Higher Pole Number Synchronous Reluctance Machines with Fractional Slot Concentrated Windings

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Abstract

This paper presents an examination of the advantages, disadvantages and remaining challenges of the application of fractional slot concentrated windings to higher pole number (pole-pairs > 2) synchronous reluctance machines. It extends previous work by assessing the effects of the available slot-pole combinations on machine performance and construction. Finite element studies and figures of merit derived from d-q axis theory are used to compare and assess performance. Manufacturing and constructional issues are also discussed.

1 Introduction

Synchronous reluctance machines (SynRM) are regaining interest for a number of reasons. Firstly, industrial motors are expected to achieve ever higher efficiency to conform to EU [1, 2] legislation. With the proposal of the IE4 super premium efficiency standard, the first commercially available mass-produced SynRM to meet that standard were brought to market in 2011 by ABB [3]. On the other hand, very high torque density electric motors for automotive traction and aerospace are sought, which contain minimal permanent magnet material primarily due to cost fluctuations, among others. The SynRM is one contender to compete against the induction machine (IM) and permanent magnet synchronous machines (PMSM) that currently dominate these sectors. The SynRM can outperform the IM under certain conditions [4] and it has been shown previously that a SynRM equipped with fractional slot concentrated windings (FSCW) outperforms the conventional technology [5]. The SynRM is almost universally designed with a distributed winding of the four pole type, characterised by long end windings with a labour intensive and costly winding process. The FSCW scheme is usually employed in PM synchronous machines [6] and have been investigated for induction motors [7], and is a standard form for the doubly salient switched reluctance machine (SRM) [8]. The fractional slot wound synchronous reluctance machine (cSynRM), can have a higher efficiency and higher volumetric and mass torque density at the cost of slightly reduced power factor and an increase in torque ripple [5]. The cSynRM has the benefits of the conventional SynRM and that of the switched reluctance, but driven by an off the shelf voltage source inverter (VSI). This paper aims to extend the previous literature by considering the options of higher pole and tooth numbers available, the benefits of this adoption, as well as the associated drawbacks.

2 Figures of Merit

The *Saliency Ratio*, ξ, is the ratio of the *d*-axis to the *q*-axis inductance, *physically relating to the level of anisotropic magnetic reluctance of the rotor*, governing the power factor and ultimately the overall performance of the machine.

$$\xi = \frac{L_d}{L_q} = \frac{L_{md} + L_{s\sigma}}{L_{mq} + L_{s\sigma}} \tag{1}$$

Where $L_{md/q}$ and $L_{s\sigma}$ are the magnetizing and stator leakage inductances respectively. The *Torque Index*, Θ, is the difference in the *d*-axis and *q*-axis inductances, *indicating the torque capability of the machine*.

$$\Theta = (L_d - L_q) = L_{md} - L_{mq} \tag{2}$$

The stator leakage inductance is important in the saliency ratio of the machine, however it does not affect the torque index. These are complemented by *Inverter Utilization*, Υ, which *indicates the kVA/kW requirement of the attached VSI*.

$$\Upsilon = \eta \cos\varphi \tag{3}$$

Where η is the machine efficiency and together, these figures of merit give an indication as to the level of performance of a synchronous reluctance machine. Higher values indicate higher performance.

3 Applicable Slot-Pole Combinations

FSCW can be categorised by the number of slots/pole/phase q, considering a three-phase machine only;

$$q = \frac{Q_s}{6p} \in \mathbb{Q} \leq 1 \tag{4}$$

Q_s, is the number of stator slots and p is the number of pole pairs. FSCW coils span a single stator slot. The applicable slot-pole combinations for this winding type with fundamental winding factors k_{w1}, are presented in Table. I. It is immediately obvious that there are limited slot-pole combinations for a number of poles lower than 6, in contrast to the large number of combinations available with traditional distributed windings. Also, the winding factors in most combinations are lower than that of many sinusoidally distributed windings. Choice of slot pole combination is important as the fundamental winding factor is proportional to the torque capability of the machine. Slot pole combinations such as 9-slots 8-poles or 9-slots 10-poles, maximise the fundamental winding factor of the machine, comparable to that of a distributed winding machine. If the limitations and consequences of applying FSCW are understood, suitable combinations with higher pole numbers could be found, making this topology even more advantageous.

TABLE I
APPLICABLE SLOT-POLE COMBINATIONS (WINDING FACTORS)

	Number of Poles				
Number of Slots	**2**	**4**	**6**	**8**	**10**
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
12				0.866	0.966
15				0.711	0.866

Table I: Applicable slot pole combinations for a cSynRM that form a three-phase balanced winding.

4 Advantages of Higher Slot/Pole Numbers with Fractional Slot Concentrated Windings

Due to the single tooth span of the coils, many advantages present themselves to indicate the FSCW as a desirable adoption. These advantages are briefly reviewed in the context of high tooth and pole number synchronous reluctance machines, a more comprehensive review focussed on PM machines is found in [9].

A. End Winding Length Reduction

Low copper loss is a major advantage in any machine and reduction in copper losses is almost always a key design criteria. End windings contribute to this loss but do not actively contribute to any torque production in the machine. The per unit average end turn length for single and double layer FSCW and distributed windings can be approximated (adapted from [10]);

$$l_{\text{end}} = 1.6P^{-1}\ ; \quad \text{Distributed} \tag{5}$$

$$l_{\text{end}} = \begin{cases} 1.36Q_s^{-1}; & \text{Single Layer FSCW} \\ 0.93Q_s^{-1}\ ; & \text{Double Layer FSCW} \end{cases} \tag{6}$$

Where Q is the number of stator slots and P is the number of poles. The end turn length is inversely proportional to the stator tooth number, effectively reducing the ratio of the end to axial conductor length and their respective resistances. For an identical sized fully pitched machine, the end winding is generally longer than the corresponding pole number FSCW machine, as depicted in Fig. 1. The dashed line is the reference line for an equivalent pole number distributed winding and all FSCW windings are relative to their respective pole number. Thus, in nearly all cases it is advantageous in terms of end winding length and copper loss to select a FSCW where the per-unit (p.u.) end length is low and the winding factor is high. Such combinations are 4-pole 6-slot, 6-pole 9-slot, 8-pole 9/15-slot and 10-pole 9/12/15 slots, where the winding factor is >0.866 and the relative end turn length is below 0.6 p.u.

B. Stator Segmentation

The single tooth span coils of FSCW allow stator segmentation. This segmentation (Fig. 2) allows coils to be pre-wound on the tooth before final stator assembly [9], thus the manufacturing is simpler than a large distributed winding system. Utilising this technique can effectively reduce manufacture time and costs of the SynRM, which becomes increasingly advantageous with higher tooth numbers.

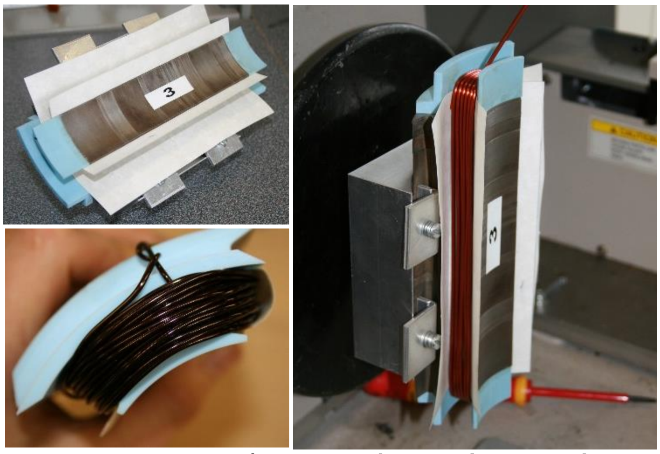

Figure 2: A stator segment of a FSCW synchronous reluctance machine. Top left: Unwound segment with end caps and insulation. Bottom left: Wound segment. Right: Bobbin winding.

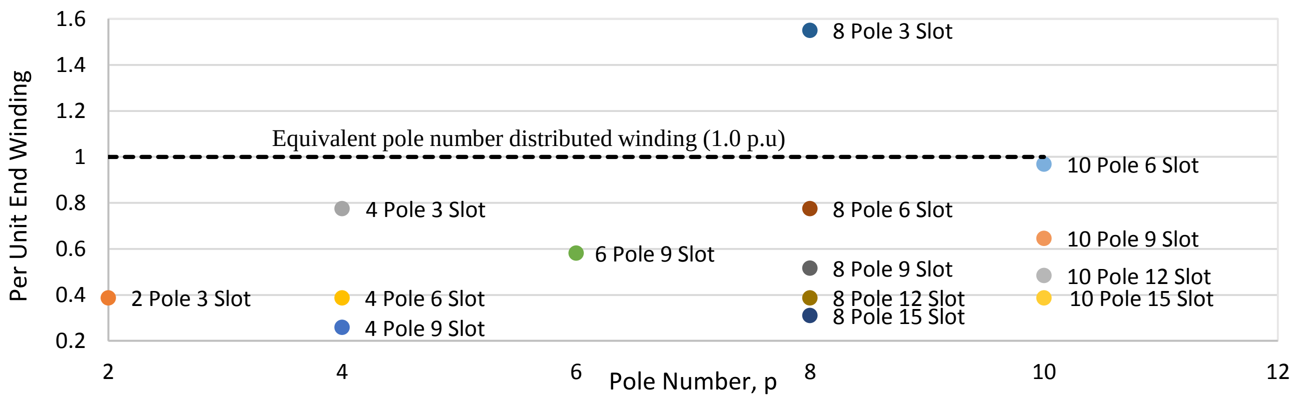

Fig 1: Relative end winding length of various slot-pole combinations of fractional slot concentrated windings and base distributed windings.

C. Fill Factor and Thermal Advantages

Due to stator segmentation, higher slot fill factors can be achieved, further reducing the copper loss (at the expense of increased copper mass). The coils can be bobbin wound on the stator tooth where it is possible that slot fill factors can reach 60% [5], where as if pre-compressed windings are used with removable teeth, fill factors upto 80% can be achieved [9], this is opposed to the conventional SynRM which will have a slot fill factor of less than 0.5. The smaller slot widths associated with higher slot/pole numbers, coupled with the high fill factors acts to increase the slot thermal conductivity [5]. This increase and the characteristic low copper loss minimises the temperature rise of the motor, which can be approximated by Brostrom's equation [11];

$$\Delta T = k_b\sqrt{P_{Cu}P_{Total}} = k_b P_{Cu} \quad (7)$$

This equation is based on empirical observations and the square root is simplified at low speed where iron losses are negligible, the empirically determined constant k_b determines the thermal configuration of the system and is machine dependant. In the case of higher fill factor and increasing slot number, both the copper loss and k_b are effectively reduced, reducing the temperature rise. This is extremely advantageous in automotive traction applications, however smaller slot widths may limit the number of turns per coil, which may have a detrimental impact.

D. General Remarks

FSCW potentially allow for very high efficiency SynRMs (IE4 or greater) or high output machines for traction applications that are simple and low cost to construct. By considering the efficiencies of the cSynRM in relation to a conventional SynRM, the efficiency increase of a cSynRM machine can be expressed;

$$\Delta\eta = \frac{1}{1+\frac{L}{K}(1-\eta_{Dist})} - \eta_{Dist} \quad (8)$$

Where L is a loss ratio and K is the shaft power ratio between the two machine types based on relative the end winding lengths, fundamental winding factors and achievable slot fill factors. Using typical values of these ratios, Figure 3 shows the increase in efficiency by adopting FSCW for the same size machine (example is a 4-pole machine to compare directly with conventional machines).

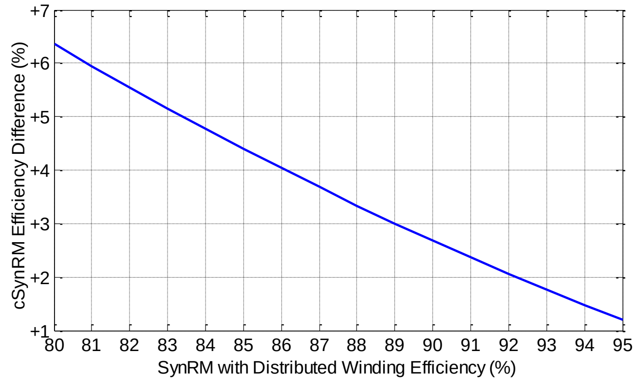

Figure 3: Machine efficiency increase due to shorter end windings and increased fill factor, taking into account lower fundamental winding factors.

This increase in efficiency acts to increase inverter utilization, however the power factor will be dominant and is investigated further in a later section. The torque index is directly dependant on the fundamental winding factor, so a machine with a lower winding factor will have a lower torque producing capability relative to a machine of the same pole number with a higher winding factor. The advantages presented provide a compelling case for the logical transition from distributed to fractional slot concentrated windings and that the benefits increase with pole number. However there are associated disadvantages which are explored in the following section.

5 Considerations for Higher Slot/Pole Numbers

It has been explained previously [5] that due to the discrete placement of coils around the airgap periphery, significant space harmonic content exists in the machine MMF profiles of machines equipped with FSCW. Increased super- and sub-harmonic content of both *odd* and *even* ordinals contribute to unwanted parasitic effects in the cSynRM. Figure 4 shows the MMF harmonic content of a 6-slot 4-pole winding and a 9-slot 8-pole winding.

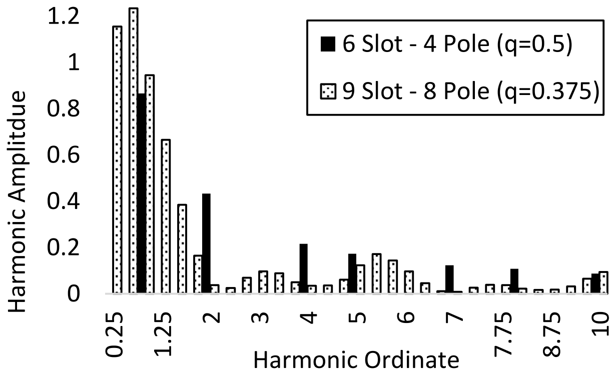

Figure 4: MMF harmonic spectrum of a fractional slot concentrated windings with q=0.5 and q=0.375.

The figure shows high space harmonic content, especially in the case of q=0.375 which contains sub-harmonics that are of greater magnitude than the fundamental. This harmonic content is not useful in torque production, only in manifesting parasitic effects within the machine, which are greatly increased over that of a distributed winding machine.

3.1 Machine Inductances

The *d*-*q* inductances (Eq. 1) of the SynRM are very important as the total rotor electromagnetic torque is related to their difference and the power factor related to their ratio. The inductances are comprised of the magnetizing, $L_{m(d,q)}$ and stator leakage $L_{s\sigma}$ components.

A. Magnetising Inductances

The magnetising inductances are largely due to the design of the rotor magnetic circuit where a large d-axis inductance and low q-axis inductance are desired. The change in stator winding from sinusoidally distributed to fractional slot concentrated does not impact upon the rotor design at first sight, however, it does impact the inductance. The magnetising inductance is expressed [12];

$$L_{m(d,q)} = \frac{6D_{\text{rotor}}\mu_0 l}{\pi\, p^2 \delta_{\text{eff}}}(k_{w1}N)^2 \qquad (9)$$

Where D_{rotor} is the rotor outer diameter, p is the number of pole pairs and N is the number of series turns per phase. Clearly the inductance obeys an inverse square law with the number of pole-pairs as with the induction machine [10]. Therefore, increasing the pole number effectively decreases the torque capability (with respect to the torque index, and consequently machine efficiency). The decrease in L_{md} is more pronounced than L_{mq} due to the difference in the effective airgap δ_{eff} between the *d* and *q* axes. This change also has a negative effect on the machine power factor by reducing the saliency ratio. As the number of poles increase, the magnetising inductances decrease and the machine draws more reactive power and hence the power factor is lower. However, the power factor of all pole number machines increases with machine power rating and the low power factor is more pronounced in lower output machines. The decrease in torque capability (efficiency) and power factor decrease the inverter utilization and therefore the size of the required inverter increases proportionally. Larger outer diameter machines are therefore required if performance is to be maintained.

B. Lumped Leakage Inductance

The leakage inductance component includes both geometric and harmonic leakage terms, the airgap leakage, end-winding leakage, tooth-tip leakage and the slot leakage components. This leakage inductance must be formally included in the analysis if iron losses are present as this prevents it being absorbed into the magnetising inductances. The geometric leakage inductances (slot, tooth tip, etc.) are less significant in FSCW than the airgap leakage, which is the only leakage flux that crosses the airgap. Rewriting the *d-q* inductances of the machine by grouping the airgap crossing inductances in a FSCW machine as in [13], the total *d-q* axis inductances are represented;

$$L_{(d,q)} = \frac{6D_{\text{rotor}}\mu_0 l}{\pi\, p^2 \delta_{\text{eff}}}(k_{w1}N)^2 \sum_{\substack{v=1 \\ v\neq p}}^{\infty}\left(p\,\frac{k_{vw}}{v k_{vp}}\right)^2 + L_{\sigma g} \qquad (8)$$

Where $L_{\sigma g}$ is the cumulative geometric leakage inductance and $\sum_{\substack{v=1 \\ v\neq p}}^{\infty}\left(p\,\frac{k_{vw}}{v k_{vp}}\right)^2$ is the airgap leakage factor σ_{ag}. In [13] Eq. (8) was experimentally validated and it was shown that careful consideration of the airgap leakage and its dominance over the airgap crossing magnetising inductance is required. If σ_{ag} is >1, the harmonic leakage crossing the airgap can actually be said to be dominant over the torque producing fundamental. The airgap leakage factor for the considered slot-pole combinations are presented in Table. II.

A. Saliency Ratio and Power Factor

There are two definitions of saliency ratio, the *magnetising saliency ratio* and the *true saliency ratio*. The former is the ratio of the direct and quadrature axis magnetising inductances, disregarding stator leakage components. The *true saliency ratio*, represented in Eq. (1) contains the stator leakage terms, including the airgap leakage inductance. If any component of the leakage inductance increases, the torque effectively remains unaffected in a salient machine, however the power factor suffers due to a reduction in the true saliency ratio, further reducing the inverter utilization. The true saliency ratio and power actor degradation depend upon the relative magnitudes of the *d-q* axis magnetising inductances and the leakage inductance, for typical values, the change with increased leakage inductance is presented in Fig. 4, along with a reasonable value of magnetising saliency ratio of '14'.

TABLE II
AIRGAP LEAKAGE FACTORS

	Number of Poles				
Number of Slots	**2**	**4**	**6**	**8**	**10**
3	0.462	4.85		22.4	35.5
6		0.462		4.85	40.1
9			0.462	2.15	3.29
12				0.462	1.95
15					0.462

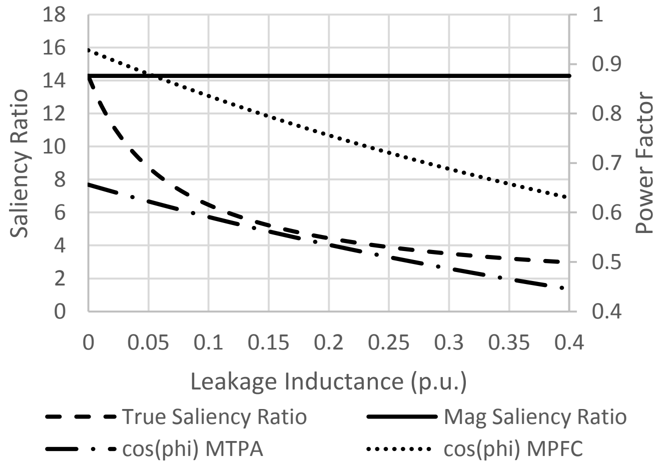

Figure 4: True saliency ratio and power factor variation with increased leakage inductance under Maximum Torque per Amp (MTPA) and Maximum Power Factor (MPFC) controls.

The selection of the slot-pole combinations is therefore very important for the achievable saliency ratio and power factor. With increased airgap leakage factor due to poor slot pole combination selection the power factor and inverter utilization is greatly reduced. The constant-power speed range is however known to be wide in permanent magnet machines with a large airgap leakage factor [13], and such a characteristic may be observed in the synchronous reluctance motor.

Another consideration is the effect on iron losses – the harmonic fluxes, especially at slot-pole combinations with high airgap leakage factors can be expected to yield higher iron losses even at low speed. However, it is beyond the scope of this paper to investigate this in depth.

6 Machine Aspect Ratio

In longer stack length machines, the end winding length is a lower percentage of the overall coil length, thus, the shorter the axial length the more dominant the end winding resistance on the copper loss. The ratio of stator outer diameter to stack length is defined;

$$\sigma_{AR} = \frac{D}{l} \tag{9}$$

Thus, in order to maximise the benefits of the fractional slot concentrated winding with higher pole numbers, the aspect ratio of the machine transitions from the usual long cylinder type machine to a pancake type machine. This ensures that the reduction in end windings length is significant compared to that axial conductor length. Larger outer diameters with short stack lengths are preferable, which may limit the machines application, depending upon space constraints.

Previously in Section 5, the statements based on identical rotor outer diameters. If the aspect ratio of the machine is changed to increase the advantage of higher pole number FSCW, the rotor outer diameter is increased. This improves the situation, and it is clear to expect an increase in efficiency. Table III outlines the performance of a 6 slot 4 pole cSynRM with an aspect ratio of 1 and 2 at the machine rated operating point (1500 rpm, 20A line current, 45 degree current angle). An appreciable increase in machine efficiency is observed.

TABLE III
ASPECT RATIO COMPARISON

Parameter	$D/l = 1$	$D/l = 2$
Stator OD [mm]	150	200
Stack Length [mm]	150	90
Volume [mm^2]	2.6e6	2.6e6
Torque [Nm]	20.2	19.7
Efficiency [%]	91.2	94.0
Winding Loss [W]	271	152
Fill Factor	0.6	0.6
Power Factor	0.475	0.474

7 Design and Manufacturing

As the number of poles increases, for a given rotor outer diameter, the available space in which to shape the flux barriers diminishes. As with a two pole rotor, the flux barrier design becomes very difficult at higher pole numbers due to the requirement of effectively shaping of the barriers to maximise performance. To adequately shape the flux barriers at higher pole numbers requires an increase in rotor outer diameter, which is advantageous in both torque capability and power factor, however may not be suitable in some applications with space restrictions as mentioned in Section 6.

In higher pole number machines, the radial and tangential ribs must remain at the smallest width possible. Rib width should reduce with increased pole number as the flux per pole reduces. Therefore, to ensure saturation and minimisation of the q-axis inductance, the ribs have to be diminishingly small. However, punching limits enforce a minimum rib width, affecting performance. Smaller ribs are possible with other forms of manufacturing such as electro-discharge machining (EDM) and pulsed laser cutting, but in general for mass production, punching is the only viable option, however the small widths increase tool wear. The mechanical performance is also affected by the rib thicknesses and lower maximum speeds will be required to be enforced with higher pole number machines.

Also, as the number of poles increases, the number of barriers required for good performance does not decrease. As a consequence the number of stamped sections increases linearly with the number of poles increasing stamping tool complexity, cost and maintenance.

8 Brief Performance Comparison

The previously presented cSynRM (6 slot 4 pole) was shown to exhibit a higher performance in efficiency and torque density that an identical size and aspect ratio SynRM. It did however have a lower power factor and higher torque ripple. [5], for which novel technique was developed for analysing and to reducing it to more acceptable levels [14]. The gains in efficiency are increased with increasing aspect ratio as outlined in Section 6.

As an extension, a designed higher pole number cSynRM is presented as a comparison. The machine is of the 9-slot 6-pole type, which has a good fundamental winding factor and a low airgap leakage factor. The machines has an identical electromagnetic volumes equal to that of the 4-pole machine in Section 7 and are controlled by a virtual drive with a 500V DC link, 20A phase current with a current angle of 45 degrees for Maximum Torque per Ampere.

A. Chosen 9 Slot 6 Pole Machine

A good machine to pursue, based on the arguments in this paper is the 9-6 cSynRM topology (Fig. 5), a fractional slot concentrated winding synchronous reluctance machine with higher pole numbers. The fundamental winding factor is 0.866, with a low airgap leakage factor of 0.46, a slot fill factor of 0.6 and an aspect ratio of 2. The machine outer diameter is 200mm and the stack length of 90mm. The base speed is 1000rpm, but is operated at 1500rpm.

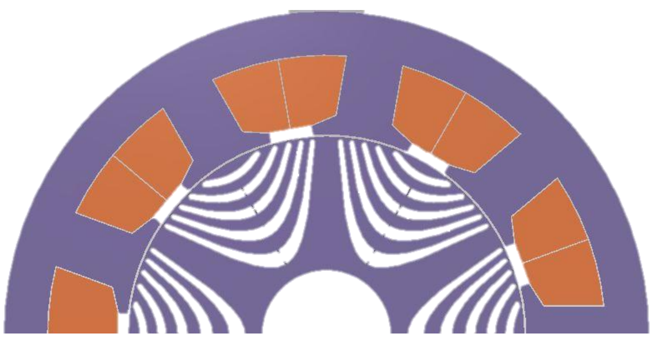

Figure 5: The designed 9 slot 6 pole machine used in the study.

Through finite element studies, it is determined that at the rated operating point, the machine develops 23Nm of torque at 1500rpm, giving a shaft mechanical power of approximately 3.6kW. This in comparison to the 4 pole 6 slot machine with the same aspect ratio studied previously, that develops approximately 20Nm at 1500rpm for the same electromagnetic volume. The end winding length is calculated as approximately 50mm, giving a copper loss of only 113W (iron loss is 82W at 1500rpm). The efficiency is therefore around 95%, which is greater than the lower pole number machine. However, it does exhibit a lower power factor due to the reduction in saliency ratio, lowering the inverter utilisation. Table IV provides a comparison between key parameters.

TABLE IV
MACHINE COMPARISON

Parameter	6 slot 4 pole	9 slot 6 pole
Stator OD [mm]	200	200
Stack Length [mm]	90	90
Volume [mm^2]	2.6e6	2.6e6
Torque [Nm]	19.7	23
Efficiency [%]	94.0	95.0
Winding Loss [W]	152	113
Fill Factor	0.6	0.6
Power Factor	0.474	0.04
Inverter Utilisation	0.44	0.38

If the fill factor is increased to 75%, which is reasonable if pre-compressed coils are used [9], the efficiency will be even greater, though an additional manufacturing process will be required. In order to increase the power factor to the value of that of the lower pole number machine, for the same output an electromagnetic volume increase is required. This has briefly shown that higher pole number synchronous reluctance machines with fractional slot concentrated windings are viable, but correct slot pole combinations and aspect must be optimised for maximum performance.

9 Conclusions

There are inherent benefits in moving to higher slot-pole combinations with fractional slot concentrated windings applied to synchronous reluctance machines. Increased efficiency (upto 6%), manufacturability and thermal properties can be achieved with a reduction in cost and complexity. However, there are certain limitation and design issues caused by the parasitic effects of fractional slot concentrated windings, especially at higher pole numbers. Careful consideration of the slot-pole combination must be observed. Increasing the pole number reduces the magnetising inductances impacting power factor and torque capability (efficiency) and larger rotor outer diameters must be used to counter this effect. Increases in stator leakage inductance due to space harmonic content can greatly reduce the power factor further, compounding the poor inverter utilization. A change in aspect ratio must be effected in order to obtain optimal performance, where again a large outer diameter with a shorter stack length is preferable and has shown that similar electromagnetic performance can be achieved with higher efficiency due to a reduction in copper losses. Based on these arguments, a 9 slot 6 pole machine is shown to exhibit higher performance that the original 4 pole machine through good choice of slot pole combination and aspect ratio. The machine exhibits a higher specific output and a higher efficiency, but its power factor and inverter utilisation are still a cause for concern. This is an area for further research.

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