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Reduction of Eddy Current Loss of Permanent-Magnet Machines with Fractional Slot Concentrated Windings

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Abstract—Fractional slots concentrated windings (FSCWs) are characterized with high magnetic motive force (MMF) harmonics which results in undesirable effects on permanent-magnet (PM) machines. A new design technique is reported in this paper in order to simultaneously reduce the sub- and high MMF harmonics. By using multiple layer windings and different turns per coil, a new 18-teeth/10-poles FSCWs PM machine is designed. Then, this machine is evaluated as compared with a conventional 12-teeth/10-poles FSCWs PM machine. Both machines are designed under the same electrical and geometrical constrains. The obtained results verify the high performances of the newly designed machine. Due to the adopted new winding type, the proposed design can effectively reduce eddy current loss in PMs as compared with the conventional design.

1. INTRODUCTION

Due to the requirements of electric vehicles (EVs), it is extremely important to improve electromagnetic performance and reliability of the motor drive. Thus, high performance driving motor has become a core technology [1, 2]. Permanent-magnet (PM) machines with fractional slots concentrated windings (FSCWs) have been widely used in EVs, owing to their short and less complex end-winding, high-power density, high efficiency, high filling factor, low cogging torque, fault tolerance, cost-effectiveness, and good field-weakening capability [3]. Furthermore, different pole and slot combinations of FSCWs are possible [4–6]. However, the magnetic field of these windings has significant space harmonics. For PM machines, only the specific magnetomotive force (MMF) winding harmonic for the armature field interacts with the PM field to produce continuous torque. The others are undesirable and will degrade machine performance, such as localized core saturation, eddy current loss in PMs [7, 8], additional core losses in rotor and stator, and noise and vibration [9, 10], which are the main disadvantages of the FSCW types. These harmonics cause flux variation in the air-gap. For PM machines, the capability of reducing the MMF harmonics would be related to the ability to reduce eddy current loss in PMs. In fact, it is very difficult in PM heat dissipation.

Considerable efforts have been devoted to investigating and reducing those harmonics, including: 1) using multi-layer tooth concentrated winding and shifting the winding systems by a specific number of slots [11–13]; 2) using different turns per coil or different turns per coil-side [14]; 3) modifying the stator yoke in specific locations by using magnetic flux-barriers in stator yoke [14]; 4) doubling the number of stator slots and using two winding systems [15, 16], 5) using delta-star windings with different turns per coil [17, 18]; 6) using the multiple three-phase concentrated windings [19–21]. Although these techniques have been adopted, the FSCW PM machines still suffer from either sub- or high MMF harmonics.

Halbach magnetised PM machines are novel in that their magnet magnetisation is self-shielding [22]. They offer many attractive features [23, 24], such as sinusoidal air gap field distribution and back-EMF, negligible cogging torque, potentially high air gap flux density and no need of rotor back-iron. Hence,

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they have always attracted many research and development interests and extensive exploitation for their applications.

The 12-slots/10-poles PM machine with double-layer tooth concentrated winding exhibits high performance and has been widely used in many industry applications. Their coils of one phase are concentrated and wound on adjacent teeth, as illustrated in Figure 1 (the arrows indicate the magnetization direction), so the phase windings do not overlap. Since the windings distribution of FSCW machines are not sinusoidal, their air-gap flux density distribution may be far from sinusoidal shape. For conventional 12-slots/10-poles winding type, the MMF distribution and corresponding harmonics are shown in Figure 2. It can be known that the 1st, 5th, 7th, 17th and 19th are the dominant harmonics for this winding type. As well known, the harmonics of the stator winding MMF can reveal the main characteristics of the electric machine. Also, the air-gap flux density, electromagnetic torque and torque ripple, magnetic radial forces and so on are directly related to the stator MMF characteristics.

By using Fourier series function, the MMF distribution for the 12-slots/10-poles winding in Figure 2(a) can be expressed as [14]:

$$\begin{cases} f(x,t) = \sum\limits_{\nu} \dfrac{3}{2} F_{\Phi v} \cos\left(\omega t - \nu\theta + \delta\right) \\ F_{\Phi v} = \dfrac{8\sqrt{2}\cdot NI}{\pi\nu} k_{wv} \\ k_{wv} = k_{dv} k_{pv} = \cos\left(\nu\dfrac{5\pi}{12}\right)\cdot\sin\left(\nu\dfrac{\pi}{12}\right) \end{cases} \tag{1}$$

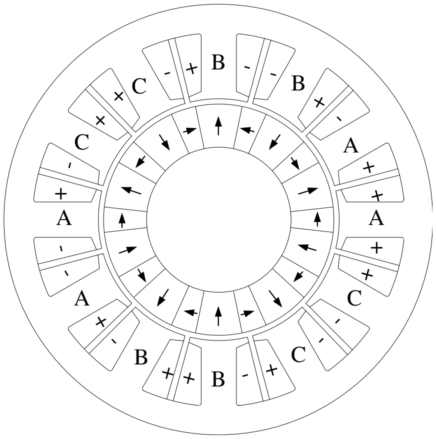
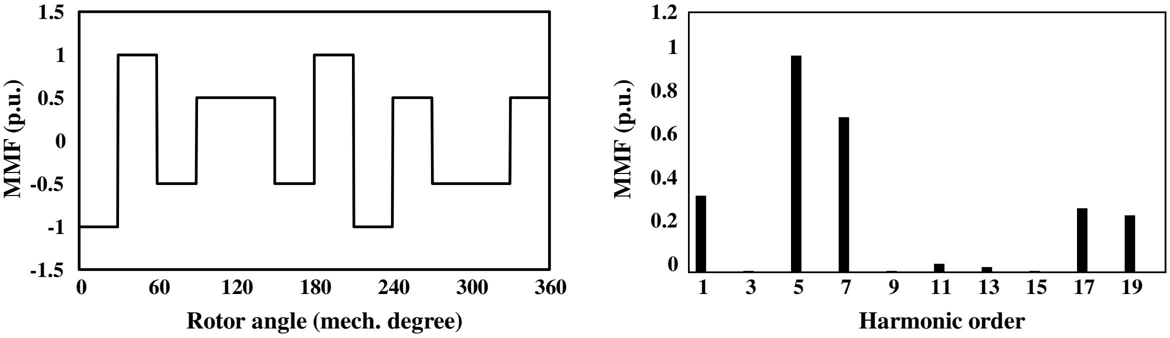


Figure 1. 12-slot/10-pole PM machine with the conventional winding topology.



(a) (b)

Figure 2. MMF winding characteristics of the conventional winding. (a) MMF distribution. (b) MMF harmonics.

where, $F_{\Phi v}$ is the amplitude of the νth MMF harmonic, k_{wv} the winding factor, k_{dv} the distribution factor, k_{pv} the pitch factor, I the phase current effective value, δ the load angle, ω the angular frequency, N the number of turns per coil, and ν the MMF harmonic order.

2. WINDING CONFIGURATION

It is well known that the MMF harmonics can be reduced by doubling the stator slot number in the FSCW machines, but this is useless because the machine winding factor is too low. Hence, this section will propose a new solution for simultaneously reducing the sub- and the high MMF harmonics of the concentrated winding, in which an 18-slots/10-poles machine is chosen as example. Then, multiple layer windings are designed to reduce or even eliminate some harmonics. As shown in Figure 3(a), the basic winding consists of two winding systems, which have an appropriate mechanical angle of $\alpha_w = 80°$. The selection of the shift angle 80° between two sectors is an additional degree of freedom in the winding design. Therefore, by using two identical winding systems shifted in space for a given shifting angle α_w, (1) can be rewritten as:

$$\begin{cases} F_{\Phi v} = \dfrac{24\sqrt{2}\cdot NI}{\pi\nu} k_{wv} \\ k_{wv} = k_{dv}k_{pv}k_{zv} = \cos\left(\nu\dfrac{11\pi}{18}\right)\cdot\sin\left(\nu\dfrac{\pi}{18}\right)\cdot\cos\left(\nu\dfrac{\alpha_w}{2}\right) \end{cases} \tag{2}$$

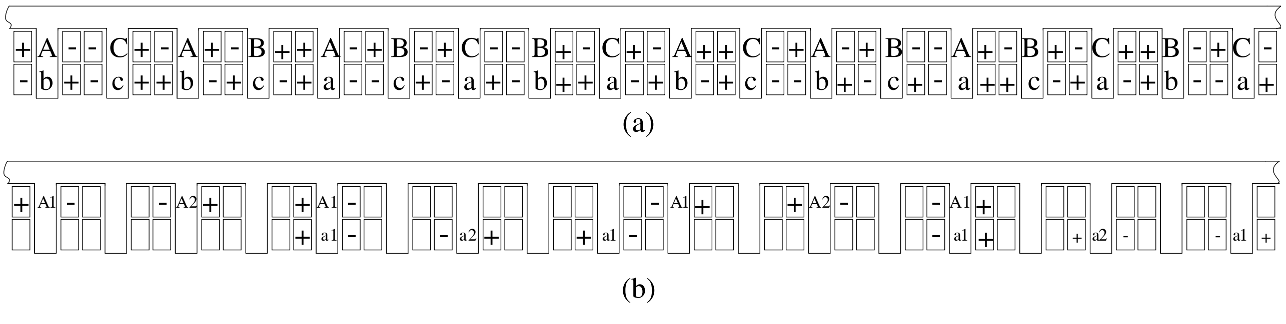
In Figure 3(a), ABC and abc denote the 3-phase windings for the first and second coil systems, respectively. The corresponding MMF harmonics are shown in Figure 4. It can be seen that the 1st sub-harmonic is still present, while the 7th high harmonic is significantly reduced. This is due to the additional degree of freedom. Furthermore, by using different turns per coil, the undesired sub-harmonic can also be reduced. As an example, only coil-A and coil-a are illustrated in Figure 3(b), in which A1 and A2 represent the coils of phase-A for the first and the second winding systems, respectively. Also, n_1 and n_2 correspondingly denote the turns per coil for the same phase winding.

In order to reduce the 1st sub-harmonic of the FSCW PM machines, n_2/n_1 should be approximately equal to 1.5. This is because the 1st distribution factor is almost equal to zero. Therefore, the winding factor k_{wv} can be expressed as

$$k_{wv} = k_{dv}k_{pv}k_{zv} = \frac{n_2 - 2n_1 * \cos\left(\nu\dfrac{2\pi}{9}\right)}{n_2 + 2n_1}\cdot\sin\left(\nu\frac{\pi}{18}\right)\cdot\cos\left(\nu\frac{\alpha_w}{2}\right) \tag{3}$$

Figure 5 compares the MMF harmonics spectra for the conventional 12-slots/10-poles winding and the newly designed 18-slots/10-poles winding. It can be concluded that, when using the improved 18-slots/10-poles winding, the 1st, 7th, 17th and 19th unwanted MMF harmonics are almost eliminated, and only the 13th harmonic is still present. The main MMF harmonic components for both conventional and proposed windings are listed in Table 1.

Figure 6 shows the geometry of the improved 18-slots/10-poles machine. The star of slots for fundamental harmonic is shown in Figure 7.



(a)

(b)

Figure 3. Winding diagrams for 18-slots/10-poles machine. (a) Basic winding. (b) Improved winding.

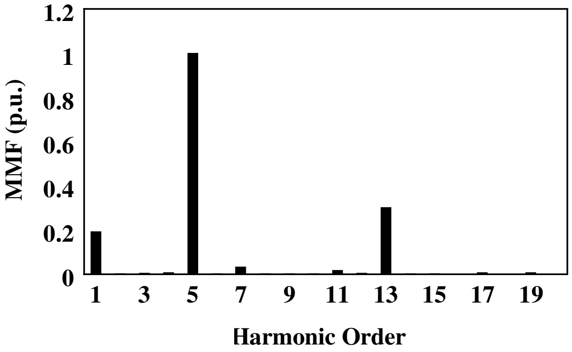


Figure 4. MMF winding harmonics for the armature field of the basic 18-slot/10-pole machine.

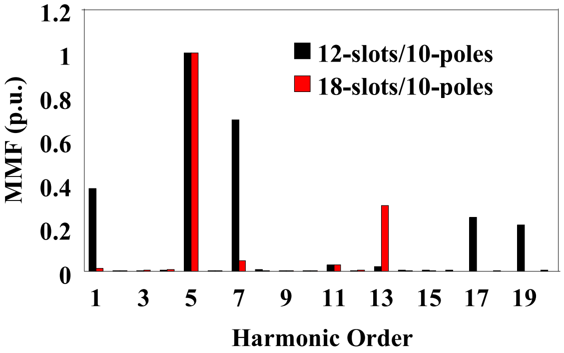


Figure 5. MMF winding harmonics for the armature field of the conventional 12-slots/10-poles and improved 18-slots/10-poles machines.

Table 1. MMF harmonic components of both conventional and improved windings.

Harmonic order	1	5	7	11	13	17	19
Conventional winding	35.9%	100%	71.4%	3.26%	2.76%	29.4%	26.3%
Improved winding	0.9%	100%	5.5%	3.5%	38%	0	0

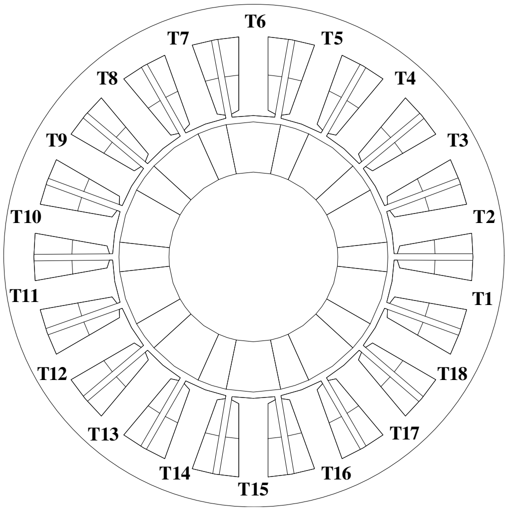


Figure 6. The geometry of the improved 18-slots/10-poles machine.

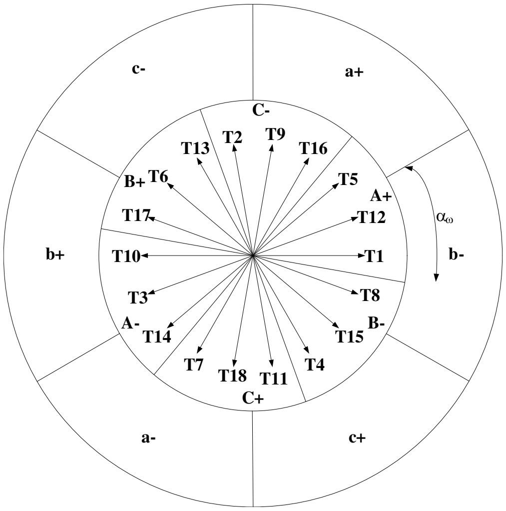


Figure 7. The star of slots for fundamental harmonic of the improved 18-slots/10-poles machine.

3. COMPARISON AND EVALUATION

The conventional 12-teeth/10-poles winding and the improved 18-teeth/10-poles winding will be compared in the following design of two FSCW PM machines. For a fair comparison, both machines have the same electrical and geometrical constrains (voltage, current and volume). Also, the same rotor is designed. It should be noted that their only difference on the machine geometries is the stator core. Table 2 lists the geometry data. The electromagnetic performances of both machines are predicted by using commercial software Ansoft/Maxwell.

Firstly, their flux density distributions are compared in Figure 8. For the conventional 12-teeth/10-

Table 2. Main geometry data.

Active length	86 mm
Outer stator diameter	80 mm
Outer rotor diameter	45 mm
Gap length	0.5 mm
Magnet length (magn. direction)	8 mm
Sleeve thickness	0.5 mm
Turns per phase (12/10)	28
Turns per phase (18/10)	10/15
Number of rotor poles	10
Rotor speed	11000 rpm
The amplitude of the phase current	21.7 A
Iron core material	WGT-200
Magnet material	YX-30
Sleeve and shaft marerial	Sleeve Ocr18ni9
Bulk conductivity (magnet)	1111111 s/m
Bulk conductivity (sleeve and shaft)	1390000 s/m

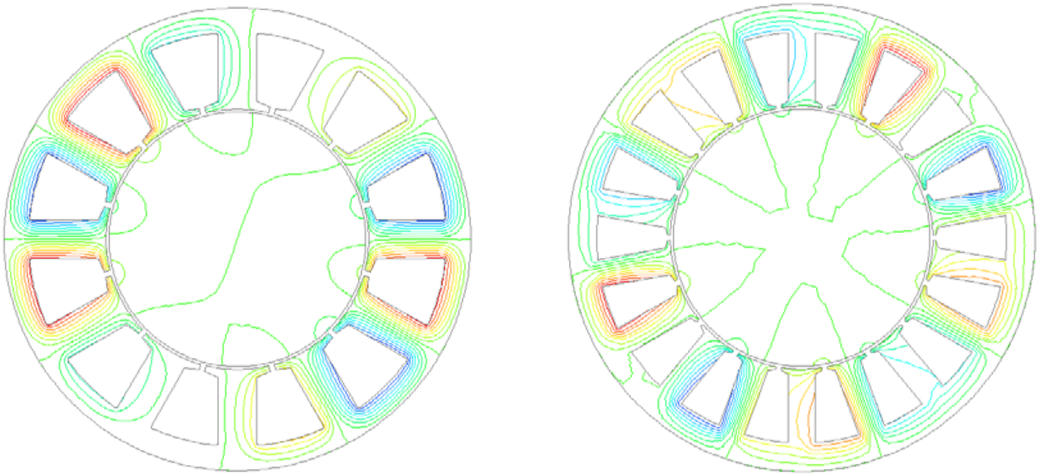

(a) (b)

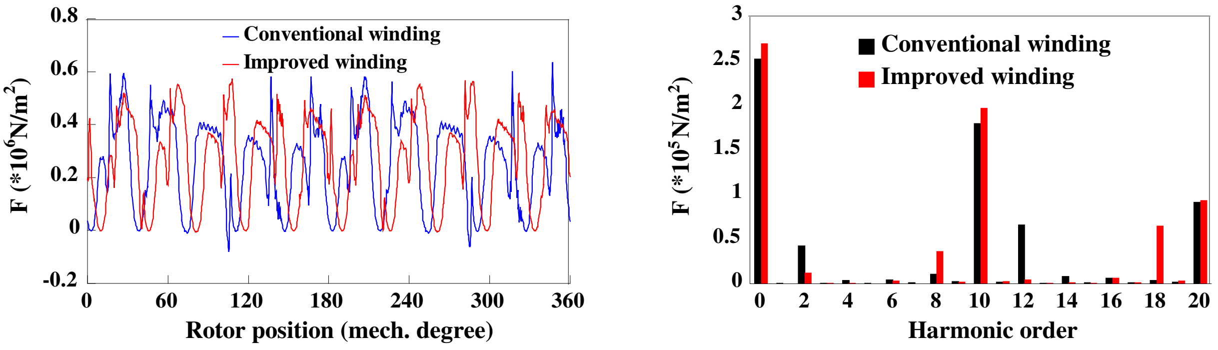
Figure 8. Flux density distributions due to armature reaction for both machines. (a) Conventional winding. (b) Improved winding.

poles PM machine in Figure 8(a), its flux distributions seems to be analogous with a two-pole machine. This is due to the 1st sub-harmonic component of this winding type. However, by using the improved 18-teeth/10-poles winding in Figure 8(b), the 1st sub-harmonic component is suppressed, hence limiting the flux density to flow around one-half of the machine.

Then, by using the air-gap flux density components, the magnetic radial forces can be calculated according to the Maxwell's stress method [10],

$$f_{rad}(\theta_s, t) = \frac{1}{2\mu_0}[B_r^2(\theta_s, t) - B_n^2(\theta_s, t)] \tag{4}$$

According to (4), the resulting radial force distribution as function of θ_s and its corresponding harmonics are analyzed in Figure 9. As can be seen, the radial force under the given load condition contains all even harmonics of orders 2, 4, 6, 8 and so on. This is due to the interaction between the odd harmonics in the PM field and the armature reaction field. The most significant radial force harmonics are 2, 4 and 6. It should be noted that in relation to acoustic behavior of the electric machines, both the amplitude and the frequency are very important. From airborne noise point of view, the significant radial force mode is the 2 order, and the reduction or a complete elimination of these modes is one of the main challenges during the design of electric machines with FSCWs. It is also the source of magnetic noise and results in magnetic unbalance. Therefore, it can be seen from Figure 9(b) that due to the adopted new winding topology, the mode-2 is reduced more than 70%. Also, the other low modes (mode-4 and mode-6) are positively influenced.



(a) (b)

Figure 9. Radial force and its corresponding harmonics. (a) Radial force. (b) Radial force harmonics.

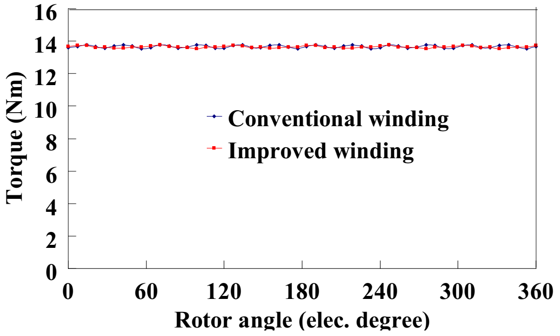


Figure 10. Electromagnetic torque.

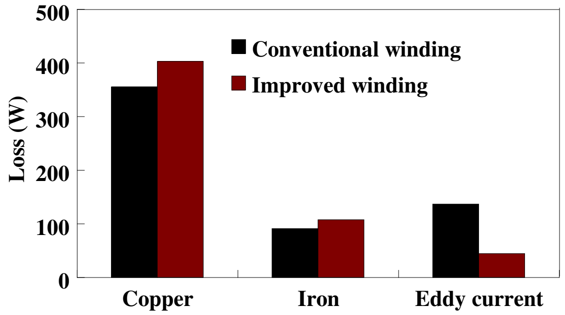
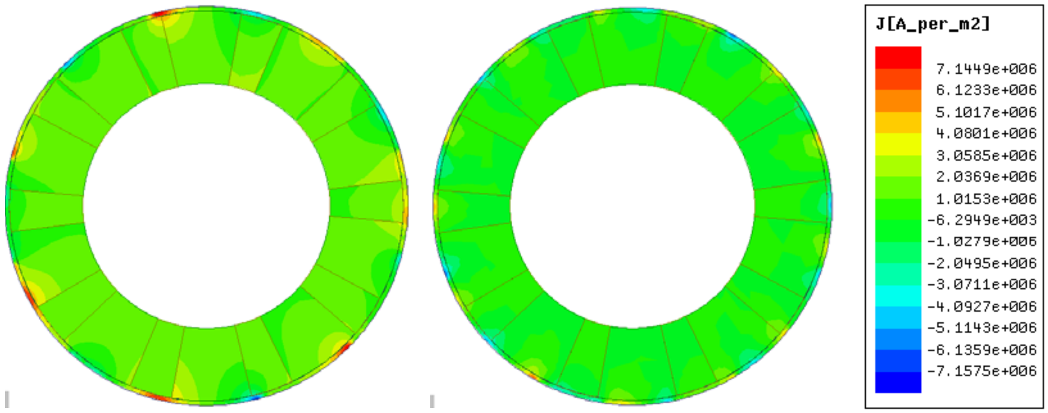


Figure 11. Machine losses.

Moreover, the performances of both machines under load condition are investigated. It is important to underline that both machines operate at the same load (torque) condition as shown in Figure 10. In addition, the machine losses for the same rotor speed are compared in Figure 11, verifying a significant improvement of the machine losses when using the new designed winding. In Figure 11, the copper losses represent the ohmic losses. It should be noted that both copper losses and iron losses are easy to heat dissipation based on good cooling condition. Meanwhile, the eddy current losses of the improved winding are significantly reduced 67.3%, which is very important for PM machines. Then, Figure 12 compares each part of the eddy-current losses for the conventional 12-slots/10-poles winding and the newly designed 18-slots/10-poles winding. It can be known that the magnet losses of the conventional winding are distributed over the entire sleeve and magnet region, but that of the improved winding type are mainly distributed at the sleeve surface.



(a) (b) (c)

Figure 12. Eddy current distributions. (a) Conventional winding. (b) Improved winding. (c) Scale.

4. CONCLUSIONS

This paper has proposed a new 18-slots/10-poles tooth concentrated winding with low MMF winding harmonics content. The new method can reduce or even eliminate some harmonics of the armature reaction, hence solving the problem of eddy current loss in PMs. According to this technique, an FSCW PM machine has been newly designed. The designed FSCW PM machine has been evaluated as compared with the conventional one. The MMF in the air gap has been analyzed, and the improvements in eddy current loss of the improved 18-slots/10-poles model has been verified as compared with the conventional 12-slots/10-poles model.

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REFERENCES

1. Guo, Y., L. Wang, and C. Liao, "Systematic analysis of conducted electromagnetic interferences for the electric drive system in electric vehicles," *Progress In Electromagnetics Research*, Vol. 134, 359–378, 2013.
2. Guo, Y., L. Wang, and C. Liao, "Modeling and analysis of conducted electromagnetic interference in electric vehicle power supply system," *Progress In Electromagnetics Research*, Vol. 139, 193–209, 2013.
3. El-Refaie, A. M. and M. Ayman, "Fractional-slot concentrated-windings synchronous permanent magnet machines: Opportunities and challenges," *IEEE Transactions on Industrial Electronics*, Vol. 57, No. 1, 107–121, 2010.
4. Bianchi, N. and E. Fornasiero, "Index of rotor losses in three-phase fractional-slot permanent magnet machines," *IET Electric Power Application*, Vol. 3, No. 5, 381–388, 2009.
5. Ishak, D., Z. Q. Zhu, and D. Howe, "Eddy-current loss in the rotor magnets of permanent-magnet brushless machines having a fractional number of slots per pole," *IEEE Transactions on Magnetics*, Vol. 41, No. 9, 2462–2469, 2005.
6. Nysveen, A., R. Nilssen, R. Lorenz, and T. Rolvag, "Influence of pole and slot combinations on magnetic forces and vibration in low-speed PM wind generators," *IEEE Transactions on Magnetics*, Vol. 50, No. 5, 6677574, 2014.

7. Fu, X., D. Xu, M. lin, and X. Li, "Calculation and analysis of rotor eddy current loss of permanent magnet-inductor hybrid excited synchronous generator," *IEEE Transactions on Magnetics*, Vol. 49, No. 5, 2389–2392, 2013.
8. Wang, J., K. Atallah, R. Chin, W. M. Arshad, and H. Lendenmann, "Rotor eddy-current loss in permanent-magnet brushless AC machines," *IEEE Transactions on Magnetics*, Vol. 46, No. 7, 2701–2707, 2010.
9. Dajaku, G. and D. Gerling, "The influence of permeance effect on the magnetic radial forces of permanent magnet synchronous machines," *IEEE Transactions on Magnetics*, Vol. 49, No. 6, 2953–2966, 2013.
10. Torkaman, H. and E. Afjei, "Radial force characteristic assessment in a novel two-phase dual layer srg using FEM," *Progress In Electromagnetics Research*, Vol. 125, 185–202, 2012.
11. Farnasiero, E., L. Aberti, N. Bianchi, and S. Bolognani, "Considerations on selecting fractional-slot nonoverlapped coil winding," *IEEE Transaction on Industry Application*, Vol. 49, No. 3, 1316–1324, 2013.
12. Cistelecan, M. and F. Ferreira, "Three phase tooth-concentrated multiple-layer fractional windings with low space harmonic content," *IEEE Energy Conversion Congress and Exposition, ECCE — Proceeding*, 1399–1405, 2010.
13. Kim, H.-J., D.-J. Kim, and J.-P. Hong, "Characteristic analysis for concentrated multiple-layer winding machine with optimum turn ratio," *IEEE Transactions on Magnetics*, Vol. 50, No. 2, 6749104, 2014.
14. Dajaku, G., X. Wei, and D. Gerling, "Reduction of low space harmonics for the fractional slot concentrated windings using a novel stator design," *IEEE Transactions on Magnetics*, Vol. 50, No. 5, 6680738, 2014.
15. Dajaku, G. and D. Gerling, "A novel 24-slots/10-poles winding topology for electric machines," *IEEE International Electric Machines and Drives Conference, IEMDC*, 65–70, 2011.
16. Jiabin, W., V. I. Patel, and W. Weiya, "Fractional-slot permanent magnet brushless machines with low space harmonic contents," *IEEE Transactions on Magnetics*, Vol. 50, No. 1, 2280838, 2014.
17. Dajaku, G. and D. Gerling, "A novel tooth concentrated winding with low space harmonic contents," *IEEE International Electric Machines and Drives Conference, IEMDC*, 755–760, 2013.
18. Abdel-Khalik, A. S., S. Ahmed, and A. Massoud, "Low space harmonics cancellation in double layer fractional slot winding using dual multiphase winding," *IEEE Transactions on Magnetics*, Vol. 51, No. 5, 6935012, 2015.
19. Chen, X., J. Wang, and V. I. Patel, "A generic approach to reduction of magnetomotive force harmonics in permanent-magnet machines with concentrated multiple three-phase windings," *IEEE Transactions on Magnetics*, Vol. 50, No. 11, 6971311, 2014.
20. Barcaro, M., N. Bianchi, and F. Magnussen, "Analysis and tests of a dual three-phase 12-slot 10-pole permanent-magnet motor," *IEEE Transactions on Industry Applications*, Vol. 46, No. 6, 2355–2362, 2010.
21. Barcaro, M., N. Bianchi, and F. Magnussen, "Six-phase supply feasibility using a PM fractional-slot dual winding machine," *IEEE Transactions on Industry Applications*, Vol. 47, No. 5, 2042–2050, 2010.
22. Shute, H. A., J. C. Mallinson, D. T. Wilton, and D. J. Desmond, "One-sided fluxes in planar, cylindrical, and spherical magnetized structures," *IEEE Transactions on Magnetics*, Vol. 36, No. 2, 440–451, 2000.
23. Zhu, Z. Q. and D. Howe, "Halbach permanent magnet machines and applications: A review," *IEE Proceedings: Electric Power Applications*, Vol. 148, No. 4, 299–308, 2001.
24. Penzkofer, A. and K. Atallah, "Magnetic gears for high torque applications," *IEEE Transactions on Magnetics*, Vol. 50, No. 11, 6971672, 2014.