A Fractional Slot Concentrated Winding (FSCW) Configuration for Outer Rotor Squirrel Cage Induction Motors

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***Abstract*-- Fractional Slot Concentrated Windings (FSCW) or tooth windings have been proved to be very beneficial for synchronous and permanent magnet (PM) motors. However, the abundance of space harmonics in the air gap flux have rendered FSCW configurations unsuitable for induction motors. This paper proposes the use of a multi-layer FSCW wound around two layers of stator slots that eliminates sub (a fraction of fundamental) and higher order space harmonics and provides a non-overlapping winding arrangement. This winding configuration has several advantages like high torque density, shorter end-winding length and easier manufacturability for outer rotor squirrel cage induction motors for pumps, fans and in-wheel hub drives. A design comparison is performed between the proposed winding configuration and a conventional distributed winding.**

***Index Terms*-- concentrated winding; fractional slot; FSCW; induction motor; MMF harmonics; non-overlapping; outer rotor; squirrel cage; tooth wound**

I. Introduction

Fractional Slot Concentrated Windings (FSCW) or tooth windings provide several advantages over conventional distributed windings such as higher torque density, non-overlapping end connections, reduced overhang, higher fill factor and easier manufacturability [1]. Recent attempts to apply FSCW to induction motors in the literature, have resulted in poor performance. The air gap flux density distribution created by using FSCW configurations is rich in sub and higher order space harmonics. Although this only translates to rotor and magnet losses in PM motors, in induction motors these harmonics induce currents in the cage rotor. This results in low average torque, high rotor copper loss as well as torque pulsations at different rotor speeds. In [2], the most commonly used FSCW slot-pole combinations for PM motors; the 1/2 slot per pole per phase (SPP) and 2/5 SPP are used with induction motors with limited success. Although the double layered 1/2 SPP is shown to provide promising results it is sub- par when compared with a conventional integral SPP distributed windings in terms of average/ripple torque and rotor losses.

Multi-layer FSCW configurations have been used in PM motors to minimize losses by reducing or cancelling some of the sub and higher order space harmonics [3]. In [4], this idea is extended to induction motors while also using a multi-layer tooth wound rotor. Although this helped minimize harmonics in the air gap flux and their interaction with the rotor, the resulting configurations still exhibited high torque pulsations. Additionally, the manufacturing advantage provided by using a rotor cage that can be die cast with aluminum or copper, is lost.

In this paper, the application of FSCW to induction motors has been further explored. The traditional tooth wound configuration for the stator winding that is usually associated with FSCW has been abandoned, but by creating two layers of stator slots it is shown that the advantages of a non-overlapping, shorter end connections and higher slot fill factor can be achieved with the proposed winding for outer rotor motors, while simultaneously preserving the cage rotor construction. Multi-layer stator windings with varying turns per coil along with a skewed rotor are used to create an air gap flux density distribution that is closer to a conventional distributed winding. The details of the slot pole combination, winding layout, stator construction and rotor design are presented. Additionally, the proposed FSCW stator is compared with a conventional integral SPP stator designed for a geared in-wheel hub motor for electric two wheelers.

II. Stator Winding Design

A. Feasible Slot Pole Combinations

For a given choice of number of poles and number of slots, independent of the SPP, there exists in the air gap, step-harmonics produced as a result of arranging the winding in slots, which are given by (1):

$$\nu = (kZ \pm p), k = 0,1,2,3 \ldots \tag{1}$$

Where,

ν = order of the step-harmonic
Z = number of stator slots

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p = number of pole pairs

For a winding with a constant slot pitch, the winding factors for the step-harmonics are the same as the fundamental ($k = 0$) [5]. Hence, the air gap MMF due to a step-harmonic of order ν has an amplitude that is p/ν of the fundamental.

For conventional FSCW the ratio of $Z/2p$ is chosen to be close to 1. This ensures that when using a tooth wound coil the fundamental pitch factor is close to unity. As a result, the first order step harmonics ($k = 1$) are closer to the fundamental and hence create MMF components that are comparable in amplitude to the fundamental. Table 1 shows the amplitude of the first order step harmonics as percentage of the fundamental for some common FSCW slot pole combinations.

TABLE 1. STEP HARMONIC AMPLITUDES FOR COMMON FSCW CONFIGURATIONS

Slot /Pole /Phase	$(Z-p)$ (% of fundamental)	$(Z+p)$ (% of fundamental)
3/8 *(9 slot 8 pole)*	80	30.8
1/2 *(12 slot 8 pole)*	50	25
2/5 *(12 slot 10 pole)*	71.4	29.4
5/14 *(15 slot 14 pole)*	87.5	31.8
3/7 *(18 slot 14 pole)*	63.6	28

The currents induced in the rotor due to step-harmonics produce asynchronous and synchronous parasitic torques that reduce the average torque and create torque pulsations that are a function of rotor speed. When compared to a distributed winding where the step-harmonics are of a much higher order relative to the fundamental, an FSCW results in an inferior design.

Increasing $(Z-p)$ to minimize the step harmonics would increase $Z/2p$ well above 1 which in turn causes the fundamental pitch factor to reduce for a tooth wound coil when compared to a distributed winding where pitch factor is typically > 0.9. Although there is less copper used for the end connections more turns are now required in the slots for comparable torque production.

A suitable compromise is achieved by using a coil pitch of two slots and creating two layers of stator slots. This configuration, which is more suitable for outer rotor motors, makes it possible to create non-overlapping and hence shorter end connections that preserve the advantage provided by FSCW in terms of better copper utilization. At the same time, the two slot coil pitch ensures that the fundamental pitch factor is still comparable with distributed windings. Details of dual slot layer stator are explained in Section III. For induction motors higher number of poles results in low magnetizing inductance and poor power factor. This in turn affects the efficiency by increasing the stator current required for a given torque and the kva rating for the inverter driving the motor. Based on these considerations a 24 slot 10 pole winding with a two slot coil pitch and a dual slot layer stator is chosen for design. The pitch factor and amplitudes of the first order step harmonics are given in Table 2.

TABLE 2. PARAMETERS OF 24 SLOT 10 POLE STATOR

Parameter	Value
Pitch Factor (K_{p5})	0.966
$19^{th}, (Z-p)$	26.3% of 5th harmonic
$29^{th}, (Z+p)$	17.24% of 5th harmonic

B. Stator Winding Configuration

Opting for a fractional SPP creates additional sub and higher order space harmonics in the air gap MMF that have the same effect on torque production of an induction motor as the step-harmonics. . However unlike the step harmonics that have the same winding factor as the fundamental, it possible to minimize or cancel these MMF harmonics by several means.

In PM motors, minimizing or cancelling these harmonics improves the efficiency of the motor and has been explored in the literature. The methods include using multi-layer windings [3], different turns per coil side [6], different turns per coil [3], and using multiple winding systems shifted in space [7]. In this paper, a multi-layer winding with varying turns per coil is designed for the 24 slot 10 pole stator.

The star of slots theory [8], is used to design the winding. Since each coil has a two slot coil span the spokes on the star now correspond to number of turns across two adjacent stator teeth instead of a single tooth. The angle between the spokes is given by (2):

$$angle\ between\ spokes\ \theta = \frac{360 \times GCD(Z,p)}{Z} \quad (2)$$

For the proposed slot pole combination this angle is 15^0. The star of slots diagram for a 24 slot 10 pole motor is shown in Fig. 1.

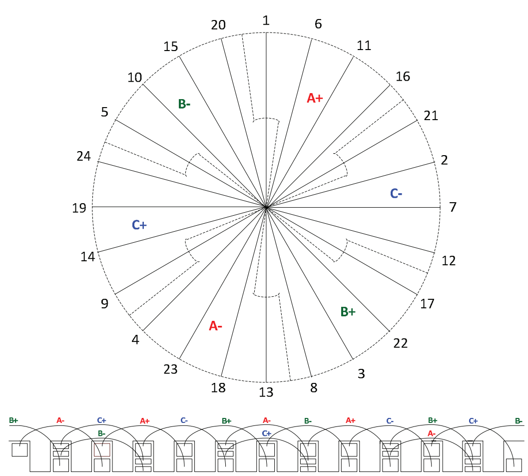

Fig. 1. Star of slots for 24 slot 10 pole multi-layer configuration with uniform turns per coil.

For the above multi-layer winding the air gap MMF waveform around the rotor periphery and its space harmonics are shown in Fig. 2. It can be seen that this winding has a high first order sub-harmonic. The other harmonics at 19, 29 and 43 are the step-harmonics produced due to placing the coils in 24 slots.

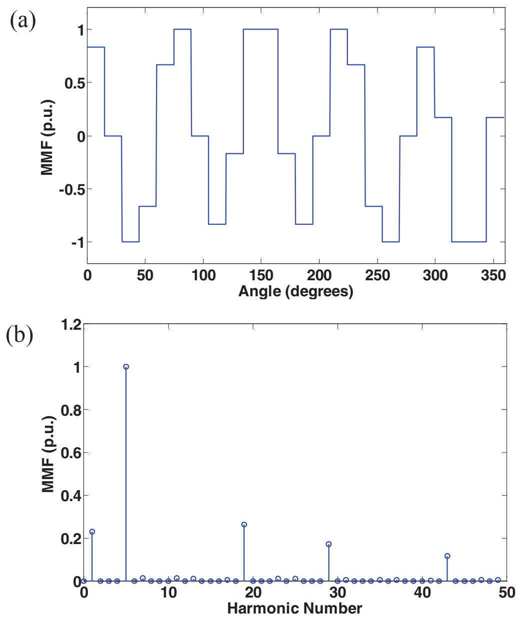

Fig. 2. (a) Air gap MMF of 24 slot 10 pole winding with uniform turns per coil and, (b) its frequency components.

While it is not possible to cancel the step harmonics additional degrees of freedom are introduced to minimize the first sub harmonic. Two variables x and y are used to denote the fraction of the total turns per coil for certain selected coils. The modified star of slot diagram is shown in Fig. 3. The values of x and y are now varied from 0 to 1. Fig. 4 shows the variation in the first sub harmonic as x and y are varied from 0 to 1.

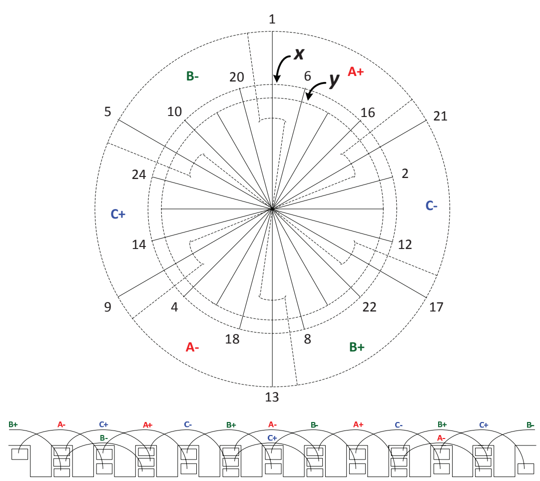

Fig. 3. Star of slots for 24 slot 10 pole multi-layer configuration with varying turns per coil.

Based on the plot in Fig. 4, it is possible to eliminate the first sub harmonic by setting $x = 0.7$ and $y = 0.5$. The resulting air gap MMF and its space harmonics are shown in Fig. 5. It can be seen that the first order sub-harmonic is completely eliminated and the only significant harmonics in the air gap are the step harmonics at 19, 29 and 43. The pitch and distribution factor for this modified winding are given in Table 3.

TABLE 3 WINDING FACTOR FOR 24 SLOT 10 POLE STATOR WITH VARYING TURNS PER COIL

Parameter	Value
Pitch Factor (K_{p5})	0.966
Distribution Factor (K_{d5})	0.9373
Winding Factor (K_{w5})	0.9054

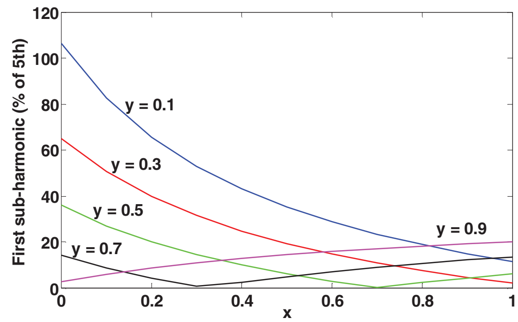

Fig. 4. Variation of first order sub-harmonic with x and y.

It is worthwhile to point out that the winding adopted in [7] is effectively a 24 slot 10 pole double layer winding with a two slot coil pitch. However, the resulting air gap MMF distribution in [7] additionally has a significant 17^{th} harmonic.

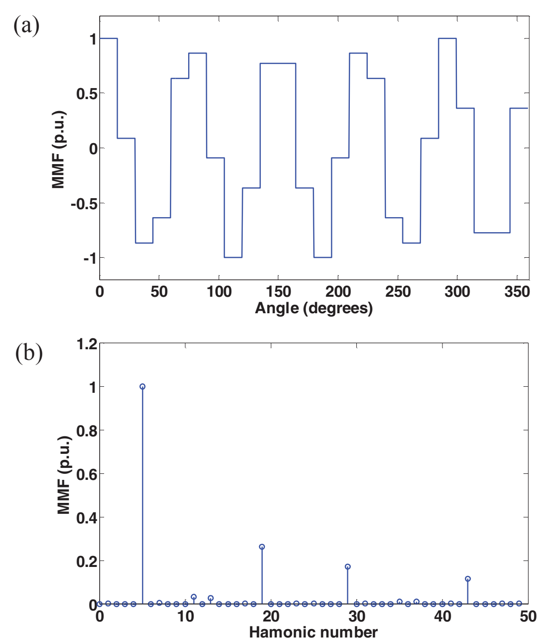

Fig. 5. (a) Air gap MMF of 24 slot 10 pole winding with varying turns per coil and (b) its frequency components.

III. DUAL SLOT LAYER STATOR

The winding configuration for a 24 slot 10 pole stator has a coil pitch of two slots. This results in an overlapping end connection which affects the copper utilization. It can be seen from Fig. 3 that the stator slots alternate between having two and three layers of coils. It is proposed to arrange the stator slots in two layers with alternate slots in a lower layer as shown in Fig. 6.

For the above winding, such a dual slot layer stator structure and an outer rotor are advantageous for the following reasons,

- Non-overlapping end connections similar to a tooth wound FSCW, Fig. 6(b).
- Lower end winding length due to shorter coil radius especially for the second layer.
- Reduction in overall motor volume due to shorter rotor back iron width required for a higher number of poles. For an external stator more back iron will be required to accommodate the second slot layer thereby increasing the total volume.
- High slot fill factor by using in-slot winding machines to wind both slot layers, shown in Fig. 7(b).

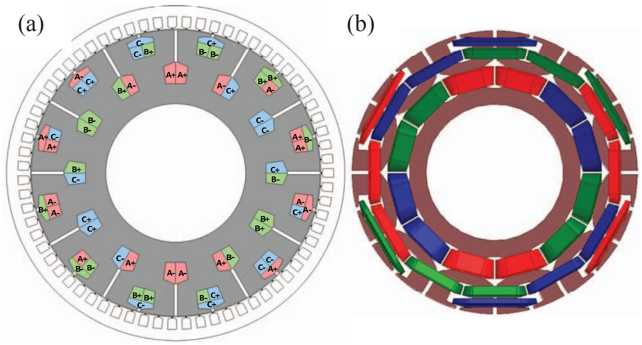

Fig. 6 (a) Dual slot layer 24 slot 10 pole stator and (b) it end connections.

This type of stator slot arrangement is commonly used in single phase outer rotor induction motors for ceiling fans as shown in Fig. 7(a). The main winding is wound in the peripheral layer and the starting or auxiliary winding in the second layer. The number of poles per layer can vary from 8 to 18. Commercially, automated in-slot winding machines are used in this application to wind the coils around each tooth in a layer making it possible to achieve higher fill factors [9]. Fig. 7 shows a ceiling fan stator and an in-slot winding machine used to create the stator winding.

Fig. 7. (a) 24 slot ceiling fan stator (b) In-slot winding machine [9].

It is important to note that, for the resulting non-overlapping 24 slot 10 pole winding with a two slot coil pitch, the end winding length is the same as a 12 slot 10 pole tooth wound 2/5 SPP winding that is widely used for PM motors.

IV. CAGE ROTOR DESIGN

For an induction motor, the stator and rotor slot combinations significantly impact the audible noise and the average/ripple torque production at different speeds. The rotor slot shape and the number of rotor slots is chosen to achieve a desired torque and efficiency characteristic by accounting for the parasitic torques caused by the stator sub and higher order MMF harmonics [5]. The change in rotor resistance and leakage inductance due to skin effect is obtained from circuit analysis by dividing the rotor slot into multiple layers [10].

For the 24 slot 10 pole stator, the dominant step-harmonics at 19 and 29 can be cancelled/reduced by skewing the rotor slots. However, the fundamental winding factor reduces as the skew angle is increased [10]. A skew angle of $2\pi/29$ radians or 12.414^0 is chosen to cancel the 29^{th} step harmonic. Table 4 shows the fundamental winding factor with a skewed rotor and the amplitudes of the lower order step harmonics as a result of skewing.

TABLE 4 WINDING FACTOR FOR 24 SLOT 10 POLE STATOR WITH SKEWED ROTOR SLOTS

Parameter	Value
Winding Factor (K_{p5})	0.861
$19^{th}, (Z-p)$	11.86% of 5^{th} harmonic
$29^{th}, (Z+p)$	0
$43^{rd}, (2Z-p)$	2.62% of 5^{th} harmonic

V. DESIGN COMPARISON

The performance of the proposed 24 slot 10 pole FSCW stator is compared to a conventional single layer concentric wound 60 slot 10 pole distributed winding stator for an outer rotor geared in-wheel hub motor for electrical two wheelers. The design constraints are

- Rotor outer diameter (OD) = 145 mm
- Stack length = 40 mm
- DC bus voltage = 48 v
- Output power = 1.1 kW at 2800 rpm (fundamental frequency = 240 Hz)

The winding factor of the 60 slot 10 pole distributed winding is given in Table 5.

TABLE 5 WINDING FACTOR FOR 60 SLOT 10 POLE STATOR

Parameter	Value
Pitch Factor (K_{p5})	1
Distribution Factor (K_{d5})	0.9659
Winding Factor (K_{w5})	0.9659

The FSCW stator has an inferior winding factor as well as a higher leakage inductance caused by the deeper slot openings of the inner slot layer. For a fair comparison, it is necessary to exploit the shorter stator end connections that are characteristic of FSCW. The effective stack length is defined as the sum of the stack length and end extension on both sides of the stator as shown in Fig. 8. The end extension and end winding length of the proposed FSCW winding and distributed winding are obtained from ANSYS

Maxwell Modeler.

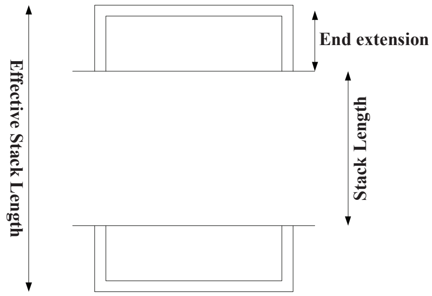

Fig. 8. Effective stack length of a stator.

It is observed that for the same effective stack length, the stack length of the FSCW stator is 48 mm as compared to 40 mm stack length for the distributed winding stator. It is worthwhile to note that concentric coils provide the lowest end extension for a distributed winding. The comparison of the stack length for the two motors is shown in Fig. 9.

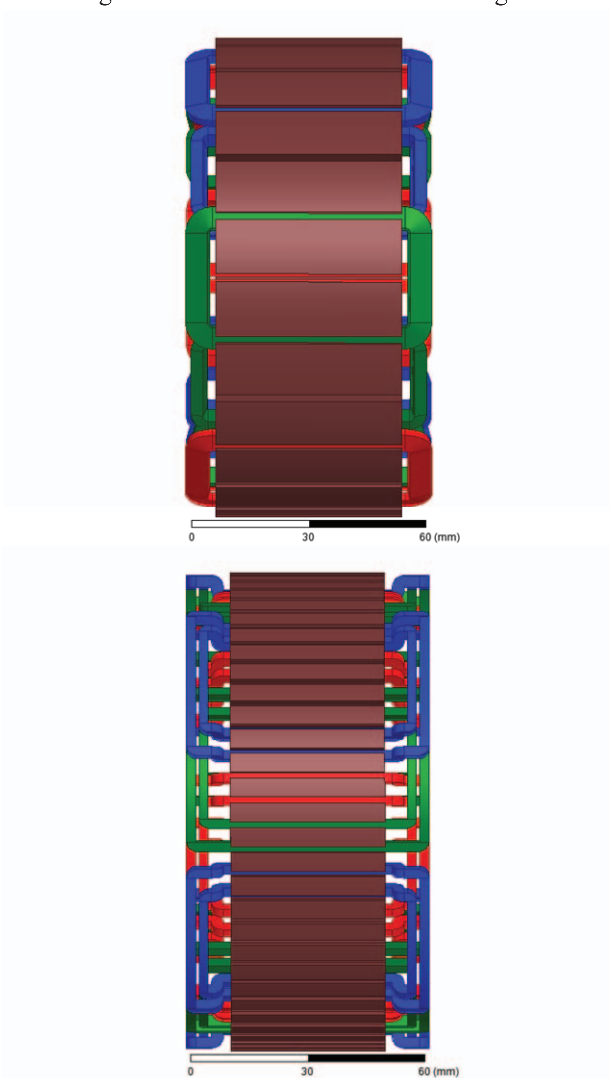

Fig. 9. Comparison of stack lengths of FSCW and distributed winding for the same effective stack length.

A 67 slot rotor with copper bars and a 0.3 mm air gap is used for both motors. The rotor of the FSCW motor additionally has a skew of 12.414^0 as explained in the previous section. The rotor slot shape is optimized for the fundamental 10 pole MMF harmonic using the standard induction motor equivalent circuit and is the same for both designs. The stator slots are designed for an rms current density of 5.6 A/mm^2. The air gap flux density distribution, including the saturation effects, obtained from transient finite element analysis (FEA) of the two motors in Cedrat Flux2D/FluxSkew is shown in Fig. 10. The FSCW motor is simulated using a layered quasi-3D model with skewed rotor slots in FluxSkew. As expected, step harmonics exist in the air gap flux but the amplitudes of the step harmonics are modulated by the slot permeance harmonics which occur at the same frequencies [5]. A comparison of the two designs is shown in Table 6. The loss calculations are obtained from FEA simulations.

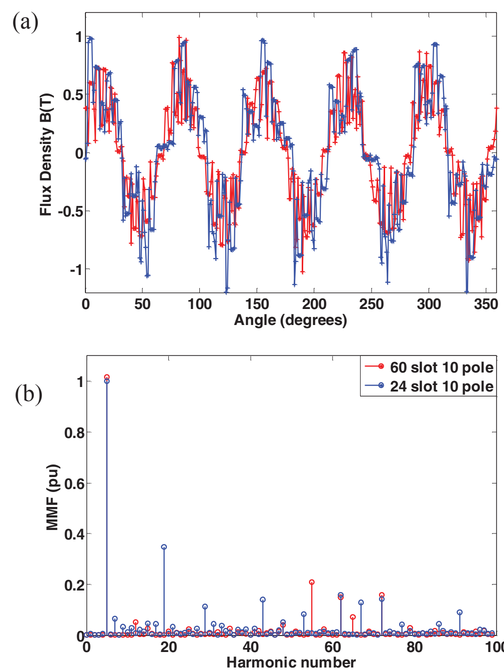

Fig. 10. (a) Air gap flux density of the FSCW and distributed winding designs from FEA and, (b) their frequency components.

TABLE 6 COMPARISON OF FSCW AND DISTRIBUTED WINDING

Parameter	24 Slot 10 Pole	60 Slot 10 pole
Stack length (mm)	48	40
Turns per phase	24 (26 strands of 22 AWG per turn)	30 (22 strands of 22 AWG per turn)
Rated Current (A)	48	40
Rated Slip	2.5%	2.25%
Stator copper loss (w)	84.5	90
Stator core loss (w)	133.69	63.81
Rated efficiency (%)	81.5	86.1
Copper volume in stator (m^3)	0.0942	0.1227
Copper volume in rotor (m^3)	0.0522	0.0424

The following observations can be made

- The FSCW has a low magnetizing inductance due to low fundamental winding factor when compared to the distributed winding resulting in a higher rated slip and higher rotor copper losses.
- The choice of turns per coil in the FSCW configuration is restricted by the condition that was derived to eliminate the first sub-harmonic in Section II B.
- Due to the non-overlapping and shorter end connection, the end winding leakage and stator resistance of the FSCW are lower compared to the conventional distributed winding. However, the presence of deep slot openings especially for the inner slot layer, increases the slot leakage.
- The additional core loss in the FSCW motor is attributed to the higher slot and harmonic leakage as well as the increase in core volume created by the longer stack length. The flux density distribution of the two designs is shown in Fig. 11.

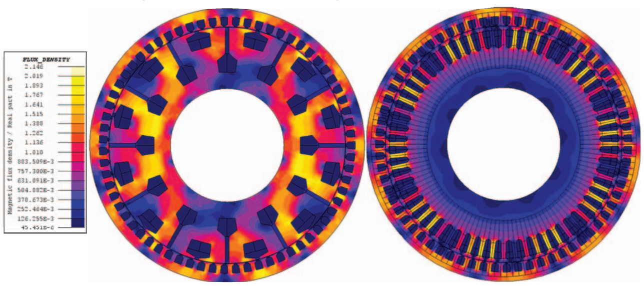

Fig. 11. Comparison of flux density distribution in the FSCW and distributed winding motors.

- Even after accounting for the increased rotor bar length due to skewing; the shorter overhang and end winding length of FSCW results in an 11.3% reduction in the copper volume for the FSCW motor when compared to the distributed winding motor.
- A comparison of the torque ripple at rated condition for the two motors obtained from transient FEA is shown in Fig. 12. The distributed winding motor has a marginally lower torque ripple but the use of multi-layered winding and a skewed rotor significantly lowers the torque pulsation for the FSCW motor.

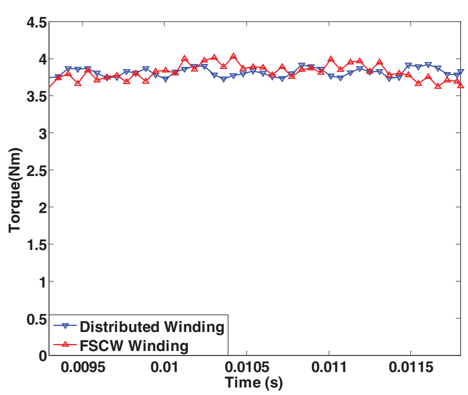

Fig. 12. Instantaneous torque of the FSCW and distributed winding motors at rated slip.

VI. Conclusion

An FSCW configuration suitable for outer rotor squirrel cage induction motors has been presented. The proposed design uses a multi-layer winding with varying turns per coil and a skewed rotor to minimize the space harmonics in the air gap MMF. A dual slot layer stator construction that is commonly used for single phase ceiling fan motors has been adopted to create a non-overlapping end-winding and a high slot fill factor, similar to the tooth wound FSCW. A cost effective winding method using in-slot winding machines has been identified.

A 24 slot 10 pole outer rotor motor with the proposed FSCW stator has been compared to a 60 slot 10 pole distributed winding motor designed for the same specification. It has been shown that when taking into account the effective stack length the FSCW motor can provide comparable performance in terms of average/ripple torque with a significant reduction in total copper usage. However, the comparatively lower fundamental magnetizing inductance and increased slot and harmonic leakage of the FSCW affects its efficiency.

Nevertheless, for an induction motor the proposed stator configuration gives the best of both worlds in terms of easy manufacturability of the cage rotor and stator winding as well as better copper utilization of FSCW without compromising on performance.

VII. Acknowledgment

The authors would like to thank ANSYS and MAGSOFT Corporation for their support of finite element analysis software.

VIII. References

[1] EL-Refaie, A.M., "Fractional-Slot Concentrated-Windings Synchronous Permanent Magnet Machines: Opportunities and Challenges," *IEEE Trans. Industrial Electronics,* vol.57, no.1, pp.107,121, Jan. 2010

[2] J EL-Refaie, A.M.; Shah, M.R., "Comparison of Induction Machine Performance with Distributed and Fractional-Slot Concentrated Windings," in *Proc. IEEE Industry Applications Society Annual Meeting, 2008. IAS '08*, vol., no., pp.1, 8, 5-9 Oct. 2008.

[3] Cistelecan, M.V., Ferreira, F.J.T.E.; Popescu, M., "Three phase tooth-concentrated multiple-layer fractional windings with low space harmonic content," *Proc. IEEE Energy Conversion Congress and Exposition (ECCE), 2010*, vol., no., pp.1399, 1405, 12-16 Sept. 2010.

[4] Alberti, L., Bianchi, N., "Design and tests on a fractional-slot induction machine," *Proc. IEEE Energy Conversion Congress and Exposition (ECCE), 2012*, vol., no., pp.166,172, 15-20 Sept. 2012

[5] Heller, B.; Hamata, V., "*Harmonic field effects in induction machines*", Amsterdam: Elsevier Scientific Pub. Co., 1977.

[6] Dajaku, G., Gerling, D., "Eddy current loss minimization in rotor magnets of PM machines using high-efficiency 12-teeth/10-slots winding topology," in *Proc. International Conference on Electrical Machines and Systems (ICEMS), 2011*, vol., no., pp.1,6, 20-23 Aug. 2011

[7] Dajaku, G., Gerling, D., "A Novel 24-Slots/10-Poles Winding Topology for Electric Machines," in *Proc. IEEE International Electric Machines & Drives Conference (IEMDC), 2011*, vol., no., pp.65,70, 15-18 May 2011.

[8] Alberti, L., Bianchi, N., "Theory and Design of Fractional-Slot Multilayer Windings," *IEEE Trans. Industry Applications,* vol.49, no.2, pp.841, 849, March-April 2013.
[9] Spark Controls Winding Machines website: www(dot)sparkcontrols(dot)com/machine_videos/ceiling_fan_stator_winding_machines
[10] Pyrhonen, J., Jokinen, T., Hrabovcova, V., *"Design of Rotating Electrical Machines"*, Chichester, UK: Wiley, 2008

IX. BIOGRAPHIES

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