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Effects of Winding Connection on Performance of a Six-Phase Switched Reluctance Machine

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Abstract— This paper investigates the effect of the stator winding connection on the performance of a six-phase Switched Reluctance Machine (SRM). Five winding connection types are proposed for the machine. Finite element analyses (FEAs) of flux distribution, output torque and core losses are presented under single-phase and multi-phase excitation for each connection and the results are used to compare the average torque and torque ripple ratio characteristics and to develop understanding of the respective contributions of mutual inductance in torque development. Experimental tests on a six-phase conventional SRM verify the torque performance and mutual inductance effects of the different winding connections. An optimum winding configuration for a six-phase SRM is proposed.

Index Terms—Core losses, Mutual inductance, Stator windings, Switched Reluctance Machine (SRM), Torque ripple.

I. INTRODUCTION

Switched Reluctance Machines (SRMs) and their drive systems have the advantages of simple structure, low manufacturing cost, high system reliability, high efficiency and a wide speed range, and are contenders for electric vehicle traction drives [1-3]. In recent years they have also been developed for the aviation industry [4, 5].

However, torque development in SRMs is fundamentally prone to high ripple giving rise to vibration and acoustic noise, and this characteristic is a significant drawback [6]. The reduction of torque ripple is an active research topic and improvement strategies include machine design optimization [7-9] and advanced control techniques [10-13].

In the wake of power electronics development, increasing the phase number is a simple and generally accepted way to reduce torque ripple. In the last two decades, machines with higher phase numbers have been considered due to their potential for lower torque ripple, less phase current for a given power rating and better fault-tolerant ability compared with traditional machines [14, 15]. In addition, the choice of winding configuration in multi-phase machines has been investigated with a view to achieving a better torque performance and more flexible control [16, 17].

As the phase number of an SRM increases, so too does the conduction overlap between adjacent phases with an ideal 180° conduction width. This can give rise to considerable interaction between phases; in this case, the common analysis based on superposition of single-phase, self-inductance characteristics is of limited application and it becomes necessary to consider mutual inductance effects. Winding connections for a 12/8 dual channel three-phase SRM have previously been investigated, and it has been suggested that connections giving rise to long flux paths exhibit better magnetic decoupling than those with short flux paths [18].

Single-phase and two-phase excitation modes are researched with a four-phase SRM in [19, 20]; in this case alternative winding connections can cause asymmetric instantaneous torque waveforms with high torque ripple. It is clear that the mutual inductance cannot be ignored in multi-phase excitation mode unless a decoupled winding connection is employed. Winding connections for a six-phase SRM are simulated in [21], indicating how the effects of mutual inductance and saturation can influence torque production. However, only a restricted set of connection types were investigated in detail. Therefore, research of a broader range of connections, interaction when three phases are conducting and the production of extensive experiments are significant.

More recently, a configuration has been proposed which enables a six-phase SRM to be driven with a three-phase full bridge inverter, thus reducing torque ripple without recourse to a non-standard converter [22]. Alternative winding connection types were investigated for this drive and a symmetric winding pattern was proposed whereby phase windings are unconventionally connected with opposing polarities, giving rise to significant phase interaction [23]. This drive has demonstrated high torque density and is proving to be a strong candidate in electric vehicles applications [24].

In this paper, winding connections are investigated in a six-phase 12/10 SRM driven by an asymmetric half bridge converter with both Finite Element Analysis (FEA) and experimental test for the first time. The distinction between opposing and reinforcing windings is introduced through FEA under single-phase excitation. Afterwards, five different winding connection types under three-phase excitation are investigated through FEA for the first time, and comparisons are made on the bases of average torque, torque ripple and core losses. Flux density fields are analyzed at various rotor positions in order to illustrate variations of torque and core losses development between winding types and to develop

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understanding of the respective contributions of mutual inductance in torque development. Finally, the analyses are verified through experimental tests on a 4kW prototype; measurement of instantaneous current and torque are presented for the different winding connections under single-phase and multi-phase excitation.

II. WINDING CONFIGURATIONS FOR A SIX-PHASE SRM

In order to investigate output torque and mutual inductance effects, five winding connection types are proposed as illustrated in Fig. 1. Owing to the greater potential for phase interaction at higher phase numbers, the long/short flux path terminology is not appropriate and so a simplified classification is proposed here. Where the coil polarities of a given phase are magnetically reinforcing, this is defined as a N-S (North-South) connection type. Conversely, opposing phase coil polarities are defined as a N-N (North-North) connection type.

For the six-phase 12/10 SRM under consideration there are five short-pitched winding configurations which preserve an equal number of north and south polarity coils, as presented in Fig. 1. These comprise two N-N types (1 and 4) and three N-S types (2, 3, and 5).

Fig. 1. The winding connections: (a) Type 1: NSNSNSNSNSNS (b) Type 2: NSNSSSNSNSN (c) Type 3: NNSSNNSSNNSS (d) Type 4: NNNSSNNSSSS (e) Type 5: NNNNNSSSSSS.

III. FINITE ELEMENT ANALYSIS

Fig. 2 shows the rotor and stator of the six-phase 12/10 SRM prototype, and Table I gives the design parameters for this machine.

(a)

(b)

Fig. 2. Six-phase 12/10 SRM prototype: (a) wound stator (b) rotor.

TABLE I
DESIGN PARAMETERS OF THE SIX-PHASE SRM PROTOTYPE

Number of Stator Teeth	12
Number of Rotor Teeth	10
Axial Length	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 Core back Depth	18.0mm
Rotor Tooth Width	11.4mm
Turns per Phase	100

A. Single-Phase FEA

The six-phase 12/10 SRM under consideration has two coils per phase which may be connected in N-S or N-N type as previously defined. Single-phase static FEA of the flux distributions arising from the two options are shown in Fig. 3.

As has previously been described [24], the N-S polarities of the single-phase connection give rise to long flux paths via the full stator and rotor core (Fig. 3 (a)), whilst the N-N polarities of the single-phase connection give rise to shorter flux paths which link adjacent teeth (Fig. 3(b)).

Fig. 3. 2D FEA flux distribution under single-phase excitation for: (a) N-S connection type (b) N-N connection type.

Fig. 4 compares the phase flux linkages from 2D FEA for the N-S and N-N connections under phase A excitation. As can be

appreciated from inspection of Fig. 3, the single-phase N-S connection gives rise to large self-inductance and negligible mutual inductance, whereas the single-phase N-N connection gives rise to a slightly reduced self-inductance but considerable mutual inductance.

Fig. 4. Six phase flux linkages of N-S and N-N connections under phase A excitation: (a) N-S connection type (b) N-N connection type.

Fig. 5 presents instantaneous motoring torque waveforms under ideal current control from 2D FEA. The single-phase torque for the N-S and N-N connections is compared with equivalent six-phase waveforms obtained by phase-shifted superposition. It is obvious that the N-S series connection develops higher torque with both single-phase excitation and six-phase superposition.

Fig. 5. Single-phase torque output and six phase torque superposition of N-S and N-N connection for a six-phase SRM.

However, it should be noted that this approach neglects the torque contribution arising from the variation of mutual inductance in adjacent phases, which may be considerable in the N-N type, as suggested by the flux linkage characteristics of

Fig. 4.

B. Multi-phase FEAs

Fig. 6 presents instantaneous motoring torque waveforms under ideal current control with full six-phase excitation for the five winding connections, obtained from 2D FEA. Table II compares average torque and torque ripple ratio (TRR) of them. Type1 has the largest mean torque and Type3 has the smallest torque ripple ratio in all the five configurations under current control.

Fig. 6. FEM torque output of five winding configurations.

TABLE II

2D FEA AVERAGE TORQUE AND TRR COMPARISON UNDER CURRENT CONTROL

	Type 1	Type 2	Type 3	Type 4	Type 5
$T_{av}(\text{Nm})$	24.4	23.9	23.2	14.2	20.4
TRR(%)	27.2	29.2	16.7	243.0	58.8

Table III compares average torque with different conduction widths under voltage control for the five winding connections, obtained from 2D FEA. Type 1 exhibits greater torque at lower conduction angles, while Types 2 and 3 are generally superior above 120° of conduction. Types 4 and 5 have poorer performances than other three types.

TABLE III

2D FEA AVERAGE TORQUE COMPARISON UNDER VOLTAGE CONTROL

	$T_{av1}(\text{Nm})$	$T_{av2}(\text{Nm})$	$T_{av3}(\text{Nm})$	$T_{av4}(\text{Nm})$	$T_{av5}(\text{Nm})$
$\theta_{con}=80^\circ$	5.8	5.5	5.3	4.5	4.9
$\theta_{con}=100^\circ$	7.3	7.4	7.3	6.1	6.8
$\theta_{con}=120^\circ$	8.5	8.9	9.1	6.5	8.4
$\theta_{con}=140^\circ$	9.3	9.6	10.5	5.8	9.0
$\theta_{con}=160^\circ$	7.9	9.3	11.2	4.7	7.6

The distinctions of average torque and TRR of five winding connection types under current control will be discussed firstly in this section. Afterwards, the reasons behind distinctions under voltage control will be analyzed furtherly in Sections IV and V.

Picking out three typical conduction combinations, with which there are obvious instantaneous torque distinctions in Fig. 6, the torque relationships between these five types are summarized by (1).

$$\begin{cases} \text{Type1} > \text{Type2} = \text{Type3} = \text{Type5} > \text{Type4}, \text{active phases} = A, E, F \\ \text{Type4} > \text{Type1} > \text{Type2} = \text{Type3} = \text{Type5}, \text{active phases} = A, B, F \\ \text{Type2} > \text{Type1} > \text{Type3} > \text{Type5} > \text{Type4}, \text{active phases} = A, B, C \end{cases} \quad (1)$$

Two separate factors can impact upon the torque production

during multi-phase excitation. One is mutual coupling effects, whilst the other is core back saturation.

The impact of stator core back saturation can readily be illustrated, to which end the FEA described at the start of section B is repeated here with the stator core back depth increased sufficiently to prevent performance limitation in any of the winding connection types.

The results are illustrated in Fig. 7, which show that the three N-S connections: 2, 3 and 5 all deliver almost identical torque. Of the two N-N connections, Type 1 delivers about 3% less mean torque, whilst type 4 performs poorly, delivering low torque for two third of the cycle. By comparing Figs 6 and 7 it is evident that the primary reason that Type 5 performs more poorly than Types 2 and 3 is that it has increased core back flux, which is becoming saturated. This could be rectified by increasing the core back depth, but only at the expense of increased size.

Fig. 7. FEA torque output of five winding configurations in the absence of any core back magnetic saturation.

Observation that all the N-S winding arrangements produce virtually identical torque in the absence of core back saturation simply confirms something that is already well known. For all N-S winding arrangements the MMF (Magnetic Motive Force) of each phase is dropped exclusively across its associated stator teeth, air-gap and the adjacent rotor teeth. It is not a significant function of the MMF in any other phase. Consequently the flux in any excited phase is almost solely a function of the MMF of that coil and rotor position: it is not affected by the MMF of any other phase. Furthermore, unexcited coils have almost no flux-linkage. This cannot be stated to be exactly true due to a small element of cross-slot leakage flux, which can produce very weak coupling between phases.

With the N-N arrangements the two coils of a phase act in direct opposition and therefore have no mutual flux linking them. Consequently the flux generated by the MMF of any one phase will return entirely through the stator teeth of other phases. Hence there is a significant degree of mutual coupling between phases. In theory this mutual coupling could produce either positive or negative additional torque contributions.

To further explain the core back saturation giving rise to the torque variations in Fig. 6, the magnetic flux plots of Fig. 8 to 10 illustrate the above assertion.

As shown in Fig. 8, although the core back flux patterns are very different, the tooth and air-gap fluxes of the N-S arrangements, Types 2, 3 and 5, are almost identical.

Fig. 8. Comparison of flux distribution when phase A,E,F are active.

Consider Type 1, in which all adjacent coils in the machine are of alternating polarity. Hence, with reference to Fig. 1 and 8, when the three adjacent phases A, F and E are excited then the flux travelling in phase F is flowing outwards, whilst in phases A and E are in inwards. The outwards flux in phase F split into two directions in the core back and flow inward to phase A and E, this unique pattern alleviates the saturation in the core back and give rise to higher flux density in active teeth. This is the main reason why Type 1 has slightly higher torque in this position in Fig. 6.

If the sum of the three fluxes in Type 1 was zero then there would be no flux at all flowing back through the unexcited phases. The torque produced by Type 1 in the absence of core back saturation would be identical to that of the three N-S arrangements (Types 2, 3 and 5). Of course, in practice the fluxes of the three phases do not quite sum to zero and some flux returns via the unexcited phases B, C and D, the flux distribution is similar with Fig. 8. This flux is crossing between rotor and stator teeth which have moved past the aligned position and must therefore produce a negative component of torque. It explains why Type 1 N-N arrangement produces approximately 3% less torque than any of the three N-S arrangements in Fig. 7.

Consider now the N-N Type 4 arrangement with regard to Fig. 1, 6 and 8. With Type 4 phase A drives flux into the rotor,

whilst phases E and F bring it back out. Phases E and F are closest to alignment and therefore carry the most flux. In comparison to Type 1, the three phase fluxes have a greater sum and so there is more flux returning via the unexcited phases. This produces a larger component of negative torque and so, as illustrated in Fig. 6, Type 4 produces significantly less torque than the other four types. The effect of core back saturation can be diminished by reducing the conduction period down from 180° to 120° so that phase E is de-energized at this position. However, further measurement and simulation shows that Type 4 continues to produce less torque than the other four types.

Fig. 9. Comparison of flux distribution when phase A,B,F are active.

Fig. 9 shows flux plots with phases A, B and F excited. As expected, with reference to Fig. 6, the three N-S arrangements produce the same torque as in the previous excitation period. Type 1 N-N arrangement also continues to have identical conditions to that of the previous excitation period: of the three phases excited the middle one (phase A) is of opposite polarity to the other two. The excitation conditions for Type 4 are now somewhat different. The phase nearest to alignment (phase F) is of opposite polarity to the other two. Phase F therefore carries the most flux, which is close to the sum of the opposing fluxes in phases A and B. Consequently the sum of the three fluxes is almost zero and there is very little negative torque produced via the unexcited phases. Type 4 therefore produces marginally more torque than Type 1. All the three N-S arrangements have more serious core back saturation and produce less torque.

Finally consider Fig. 10, in which phases A, B and C are excited. With Type 4 and Type 5, all three conducting phases

drive flux inwards across the air-gap. This produces a large net flux which returns via the non-conducting phases, which have all moved past alignment, resulting in a high negative torque contribution. The torque produced by Types 4 and 5 during this period is consequently greatly reduced.

Fig. 10. Comparison of flux distribution when phase A,B,C are active.

To summarize, in the presence of the core back saturation, despite the N-N arrangement of Type 1 having a small element of negative torque due to mutual coupling, it produces more torque than any of the N-S arrangements. Mean torque of Type 1 is 2% greater than Type 2, 5% greater than Type 3 and 19% greater than Type 5. Type 1 has the least core back saturation because it has the shortest flux loops. Of all the types, it is the only one to have all adjacent teeth of opposite polarity. In the absence of core back saturation, all the N-S winding arrangements produce almost identical torque. The N-N arrangements have a component of flux which returns through unexcited phases that are past the aligned position, producing an element of negative torque. This effect is small in Type 1, producing 3% less mean torque, but it is very large in Type 4, greatly reducing performance.

The above discussion reveals that Types 4 and 5 are inferior to Types 1, 2 and 3. They are therefore discarded and will not be discussed further in the subsequent sections of the paper.

C. Core losses analysis

In order to analyze the effect of winding connection on core losses, the iron loss is predicted at 4000r/min using time stepping FEA. At this speed the machine is operating under voltage control, with a conduction angle of 140° . Loss

prediction is based on Epstein Frame loss measurements, using the Steinmetz equation augmented with an eddy current term to split the total iron loss into two components; hysteresis with anomalous losses and eddy current losses. Each of the different winding connection types are studied in turn in addition to the losses produced by a single phase with N-N and N-S connections. Eddy current loss P_{eddy} and hysteresis loss P_{hys} in the stator and rotor are presented in Table IV.

TABLE IV
2D FEA LOSSES AND EFFICIENCY COMPARISON

	N-N	N-S	Type1	Type2	Type3
Stator P_{eddy} (W)	10	12	44	56	89
Stator P_{hys} (W)	19	25	72	91	136
Rotor P_{eddy} (W)	5	5	23	25	32
Rotor P_{hys} (W)	13	11	46	51	65
Total stator core losses (W)	29	37	116	147	225
Total rotor core losses(W)	18	16	69	76	97
Total core losses(W)	47	53	185	223	322
P_{eddy} percentage in stator (%)	34	32	38	38	40
P_{hys} percentage in stator (%)	66	68	62	62	60
P_{eddy} percentage in rotor (%)	28	31	33	33	33
P_{hys} percentage in rotor (%)	72	69	67	67	67
Stator losses percentage (%)	62	70	63	66	70
Rotor losses percentage (%)	38	30	37	34	30
Torque/loss(Nm/W)	0.031	0.029	0.049	0.043	0.044

Since the single-phase N-S connection has long flux loops through the whole stator core back, it has over 25% higher stator core losses compared with N-N connection. The rotor core losses of two single-phase connections are almost identical. For multi-phase FEAs, Type 1 has the smallest total core losses in all five types, Type 2 has slightly higher core losses than Type 1, whilst Type 3 has the highest core losses. For all connection types, hysteresis losses account for 62% to 72% of total core losses. Furthermore, 62% to 70% of total core losses are from stator.

In addition, considering the efficiency of different winding connection types, the torque/loss is compared in Table III as a significant machine design criteria. Since two single-phase connection types have similar average torque and losses, the torque/loss of them are about 0.03. For multi-phase FEAs, Type 1 has the highest torque/loss due to its lower losses. Type 2 and Type 3 has 12% and 10% lower torque/loss than Type 1.

To further explain core losses variations between different connection types, the flux distribution at six typical rotor positions in one electrical cycle of Types 1 to 3 are presented in Fig. 11 to Fig. 13, with the sequence of flux distribution shown by the red arrows. Sharing the same color scale, the flux density in different connection types can be compared easily. Since Type 1 always has short flux loops at all six positions, the amplitude and change of flux density are not significant in the core back in Fig. 11, which helps Type 1 have the lowest core losses.

Type 2 in Fig. 12 has identical flux distribution to Type 1 in positions 4, 5 and 6, however, at the other three positions Type 2 has a mix distribution of short and long flux loops, creating higher core back flux density than in Type1 and consequently higher core losses than Type 1.

Fig. 11. Flux distribution at six positions in one electrical cycle of Type 1

Fig. 12. Flux distribution at six positions in one electrical cycle of Type 2

Fig. 13. Flux distribution at six positions in one electrical cycle of Type 3

Type 3 in Fig. 13 has a mix distribution of long and short flux loops at positions 1, 3 and 5, whilst it has short flux loops at positions 2, 4 and 6. The constant changing between short and long flux loops creates greater rate of change of flux and so Type 3 has the highest eddy current losses in both the rotor and stator. Compared with Type 1, Type 3 has higher flux density in the stator core back giving rise to high hysteresis core losses.

To summarize, the core losses of Type 1 is 20% lower than Types 2, 50% lower than Types 3. Of all the Types, Type 1 is the only one to have all adjacent teeth of opposite polarity, which gives short flux loops with low flux density in the core back all the time. The connection types having high flux density and fast flux change in the core back produce higher core losses.

IV. MUTUAL COUPLING EFFECTS IN A SIX-PHASE SRM

For a six-phase SRM, phase flux linkages can be expressed:

$$\begin{bmatrix} \psi_A \\ \psi_B \\ \psi_C \\ \psi_D \\ \psi_E \\ \psi_F \end{bmatrix} = \begin{bmatrix} L_A & M_{AB} & M_{AC} & M_{AD} & M_{AE} & M_{AF} \\ M_{AB} & L_B & M_{BC} & M_{BD} & M_{BE} & M_{BF} \\ M_{AC} & M_{BC} & L_C & M_{CD} & M_{CE} & M_{CF} \\ M_{AD} & M_{BD} & M_{CD} & L_D & M_{DE} & M_{DF} \\ M_{AE} & M_{BE} & M_{CE} & M_{DE} & L_E & M_{EF} \\ M_{AF} & M_{BF} & M_{CF} & M_{DF} & M_{EF} & L_F \end{bmatrix} \times \begin{bmatrix} i_A \\ i_B \\ i_C \\ i_D \\ i_E \\ i_F \end{bmatrix} \quad (2)$$

Mutual inductances between non-conducting phases may be ignored, giving:

$$\begin{bmatrix} \psi_{k-1} \\ \psi_k \\ \psi_{k+1} \end{bmatrix} = \begin{bmatrix} L_{k-1} & M_{(k-1)k} & M_{(k-1)(k+1)} \\ M_{(k-1)k} & L_k & M_{k(k+1)} \\ M_{(k-1)(k+1)} & M_{k(k+1)} & L_{k+1} \end{bmatrix} \times \begin{bmatrix} i_{k-1} \\ i_k \\ i_{k+1} \end{bmatrix} \quad (3)$$

Where $M_{(k-1)k}$, $M_{(k-1)(k+1)}$ and $M_{k(k+1)}$ are mutual inductances between three adjacent, conducting phases. Phases $k-1$, k and $k+1$ are out-going phase, intermedia phase and in-coming phase individually. Assuming fixed phase current I in each phase, flux linkages of three active phases are given:

$$\begin{cases} \psi_{k-1} = L_{k-1}I + M_{(k-1)k}I + M_{(k-1)(k+1)}I \\ \psi_k = L_kI + M_{(k-1)k}I + M_{k(k+1)}I \\ \psi_{k+1} = L_{k+1}I + M_{(k-1)(k+1)}I + M_{k(k+1)}I \end{cases} \quad (4)$$

Solving (4) the mutual inductances are given:

$$M_{(k-1)k} = \frac{(\psi_k + \psi_{k+1} - \psi_{k-1}) - I(L_k + L_{k+1} - L_{k-1})}{2I} \quad (5)$$

$$M_{(k-1)(k+1)} = \frac{(\psi_{k-1} - \psi_k + \psi_{k+1}) - I(L_{k-1} - L_k + L_{k+1})}{2I} \quad (6)$$

$$M_{k(k+1)} = \frac{(\psi_{k-1} + \psi_k - \psi_{k+1}) - I(L_{k-1} + L_k - L_{k+1})}{2I} \quad (7)$$

The variation of mutual inductance in each phase across an electrical cycle is obtained from 2D FEA with phase current $I = 15A$ for winding connection Types 1, 2, and 3 (4 and 5 being clearly inferior as described in section III). The mutual inductance between active phases is shown in Fig. 14. As expected, Types 1 to 3 have very similar and small mutual inductance values during the active period, all being between -1.0mH to 1.0mH and less than 10% of the self-inductance. The mutual inductances in Type 1 and Type 3 are symmetric in every electrical cycle and every other cycle respectively, whilst mutual inductances in Type 2 are obviously asymmetric.

There has been earlier research showing how mutual coupling can make a significant contribution to torque production [25, 26]. Because in here the rate of change of mutual-inductance is an order of magnitude smaller than that of the self-inductance, it does not significantly influence the average torque, but can affect both torque ripple and the stability of the current controller.

Fig. 14. Mutual inductance in active phases of three different winding connection types excited by 180° 15A current: (a) Type 1 (b) Type 2 (c) Type 3.

When a phase is inactive, all flux linkage in this phase is coupled from other active phases. This mutual flux linkage in the inactive phase is shown in Fig. 15 to present the mutual coupling level in this period.

Fig. 15. Mutual flux linkage in inactive phases of three different winding connection types excited by 180° 15A current: (a) Type 1 (b) Type 2 (c) Type 3.

The mutual flux linkage in the inactive period has clear distinctions. Phase mutual flux linkages are close to 0.04Wb and -0.025mH for Type 1 in the inactive period, whilst Type 3 exhibits a maximum value of 0.028Wb. Only three phases have obvious mutual inductance in Type 2 with a maximum value less than 0.03Wb.

Combining these observations with the output torque results in Fig. 6, it is clear that the asymmetric mutual inductances result in a larger torque ripple in Type 2. In addition, the large positive mutual flux linkage after the active period could delay the demagnetization time at low speed and can cause current distortion in a real-time system especially at higher speed.

Fig. 16. Current waveforms at different rotational speeds three different winding connection types excited by 180° 15A current: (a) Type 1 (b) Type 2 (c) Type 3.

Fig. 16 presents the phase current waveforms at different rotational speeds for Types 1 to 3. The DC link voltage is 400V at 200r/min and 2000r/min. It is obvious that the current

distortion is more serious at 2000r/min due to flux linkage coupled from other active phases after the turn-off of this phase. Since Types 1 and 3 have more significant coupling as analyzed in Fig. 14 and Fig. 15, the tail current of these two types are wider in Fig. 16.

V. EXPERIMENTAL VERIFICATION

In order to compare the characteristics of the five winding connection types, and verify the simulation results and conclusions of the preceding sections, experimental work was undertaken. The test rig consists of: the prototype six-phase SRM; a Permanent Magnet Synchronous Machine (PMSM) acting as a load; and a six-phase asymmetric half bridge converter and its controller as shown in Fig. 17.

Fig. 17. Photos of test rig: (a) Electrical part (b) Mechanical part.

A. Single-phase excitation experimental results

Table V compares single-phase excitation torque measurement with the predictions of FEA. In this test, the conduction width is 180° , the advance angle is 0° , the current reference is 15A, the DC link voltage is 100V, the control frequency is 10kHz and the rotational speed is 200r/min. The experimental results verify that the N-S connection can produce greater mean torque from single-phase excitation. Variation between FEA and measured results is mainly due to the 2D FEA approach which neglects end leakage and thus over predicts torque.

TABLE V
SINGLE-PHASE AVERAGE TORQUE COMPARISON BETWEEN FEA AND EXPERIMENTAL TEST

	N-S(FEA)	N-S(Test)	N-N(FEA)	N-N(Test)
Tav(Nm)	3.75	3.55	3.30	3.15

B. Multi-phase excitation experimental results

1) Current control mode

Fig. 18 presents the instantaneous torque and phase A current waveform for the five different winding configurations. The same current reference values are applied to all six phase windings, and all the other parameters are the same as those for

single-phase excitation.

Fig. 18. Torque output waveforms of multi-phase excitation tests at 200r/min: (a) Type 1 (b) Type 2 (c) Type 3 (d) Type 4 (e) Type 5.

TABLE VI
EXPERIMENTAL AVERAGE TORQUE AND TRR COMPARISON

	Type 1	Type 2	Type 3	Type 4	Type 5
Tav(Nm)	22.6	20.8	19.7	10.2	12.5
TRR(%)	29.2	36.7	25.6	126.3	52.1

The measurements at Table VI show that Type 1 has the largest average torque, and Type 3 has the smallest torque ripple as predicted by FEA. There are three reasons behind differences between predicted and measured torques:

1. The 2D FEA prediction does not include end effects.
2. Predictions assume perfect square waves of current and therefore neglect the rise and fall current periods.
3. The torque transducer has a limited bandwidth and torque measurements are damped by inertia of the rotor. Consequently the higher frequency elements of electromagnetic torque are not properly captured by the measurement system.

In addition, it is clear that the phase current of Type 1 in Fig. 18(a) exhibits some noise which arises from the presence of a high level of mutual coupling throughout this period as observed in the analysis of Fig. 15(a).

In order to illustrate the effects of mutual inductance, the full six phase current waveforms of Type 3 are shown in Fig. 19. With reference to the falling current at the point of commutation, two different characteristics can be observed: phases A, C and E (encircled in red) and phases B, D and F (encircled in black). It is clear that the currents encircled in red fall more quickly than those encircled in black. This compares well with the binary phase groupings of mutual inductance observed in Fig. 15 (c).

Fig. 19. Six phase current waveforms of Type 3 under current control.

Fig. 20 presents the average output torque and torque ripple with excitation current varying from 0 to 20A. Types 1 to 3 exhibit greater average output torque (Fig. 20), and Type 2 exhibits the smallest torque ripple (Fig. 21) over the range of current.

Fig. 20. Average output torque under current control

Fig. 21. Torque ripple ratio under current control

2) Voltage control mode

In order to further investigate the mutual inductance effect on torque performance at higher speed, the Angle Position Control (APC) method is employed. In this test, current is not controlled by chopping and is now a function of the applied voltage and machine impedance. Hence this test brings further insight into the effects of mutual inductance. Fig. 22 to Fig. 24 show measured phase currents for multi-phase excitation under voltage control at 800r/min. The conduction period is 140°, and the advance angle is 10°. Again, more pronounced current distortion is evidence of greater mutual coupling in Type 1 by comparison with Types 2 and 3.

Fig. 22. Six phase current waveforms in Type 1 of multi-phase excitation tests at 800r/min

Fig. 23. Six phase current waveforms in Type 2 of multi-phase excitation tests at 800r/min

Fig. 24. Six phase current waveforms in Type 3 of multi-phase excitation tests at 800r/min

Fig. 25 shows experimental results for average output torque with different conduction angles for the five winding connection types at 800r/min. Types 2 and 3 are generally superior above 120 degrees of conduction owing to better decoupling which means more current coincides with increasing inductance (more torque) and the shorter tail on the current waveform gives a reduced negative torque contribution, as shown in Fig. 25. Type 1 exhibits greater torque at lower conduction angles, but at higher angles the current distortion is considerable as shown in Fig. 22, and this compromises the torque output.

Fig. 25. Experimental results of average torque under voltage control.

VI. CONCLUSION

In this paper, five different winding connection types for a six-phase SRM are investigated and compared on the bases of torque performance, core losses and mutual inductance effects. The predictions of FEA and the results of experimental tests including single-phase excitation and multi-phase excitation are examined and compared.

It is shown how windings which have N-S arrangement produce almost identical torque in the absence of magnetic saturation in the core back. In the presence of core back saturation the winding configurations with the shortest flux loops produce more average torque. Windings with N-N arrangement have an element of negative torque due to the mutual coupling between phases. However, this can be small in some cases. Overall, with a six-phase machine the shortest flux loops occur with N-N winding arrangement. At rated torque the small negative effect of mutual coupling is more than compensated by a reduction in core back saturation, so that this arrangement outperforms the N-S arrangement. All results are verified by experimentation.

Of all the Types, Type 1 is the only one to have all adjacent teeth of opposite polarity, which gives short flux loops with low flux density in the core back all the time and has the lowest core losses. The connection types having high flux density and fast flux changes in the core back produce higher core losses. However, owing to the considerable mutual inductances in Type 1, phase currents are more difficult to control and exhibit serious distortion at high speed; therefore, although Type1 has the biggest average torque at low speed and less core losses at high speed, it is not an ideal winding connection type for the six-phase SRM. Types 4 and 5 have inferior performances throughout the whole speed range; they are obviously not suitable for the six-phase SRM. The proposed Types 2 and 3 have reasonable average torque and less mutual inductance throughout the whole speed range. However, Type 2 has large torque ripple due to its asymmetric connection type. Consequently Type 3 is selected to be the optimum winding connection type for the six-phase SRM prototype.

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