Winding Configurations for a Six Phase Switched Reluctance Machine

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

Abstract – **Winding configurations are investigated and evaluated for a six phase, 12-10 switched reluctance machine driven by a conventional three phase full bridge converter with the addition of six diodes. A new winding configuration is proposed and shown to develop more torque with less torque ripple than a conventional winding in this application. Finite element modelling is used to investigate the electromagnetic behaviour and compare the output of different winding configurations. Some initial experimental tests are described in verification of the modelling predictions. The novel drive and new winding configuration offer significant advantages over a standard three phase machine and drive, giving increased mean torque with lower torque ripple and acoustic noise, as well as reduced converter complexity and potentially cost.**

Index Terms-- **AC machines, Brushless machines, Motor drives, Rotating machines, Rotors, Stator windings, Torque, Variable speed drives, Windings, Reluctance motors**

I. Introduction

It has been shown in a previous paper [1] that a six phase switched reluctance machine (SRM) can be operated from a three phase full bridge converter through the simple addition of six rectifier grade diodes. This arrangement was shown to compare favourably with a three phase SRM driven from a conventional asymmetric half bridge, offering the following features:

- Standard three phase inverter drive;
- Only three connections between motor and drive;
- Only two current sensors;
- Low torque ripple;
- No increase in motor loss; and
- Very similar converter VA rating.

The electrical winding of the prototype six phase machine described in [1] can be arranged in various configurations. Alternative SRM winding configurations and flux paths have previously been reported. Miller [2] described short flux paths arising from paired groupings of stator poles, as well as from four-pole field configurations, giving the example of a three phase 12/8 machine which is effectively a 6/4 machine with a 'multiplicity' of 2. Michaelides and Pollock described five and seven phase machines with short flux paths arising from adjacent stator poles with opposing magnetic polarities, [3]. Fully pitched windings giving rise to torque production entirely from changing mutual inductance between phases were introduced by Mecrow [4]. Later, Mecrow et al [5] described a novel, segmental rotor SRM where stator slots contain only the winding of a single phase, and segments on the rotor modulate the permeance of short flux loops around individual slots. Liu et al [6] compared unipolar and bipolar excitations in SRMs and Celik [7] described the principal of deriving a six phase unipolar supply from a conventional three phase inverter, investigating winding options in both conventional and segmental rotor SRMs.

In this paper, the six phase prototype machine and adapted three phase drive configuration examined in [1] are first summarised. Different winding patterns are then investigated and a new configuration proposed, which utilises short flux paths and relies on some mutual interaction between phases for torque production. Finite Element (FE) modelling is used to investigate the electromagnetic behaviour, illustrating the various flux paths and predicting the current, flux linkage, and torque characteristics arising in the prototype machine from different winding arrangements. Experimental tests on the prototype machine are described and the results used to verify the FE predictions. It is concluded that the new winding arrangement produces more torque with less torque ripple than more conventional options and that the resultant topology generates torque through a combination of self and mutual inductance variation.

II. The Prototype Machine and Drive

Fig. 1 shows how six antiparallel diodes convert the bipolar current output from each phase of the three phase inverter into two unipolar half waveforms. The machine was connected in star for the FE modelling and experimental tests described in this paper, but both star and delta connections have been shown to work in practice [1].

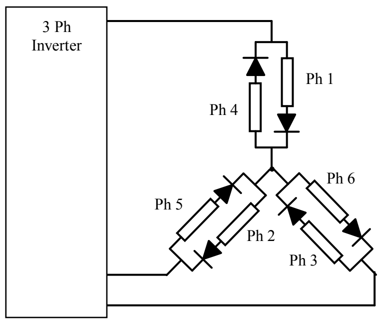

Fig. 1: Six phase SRM driven by a three phase full bridge converter

The design of the SRM for this application was based on standard best practice for a conventional, doubly-salient SRM having twelve stator teeth (two per each of six phases), and ten rotor teeth. In order to maximise the torque capability, the tooth width to rotor pole pitch ratio was set to 0.4. The core backs of the machine are relatively deep compared to the tooth width since three phases will be conducting at any given time in this drive configuration. Increased core back depth also increases the stiffness of the machine and thereby helps to reduce acoustic noise due to torque ripple. Machine dimensions are summarised in Table 1.

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TABLE 1
SIX 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
Stator Inner Diameter	91.4mm
Stator Core Back Depth	11.0mm
Stator Tooth Width	11.4mm
Airgap Length	0.3mm
Rotor Outside Diameter	90.8mm
Rotor Insider Diameter	36.0mm
Rotor Coreback Depth	18.0mm
Rotor Tooth Width	11.4mm
Turns per Phase	100

Photographs of the prototype machine are shown, fig. 2 and fig. 3.

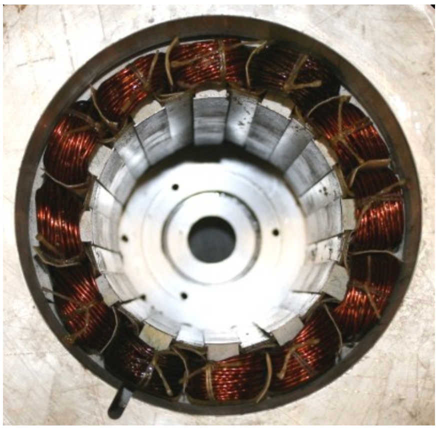


Fig. 2: Constructed six phase prototype SRM

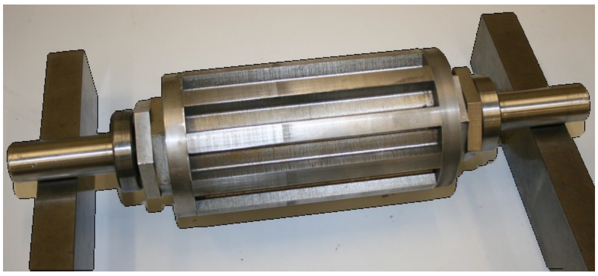


Fig. 3: Rotor from the six phase prototype SRM

III. WINDING CONFIGURATIONS

The stator of the prototype machine has twelve teeth and so six phases comprise two tooth-wound coils each. This gives a number of possibilities for winding the machine and the prototype was built with this in mind, having interchangeable coil connections as well as oversized stator and rotor core backs.

Conventionally, the two coils of each phase would be connected in series such that the resulting MMFs reinforced each other. Thus, single phase energisation would give rise to 'long' flux paths crossing the rotor and utilising the full rotor core back so as to give a two-pole field. Alternatively 'short' flux paths, resulting from other winding configurations, are defined as paths where the flux does not fully cross the rotor but rather makes shorter loops utilising more proximate teeth for the return path. The general distinction is illustrated in fig. 4, and four specific winding configurations are illustrated in fig. 5 and described below.

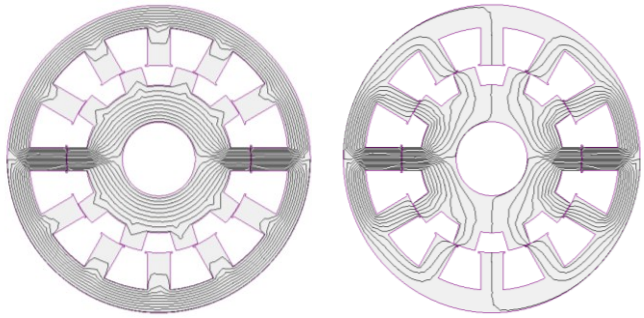


Fig. 4: General distinction between 'long' flux paths (left) and 'short' flux paths (right) in a six phase 12-10 SRM

Winding each phase for conventional, 'long' flux paths would yield an arrangement where ten of the twelve slots would contain the 'go' conductors of one phase and the 'return' conductors of the adjacent phase. Hence this is referred to as the 'dot-cross' configuration. With an even number of phases and where phase MMFs reinforce it is not possible to wind the machine so as to give symmetry, so two of the twelve slots contain 'dot-dot' and 'cross-cross' orientations. However, unipolar six phase operation would give rise to a field consisting of predominantly 'long' flux paths. This is referred to as the asymmetric 'dot-cross' winding and is illustrated in fig. 5 where the dotted line indicates the discontinuity in the pattern.

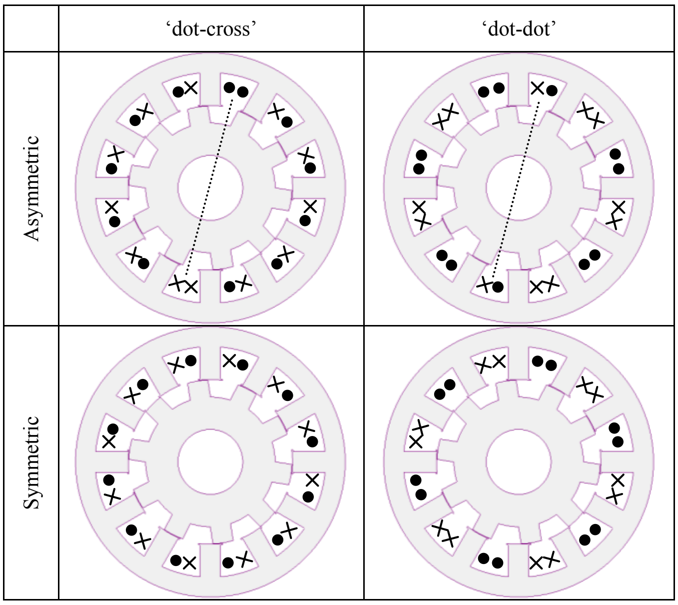


Fig. 5: Illustration of possible six phase winding configurations in the 12-10 prototype SRM where the dashed line indicates the discontinuity in the winding pattern arising in the cases where phase MMFs reinforce

'Short' flux paths can be realised by simply reversing the orientation of every second coil in the conventional configuration so as to yield a predominantly 'dot-dot' configuration. Again, where phase MMFs reinforce, the six phase configuration is asymmetrical and in this case, unipolar six phase operation would give rise to a field consisting of predominantly 'short' flux paths. This is referred to as the asymmetric 'dot-dot' winding and is similarly illustrated in fig. 5.

In both configurations described, the asymmetry in the conductor arrangement gives rise to discontinuities in the winding pattern which could cause excess torque ripple as well as localised saturation in the stator and rotor core backs.

Michaelides and Pollock [3] stated that: *"Motors with an even number of phase windings cannot be wound to successfully implement the short flux loops. There are always discontinuities in the flux pattern, forcing some flux across the rotor"*, and went on to suggest that five or seven phase machines are better suited to short flux paths.

However, in the case of the six phase machine and drive under consideration here, the authors believe that this asymmetry may be avoided by connecting the two coils of each phase such that the resultant MMFs oppose. In this case, single phase energisation would give rise to 'short' flux paths in both 'dot-dot' and 'dot-cross' configurations. Hence this gives the two 'symmetric' windings shown in fig. 5.

IV. FE MODELLING

The prototype machine was modelled using a commercially available FE package. Initially, magnetostatic models were developed in 2D for the visualisation of the various winding configurations. Assuming sinusoidal current waveforms for simplicity, the six phase machine driven by a three phase bridge as described in a previous paper [1] can be modelled magnetostatically in different states of energisation by recognising that each phase ideally conducts a half-sinewave and therefore only three adjacent phases conduct at any one time, as shown in fig. 6.

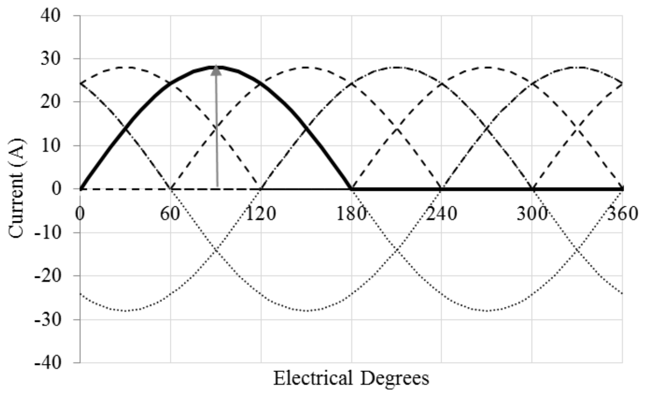


Fig. 6: Illustration of three phase bipolar currents (dotted lines) and the six phase unipolar currents arising from this drive configuration (dashed lines) with one of the six phases shown with a heavy solid line for clarity

Considering the instant where a given phase is in the position of maximum torque production (e.g. as shown by the vertical line at 90 degrees electrical in fig. 6): that phase would conduct peak current and the two adjacent phases would conduct half the peak current. Fig. 7 compares flux plots arising from such energisation with different winding configurations, where the phase receiving peak current is on the horizontal with the rotor in the position for maximum torque from that phase. Some initial observations can be made. Firstly, the symmetric 'dot-cross' may be discounted as flux lines with regard to the rotor position in fig. 7 indicate that the torques developed at different teeth act in almost perfect opposition. Secondly, both of the 'dot-dot' configurations appear to be quite similar, giving rise to predominantly short flux paths, with flux density shading (not shown) indicating saturation in the teeth as a limiting factor on the flux. Finally, the asymmetric 'dot-cross' gives rise to predominantly long flux paths with flux density shading (not shown) indicating lower flux density levels in the teeth, with the stator core back appearing to be the limiting factor.

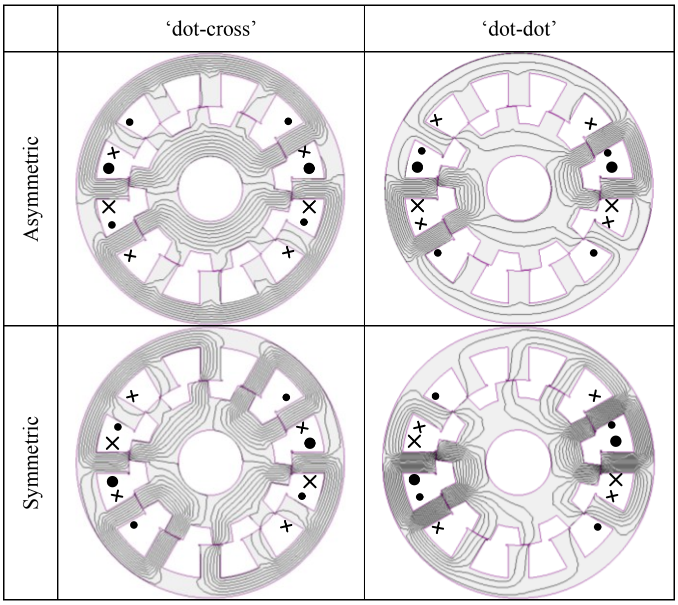


Fig. 7: Comparison of FE derived flux lines for different winding configurations.

A transient FE solution with rotation at 1000rpm was used to show how these field patterns rotate with sinusoidal current sources of 28A peak, which roughly equates to a current density of $10A/mm^2$. This demonstrated the effect of asymmetry which gave similar effects in both 'dot-dot' and 'dot-cross' configurations, consisting of the predominant field rotating for the majority of the mechanical cycle, with a temporary switch to the counterpart field at the point of discontinuity. Transient FE results also yielded the torque output for the different configurations, shown in fig. 8.

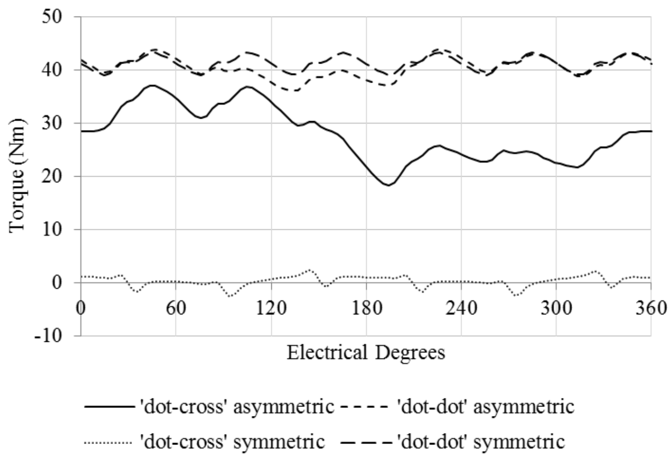


Fig. 8: FE simulated torque output for different winding configurations driven from a three phase bridge under sinusoidal current control

Fig. 8 confirms that the symmetric 'dot-cross' arrangement produces no useful torque. On the basis of the FE flux density illustrations (not shown) it was suggested that the stator core back was a limiting factor in the 'dot-cross' configuration. Fig. 8 shows the associated reduction in average torque and increase in torque ripple. Stator core back saturation may also explain the slight reduction in torque in the asymmetric 'dot-cross' configuration by comparison with the symmetric version; namely that the temporary switch to long flux paths at the discontinuity in the winding configuration gives a temporary reduction in average torque. This was verified by repeating the simulation for the asymmetric winding options, with the stator core back thicknesses increased by 50%. The torque waveforms from the three configurations were very similar, with the new symmetric ‘dot-dot’ arrangement still producing slightly more torque. Hence it is concluded that, on the basis of this FE modelling with sinusoidal current control, the new arrangement is preferable in the case of this six phase SRM driven from a three phase bridge, since the torque output can be achieved with a reduced stator core back thickness and therefore a smaller overall machine. In order to understand this new winding configuration, further FE simulation work was carried out.

Fig. 9 shows the flux linkage versus current (psi-i) characteristics measured in a single phase in this new winding arrangement. The dynamic loop under single phase operation is what might conventionally be expected with reference to the static characteristics. However, the dynamic loop arising from full six phase operation is rather different, indicating significant mutual effects whereby adjacent phases increase the flux linkage in a given phase thus increasing the torque output. This mutual activity can clearly be seen in the flux plots of fig. 7 where those arrangements with short flux paths exhibit considerable interaction between phases. The dynamic loops in fig. 9 also indicate that the peak current under six phase operation exceeds that under single phase operation; this is considered further, below.

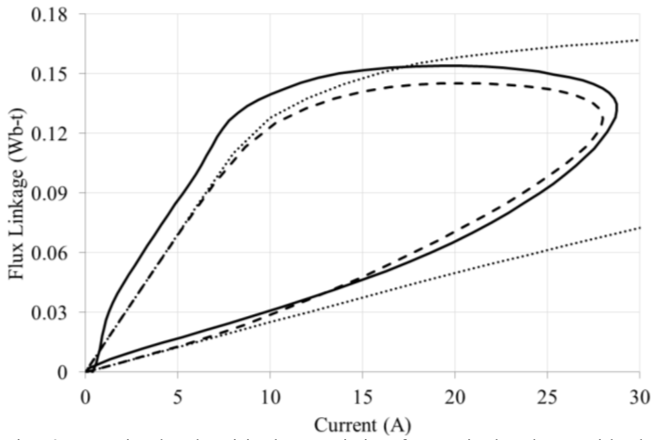


Fig. 9: FE simulated psi-i characteristics for a single phase with the symmetric ‘dot-dot’ winding configuration, showing static characteristics in the unaligned and aligned positions (dotted lines), a single phase dynamic loop (dashed line), and a dynamic loop arising from full six phase operation (solid line)

It was previously explained that the thickness of the stator core back was a limiting factor in the torque output of the asymmetric ‘dot-cross’ configuration and that increasing the core back thickness in the FE model caused the torque output to equal that of the new winding configuration. Since that configuration was shown to give predominantly ‘long’ flux paths with little apparent mutual interaction, some key differences should be apparent from the psi-i characteristics. Fig. 10 shows the psi-i characteristics for the conventional ‘dot-cross’ configuration and fig. 11 makes comparisons with the new configuration. In order to avoid the limitation of core back saturation and thus facilitate a useful comparison, the ‘dot-cross’ version was again modelled with the stator core back thickness increased by 50%.

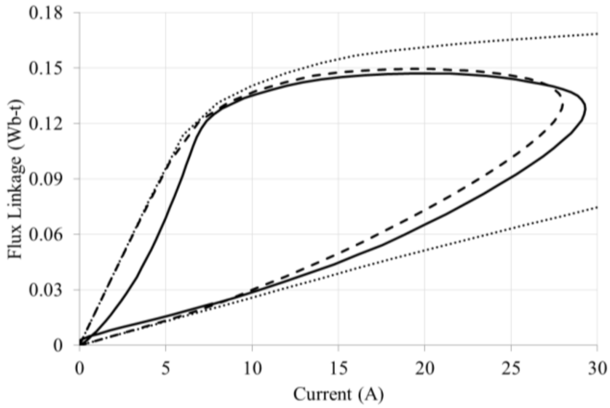
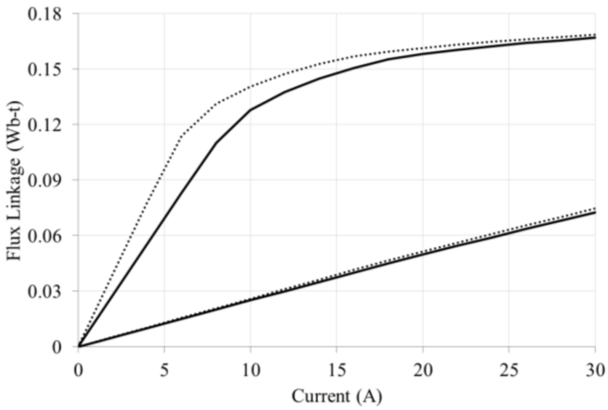
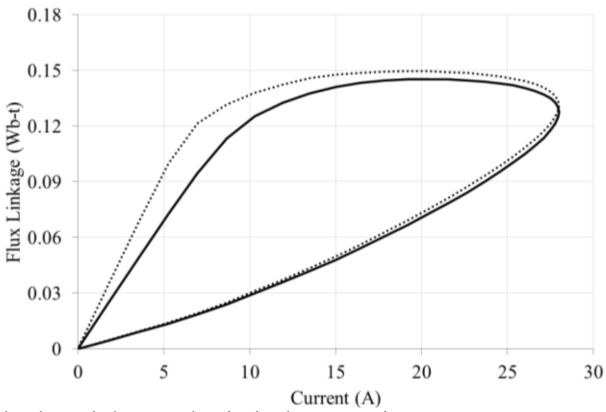


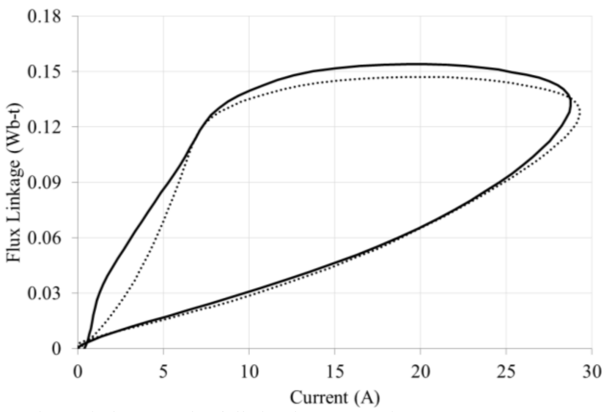
Fig. 10: FE simulated psi-i characteristics for a single phase with the asymmetric ‘dot-cross’ winding configuration, showing static characteristics in the unaligned and aligned positions (dotted lines), a single phase dynamic loop (dashed line), and a dynamic loop arising from full six phase operation (solid line)



a - static characteristics



b - dynamic loops under single phase operation



c - dynamic loops under full six phase operation

Fig. 11: FE simulated psi-i comparisons for a single phase between the asymmetric ‘dot-cross’ (dotted line) and the symmetric ‘dot-dot’ (solid line) winding configurations

The following observations can be made from fig. 10 and fig. 11:

- In the asymmetric 'dot-cross' case (fig. 10) the single phase dynamic loop remains within the static aligned and unaligned characteristics;
- Similarly, the full six phase dynamic loop (fig. 10) remains within the static characteristics and encloses a similar area to the single phase loop whilst having a slightly different loci;
- The symmetric 'dot-dot' configuration has slightly inferior static characteristics (fig. 11a) and a smaller single phase dynamic loop (fig. 11b) owing to the increased reluctance of the short flux paths where the air gap is crossed twice per coil; and
- The symmetric 'dot-dot' configuration exhibits a larger six phase dynamic loop (fig. 11c) which arises from self plus additional mutual effects and accounts for the increased torque capability overall.

It is concluded that, whilst the two machines are broadly similar (allowing for extra back iron in the 'dot-cross' case), there are subtle differences in the mode of operation, giving rise to slightly improved torque in the symmetric 'dot-dot' configuration through mutual interaction between phases. Hence it is suggested that the new winding configuration is superior (giving enhanced torque capabilities for a smaller machine), and that the conventional approach of ignoring mutual interaction between phases is questionable in this particular case.

Lastly, it is clear from fig. 10 and fig. 11 that the dynamic loop from six phase operation reaches higher current levels than both the single phase loop and the peak value of 28A from the current source. This must be a result of circulating currents between the two, 180 electrical degree separated phases sharing a single leg of the three phase bridge. Fig. 12 illustrates this. The resultant phase currents in fig. 12 do sum to the current source but are not perfect half sine waves, thus indicating the presence of currents circulating between the phases.

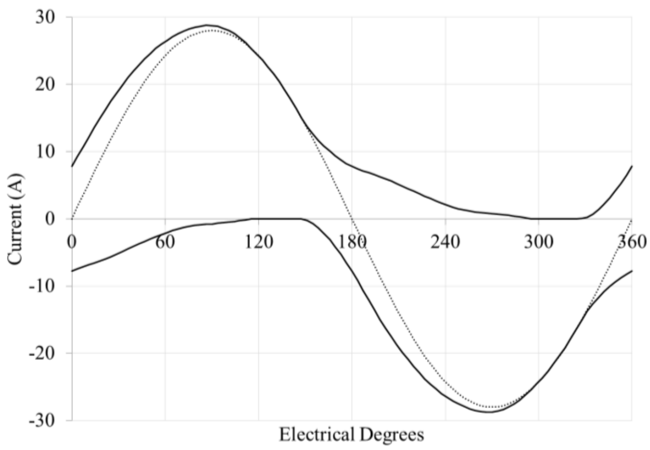


Fig. 12: FE simulated current plots for the six phase symmetric 'dot-dot' configuration driven from a three phase bridge, showing a single sinusoidal current source (dotted line), and the resultant 180 degree separated phase currents (solid line)

In summary, the FE modelling has given some insight into the different winding configurations both in predicting the performance and assisting with the understanding of the differences. The new symmetric 'dot-dot' winding arrangement described here is the preferred option in the case of this six phase SRM driven from a three phase bridge. The next section describes some experimental tests of the prototype machine with different winding configurations.

V. Experimental Testing of the Prototype Machine

The prototype six phase SRM was tested in the laboratory with the different winding configurations described above, all in star connection and with a floating star point.

A Control Techniques SP3410 three phase drive was used under speed control operation. The drive is rated at 18kW and has a dc link voltage of 560V and a switching frequency of up to 16 kHz. In the absence of a directly relevant setting, the drive was configured to feed a twenty-pole permanent magnet machine, with ten magnet pole-pairs being emulated by the ten rotor teeth. It was then possible to 'autotune' the drive parameters as a basis for testing each winding configuration, although manual adjustment of the encoder phase offset angle was required so as to minimise the motor phase currents for a given torque/speed operating point.

Initially, the symmetric 'dot-cross' configuration was tested. This was predicted to produce zero useful torque on the basis of FE modelling and consideration of the flux paths present with respect to the rotor teeth. In practice, the drive did manage to develop a small amount of torque although the machine was acoustically very noisy and the phase currents quickly exceeded the rating.

For each of the remaining three winding configurations, the machine was tested from standstill up to 4000rpm. The load at each operating speed was steadily increased until torque could not be sustained. The results are shown in fig. 13. It should be noted that the limit of the load machine is 40Nm and this restricts the measurable performance of the 'dot-dot' configurations at low speed. In the case of the conventional 'dot-cross' winding, the performance at low speed was limited by the maximum current of the inverter drive.

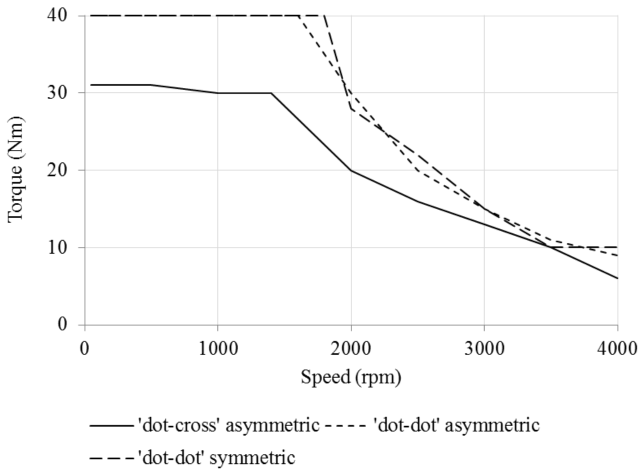


Fig. 13: Measured peak torque capabilities of the six phase prototype driven from a three phase full bridge with different winding configurations (note 40Nm load torque limit)

The results of these initial load tests broadly confirm what the FE modelling suggested, namely that the torque capabilities of both 'dot-dot' configurations are similar and that the conventional 'dot-cross' winding is inferior in this context owing to stator core back saturation. It was also observed that the conventional 'dot-cross' winding was acoustically more noisy by comparison with the 'dot-dot' configurations. With reference to the FE modelling, it is expected that this excess noise arises from the increased torque ripple, again as a result of stator core back saturation.

Hall-effect current probes were also used to capture the line current and the two associated phase currents arising from the anti-parallel diode set up. Sample waveforms are shown in fig. 14 for illustration of the concept and comparison with the FE modelled waveforms shown in fig. 12.

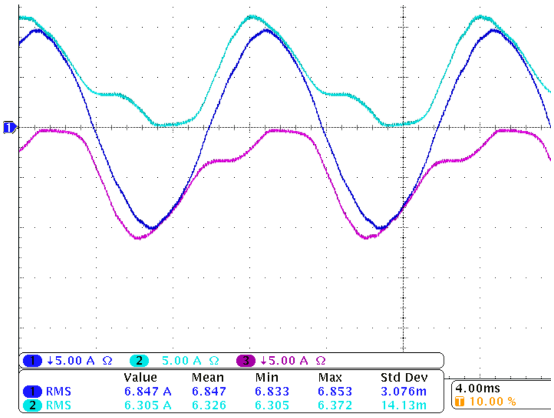


Fig. 14: Measured current waveforms for the six phase symmetric 'dot-dot' configuration driven from a three phase bridge and developing 10Nm torque at 500rpm. The line current and the two associated motor phase currents are shown.

Again, it was verified that the resultant phase currents do sum to the line current from the drive, but the non-sinusoidal nature of the motor phase currents indicates the presence of currents circulating between the phases.

VI. CONCLUSIONS

A prototype 12-10 six phase SRM driven from a three phase full bridge inverter has been described. Potential winding configurations for this machine have been illustrated and investigated using FE modelling. Modelling results were verified through some initial experimental tests on the prototype.

In particular, a new winding arrangement has been proposed and shown to develop more torque with less torque ripple than a conventional arrangement. Investigation of the electromagnetic behaviour of this machine has shown that torque is developed through a combination of self and mutual inductance variation.

VII. REFERENCES

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VIII. BIOGRAPHIES

James Widmer joined Newcastle University in December 2009 from a senior position in the aerospace industry. James coordinates the Newcastle University Centre for Advanced Electrical Drives, which provides industry with expert design and research services in electrical machines and their associated electronics. He also undertakes research into novel electrical machines. James has a MEng in Electrical and Electronic Engineering from the University of Bristol and is in the process of completing a PhD in electrical machines.

Richard Martin obtained MEng and PhD degrees from Durham University and is now a Research Associate in the Power Electronics, Drives and Machines Research Group at Newcastle University.

Christopher Spargo was awarded a BEng (Hons) degree in Electrical and Electronic Engineering from Newcastle University in 2011; he is currently a PhD student in the Power Electronics, Machines and Drives research group at the same university in the School of Electrical, Electronic and Computer Engineering. His research interests include switched and synchronous reluctance machines.

Barrie Mecrow is Professor of Electrical Power at Newcastle University and is also the Head of Power Electronics, Drives and Machines Research Group. His research interests include permanent magnet and reluctance machines and drives for aerospace, automotive and consumer products.

Tuncay Celik has been with Dyson Ltd. since 2006. He did his MSc degree at the University of Newcastle in 2001 for which he received British Council scholarship. He was then sponsored by the UK Overseas Research Scholarship (ORS) for his PhD work at the University of Newcastle. His PhD research was on the six-phase segmental rotor switched reluctance drives. His research interests are design and control of novel PM and SR machines.