Use of a 3 Phase Full Bridge Converter to drive a 6 Phase Switched Reluctance Machine

J. D. Widmer, B. C. Mecrow*, C. M. Spargo*, R. Martin* and T. Celik†*

** Newcastle University, UK, +44(0)191 2223016, james.widmer@ncl.ac.uk*
†Dyson, UK, tuncay.celik@dyson.com

Keywords: SRM, Full Bridge Converter, Torque Ripple Reduction, Low Cost Drive.

Abstract

This paper explores how the use of a modified full bridge converter, coupled to a 6 phase switched reluctance motor, can produce a torque dense drive with low torque ripple, combined with standard drive electronics and a good converter VA rating. A description is provided of the new drive configuration: a prototype motor and drive are constructed and test results provided. Results are compared with those to be expected from the same switched reluctance machine driven from a conventional, asymmetric half bridge converter.

1 Introduction

Two reasons are often cited as contributing to the under-utilisation of Switched Reluctance Machine (SRM) technology for commercial applications. These are:

(a) high torque ripple;
(b) non-standard asymmetric half bridge converters [1].

However, there are undoubted benefits associated with the use of SRM technology. These include extremely robust construction, high torque density and low cost, even compared to the induction machine [2]. Therefore, a drive topology which can overcome the SRM's limitations is welcome.

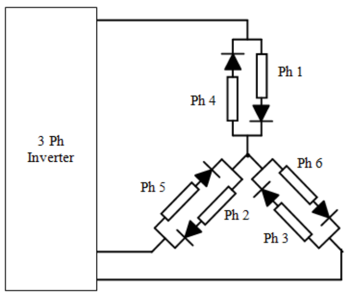
In [3] a basis for estimating the kVA requirements for an SRM drive is presented and results compared with the requirements of induction machine drives. In [4] and [5] schemes are proposed for operating star/delta connected SRMs from conventional AC full bridge converters. A later publication [6] reports that these configurations reduce torque ripple, but suffer in terms of reduced average motor torque capability. However, these configurations benefit through a reduction in the number of connections between drive and motor (from 6 to 3 for a three phase machine) and the reduction in the number of current and voltage measurement devices needed from three to two.

In [7] the authors present a drive configuration which would allow a three phase SRM, with windings connected in a delta configuration, to be driven from a 3 phase full bridge converter. This utilises diodes in line with each phase in order to convert the bipolar output of the full bridge converter into a unipolar waveforms, allowing the emulation of a half bridge converter. The paper concludes that this drive configuration does not significantly impact the torque / speed or efficiency performance of a 3 phase machine and provides comparable performance to an induction machine.

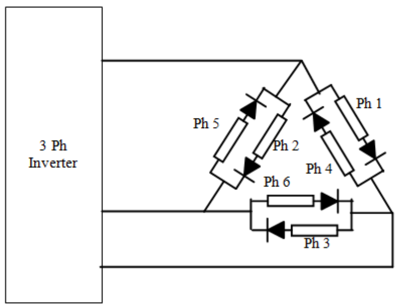
This paper takes this research to its logical extension, exploring how such a methodology would allow a 6 Phase SRM to be driven from a conventional AC Full Bridge Converter.

2 Proposed Drive Configuration

Fig. 1 shows how diodes, arranged alternately between phases, can be used to convert the bipolar current waveform output from each phase of the converter into two unipolar half wave forms, relating to the positive and negative regions of the waveform respectively. Consequently the three phase converter is able to supply a six phase SRM, whilst having only three power connections between inverter and motor. Configurations based on both star or delta configurations are possible [8], and this paper will show examples of both.



(a) Star connection



(b) Delta connection

Figure 1: Six-phase SRM driven by a 3-phase Full Bridge converter

With the above configuration the inverter is behaving exactly as though it is supplying a three phase ac machine. It could be configured to supply sinusoidal or quasi-square wave outputs. In this work the converter is a standard commercial drive, with a sinusoidal output current.

Fig. 2 shows idealised current waveforms for the six phase SRM in the star configuration.

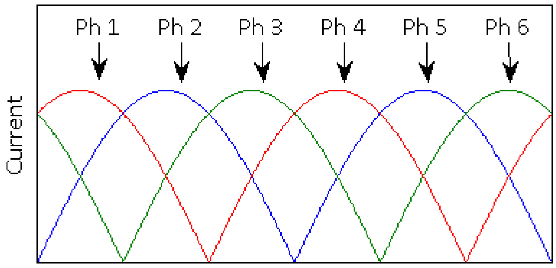


Figure 2: Current waveforms for a SRM being driven under current control by the new unipolar full bridge configuration in a star configuration. The colour of each phase in the diagram relates to the output phase of the power converter.

3 6 Phase SRM Magnetic Design

The design of the SRM for this application is based on standard best practice: machine dimensions are summarised in Table 1. To maximise the torque capability the tooth width to rotor pole pitch (t_w/λ) ratio has been chosen to be 0.4.

Table 1: 6 Phase SRM design parameters

Number of Stator Teeth	12
Number of Rotor Teeth	10
Axial Length (Lamination Stack)	150.0mm
Stator Outer Diameter	150.0mm
Turns per Phase	100

The core backs of the machine are relatively deep compared to the tooth width. This is necessary because three phases will be conducting at all times and so the core backs have to simultaneously carry the flux of several phases.

The six phase machine has twelve stator teeth and so the natural manner of excitation is to wind around single teeth, with each phase comprising two coils. Fig. 3 illustrates such an arrangement: the two coils of one phase are geometrically opposite and wound in such a manner that the two coils share the same flux.

Figs. 4 and 5 show photographs of the constructed prototype motor.

4 Static Test Results

Experimentally derived Flux-Linkage MMF and static torque characteristics are shown in Figs. 6 and 7, compared with 2D FE results.

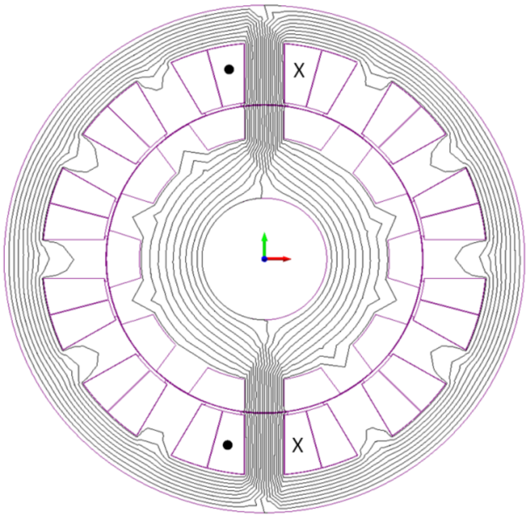


Figure 3: 6 Phase SRM with a single phase excited.

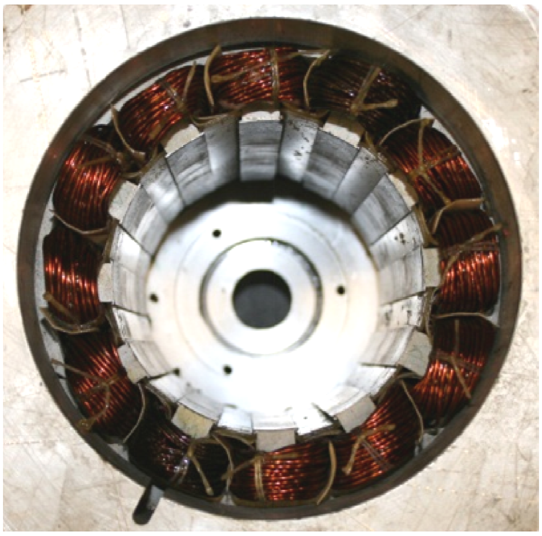


Figure 4: Constructed 6 Phase SRM.

Figure 5: 10 pole conventional rotor.

For this machine the measured unaligned flux-linkage results are higher than predicted by finite element modelling, because the 2D model neglects end winding effects upon motor performance. In the aligned position, for low currents, the measured flux-linkage indicates that the air-gap length is slightly larger than the design value. These effects can also be seen in the torque curves, with average measured torque slightly less than predicted.

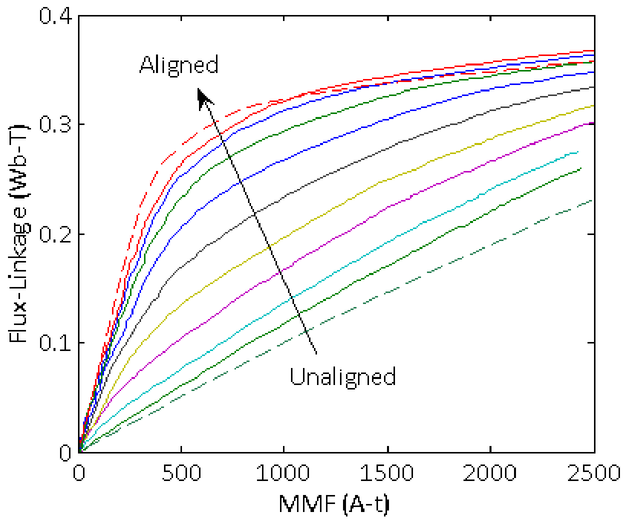


Figure 6: Experimental static magnetization curves (solid lines) shown with modelled data (dashed lines).

It is generally assumed that mutual coupling effects in SRMs are negligible; this assumption is also made in the simulated results presented. Whilst transient FE modelling has demonstrated how for this motor mutual coupling may have a more significant, the purpose of this paper is to concentrate upon the converter and so this effect will not be addressed further.

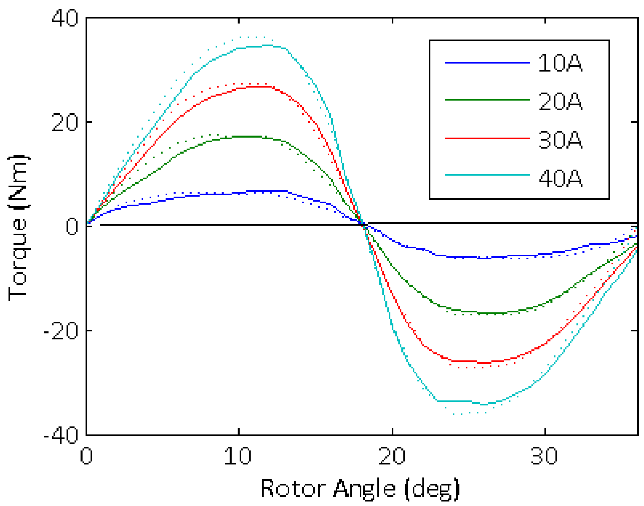


Figure 7: Experimental static torque (solid lines) curves shown with modelled data (dashed lines).

5 The Converter Configuration

When driving an SRM from an asymmetric half bridge there is complete control over the magnitude and polarity of the voltage applied to each phase. With the three phase bridge configuration this is no longer the case.

Each motor phase is connected in parallel with another one via two diodes. The two motor phases are one half electrical cycle apart so that, ideally, when one conducts the other does not. The voltage applied to the two phases is equal in magnitude and of opposite sign. Consequently the voltage applied to a phase switching on is identical to that of one switching off.

In the case of a star connection each inverter line output current is directly fed into two back-to-back phases. There is no access to the star point, so there is no direct control of the voltage applied to each pair of phases.

In contrast in the case of a delta connection there is direct control over each phase voltage, with the condition that the phase voltages V1+V3+V5=0 and V2+V4+V6=0. The inverter line currents are controlled, but there is no direct control over motor phase currents.

6 Dynamic Test Results

In order to demonstrate that this 6 Phase SRM can be driven from a commercial, three phase AC drive it was tested using a Control Techniques SP3410 3-phase drive cabinet under speed control with a DC link voltage of 560V and switching frequency of 16 kHz. The output of the motor drive was connected directly to the diode conversion unit, previously described in Fig. 1. This diode unit houses three 60A diode pairs mounted on a heat sink, which converts the 3-ph bipolar output of the drive to the required 6 unipolar signals which are fed into the prototype machine.

It was possible to ‘Autotune’ the drive parameters so that PI controller values were correctly and automatically identified. The motor was configured as a 20 pole, synchronous PM servo motor; the expected 10 bipolar poles being emulated by the 10 unipolar rotor teeth.

The machine was tested from standstill to up to 4000rpm maximum speed. The load at each operating speed was steadily increased until torque could not be sustained. To achieve the best torque per unit current it was necessary to manually advance the phase offset angle to up to 90 electrical degrees at 4000rpm.

Fig. 8 shows measured currents with the star connection, generating 10Nm at 3000 rpm. The line current output from the converter is controlled to be sinusoidal, but the phase currents associated from this line current deviate significantly from half sinusoids. Current in a phase ramps up quickly, but continues to flow after the incoming line current has changed polarity. This is because there is a significant current flowing round the loop created by the two back to back phases.

Operation with the delta connected configuration is shown in Fig. 9 generating a mean torque of 20Nm at a speed of 3000 rpm. In general, operation is similar to that of the star connection, though of course the phase voltage can now equal the dc link voltage. The controlled current continues to be the inverter line current, which comprises the sum of four phase currents. There is therefore less direct control over phase current, but this does not seem to have a significant effect upon performance.

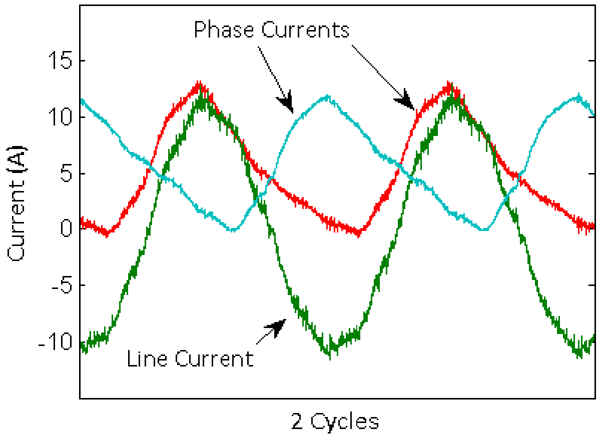


Figure 8: 3000rpm at 10Nm load with the star connection, showing measured inverter line current for phase A and motor phase currents in phases 1 and 4.

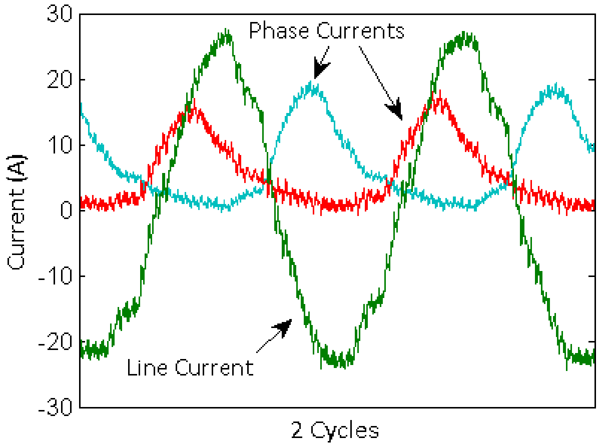


Figure 9: 3000rpm at 20Nm load with the delta connection, showing inverter line current for phase A and motor phase currents in phases 1 and 4.

Subjectively noise levels were perceived to be lower for this machine, probably as a result of its low torque ripple, as compared to a conventional 3 phase SRM though still higher than for an equivalent PMBL machine.

7 Operation under Voltage Control

As the speed rises the drive needs to move from current to voltage control. Ultimately the inverter reaches a position where the output voltage from each line of the inverter becomes simply a square wave. The commercial drive was not designed to operate in this mode and so simulation results will be used to examine performance under these conditions.

The same machine, driven from six asymmetric half bridges, will be used for comparison in the sections below for operation at 8000 rpm.

7.1 Asymmetric Half Bridge

Fig. 10 shows the flux-linkage current loci for one phase of the machine, driven from an asymmetric half bridge under full voltage control. 180° conduction is employed to maximise the torque capability. The phase advance angle is varied to help choose the optimum angle for torque production. Fig. 11 shows the resultant current waveforms. There is little change in the mean torque produced for advance angles in the range 80 to 120 degrees, but increased advance angle gives much larger phase currents. For this reason an advance angle of 80° was chosen, combining high torque with low current.

Fig. 12 shows the instantaneous shaft torque produced by the machine: this has a mean value of 17.4 Nm, with much less ripple than most SRMs under voltage control because of the high phase number.

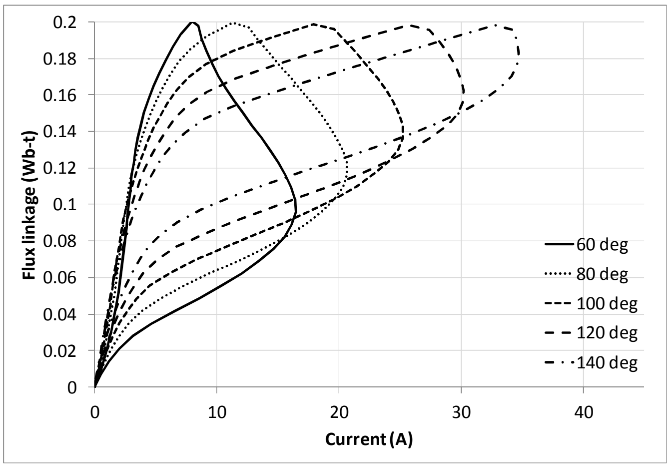


Figure 10. Flux-linkage loci for one phase with an asymmetric half bridge. 8000 rpm Voltage control (180° conduction.) Range of advance angles shown.

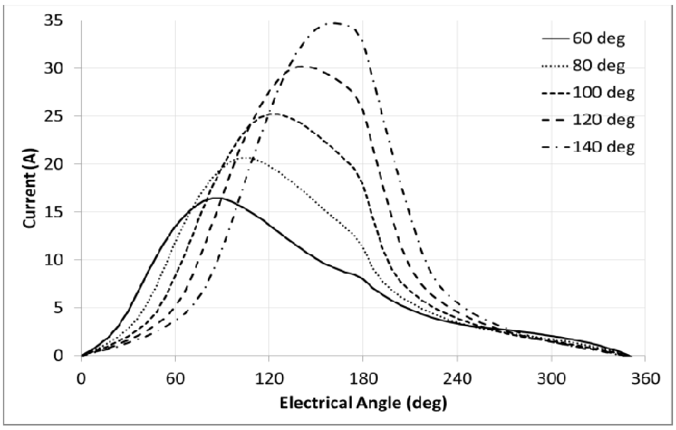


Figure 11. Current waveforms for one phase with an asymmetric half bridge. 8000 rpm Voltage control (180° conduction.) Range of advance angles shown.

7.2 Three phase bridge, delta connection.

With the delta connection the voltage applied to any one phase becomes 120° of positive voltage, then 60 degrees of freewheeling, before negative voltage is applied to bring the flux-linkage back down to zero, as shown in Fig. 13 below. Compared to the asymmetric half bridge the peak flux-linkage is reduced by one third and there is consequently a significant reduction in current and torque. In order to produce the same torque under current control it is therefore necessary to reduce the number of turns in the machine. The following results correspond to the same machine, but with the number of turns per phase reduced from 50 to 40. The same slot fill factor is used, with the conductor cross-section adjusted accordingly. In reducing the number of turns by 20% the overall effect upon phase resistance is therefore a reduction to 64% of the original value.

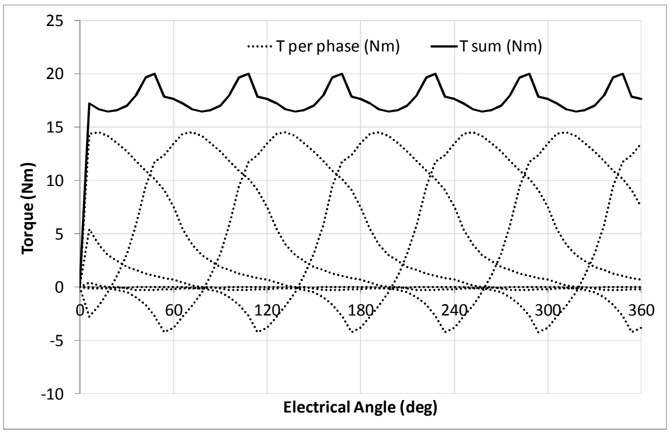


Figure 12. Total torque produced with an asymmetric half bridge. 8000 rpm Voltage control (180° conduction.)

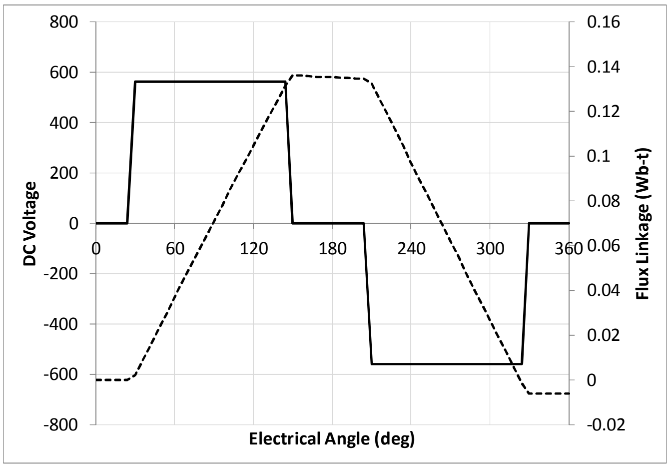


Figure 13. Voltage and flux-linkage in one phase with a delta connection.

Fig. 14 shows the flux-linkage current loci for one phase of the machine. The period of zero voltage applied to the phase, whilst conducting, results in a period when the flux-linkage is constant, resulting in flat topped loci. Fig. 15 shows the resultant motor phase currents. In this case an advance angle of 90° was judged to form the best compromise between torque capability and current requirement. The inverter line currents for this condition are shown in Fig. 16, showing how they remain relatively close to sinusoidal in nature.

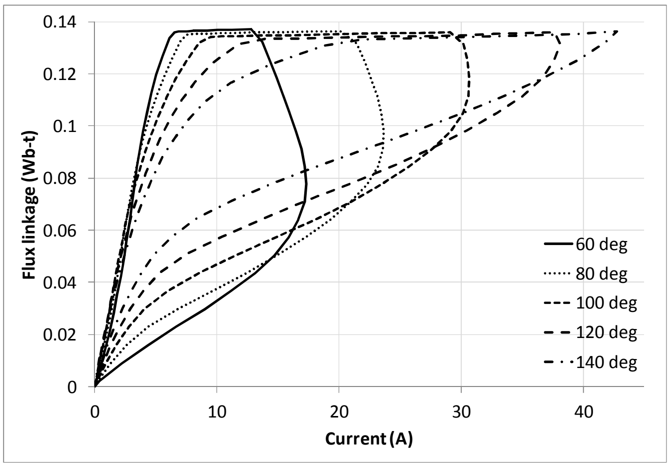


Figure 14. Flux-linkage loci for one phase with the delta connection. 8000 rpm Voltage control. Range of advance angles shown.

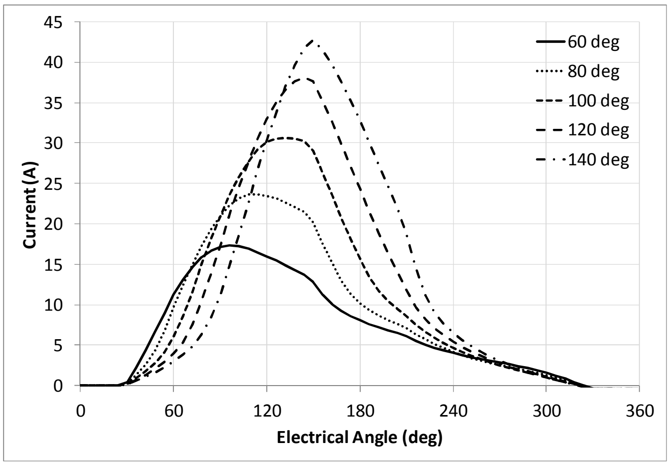


Figure 15. Motor phase current waveforms for one phase with the delta connection. 8000 rpm Voltage control. Range of advance angles shown.

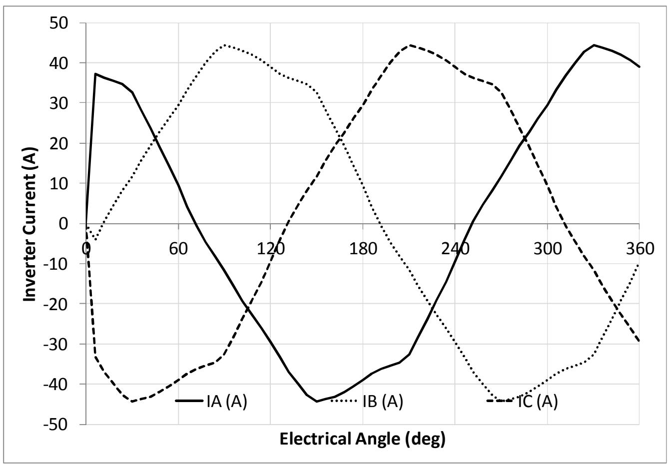


Figure 16. Inverter line current for the delta connection. 8000 rpm.

Fig. 17 shows the instantaneous shaft torque which, at 17.4 Nm, is virtually identical to the torque produced with the asymmetric half bridge arrangement. Once more, the torque ripple is very small, despite being under full voltage control.

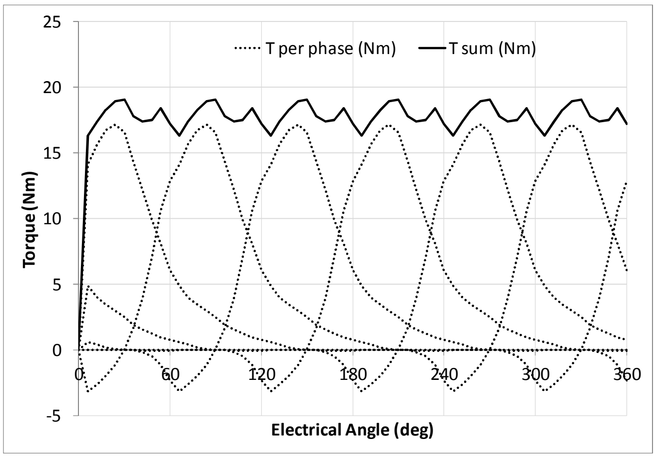


Figure 17. Total torque produced with a delta connection. 8000 rpm Voltage control.

7.3 Comparison between Converter Arrangements.

A fair comparison between arrangements must take into account a range of factors, relating both to the machine and the converter. Table 2 summarises the findings, based upon the above results.

The results show that both configurations produce the same torque, with virtually identical winding loss. It seems therefore that the machine size is unaffected by the choice of converter. The three phase bridge configuration has only half the number of IGBTs, but each IGBT has to take around double the peak current, so the overall converter volt-ampere rating is little changed.

The converter kVA/kW ratings are similar to those described in [3] where a rating of 10.5 was determined experimentally for an 8/6 four-phase SRM and contrasted with a rating of 9.2 for a comparable induction machine.

8 Conclusions

This paper has demonstrated the feasibility of operating a 6 Phase SRM from a three phase, AC full bridge converter through the simple addition of 6 rectifier grade diodes.

The arrangement requires the addition of six rectifier diodes, but it offers the following features:

- A standard three phase inverter;
- Only thee connections between motor and inverter;
- Only two current sensors;
- Low torque ripple throughout the operating range;
- No increase in motor loss, compared to standard SRM drives;
- Very similar converter VA rating.

Table 2. Comparison between converter arrangements

	Asymmetric half bridge	**3 phase bridge (delta connected)**
Number of IGBTs	12	6
Additional diodes	none	6, rectifier grade
No. of power cables between converter & motor	12	3
No of current sensors	6	2
No. Of motor turns per phase	100	80
Phase resistance	0.627 Ohms	0.401 Ohms
DC link voltage	560V	560V
Speed	8000 rpm	8000 rpm
Mean torque	17.4 Nm	17.5 Nm
Motor phase rms current	10.5 A	13.1 A
Motor winding loss	418	418
Peak IGBT current	20.7 A	44.3 A
Inverter peak VA rating	69.5 kVA	74.5kVA
kVA/kW	9.5	10.2

References

[1] T. J. E. Miller, “Electronic Control of Switched Reluctance Machines”, Newnes, 2001
[2] D. Dorrel, A. Knight et al, “Comparison of different motor design drives for hybrid electric vehicles”, IEEE ECCE, 2010
[3] T. J. E. Miller, “Converter Volt-Ampere Requirements of the Switched Reluctance Motor Drive”, Industry Applications, IEEE Transactions on, vol. 21, pp. 1136-1144, 1985.
[4] A. Jin-Woo, O. Seok-Gyu, M. Jae-Won, et al., “A three-phase switched reluctance motor with two-phase excitation”, Industry Applications, IEEE Transactions on, vol. 35, pp. 1067-1075, 1999.
[5] P. Somsiri, K. Tungpimonrut and P. Aree, “Three-phase full-bridge converters applied to switched reluctance motor drives with a modified switching strategy”, Proc. of IEEE ICEMS, Conf., pp. 1563-1567, 2007.
[6] X. Liu, Z. Q. Zhu, M. Hasegawa, et al., “Performance comparison between unipolar and bipolar excitations in switched reluctance machine with sinusoidal and rectangular waveforms”, in Energy Conversion Congress and Exposition (ECCE), 2011 IEEE, 2011, pp. 1590-1595.
[7] A. Clothier, B. C. Mecrow, “Inverter Topologies and Current Sensing Methods for Short Pitched and Fully Pitched Winding SR Motors”, APEC, 1999
[8] T Celik, “Segmental Rotor Switched Reluctance Drives”, Newcastle University, August 2011