A New Space Harmonics Minimization Strategy for Fractional Slot Concentrated Windings

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***Abstract*- A new winding concept for fractional slot concentrated winding (FSCW) is proposed that can simultaneously cancel both sub and higher order harmonics of stator MMF. The new winding concept proposes two sets of three-phase windings by doubling the number of stator slots connected in wye-delta configuration. These two winding sets are shifted in space with respect to each other and are connected in series. The wye-delta configuration eliminates sub-harmonics and enhances the torque-producing component whereas their relative shifting angle eliminates the dominant higher order harmonics to provide a cleaner and enhanced spectrum. This concept is effective when the stator slot number is multiple of twelve. The application of the proposed winding to a PM machine demonstrated dominant sub and higher order harmonics cancellation, THD reduction, torque ripple reduction, and magnetic loss reduction along with torque density and power factor improvements.**

I. INTRODUCTION

Permanent Magnet Synchronous Machines (PMSMs) exhibit high torque-density, high power-density and high efficiency because of high-energy permanent magnets in the rotor [1]. Commonly used winding configurations in PMSMs are distributed overlapping winding and non-overlapping concentrated winding. Single and double layer tooth concentrated windings in permanent magnet (PM) synchronous motors are gaining interest due to the advantages of high power-density, high efficiency, shorter end winding length [2-3], high slot fill factor, low cogging torque, good fault tolerance, and zero mutual coupling between phases. However, due to the low slot/pole/phase, the magnetic field of these windings has more space harmonics including sub-harmonic components that rotate asynchronously with the rotor and create eddy current losses in the permanent magnet and rotor iron core. The excessive heating in the permanent magnet may lead to undesirable PM demagnetization [4]. Moreover, these unwanted harmonics lead to the undesirable effects of localized iron core saturation, noise, and vibration [5].

Several research works have been reported to improve the performance of FSCW, by reducing the eddy current loss through the minimization of space harmonic contents of stator MMF. Going from single layer to double layer and double layer to four-layer result in substantial reduction of sub-harmonics for this type of winding. In [6] and [7], multilayer tooth concentrated windings are used to reduce only the sub-harmonics of stator MMF. In [8], a stator flux barrier in a specific location of back yoke is designed to reduce the sub harmonics. In these works, the reduction of sub-harmonics comes at a cost of 3-4% reduction of average torque. A combined $Y-\Delta$ winding in double layer fractional slot concentrated winding shows that this combination can effectively cancel the sub-harmonics while increasing the torque-producing component by 3.5% [4]. However, the higher order harmonics still exist in the MMF spectrum which causes undesirable rotor losses, noise, and vibration [9]. Dajaku and Gerling [9] proposed a 24-slot/10-pole winding configuration to reduce higher order harmonics where they have created two-sets of series windings while arranging them with a mechanical phase shift. Uneven turns number for neighboring phase coils are employed to reduce the sub-harmonics. However, the sub-harmonic is not reduced to zero and at the same time, the fundamental winding factor reduces by 2-3%. In [10], a six-phase machine is designed where two sets of three phase windings are created, those are mechanically shifted in space, and a time domain shift is also created using two three phase inverter. However, the effect on rotor loss, and increment in system cost with higher phase numbers were not investigated.

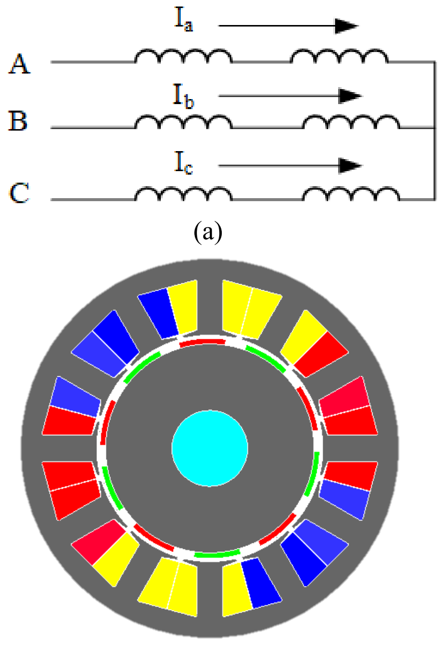
In this work, a double layer winding is proposed to simultaneously cancel both the sub-harmonics and the dominant higher order harmonics. A combined $Y-\varDelta$ winding is applied to the widely used 12-slot/10-pole configuration. Two sets of windings are created using this $Y-\varDelta$ concept and windings are space shifted with respect to each other by a particular mechanical angle depending on their slot pole combination. The effective number of slots for the resultant stator is doubled compared to the original machine. The fundamental winding factor is increased compared to the conventional double layer winding while higher order harmonics are substantially reduced. The proposed winding is applicable to the machines where the stator slot number Q is multiple of twelve ($Q=12*n$, where n is an integer number). The concept is equally suitable to reluctance machines, induction machines, and permanent magnet machines having either distributed or concentrated windings. Moreover, the common mode voltage problem in inverter fed electric machine can also be reduced using the proposed winding concept. Additionally, a single three-phase inverter can be used to energize the winding.

II. CONVENTIONAL DOUBLE LAYER (DL) FSCW

The air-gap MMF of DL FSCW contains sub-harmonics as well as higher order space harmonics (super harmonics) in addition to the main torque-producing component. If P and Q are the pole number and slot number, respectively, then the MMF spectrum contains the 1^{st} and $(k \cdot Q \pm P/2)$ space harmonics where k is an integer number. The conventional DL FSCW for 12-slot/10-pole is shown in Fig. 1. Two non-adjacent series coils are represented by a single coil in Fig. 1(a). Assuming that a_1 and a_2 are the spatial MMF axes of neighboring coils, MMF vector diagram for sub-harmonics and torque-producing component is shown in Fig. 2 (a); the resultant space sub-harmonics is 35.2% of the fundamental component. Air-gap MMF distribution can be expressed as

$$MMF_{YY} = \sum_{\nu=1,-5,7}^{\infty} \frac{12NI}{\nu\pi} \sin\left(\frac{\nu\pi}{12}\right) \sin(\nu\theta - \omega t - \nu\pi/12) \ldots\ldots (1)$$

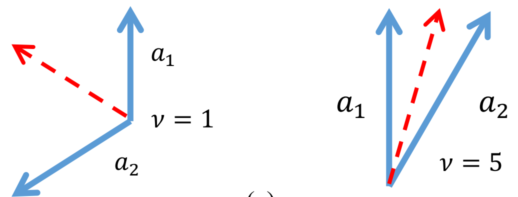
Here, N is the turn number, ν is the harmonic order and θ is the space angle. The corresponding harmonics spectrum is shown in Fig. 2(b). For 10-pole motor the 5^{th} order harmonic is the main torque producing harmonic. The other space MMF harmonics, particularly $1^{st}, 7^{th}, 17^{th}$, and 19^{th} have larger magnitudes and create undesirable effect such as core loss, core saturation, and torque ripple, as well as noise and vibration [9].



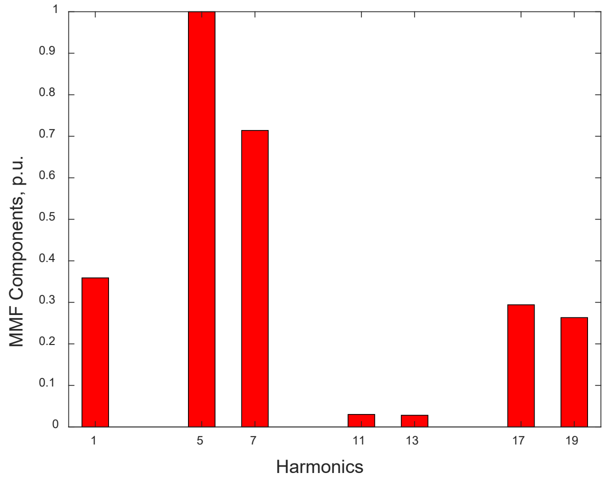
(a)

(b)

Fig. 1. 12-slot/10-pole, winding (a) connection (b) arrangement



(a)



(b)

Fig. 2. 12-slot/10-pole, (a) MMF vector diagram $\nu = 1$ and $\nu = 5$ (b) Harmonic spectrum.

III. PROPOSED WINDING CONCEPT

Among different slot/pole combinations, 12-slot (Q)/10-pole (P) has shown potential over other slot/pole configurations for different applications. The effectiveness of the proposed winding concept is analyzed for 12-slot/10-pole machine. The angular difference between the MMF of adjacent coils is 150^o (180^0-$\nu.2\pi/Q$) for sub-harmonic $\nu = 1$ and 30^o (180^0-$\nu 2\pi/Q$) for $\nu = 5$ as shown in Fig. 2(a) for conventional DL winding. It is possible to cancel out the sub-harmonic ($\nu = 1$) by shifting the MMF of one coil group by $+\nu.2\pi/Q$ (30^o) which also yields 3.5% increment in torque-producing component as illustrated in Fig. 3. In this proposed method, the two coil groups are connected in $Y - \Delta$ configuration to avail the advantage of 30^o phase shift which is required to cancel the sub-harmonic. This connection also yields a current ratio of $\sqrt{3}$ between the coil groups. Hence, for maintaining MMF balance, the number of turns in delta-coil should be maintained $\sqrt{3}$ times that of the wye-coil. The area of each conductor is balanced by appropriate conductor size considering the effective current ratio.

Two sets $(W1, W2)$ of three phase $Y - \Delta$ windings, as presented in Fig. 4(a), are created; windings are shifted by θ_{sh} in space and connected in series as illustrated in Fig. 4(b). The

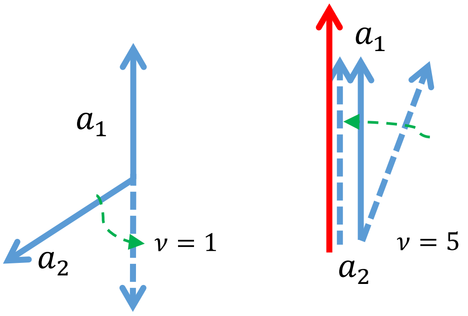
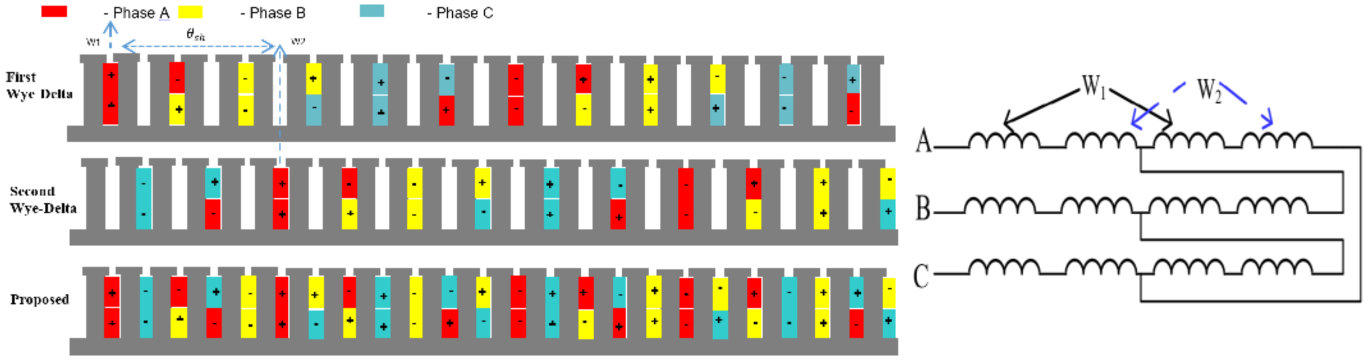


Fig. 3. MMF vector diagram of Y-Δ winding



(a) (b)

Fig. 4. (a) Winding distribution of proposed concept, (b) Winding connection

resultant stator design has twice the number of slots (24-slot/10-pole) compared to conventional concentrated wound design (12-slot/10-pole). Air-gap MMF for both winding sets W_1 and W_2 is calculated using Fourier series expansion of MMF distribution-

$$MMF_{Y,W1} = \sum_{\nu=1,-5,7,..}^{\infty} \frac{6N_Y I_Y}{\nu\pi} \sin(\nu\pi/12)\cos(\nu\theta - \omega t) \ldots\ldots\ldots. (2)$$

$$MMF_{\Delta,W1} = -\sum_{\nu=1,-5,7,..}^{\infty} \frac{6N_\Delta I_\Delta}{\nu\pi} \sin(\nu\pi/12)\cos(\nu(\theta - \frac{\pi}{6}) - (\omega t - \frac{\pi}{6})) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \quad (3)$$

$$MMF_{W1} = Eqn.\ 2 + Eqn.\ 3$$

$$= \sum_{\nu=1,-5,7,..}^{\infty} \frac{12NI}{\nu\pi} \sin\left(\frac{\nu\pi}{12}\right) \sin((\nu-1)\pi/12)\sin(\nu\theta - \omega t - \frac{(\nu-1)\pi}{12}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (4)$$

$$MMF_{W2} = \sum_{\nu=1,-5,7,...}^{\infty} \frac{12NI}{\nu\pi} \sin\left(\frac{\nu\pi}{12}\right) \sin((\nu-1)\pi/12)\sin(\nu\theta - \omega t - \frac{(\nu-1)\pi}{12} - \nu\theta_{sh}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (5)$$

The total airgap MMF distribution is given by,

$$MMF_T = \sum_{\nu=1,-5,7,....}^{\infty} \frac{24NI}{\nu\pi} \sin\left(\frac{\nu\pi}{12}\right) \sin((\nu-1)\pi/12)\cos(\nu\theta_{sh}/2)\sin(\nu\theta - \omega t - \frac{(\nu-1)\pi}{12} - \nu\theta_{sh}/2) \ldots. (6)$$

It is evident from (6) that ν=1 makes the MMF sub-harmonics zero. Moreover, to cancel one particular higher order harmonic $\cos(\nu\theta_{sh}/2)$ needs to be equal to zero or $\theta_{sh} = \pi/\nu$ or $\theta_{sh} = 3\pi/\nu$ in (6). For 12-slot/10-pole with conventionally wound design, 7th space harmonics is the dominant higher order harmonic and it is 71% of torque-producing (5th) component as shown in Fig. 2(b). To cancel 7th space harmonic, $\cos\left(\frac{7\theta_{sh}}{2}\right)$ term in (6) has to be zero and this is possible by selecting $\theta_{sh} = 77.15^0 = 5.15\alpha_s$, where α_s represents slot pitch of the resultant stator. MMF harmonic spectrums for the conventional, Y-Δ [4], phase-shift [9], and the proposed winding are shown in Fig. 5. It is noted that the proposed concept provides a cleaner MMF spectrum. The Y-Δ winding in [4] can effectively cancel the sub-harmonic (ν=1) but it still has 7th, 17th, and 19th in its spectrum. The results in [8] show that the phase-shift winding can cancel the 7th harmonic, but it still has substantial sub-harmonic. In comparison, it is shown that the main unwanted sub-harmonic and 7th harmonic are completely cancelled by the proposed winding concept. Moreover, the 17th harmonic is also reduced by more than 50%. Additionally, the main torque-producing component is increased by 1%, which lends to an increase in torque density of the machine.

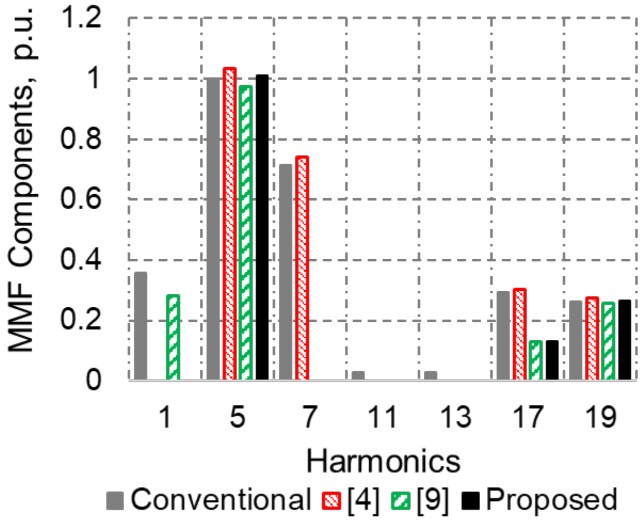


Fig. 5. MMF spectrum of Y-Δ [4], phase-shifted [9], and the proposed winding

Moreover, the new winding is expected to have the same equivalent phase resistance as the conventional DLCW. The equivalent resistance of the wye-coil in each phase can be calculated using (7). The equivalent resistance of the delta-coil group is calculated using (8).

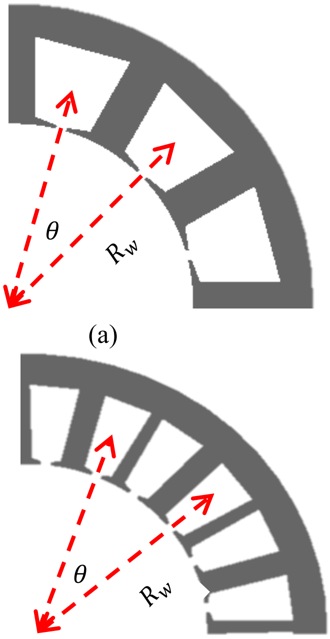
$$R_{Y,proposed} = \frac{\rho L}{A_{Slot} \cdot F} N^2 \cdot \frac{Q_{proposed}}{m} \dots\dots\dots\dots (7)$$

$$R_{\Delta,Proposed} = 3R_{Y,Proposed} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (8)$$

where, $L = L_{stack} + L_{end}$, $Q_{proposed}$ = slot number, m= phase number, N is the turns number, A_{slot} is the total area of slot, ρ is material resistivity at operating temperature, F is the fill factor. The end winding length of the proposed winding are the same as that of the conventional double layer concentrated winding because of same angular span of the coil as in Fig. 6. The end winding length can be calculated using the following (9) [3]-

$$L_{end} = 0.93 \frac{2\pi R_w}{Q} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (9)$$

Here, R_w is the average slot radius, Q is the total number of slots. The resistance of the delta coil is 3 times of wye coil because it has √3 times turn compared to the wye coil. The total stator copper loss in the proposed winding and conventional winding will be the same for the fundamental excitation frequency as the total copper volume, and the rated current is the same. However, there will be an additional loss in the delta winding due to the 3^{rd} order harmonic in delta coil's current. This loss can be reduced by proper design of the rotor of the permanent magnet machines.



(a)

(b)

Fig. 6. Coil span, (a) DLCW, (b) proposed

IV. PERFORMANCE ANALYSIS

Four different PM machines, namely, (a) conventional DL wound 12-slot/10-pole, (b) DL Y-Δ winding with 12-slot/10-pole [4], (c) DL phase-shifted winding with 24-slot/10-pole [9], and (d) the proposed 24-slot/10-pole windings are designed. All the PM machines are designed under the constraints of the same magnet volume, rotor dimension, outer diameter, copper volume, and phase current. The parameters for the designed machines are given in Table I.

TABLE I

DESIGN SPECIFICATIONS

Parameters	**Value**
Outer Diameter, D_{out}	100 mm
Axial Length, L_{stk}	100 mm
Number of poles, P	10
DC Link Voltage, V_{dc}	48 V
Speed, ω_{rated}	600 rpm
Power	1 kW
I_{rated} (rms)	18 A

To prove the proposed concept, the air-gap flux density due to stator excitation are derived from 2D finite element analysis (FEA) for the 24-slot/10-pole machine. A solid rotor is used to avoid rotor contribution to the airgap MMF. The flux path due to armature reaction is shown in Fig. 7. Moreover, the flux lines crossing the rotor indicates the presence of high amplitude sub-harmonics as in Fig. 7(a) and the absence of rotor crossing flux lines in Fig. 7(b) indicates that the proposed winding can successfully cancel the high amplitude sub-harmonics. The airgap MMF of the proposed winding with its corresponding spectrum are presented in Fig. 8. FEA results in Fig. 8 validate the analytical proposition of $\theta_{sh} = 77.15^0$ for the new $Y - \Delta$ winding for the 24-slot/10-pole motor. It is evident that 1st and 7th harmonics become zero and 17th harmonic is also substantially reduced which matches with the analytical model. The cancellation of the sub and super harmonics are expected to reduce the torque ripple, noise and vibration, core loss, and demagnetization of PM.

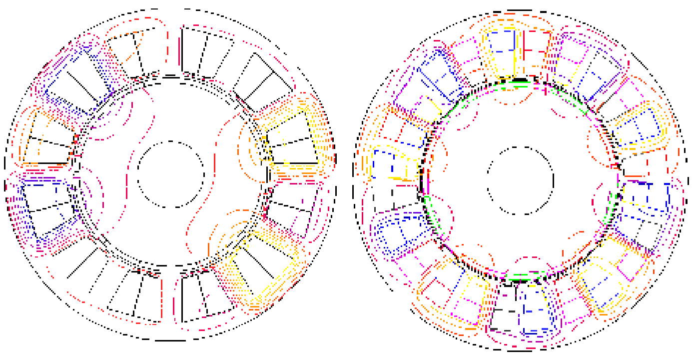
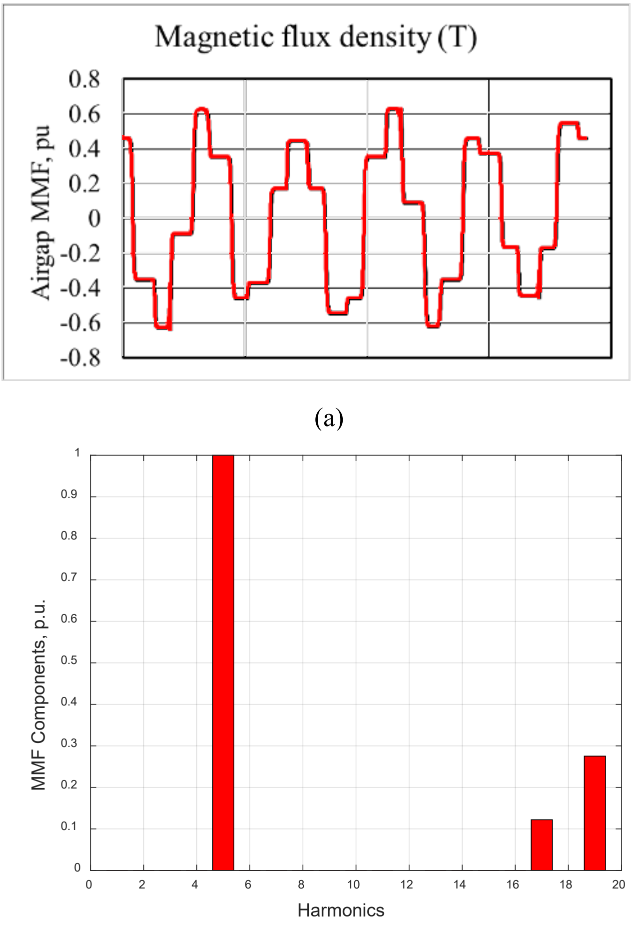

(a) (b)

Fig. 7. Armature reaction flux lines using FEA, (a) DLCW, (b) proposed



(a)

(b)

Fig. 8. (a) MMF distribution, (b) harmonic spectrum (FEA) of proposed 24-slot/10-pole machine

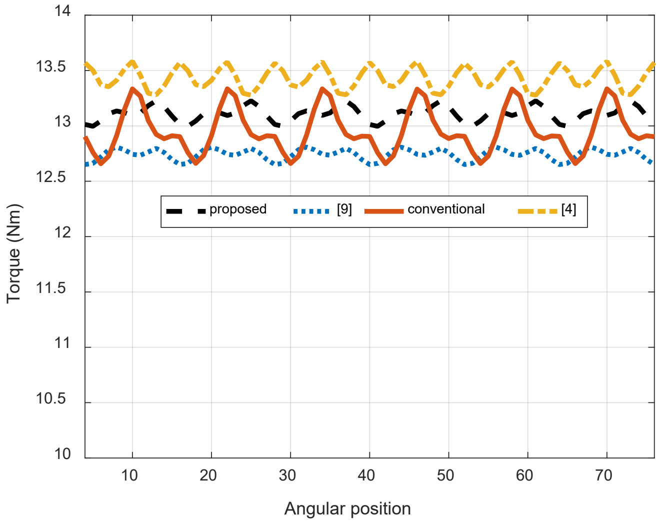
The electromagnetic performances of the proposed winding using FEA are compared with the conventional DLCW as presented by Ayman et al. [4] and Dajaku et al. [9], and the relative advantages are shown in Table II. The electromagnetic torque profile at rated speed with rated current as in Fig. 9 shows that the average torque is 13.1 Nm compared to the 12.95 Nm of conventional DLCW. It also validates the analytical proposition of torque density improvement of more than 1%. However, the optimum shifting angle is found to be 76^0 from FEA for the design in comparison to 77.15^0 for the ideal condition in mitigating the effects of rotor magnets, stator slots, and teeth saturation. Moreover, the torque ripple comes from the interaction of stator harmonics and rotor harmonics along with the cogging torque of the machines. Therefore, the ripple reduction of the presented winding is 70% due to the cancellation of both sub and super harmonics compared to the conventional DLCW. The designed machine also achieves a very low 1.1% THD in the line voltages as in Fig. 9 compared to 4.6% THD of conventional DLCW. In comparison with other windings, the winding of Dajaku et al. [9] achieves 76% torque ripple reduction and 1.60% THD in the line voltages at the expense of 1.6% reduction in average torque compared to the conventional design following the optimized shifting angle to 76^0. Moreover, winding of [4] achieves a reduction of 60% in torque ripple and 2.70% THD in line voltages along with 3.5% improvement in the average torque. Therefore, the proposed winding concept can achieve better torque ripple and torque density.

TABLE II

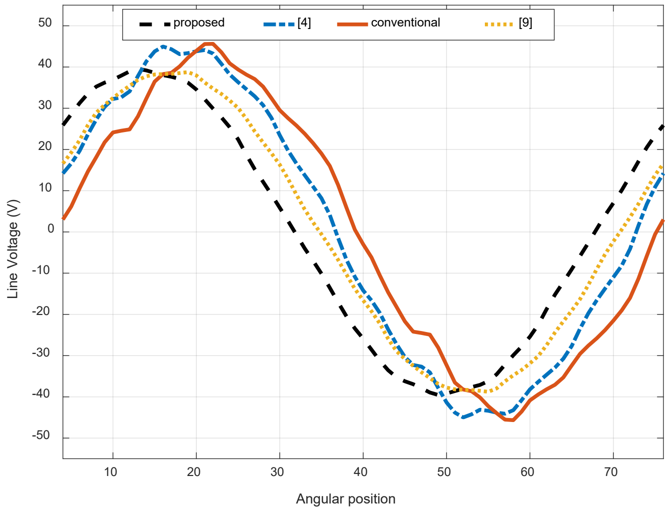
RATED PERFORMACNE COMPARISON

Parameters	**Conventional**	**Proposed**	**[4]**	**[9]**
T_{AVG} (Nm)	12.95	13.10	13.43	12.75
T_{Ripple} (%)	5.30	1.60	2.50	1.25
$THD_{V_{LL}}$ (%)	4.60	1.10	2.70	1.63
P_{core}	4.35	3.71	4.22	3.89
I^2R	128.4	129.8	129.8	128.4
Power factor	0.90	0.96	0.89	0.95
Harmonic in Δ winding	0	1.60	1.52	0

Similar stator copper loss is expected for all the designed machines as they have the same dimensions and copper volume. However, the introduction of 3rd harmonics in delta current may lead to increase in stator copper loss for the proposed winding. This extra loss depends on the PM design and magnetization. Moreover, PM design is optimized for the proposed design to keep this extra loss very negligible (1%) as in Table II. However, the proposed winding can reduce the total magnetic loss by substantial amount (15%) compared to the conevntional DLCW. Moreover, the presented winding achieves the minimum core loss (3.7 W) compared to 4.22 W in [4] and 3.9 W in [9] due to the simultaneous cancellation of sub-harmonics and super harmonics. The presence of sub and super harmonics in DLCW increases the harmonic leakage inductance and hence, degrade the power factor. Therefore, the cancellation of harmonics leads to an improved power factor as shown in Table II. The proposed winding enhances the power factor to 0.96 compared to 0.90 of DLCW.



(a)



(b)

Fig. 9. (a) Torque profile, (b) line voltages (FEA) of proposed 24-slot/10-pole machine

The proposed winding introduces the disadvantages of non-overlapping winding as the two three phase winding sets are used to cancel the higher order harmonics. There is the possibility of slightly higher end winding length compared to the conventional DLCW. Even though the cancellation of sub and super harmonics improves the core loss, torque ripple, power factor and THD performances, this proposed winding will degrade the flux weakening performance. The harmonics associated in the concentrated winding increase the harmonic leakage inductance and consequently, the direct axis inductance. The absence of sub and super harmonics reduces the direct axis inductance, and hence, increases the characteristic current $(I_{ch} = \psi_m/L_d)$. The increase in characteristic current may degrade the flux weakening performance.

V. CONCLUSION

In this paper, a winding concept is proposed to cancel simultaneously both the sub and higher order harmonics of stator MMF along with an increment in the torque density. The proposed winding is based on two sets of three-phase Y-Δ winding connected in series but shifted in space with respect to each other. The winding pattern doubles the number of slots. The designed machine with this winding shows 1.25% increment in average torque, with 1.6% torque ripple, and 1.1% THD compared to conventional FSCW (torque ripple 5.3% and THD of 4.6%). The simultaneous cancellation of sub and super harmonics increases the power factor of the machine by 7% and improves the core loss performance compared to the DL FSCW. Most of the reported works on harmonic reduction can only reduce one particular harmonics with a sacrifice or no improvement in the average torque. However, the proposed concept has the advantage of cancelling most of the unwanted harmonics without sacrificing torque density of the machine. Torque ripple and THD reduction without pole shaping or skewing further reduces the manufacturing complexity. The proposed concept is equally applicable to reluctance machines and induction machines with either concentrated or distributed wound stator. Future work from this research will include experimental results.

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