Proposal of a Novel Topology of Five-Phase Fractional Slot Concentrated Non-Overlapping Winding with Selective MMF Harmonic Elimination

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***Abstract*—In this paper, a novel topology of five-phase fractional-slot concentrated winding (FSCW) with selective magnetomotive force (MMF) harmonic elimination is proposed. Compared to traditional FSCW with stator shift technique, not only the parasitic sub- or sup-order harmonics of the MMF can be selectively reduced or eliminated, the non-overlapping characteristic is also kept. Firstly, based on 20-slot/22-pole single-layer (SL) winding topology, a dual five-phase 40-slot/22-pole one of SL winding with 1st harmonic elimination is introduced. Secondly, a new 40-slot/22-pole of double-layer with selective harmonic reduction is presented. Finally, the high performances of the machine with the proposed winding topology are evaluated using finite element analysis (FEA), including air gap flux density, output torque, machines losses, etc.**

***Keywords*—5-phase PM machine, FSCW, FEA, Selective Harmonic Elimination.**

I. INTRODUCTION

Compared to traditional integer slot winding, the FSCW are more and more concerned for electrical vehicle application, due to the short end-winding, field-weakening capability, the facilities of making, recycling and repairing. In addition, the machine stator with FSCW can be modulated designed, which can improve the fault-tolerant capability and the efficiency of mass market production.

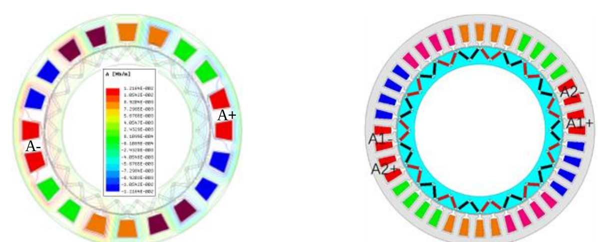
The common disadvantage of FSCW is the rich harmonic content of MMF [1] which, in certain case, can cause high eddy-current magnet rotor losses and furthermore restrict the performance of the machines, especially for high-speed applications.

Reference [2] proposed a novel 5-phase/20-slot/22-pole winding topology by a stator shift technique combined with a star/pentagon winding connection. Compared to the conventional configuration, the first harmonic of MMF in the new winding is eliminated. Moreover, the non-overlapping characteristics of FSCW are kept. However, the method cannot selectively eliminate harmonics. This paper proposed a new topology of five-phase FSCW with selective harmonic elimination, which can completely eliminated the 1st harmonic and significantly reduce the 9th harmonic. Moreover, the output torque is almost the same value. This method can also be extended to higher number of phase winding design.

II. BASIC WINDING LAYOUT

The SL winding is often preferred with high fault-tolerant machine design due to the isolation features, and the DL solution is preferred due to its advantages of rotor losses for the high speed applications.

Fig. 1 presents the winding layouts of 20-slot/22-pole SL machine and 40-slot/22-pole SL machine. For the two both configurations, the 11th harmonic of MMF is the working harmonic. And the 1st MMF harmonics of 40-slot/22-pole SL machine is greatly reduced. However, the pitch factor of the 40-slot/22-pole SL winding is slightly reduced. Moreover, there are still many non-working harmonics, e.g. the 9th, 29th and 31st etc.



(a) 20S/22P SL (b) 40S/22P SL

Fig. 1. Winding layouts of conventional 20-slot/22-pole SL machine and 40-slot/22-pole SL machine

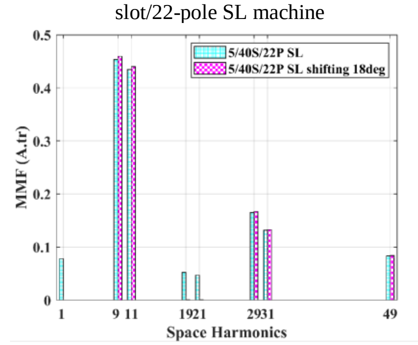


Fig. 2. MMF harmonic of 40slots/22poles SL machine

In order to further improve the MMF harmonic content, the selective harmonic elimination technique will be proposed and presented in the following section.

III. NEW 40-SLOT/22-POLE DOUBLE-LAYER WINDING

A. Elimination of the 1st harmonic

The MMF expression of the conventional five-phase 40-slot/22-pole SL winding shown in Fig. 1(b) can be expressed as Fourier series as (1) (2).

$$F(\theta,t)=\sum_{k=1,-9,11...}^{\infty} v_k \sin\left(k\theta-\omega t-\frac{k\pi}{40}\right) \quad (1)$$

$$v_k=\frac{20NI}{k\pi}\sin\left(\frac{k\pi}{40}\right)\sin\left(\frac{k\pi}{40}\right) \quad (2)$$

Where v_k is the amplitude of the k^{th} MMF space harmonic; N is the number of turns of each coil; I is the RMS value of the injected fundamental current; θ is the space angle; ω is the angular velocity.

Fig. 1(b) shows that the phase difference in space of the two adjacent coils A1 and A2 is 18° in mechanical, and the corresponding electrical angle is also 18° (18×11-180). If the injected currents for the two groups of winding are also shifted by 18° respectively in time, the winding of machine can be considered as dual five-phase one. The resultant MMF of the dual five-phases winding can be expressed as (3) (4).

$$F_d(\theta,t)=\sum_{k=1,-9,11...}^{\infty} v_{dk} \sin\left(k\theta-\omega t-\frac{k-1}{20}\pi\right) \quad (3)$$

$$v_{dk}=\frac{20NI}{k\pi}\sin\left(\frac{k\pi}{40}\right)\sin\left(\frac{k-1}{20}\pi\right) \quad (4)$$

Where v_{dk} is the amplitude of the k^{th} MMF space harmonic; It can be seen from **Erreur ! Source du renvoi introuvable.** that the amplitude of the 1st-order harmonic v_{d1} is equal to 0 with k=1, i.e. the 1st-order harmonic is completely suppressed in dual five-phase winding. The MMF space harmonic spectrum is shown in Fig. 2. It can also be seen that the working harmonic (the 11th) is increased by 1.2%, while the 19th, 21st, 39th, and 41st are both eliminated.

B. New five-phase 40-slot/22-pole DL winding

Based on the concept of stator shifting technique and the novel 40-slot/22-pole SL winding, another dual five-phase winding is added, with the same winding distribution as the first dual five-phase one, but with a specific mechanical shifting angle α between the two windings, and thus the novel 40-slot/22-pole DL winding topology is constructed. The final amplitude of MMF of the novel windings topology is expressed in **Erreur ! Source du renvoi introuvable.** (6).

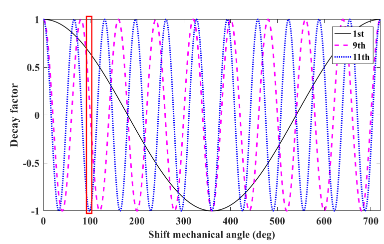
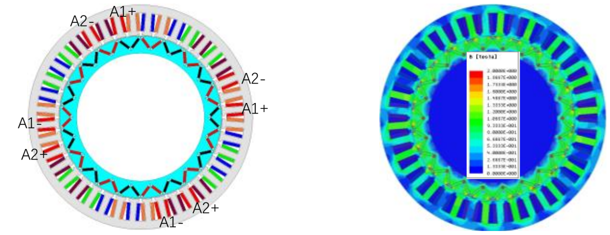


Fig. 3. Effect of the shift mechanical angle on winding factors of 1st, 9th, and 11th harmonics



(a) Winding layout (b) Flux density

Fig. 4. 40slots/22poles DL machine

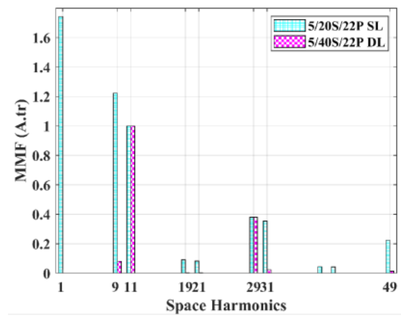


Fig. 5. MMF harmonic of conventional 20slots/22poles SL machine and 40slots/22poles DL machine

$$v_{\alpha k}=v_{dk}\cos\left(\frac{k\alpha}{2}\right) \quad (5)$$

$$\alpha = j\times 360^{o}/Q\,,\ \ j=1,2,3... \quad (6)$$

Where v_{dk} is the amplitude of the k^{th} MMF harmonic of a single double five-phase winding; α is the mechanical shift angle which is a discrete number and Q is the number of stator slots; cos($k\alpha$/2) is defined as the decay factor. For each harmonic, the decay factor varies in a sinusoidal form with respect to the mechanical shifting angle α as shown in Fig. 3.

In order to reduce or eliminate the 9th harmonic of MMF, it is necessary to choose an appropriate angle α leading to $v_{\alpha 9}$ close to zero, while keeping $v_{\alpha 11}$ big value. As can be seen from Fig. 3, the angle α=99° is a good choice, which corresponds to 11 slots of a 40-slot/22-pole machine. The related decay factors of $v_{\alpha 9}$ and $v_{\alpha 11}$ are -0.0785 and -0.9969, respectively.

Fig. 4 shows the novel winding layout and flux density of the 40-slot/22-pole machine. It is a DL winding without over-lapping of end-windings. Each phase consists of eight coils which can be divided into two groups: A1&A2. The four coils of A1 or A2 are connected in series. The current supply of the five-phase machine is achieved using the method by combining the star and pentagram coils connection.

Fig. 5 shows the comparison of MMF between the 20-slot/22-pole SL winding and the 40-slot/22-pole DL winding. It can be seen that the 1st harmonic is completely eliminated, and the 9th harmonic is significantly reduced to 8%. The total harmonic distortion (THD) of the two windings are 220.7% and 38.9%, respectively.

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