power switches to safe operating levels was first proposed by Baker (3) and Nabae et al (4). This three-level inverter circuit is commonly known as the neutral point clamped (NPC) inverter, while the general class of multilevel inverters are referred to as diode-clamped inverters. This voltage clamping approach can be applied to an asymmetric converter in a similar fashion and the three-level diode-clamped asymmetric multilevel converter for one phase is shown in Figure 2. The circuit requires 4 power switches, 8 power diodes and 2 capacitors for its implementation. The separate diodes clamp the midpoints between the main converter power devices to the half dc-link point on the capacitor chain. There are 16 possible converter operating modes dependent on the power switch states. These operating modes are listed in Table 1. Seven of these switch states are not allowed since they would lead to excessive voltage across one of the power switches. This is because the inner switch cannot be in the off state unless the other switch in its limb is off. Besides the basic full positive and negative voltage modes, there are modes of operation that can flux or de-flux the machine at a half of the dc-link voltage level. There are also three freewheeling modes in which there is zero voltage applied across the phase winding.

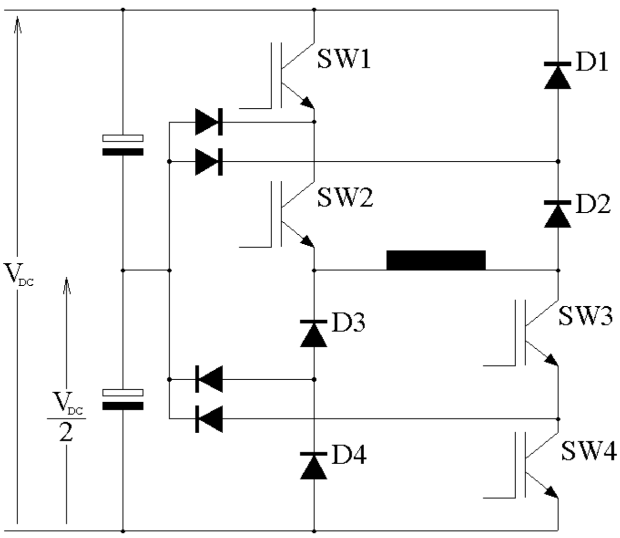

Figure 2: Diode-clamped multilevel asymmetric power converter

Operation of the converter when using current paths through the split capacitor chain must ensure that the centre point voltage is kept balanced to avoid over-voltage in the power devices. Clamping diodes on the centre point of the diodes only function for protection, and do not conduct during normal operation. This circuit was first described in a patent by Davis (5). The preferred embodiment in the patent replaces the two diodes in each power limb with a single higher voltage diode, thus removing the need for two of the clamping diodes.

TABLE 1 - Diode-clamped converter operating modes

Mode	**SW1**	**SW2**	**SW3**	**SW4**	V_{phase}
0	OFF	OFF	OFF	OFF	$-V_{dc}$
1	ON	OFF	OFF	OFF	N/A
2	OFF	ON	OFF	OFF	$-V_{dc}/2$
3	ON	ON	OFF	OFF	0
4	OFF	OFF	ON	OFF	$-V_{dc}/2$
5	ON	OFF	ON	OFF	N/A
6	OFF	ON	ON	OFF	0
7	ON	ON	ON	OFF	$+V_{dc}/2$
8	OFF	OFF	OFF	ON	N/A
9	ON	OFF	OFF	ON	N/A
10	OFF	ON	OFF	ON	N/A
11	ON	ON	OFF	ON	N/A
12	OFF	OFF	ON	ON	0
13	ON	OFF	ON	ON	N/A
14	OFF	ON	ON	ON	$+V_{dc}/2$
15	ON	ON	ON	ON	$+V_{dc}$

N/A - not allowed

CAPACITOR-CLAMPED MULTILEVEL CONVERTER

Capacitor-clamping in multilevel ac inverters is already known from the work of Meynard and Foch (6 and 7), and this technique again can be applied to a unipolar current multilevel power converter. The capacitor-clamped converter, one phase shown in Figure 3, dispenses with the clamping diodes and instead relies on two flying capacitors connected between the centre points of the switches and diodes in each converter limb. Each capacitor's voltage is maintained around half the dc-link voltage. Therefore, the maximum voltage stress seen by the switches in the blocking state is only half the dc-link voltage. The 16 possible switch state modes are listed in Table 2. This circuit also includes a number of intermediary voltage modes applying only half the dc-link voltage level to the phase winding. Unlike the diode-clamp converter, there is no restriction placed on using any of the operating modes. The control must ensure capacitor balancing when operating with any intermediary switching mode by keeping the average energy circulating in each capacitor at zero.

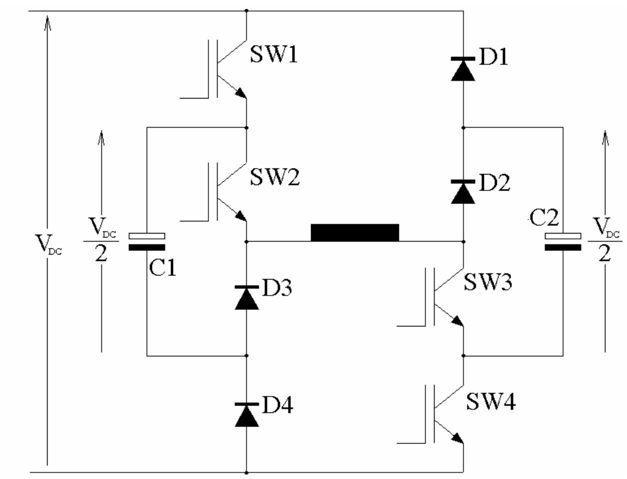

Figure 3: Capacitor-clamped asymmetric multilevel power converter

TABLE 2 - Capacitor-clamped and cascaded-cell converter operating modes

Mode	SW1	SW2	SW3	SW4	V_{phase}
0	OFF	OFF	OFF	OFF	-Vdc
1	ON	OFF	OFF	OFF	-Vdc/2
2	OFF	ON	OFF	OFF	-Vdc/2
3	ON	ON	OFF	OFF	0
4	OFF	OFF	ON	OFF	-Vdc/2
5	ON	OFF	ON	OFF	0
6	OFF	ON	ON	OFF	0
7	ON	ON	ON	OFF	+Vdc/2
8	OFF	OFF	OFF	ON	-Vdc/2
9	ON	OFF	OFF	ON	0
10	OFF	ON	OFF	ON	0
11	ON	ON	OFF	ON	+Vdc/2
12	OFF	OFF	ON	ON	0
13	ON	OFF	ON	ON	+Vdc/2
14	OFF	ON	ON	ON	+Vdc/2
15	ON	ON	ON	ON	+Vdc

CASCADED-CELL MULTILEVEL CONVERTER

The cascaded-cell approach is now becoming common for inverters and was first disclosed by McMurray (9) in the 1960s, and this technique can also be applied to a unipolar current power converter (10). The cascade-cell converter uses individual conventional asymmetric half-bridge converters operating off separate power sources to produce a combined high voltage multilevel converter, as shown for one phase in Figure 4. The switching modes are equivalent to that of the capacitor-clamped converter, listed in Table 2. Capacitor balancing is not an issue in this topology, but the intermediary voltage modes must be sequenced to ensure that there is good thermal balancing on all the power switches. The cascaded-cell converter requires two isolated dc supplies at half the equivalent voltage level to the diode- and capacitor-clamped converters. This would normally be achieved by using separate secondary windings on a mains transformer with bridge rectifiers.

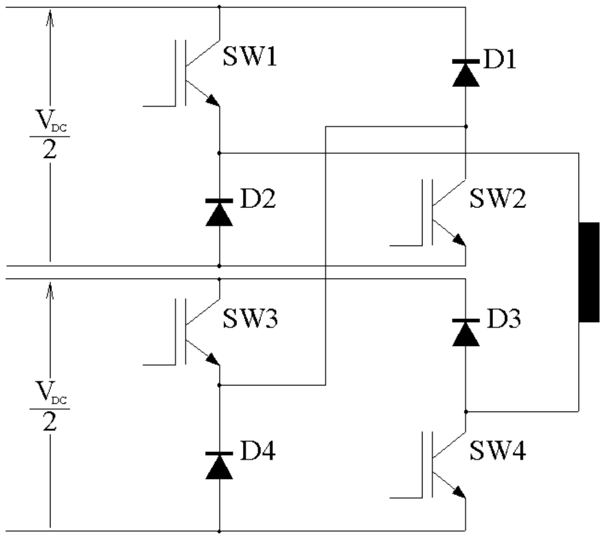

Figure 4: Cascaded-cell asymmetric multilevel power converter

BALANCED CONVERTER OPERATION

All three power converters have more than one mode of operation which can apply an intermediary output voltage. Each of the switching modes does not utilise all the power switches in the circuit and operation limited to only one of these modes will lead to power converter thermal imbalance. In the case of the diode- and capacitor-clamped topologies, current paths at any of the intermediary voltages will incorporate one or more of the converters' capacitors and so balanced operation must ensure that the net change in charge in each capacitor is zero in the steady-state. For instance, in the capacitor-clamped converter, operating modes 13 and 14, shown in Figure 5, both apply half the dc-link voltage across the phase winding, and cause charging and discharging in C1 respectively. A simple balancing strategy would be to alternate the modes between consecutive phase energisation cycles, ensuring that this occurs over identical angular positions in each case. This operating mode cycling strategy will also mean that the power losses in SW1 and SW2 are equal. At low speeds, where chopping is employed to constrain the peak phase current, it may be necessary to include a capacitor voltage feedback to the control so that mode selection is performed in order to maintain the capacitor voltage within a controlled band. Capacitor voltage feedback will also be necessary when the drive system predominantly operates under transient conditions.

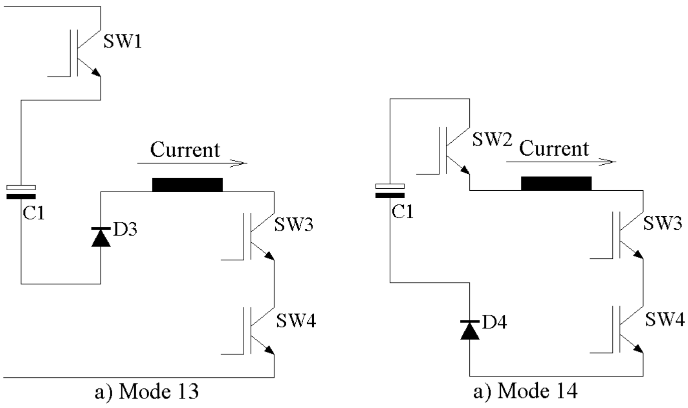

Figure 5: Half-voltage operating modes

MULTIPLE VOLTAGE SRM DRIVE OPERATION

The extra flexibility offered by a multilevel power converter can lead to efficiency improvements especially at lower operating speeds compared to fixed voltage operation in a conventional asymmetric half-bridge converter. Chan and Bolton (9) and Kwon (10) have shown that system performance improvements can be achieved by varying the applied phase dc-link voltage in an SRM drive. Multilevel power converters can switch between different voltage levels without the need for a front-end boost converter.

In order to illustrate the potential benefits of operating with multiple voltages in an SRM, a high-speed compressor sized 6/4 motor with a peak operating power of 2 MW at 18000 rev/min has been simulated with a two-level power converter. The simulated power device model includes the nonlinear conduction and switching loss characteristics of a 2.5 kV, 1000A IGBT/diode module to accurately predict the power electronics losses. Figure 6 shows the phase waveforms for the conventionally control SR machine with flat-topped chopped current control at a maximum efficiency operating point at 1000 Nm, 7500 rpm. The unsaturated inductance waveform is shown for the purpose of correlating the switching angle positions. The machine model used in the simulations does include the impact of magnetic saturation. With the hysteresis current control and on-freewheel chopping strategy, the switching frequency is dependent on the hysteresis band. With a two-level converter, the voltage across the winding can be halved when chopping, which will lead to a reduced switching frequency for the same hysteresis current band. This is because the rate of change in flux-linkage is halved and so the rate of change of current is also halved at equivalent angular positions. Figure 7 shows the typical phase waveforms associated with half-voltage Operation at the same load and speed as in Figure 6. The energisation is a single voltage pulse and the current waveform is more indicative of higher operating speeds in a conventionally powered SRM.

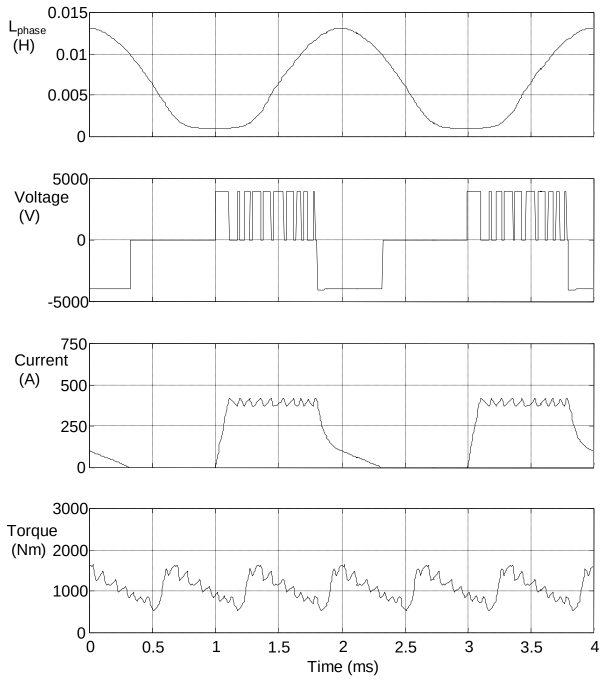

Figure 6: Conventional full-voltage energisation

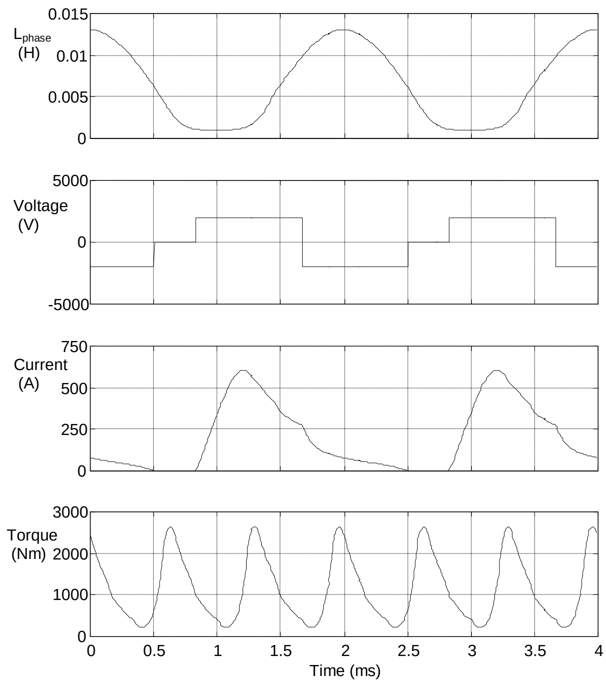

Figure 7: Half-voltage energisation

The system efficiency is increased because of the reduced power converter switching frequency and the use of more optimised switching angles. These simulation results are compared in Table 4 and suggest that system efficiency improvements of nearly 5% can be achieved by using the additional voltage levels available in multilevel power converters. Some reduction in iron loss would also be expected due to the lower rates of change in flux and reduced high frequency harmonics.

TABLE 4 – Full- and half-voltage performance comparison

	Full-Voltage	Half-Voltage
Speed	7500 rpm	7500 rpm
Torque	1000 Nm	1003 Nm
Output Power	786kW	788kW
Input Power	835 kW	800 kW
Power Converter Losses	46 kW	7 kW
Efficiency	94.0 %	98.5 %

TORQUE RIPPLE AND ACOUSTIC NOISE

Two of the major problems associated with overall SRM performance are high torque ripple and excessive machine vibration leading to undesirable acoustic noise. A great deal of research work has been undertaken to understand the mechanisms involved and to try to minimise these features to acceptable levels. Apart from modifications in machine geometry and construction, the emphasis has to be on the way the phases are energised. Both issues can be addressed by introducing some form of current profiling when energising the phase, rather than the conventional approach of flat-topped current chopping at lower speeds. Even at higher speeds, the simple addition of some timed freewheeling is a form of current profiling. Lovatt and Stephenson (13) have shown that torque ripple can be reduced significantly if the phase current is profiled. One of the limitations in this technique, however, is the maximum allowable power converter switching frequency which affects the current waveform and in turn the torque ripple. The additional multilevel voltage capability offers the possibility of reduced high-frequency torque ripple without excessive power converter switching losses. Modifications to phase firing energisation, such as the methods proposed by Pollock and Wu (14) where additional energisation pulses are added in the high-speed region, can also be extended using the extra voltage capabilities of the new converters. The aim being to modify the normal force on the machine's salient poles which in turn leads to machine vibrations and acoustic noise, especially when a harmonic of force coincides with one of the machines natural resonances.

The multiple voltage levels available from the multilevel power converters open up a great deal of possibilities in control and can be used to achieve flexible current profiling but with the added benefit of lower switching frequencies and hence less converter losses. To illustrate the potential benefits of a multilevel power converter for SRM applications

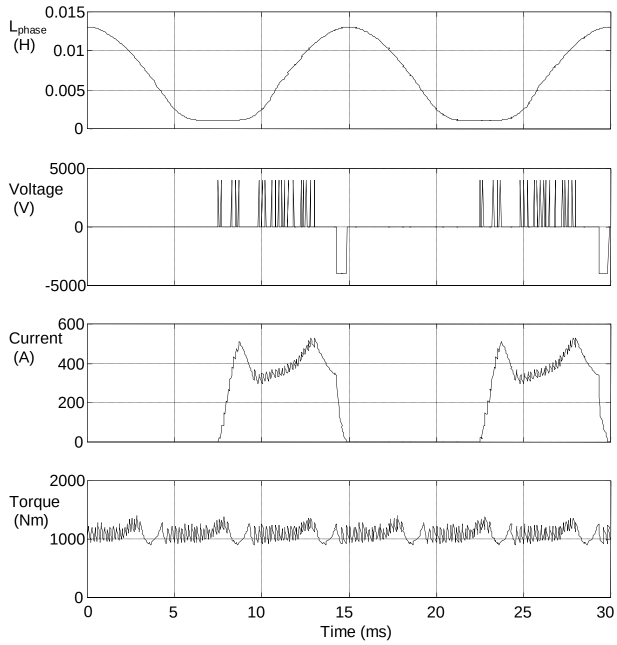

Figure 8: Full-voltage current-profiling (1000 rpm, 1000 Nm)

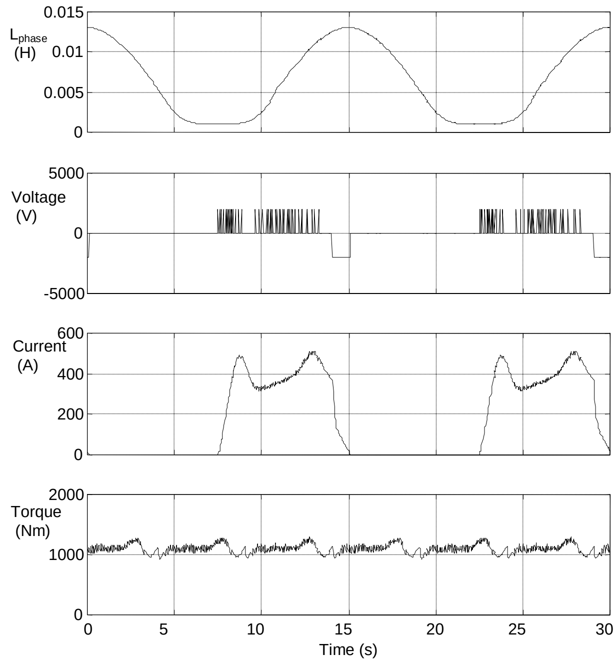

Figure 9: Half-voltage current-profiling (1000 rpm, 1000 Nm)

requiring some form of current profiling, simulations using full dc-link voltage and half dc-link voltage were performed using a simple current profile. Figures 8 and 9 show the waveforms obtained using the two power converters. In the half voltage case, tighter tracking of the current profile can be achieved without incurring additional power electronics losses. Even though the selected current profile is not optimal with respect to torque ripple, the operation with only half dc-link voltages leads to a reduction in high frequency components in the torque ripple. The results are compared in Table 5 and show a similar efficiency performance.

TABLE 5 – Full- and half-voltage current-profiling performance comparison

	Full-Voltage	**Half-Voltage**
Speed	1000 rpm	1000 rpm
Torque	1003 Nm	1006 Nm
Output Power	105 kW	105 kW
Input Power	129 kW	129 kW
Power Converter Losses	19 kW	20 kW
Efficiency	81.53 %	81.47 %

CONCLUSIONS

This paper has introduced the family of multilevel asymmetric power converters which are capable of supplying unipolar currents in a switched reluctance machine. Apart from their potential in high-voltage, high-power SRM drives, it has been shown that the additional control flexibility offered by the multiple voltage modes of operation can help to improve system performance, especially at low speeds. Further work is required to investigate thoroughly the control aspects of multilevel power converters in SRMs. There is also great potential in improving low speed generator performance which could be important in development of future large switched reluctance wind-turbines.

REFERENCES

1. Lawrenson P.J., Stephenson J.M., Blenkinsop P.T., Čorda J. and Fulton N.N., 1980, "Variable-speed switched reluctance motors", IEE Proc. Pt. B, 127, 253 – 265.
2. Fulton N.N., Lawrenson P.J., Stephenson J.M., Blake R.J., Davis R.M. and Ray W.F., 1985, "Recent developments in high-performance switched reluctance drives", EMD '85 Proc., 130 – 133.
3. Baker R.H., Filed 1978, "High-voltage converter circuit", Pat. No. US4203151.
4. Nabae A., Takahashi J. and Akagi H., 1980, "A new neutral-point-clamped PWM inverter", IEEE-IAS '80 Record, 761 – 766.
5. Davis R.M., Filed 1994, "Switching circuit", Pat. No. EP0608979A1.
6. Meynard T.A. and Foch H., Filed 1991, "Dipositif électronique de conversion d'énergie électrique", Pat. No. FR2679715A1.
7. Meynard T.A. and Foch H., 1992, "Multi-level choppers for high voltage applications", EPE Journal, 2, 45 – 50.
8. Watkins S.J., Filed 2000, "Power converter", GB Pat. App. No. GB0024760A.
9. McMurray W., Filed 1969, "Fast response stepped-wave switching power converter circuit", Pat. No. US3581212.
10. Watkins S.J., Filed 2001, "Cascaded asymmetric power converter", Pat. App. No. GB0114034A.
11. Chan S. and Bolton H.R., 1993, "Performance enhancement of single-phase switched-reluctance motor by DC link voltage boosting", IEE Proc. B, 140, 316 – 322.
12. Kwon Y.-A., 1996, "Computation of optimal excitation of a switched reluctance motor using variable voltage", IEEE Trans. IE, 45, 177 – 180.
13. Lovatt H.C. and Stephenson J.M., 1994, "Computer-optimised current waveforms for switched-reluctance motors", IEE Proc. Pt. B, 141, 45 – 51.
14. Pollock C. and Wu C.-Y., 1995, "Acoustic noise cancellation techniques for switched reluctance drives", IEEE-IAS '95 Record, 448 – 455.