Application of Fractional Slot Concentrated Windings to Synchronous Reluctance Machines

C. M. Spargo, *Member, IEEE*, B. C. Mecrow, *Member, IEEE* and J. D. Widmer

***Abstract*—Due to the advancement of electric vehicles, the desire for high torque density electric motors for traction applications is steadily increasing. It is advantageous to design such a motor with little or no rare earth permanent magnet (PM) material due to the associated environmental, political and economic challenges with its extraction and processing. This paper explores a novel synchronous reluctance machine (RSM), with fractional slot concentrated windings (cRSM) as an alternative to PM, induction machine (IM) and switched reluctance (SRM) traction motors. The impact of applying fractional slot concentrated windings to RSMs is presented and the outline of the design options for such a machine is detailed. Scaling of the fractional slot wound synchronous reluctance motor is also briefly discussed, in order to realise a torque dense synchronous reluctance machine for future traction applications. A finite element analysis comparison between IM and conventional synchronous reluctance with the proposed cRSM is also presented.**

***Index Terms*— Electric vehicles, Fractional slot concentrated windings, synchronous reluctance, traction motor**

I. Introduction

SYNCHRONOUS reluctance machines are AC synchronous motors that develop only a reluctance torque and were first introduced by Kostko [1] in 1923. As the demand for pure (PEV) and hybrid HEV) electric vehicles increases, the challenge to design and manufacture high torque density, wide speed range electric motors for these demanding applications is highlighted. Permanent magnet based brushless-DC motors, such as the interior (IPM) and surface (SPM) permanent magnet types of machine have been heavily explored, such as those in [2-4]. Induction motor drives have also been considered [5,6] and a recent resurgence in switched reluctance (SRM) technology is being investigated for future traction applications. The RSM on the other hand is another alternative and the permanent-magnet assisted RSM (PMA-RSM) has raised some interest in this area [7]. However, pure reluctance RSMs have been neglected due to their poor power factor. The considered PMA-RSMs, and indeed the pure reluctance torque RSMs, have in the literature consisted solely of polyphase distributed wound stators [8,9,10]. PM based machines and SRM drives typically utilise fractional slot concentrated windings due to their inherent advantages [11]. Many PM machine designs have been presented [12,13] with one IM being presented [14] and SRM technology having this winding type as a fundamental aspect of their conventional topology [15], but have also been known to incorporate fully pitched windings. To the authors' knowledge, no analysis of a RSM with fractional slot concentrated windings (FSCW) has been presented in the literature. The authors hereby introduce the concept of a fractional slot concentrated wound synchronous reluctance machine (cRSM), illustrated alongside a conventional synchronous reluctance motor in Fig. 1. In modern traction drives, for applications such as rail and automotive, factoring in the rare earth challenges the engineering industry faces, reluctance motors are a contender for the future of transportation. Application of FSCWs' to RSMs in order to synthesize a high performance cRSM suitable for such applications, is the focus of the authors' research.

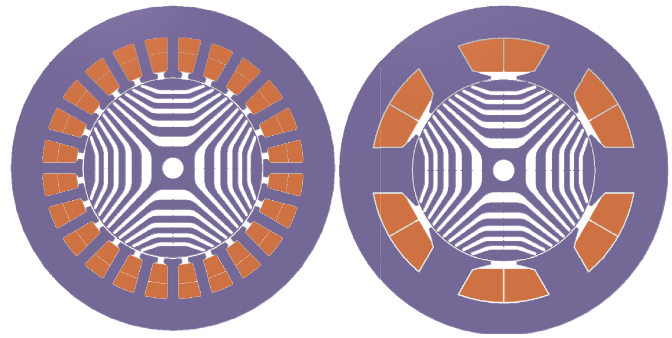

Fig. 1. Synchronous reluctance machines. Polyphase distributed winding (left) and a polyphase fractional slot concentrated winding (right).

II. Advantages of a cRSM

There are various inherent advantages in utilizing fractional slot concentrated windings in synchronous reluctance machines, regarding both machine performance and machine manufacturing, this is due to the non-overlapping single tooth coils. They serve to reduce machine copper loss, which for an m phase machine, with n coils per phase, N series turns per phase, with electrical conductivity, σ_e, a RMS stator current, I_s enclosed in a slot of area, A_{slot} and slot fill factor, S_{FF} can be expressed;

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$$P_{Cu} = mnI_s^2N^2\left[\frac{l_{\text{ave}}}{\sigma_e A_{slot} S_{FF}}\right] \qquad (1)$$

where, $l_{\text{ave}} = 2L + l$, L is the active conductor length of a coil and l is the end winding length per coil.

A. Short End Windings

Switched reluctance machines inherently use single tooth windings and therefore enjoy short end windings, both axially and circumferentially. In a distributed winding, universally used in synchronous reluctance machines, the coil spans one rotor pole pitch if the stator winding is fully pitched. This leads to long overhanging lengths, l, of end winding which comprises inactive material that does not contribute to torque production but does contribute to the machine Joule losses. A single tooth wound coil, however, spans only a single tooth pitch, which leads to greatly reduced end winding length circumferentially. The average winding length can be calculated [16] (where, r_w, is the average coil radius);

$$l_{\text{ave}} = \begin{cases} L + 1.60\left(\dfrac{2\pi r_w}{p}\right), & \text{Distributed} \\ L + 1.36\left(\dfrac{2\pi r_w}{Q_s}\right), & \text{Single Layer FSCW} \\ L + 0.93\left(\dfrac{2\pi r_w}{Q_s}\right), & \text{Double Layer FSCW} \end{cases} \qquad (2)$$

Where the double layer FSCW is found to have the shortest end windings. This effectively reduces copper loss and also facilitates a weight reduction. Another feature of FSCW single tooth windings is that non-overlapping coils form neat end windings that are shorter axially.

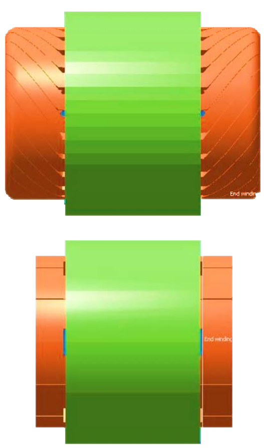

Fig. 2. Synchronous reluctance machines. Polyphase distributed winding (upper) and a polyphase fractional slot concentrated winding (lower).

The axial extent is important, as shorter axial extents promote the possibility of a reduction in frame size or increased active length. The end windings of distributed and double layer fractional slot concentrated winding machines are illustrated in Fig. 2. Double layer fractional slot windings provide the most fitting basis for a low loss, low mass and compact synchronous reluctance machines. If the axial extent of the end windings is reduced by 15%, the torque density of the cRSM can potentially be increased by the same amount, when compared to a conventional machine with the same frame size.

B. High Fill Factor

With fractional slot concentrated windings, is it is possible to achieve a fill factor of greater than 60%, with further improvements being made by using compressed coils with a segmented stator up to 85% fill factor [11]. Copper loss as a function of slot fill factor is presented in Fig. 3. This advantage derives from the less random nature of winding a coil, or winding the coil on the tooth rather than pre-winding and fitting, as in many industrial motors. An increase in fill factor from 30% to 60% effectively halves the Joule loss, facilitated by an increase in copper area by increased wire diameter. Conventionally wound synchronous reluctance motors can expect a fill factor of no higher than 30-40%, therefore an increase in fill factor gained by adopting FSCW, is significant in reducing the loss in the machine. If desired, an increase the torque density of the machine can be made, based on this principle, with the machine exhibiting higher output torque for a given loss when compared to a conventional machine. The drawback of increased fill factor is the increase in copper mass with increasing copper volume. If weight is a major constraint in the given application, it is possible to design the synchronous reluctance machine with compressed windings, utilizing a material with a lower mass density, with a higher fill factor to compensate the lower electrical conductivity.

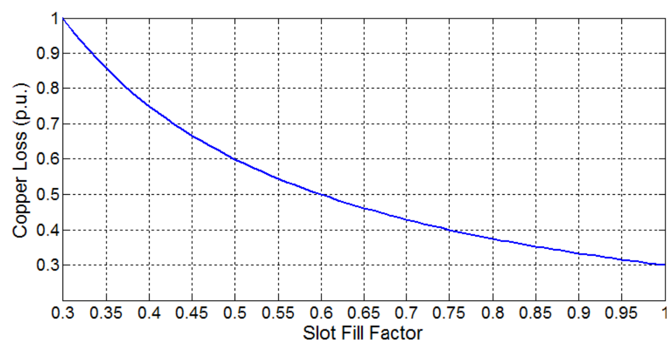

Fig. 3. Copper loss as a function of slot fill factor, normalized to a slot fill factor of 30%.

C. Increased Slot Thermal Conductivity

Increasing the fill factor directly reduces the amount of air in the slot. Air has a low thermal conductivity λ_{Air}, but the copper used in windings obviously have a relatively high thermal conductivity λ_{Cu}, as a comparison, 0.025 and 390 $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$ respectively. So, by increasing the fill factor, the effective slot thermal conductivity increases also. Neglecting wire insulation, as a first order approximation the effective slot thermal conductivity can be written as [17];

$$\lambda_{\text{eff}} = \frac{(1+S_{\text{FF}})\lambda_{\text{Cu}} + (1-S_{\text{FF}})\lambda_{\text{Air}}}{(1-S_{\text{FF}})\lambda_{\text{Cu}} + (1+S_{\text{FF}})\lambda_{\text{Air}}} \qquad (3)$$

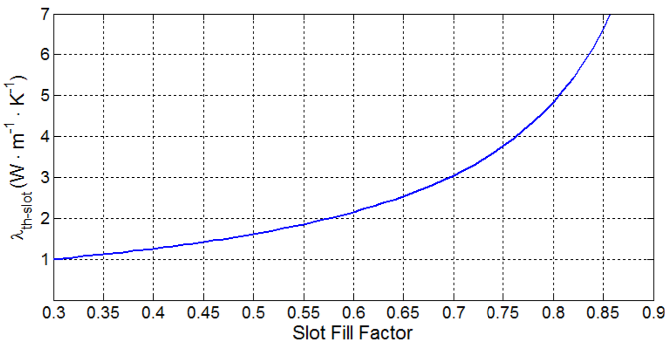

Fig. 4. Effective slot thermal conductivity as a function of slot fill factor.

As is evident in Fig. 4, for an increase in slot fill factor from 30% to 60%, the slot thermal conductivity doubles, effectively halving the winding temperature. The cRSM therefore has a thermal advantage over the conventional machine.

D. *Improved Fault Tolerance*

It is well known that the most common fault in polyphase electrical machines is the phase to phase short circuit fault. Usually caused by insulation degradation between overlapping phases in the end winding region. With fractional slot concentrated windings, this fault is eliminated in single layer windings, and with a greater degree of electrical insulation in double layer windings. This increases the fault tolerance of the machine when compared to RSMs with overlapping polyphase distributed windings of either single or double layer.

E. *Stator Modularity*

As fractional slot concentrated windings only span one tooth pitch, it is possible to segment the machines stator for ease of winding and construction. Large distributed winding machines require a labour intensive and complicated winding procedure. The segmentation of the stator removes this costly and time consuming manufacturing difficulty. Coils can be wound individually and assembled with ease, increasing the manufacturability and achievable fill factor of synchronous reluctance machines by application of FSCW.

III. Advantages Over Induction Machines

RSMs can be derived from induction machines, simply by removing rotor bars and introducing saliency to the rotor. Around 80% of the torque can be retained for 50% of the loss [18], hence the RSM is more desirable than the IM in terms of torque per unit loss. Inherent advantages of RSM technology over IM technology include;

- Rotor synchronicity
- No rotor conductors
  - Increased robustness
  - Lower maintenance / cost
- No rotor copper loss
  - Thermal improvements
- Overall higher efficiency [19]
- Higher torque density [20]
- Lower rotor inertia
  - Faster torque dynamics

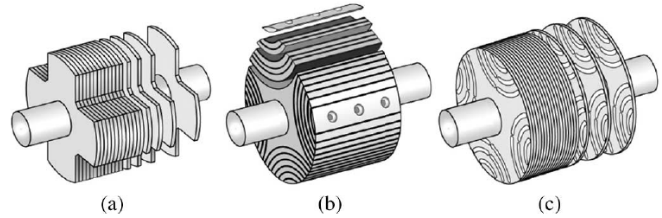

Fig. 5. Synchronous reluctance machine constructions. (a) Simple salient pole, transversely laminated. (b) Axially laminated. (c) Flux guide, transversely laminated. [31]

Thus, taking into account the advantages introduced by application of fractional slot concentrated windings and the RSMs inherent advantages over induction machines, it appears that the cRSM has a high development potential for future traction motors. Its stator construction is similar to that of the switched reluctance machine but is a true AC rotating field machine. Traditionally synchronous reluctance machines retain the induction machine stator and only the rotor is modified. The various robust rotor construction types of synchronous reluctance machines are illustrated in Fig. 5.

IV. Disadvantages of a cRSM

Despite the appealing advantages, there are however associated challenges with this synthesis of synchronous reluctance technology and fractional slot concentrated windings. The root cause of these disadvantages is high space harmonic content in the stator MMF and the availability of slot-pole combinations that support fractional slot concentrated windings. The winding types, fractional slot concentrated (FSCW), fractional slot distributed (FSDW) and integer slot distributed (ISDW) can be categorised by the number of slots/pole/phase (considering a three phase machine hence forth);

$$q = \frac{Q_s}{6p} = \frac{z}{n} = \begin{cases} \in \mathbb{Q} \leq 1, & \text{FSCW} \\ \in \mathbb{Q} > 1, & \text{FSDW} \\ \in \mathbb{Z} > 1, & \text{ISDW} \end{cases} \quad (4)$$

where Q_s, is the number of stator slots and p, is the number of pole pairs. Windings can be both single and double layer (or even higher), the latter of the two reduces the harmonic content due to an increase in the number coils, which are more evenly distributed around the airgap periphery. We can then split the FSCW category into Grade I and Grade II windings, based upon the following criteria [21];

$$\text{Grade} = \begin{cases} I, & n \in \text{even} \\ II, & n \in \text{odd} \end{cases} \quad (5)$$

In these windings, a machine that has a slot/pole/phase of 0.5 or lower, it is possible that the main flux path in the air gap region over one pole pitch may consist of one slot and one tooth. Thus, it may be such that the flux distribution is asymmetrical, this and the discrete placement of coils around the airgap periphery manifests significant space harmonics, causing parasitic effects in the machine. These harmonics are observed in the winding factors, where the winding factor of harmonic of order v, is calculated [21];

$$k_{wv} = \begin{cases} \sin\left(\frac{\pi p}{Q_s}\right) \frac{\sin\left(\frac{v\pi}{6}\right)}{nq \sin\left(\frac{v\pi}{6nq}\right)}, & \text{Grade I} \\ \sin\left(\frac{v\pi}{2}\right) \sin\left(\frac{v\pi}{6}\right) \frac{\cos\left(\frac{\pi p}{Q_s}\right)}{nq \sin\left(\frac{v\pi}{6nq}\right)}, & \text{Grade II} \end{cases} \quad (6)$$

Where the applicable harmonics generated by the winding are defined as;

$$v = \begin{cases} \pm n^{-1}(6g+2), & \text{Grade I} \\ \pm n^{-1}(6g+1), & \text{Grade II} \end{cases} \quad (7)$$

The harmonic subordinate *g*, takes on the values, $\pm 0, \pm 1, \pm 2, \pm 3$ ... etc. It is these harmonics that cause the unwanted parasitic effects in the cRSM, and any machine utilizing fractional slot concentrated windings. As an example, MMF harmonics for an integer slot distributed winding and a fractional slot concentrated winding are plotted in Figs. 6 and 7 respectively.

The fractional slot concentrated winding MMF waveform can contain both odd and even harmonics due to asymmetrical waveforms, it is also possible that sub-harmonics exist in certain slot-pole combinations which rotate with a greater angular velocity than the fundamental, contributing greatly to the iron losses in the machine.

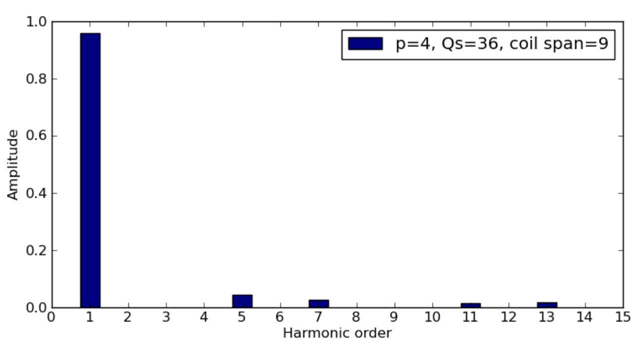

Fig. 6. MMF harmonics of a 36 slot, 4 pole integer slot distributed winding. [30]

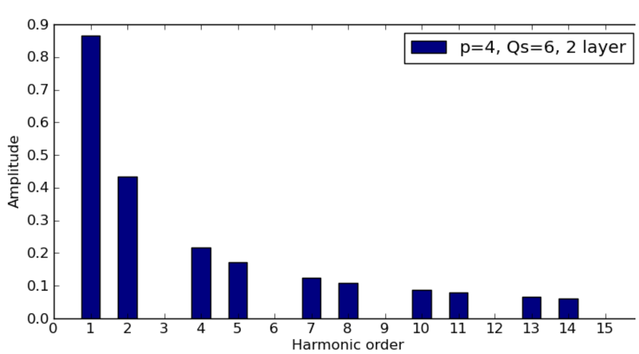

Fig. 7. MMF harmonics of a 6 slot, 4 pole fractional slot concentrated winding. [30]

A. Torque Ripple

In electrical machines, an electromagnetic torque is caused by tangential Maxwell stresses in the airgap of the machine acting upon a rotor. The tangential stress is calculated as;

$$\sigma_\theta = \frac{B_\theta B_r}{\mu_0} \quad (8)$$

The tangential B_θ and radial B_r fields contain harmonics, derived from the machine MMF and permeance functions. These harmonics create parasitic perturbations in the Maxwellian stress, leading to high torque ripple in the cRSM with FSCW. The harmonic content in a distributed winding synchronous reluctance machine is significantly lower, leading to higher torque quality. This torque ripple also leads to increased acoustic noise and vibration, which is undesirable. This issue must therefore be addressed in order to further develop the cRSM. The torque of a synchronous reluctance machine is calculated in the power invariant d-q frame by;

$$T_{\mathrm{em}} = p\left(L_d - L_q\right) i_d i_q \quad (9)$$

This d-q theory becomes less accurate when fractional slot concentrated windings are considered, as one of the fundamental assumptions of d-q theory, is sinusoidal distributed windings and no (or very low) space harmonic content, as exhibited by the conventional RSM.

B. Increased Iron Loss

Due to the increased magnetic harmonic content in the airgap and the machine magnetic circuit, the iron losses, approximated by the Steinmetz equation (accounting for all harmonics) will be higher when compared to the iron loss of a conventional synchronous reluctance machine.

$$P_{\mathrm{Fe}} = \overbrace{\frac{\pi^2}{6}\left(\frac{\sigma_{\mathrm{Fe}}}{\rho_{\mathrm{Fe}}}\right) m_{\mathrm{Fe}} d^2 f^2 \sum_{v=1}^{\infty} v^2 \left(B_{\theta n}^2 + B_{rn}^2\right)}^{\text{Eddy Loss}} + \underbrace{c m_{\mathrm{Fe}} \left(\frac{f}{100}\right) \sum_{v=1}^{\infty} v^2 \left(B_{\theta n}^2 + B_{rn}^2\right)}_{\text{Hysteresis Loss}} \quad (10)$$

Both hysteresis and eddy current losses would be expected to increase in the cRSM. Where, σ_{Fe}, ρ_{Fe}, m_{Fe}, d and c are the lamination conductivity, mass density, mass, thickness and material hysteresis constant. $B_{\theta n}^2$ and B_{rn}^2, are the harmonic components of the tangential and radial magnetic flux densities in the iron. To minimise both of these losses, careful consideration of the lamination material and thickness is required, but the stacking factor must also be taken into account as to not reduce the flux carrying capability of the core, decreasing performance.

C. *Decreased Power Factor*

In synchronous reluctance machines the *saliency ratio* ‘ζ’ of the machine effectively determines the maximum power factor of the machine. This saliency ratio is derived from d-q axis theory and is defined as;

$$\xi = \frac{L_d}{L_q} \quad (11)$$

Where L_d and L_q are the direct and quadrature axis inductances respectively. For modern synchronous reluctance machines with a transversely laminated rotor, saliency ratios of greater than 5 are common [22] and some as high as 10 have been recorded. Generally for a distributed winding synchronous reluctance machine, the power factor is around 0.7 to 0.8. The maximum power factor can be shown to be approximated as;

$$\cos(\phi)_{\max} = \frac{\xi - 1}{\xi + 1} \quad (12)$$

The higher the saliency ratio, the higher the power factor. However, the d- and q-axis inductances contain the stator leakage inductance term $L_{s\sigma}$ and the purely magnetizing components, L_{md} and L_{mq} respectively.

$$\begin{aligned} L_d &= L_{md} + L_{s\sigma} \\ L_q &= L_{mq} + L_{s\sigma} \end{aligned} \quad (13)$$

In the cRSM, the extra leakage flux caused by the air gap field harmonics increases the stator leakage inductance, effectively reducing the saliency ratio, having a negative impact of the power factor of the machine. Also, the limiting value of L_q is in fact $L_{s\sigma}$, so the smaller the q-axis magnetizing component (which is the aim) the higher leakage has a more pronounced effect.

D. *Applicable Slot-Pole Combinations*

As the d-q inductances are of great importance in the synchronous reluctance machine, it is important that L_d is maximised and L_q is minimised. There is however another consideration required, most synchronous reluctance machines in the literature are of $p \leq 2$ type. This is due to a detail in the expressions for the d-q magnetizing inductances [23];

$$L_m = \frac{6\tau_p \mu_0 l}{\pi^2 p \delta_{\text{eff}}} (k_{w1} N)^2 \quad (14)$$

δ_{eff} is the effective airgap length and *N* is the number of series turns per phase. Equation (14) shows that the magnetizing inductance is proportional to the reciprocal of the pole pairs for constant rotor pole pitch τ_p. Therefore, for maximum torque production and high power factor a low pole number is required to be selected. In order for concentrated windings to be applicable, $q \leq 0.5$ and thus the available slot pole combinations are presented in Table 1.

TABLE I
APPLICABLE SLOT-POLE COMBINATIONS (WINDING FACTORS)

	Number Of Poles ($2p$)					
Number of Slots (Q_s)	***2***	***4***	***6***	***8***	***10***	***12***
3	0.866	0.866		0.866	0.866	
6		0.866		0.866	0.500	
9		0.617	0.866	0.945	0.945	0.866
12				0.866	0.966	
15				0.711	0.866	
18				0.617	0.735	0.866
21				0.538	0.650	

For low pole numbers, the number of stator teeth that allow fractional slot concentrated windings are low, with fundamental winding factors which are usually considered on the minimum requirement for consideration of a winding. The lower end winding factor will limit the torque, when compared to a machine with a higher fundamental winding factor. It is evident in Table. 1 that there are more pole-slot combinations for 8 and 10 pole machines. However, the effect on the magnetizing inductances is to significantly reduce power factor and the torque capability.

V. DRIVE AND CONTROL CONSIDERATIONS

In the two main types of reluctance machine, switched and synchronous, the drive topologies are significantly different. The difference is due to the manner in which the machines operate, switched reluctance machines are not rotating field machines, whilst synchronous reluctance machines are. This

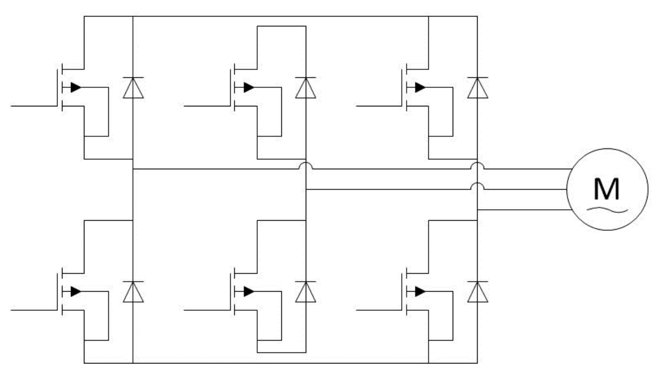

Fig. 8. Synchronous reluctance and induction motor, three-phase voltage source inverter.

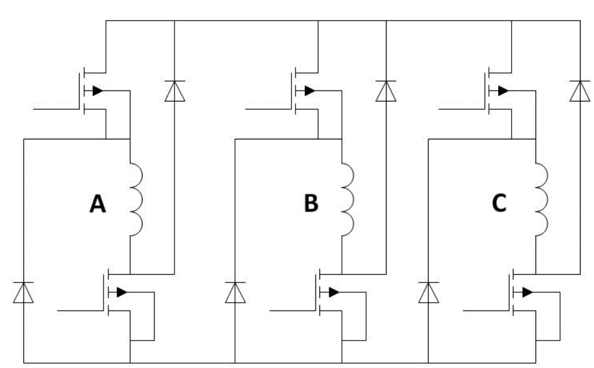

Fig. 9. Switched reluctance motor, three-phase asymmetric half bridge converter.

allows the synchronous reluctance motor, both the conventional RSM and the cRSM, to be supplied by an off-the-shelf voltage source inverter (VSI) (Fig. 8), as used with induction machines. The switched reluctance machine however, usually requires an asymmetric half bridge converter [24] (Fig. 9), which is not readily available off-the-shelf. Therefore there is immediate advantage of the cRSM over the SRM in terms of the electric drive. (The authors have, however, recently published work that allows six-phase SRMs to be fed by a three phase VSI [25], and explore different winding configurations in order to obtain maximum performance [26].)

The converter VA requirement of a VSI for synchronous reluctance machines is obviously greater than that for an equivalent size induction machine, due to their lower power factor. It is expected that the converter for a cRSM is greater again, due to their low power factor. This is an issue that is required to be investigated, however, with the fall in cost of power electronic devices, this issue is becoming incrementally diminished.

Control of synchronous reluctance machines is achieved in the same manner as that of induction motors, where closed loop vector [27] and direct torque [28] control can be used. A simple shaft encoder can provide position feedback, or sensorless control can be also achieved [29].

VI. Machine Design and Scaling

From the advantages and disadvantages outlined, it is possible to view the cRSM as a machine with high potential, but with associated challenges. Those discussed have been mainly of an electrical nature, whereas for electrical machine design, a multidisciplinary approach must be taken.

In any synchronous reluctance machine, mechanical design is important, both from a manufacturing and a structural perspective. The number of rotor poles directly determines the minimum stator and rotor yoke depths t_y, with higher pole numbers minimising the volume of iron in the machine, allowing increased space for windings or, by increasing t_y above minimum to increase the machines magnetic overload capability.

$$t_y = \left(\frac{B_{\text{airgap}}}{B_{\text{yoke}}}\right)\left(\frac{\pi D}{4p}\right) \quad (15)$$

Increasing the number of poles would also increase the available slot-pole combinations such that it enables choice of a higher stator tooth number, and by (2), the end winding length reduced further. However, the shape or aspect ratio must be considered in order to maximise the potential advantages of fractional slot concentrated windings, in particular their short end windings. A machines aspect ratio can be defined;

$$\text{A.R.} = \frac{L}{D} \quad (16)$$

A large aspect ratio suggests the machine is a long cylindrical machine and a small ratio suggests a pancake type machine. It is immediately evident that machines with small aspect ratios have greater benefit of short end windings. This type of machine may also be applicable for higher pole numbers as the rotor pole pitch τ_p, is calculated;

$$\tau_p = \frac{\pi D}{2p} \quad (17)$$

Plugging into (12), the magnetizing inductance becomes;

$$L_m = \frac{3\mu_0 l D}{\pi p^2 \delta_{\text{eff}}}(k_{w1}N)^2 \quad (18)$$

Where, as we increase the outer diameter in order to decrease the aspect ratio, the magnetizing inductance increases. Thus migration to higher pole numbers may be possible, maximising the potential of the cRSM.

VII. Example cRSM Performance

Finite element analysis of an induction machine, a conventional synchronous reluctance machine and a novel synchronous reluctance machine with non-overlapping fractional slot concentrated windings is now presented. End winding losses are taken into account and all machines are operated at the same base speed with three phase balanced currents for the same machine total loss of 340W. All machines have identical stator and rotor outer diameters and stack lengths. The modelled machine are illustrated in Fig. 1 (Reluctance machines) and Fig. 10. (Induction machine).

TABLE 2
Machine Comparison I

	Machine		
Parameter	***IM***	***RSM***	***cRSM***
Rotor core mass (kg)	4.98	4.03	4.03
Rotor bar mass (kg)	0.52	0	0
Rotor end ring mass (kg)	0.12	0	0
Stator core mass (kg)	8.88	8.88	8.39
Stator winding mass (kg)	3.33	3.33	3.15
TOTAL MASS (kg)	17.83	16.24	15.57
Loss - Stator Winding (W)	176.5	310.0	296.0
Loss - Rotor cage (W)	140.0	0	0
Loss - Iron (W)	24.6	33.2	47.9
TOTAL LOSS (W)	341.1	343.2	343.9
Speed (rpm)	1425	1500	1500
Slip (%)	5	0	0
Current (RMS)	13.00	17.25	90
Stator Coil Turns	12	12	12
Number of Stator Coils	24	24	6
Torque (Nm)	17.8	21.00	23.56
Power (kW)	2.65	2.27	3.29
Power Factor	0.73	0.55	0.46
Efficiency	88.64%	90.52%	91.47%
Fill Factor	0.4	0.4	0.4
Stator Current Density (A/mm^2)	5.83	7.75	8.02

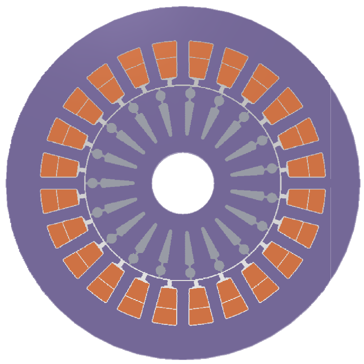

Fig. 11. Modelled induction motor, 24 stator slots and 20 aluminium rotor bars.

Finite element results for constant fill factor of 40% are presented in Table. 2. The rotor mass of the synchronous reluctance motors is lower, due to lack of the aluminium rotor conductors and thus has a lower inertia, leading to faster torque response. The stator winding mass is reduced in the cRSM, leading to an overall weight reduction of approximately 5%, due to short end windings. In the reluctance machine, the lack of rotor copper loss allows an increase in the stator current for the same machine total loss. The iron losses in the RSM and cRSM are higher than that of the IM, with the cRSM exhibiting the highest iron loss, as expected. For the same loss condition the reluctance machines have higher torque densities, with the cRSM having the largest torque density. However, the power factor suffers in the reluctance machines, the cRSM has a low power factor of 0.46, lower than that of the conventional RSM, again, as expected, but greater than a typical SRM.

TABLE 3
MACHINE COMPARISON II – CONSTANT 340W LOSS

	Parameter				
Fill Factor	***Torque (Nm)***	***Power Factor***	***Efficiency (%)***	***Winding Mass (kg)***	***Slot Thermal Conductivity (W/m.K.)***
0.4	23.56	0.46	91.47	3.15	2.33
0.5	26.45	0.45	92.49	3.46	2.98
0.6	28.95	0.44	93.31	3.78	3.99
0.7	31.32	0.43	93.83	4.09	5.66
0.8	32.90	0.42	94.33	4.41	8.99

In terms of increasing the fill factor, comparative results are presented in Table. 3 for the constant loss of 340W, consisting of both copper and iron loss. It is evident that we can significantly increase the torque density of the cRSM by increasing the fill factor. An increase in fill factor from 40% to 80% provides approximately a 40% increase in torque density and over a 3% increase in efficiency. The slot thermal conductivity increases almost four-fold, so the machine with higher fill factor will run significantly cooler than a low fill factor machine. These performance benefits are accompanied by an 8% reduction in power factor and a 40% increase in machine weight, which are undesirable. The power factor decreases due to the increase in stator MMF, creating higher magnitude harmonic fluxes, contributing to an increase in stator leakage inductance. It is unlikely that unless compressed coils are used, a fill factor of 80% will be achieved in practice and a more reasonable value would be around 60%. When increasing the fill factor in order to increase the torque density of the cRSM, it is important to note that the increase in stator current has an upper limit, even for constant winding copper loss. The increased stator MMF will also increase the magnetic operating point, leading to higher iron loss and saturation. This saturation affects the magnetizing inductance and fundamentally limits the torque capability of a given geometry. The converter needs to be taken into account also, with device selection and cooling becoming an issue at higher current levels. From these results, it is clear that development of the cRSM idea is warranted, but design constraints and limitations must be taken into account, or explored further.

VIII. CONCLUSION

This paper presents a first look at the considerations in machine design of a synchronous reluctance machine with fractional slot concentrated windings. The advantages of developing a synchronous reluctance machine with non-overlapping fractional slot concentrated windings are clear. This winding type allows an increase in torque density and efficiency, whilst making the machine easier to construct, with increased robustness, increased fault tolerance and added thermal improvements. The short end windings and stator modularity facilitate these performance increases. Unlike the SRM, the cRSM can be driven by an off the shelf three phase VSI, but still enjoys the benefits of single tooth coils.

However, the associated challenges in machine design have also been outlined. High MMF space harmonic content impairs performance due to parasitic effects. Torque ripple, low power factor and increased iron loss deserve special consideration when designing a synchronous reluctance machine with fractional slot concentrated windings. The lack of slot-pole combinations available, in conjunction with the low rotor pole number requirement fundamentally limit the topology. One route of investigation lies in designing for a small aspect ratio to take greater advantage of the short end windings and allow greater pole numbers to be used.

FE analysis has shown the high potential of the cRSM. A significant increase in torque density can be achieved, along with efficiency and thermal improvements. However, poor power factor is a major issue. Further development of the idea is required in order to maximise its potential as an automotive traction motor, or for other applications where low cost and robust machines are required.

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