Eddy Current Loss Minimization in Rotor Magnets of PM Machines using High-Efficiency 12-teeth/10-poles Winding Topology

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Abstract — Using winding coils with different turns per coil side for the fractional slots, tooth-concentrated winding it is possible to reduce or even to cancel some space harmonics of low order resulting in lower rotor losses induced by the armature reaction field. This technique is applied to the 12-teeth/10-poles winding during investigation of the eddy current losses for two PM machines. The obtained results show that, using the new winding the magnet losses are reduced by about 80% compared with the conventional winding.

I. Introduction

In the last years, permanent magnet (PM) brushless machines with tooth concentrated winding are increasingly used in several industry applications. High-power density, high efficiency, short and less complex end-winding, high filling factor, low cogging torque, fault tolerance, and cost-effectiveness are the main advantages that characterize the fractional-slot concentrated winding (FSCW) compared with the distributed winding. Using FSCW different combinations of numbers of poles and numbers of teeth are possible [1-3]. However, the magnetic field of these windings has more space harmonics, including sub-harmonics. These unwanted harmonics lead to undesirable effects, such as localized core saturation, eddy current loss in the magnets [4, 5], and noise and vibration [6-9], which are the main disadvantages of these winding types.

There have been several works in the last decade devoted to improve the performances of the FSCW regarding to reduction of winding sub-harmonics [8-10]. The technical solution developed in these works is essentially based on doubling the tooth concentrated winding and shifting the winding systems by a specific number of slots. In this way the sub-harmonics of the considered winding are reduced or even canceled, however using this technique also the fundamental winding factor is reduced by 3.4%. Further, a new method for simultaneously reducing the sub- and high winding space harmonics by doubling the number of stator slots and using two winding systems is presented in [11-12].

A novel method for reducing the winding sub-harmonics without negatively effecting the fundamental winding factor and the manufacturing process is presented in [13]. Different from [8-12], the reduction of sub-harmonics according to the new technique is realized using concentrated coils with different number of turns per coil-side. In [13], the proposed technique is used for reduction of sub-harmonics of the 12-slot/10-poles winding, however of course this technique is also applicable to any concentrated winding topology.

In this paper, the eddy current losses of two PM machines with the conventional and the new tooth concentrated 12-teeth/10-poles winding are investigated. The simulation results show that using the new technique (new winding type) the eddy current losses are reduced by about 80% compared with the conventional winding.

II. Conventional 12-Slot/10-Poles Winding Topology

A PM machine with 12-slots and 10-poles is illustrated in the following figure 1. Its stator winding differs from that of conventional PM machines in that the coils which belong to each phase are concentrated and wound on adjacent teeth, as illustrated in figure 1, so that the phase windings do not overlap. In machines with fractional slot windings, the windings are not sinusoidally distributed and the resulting air-gap flux density distribution may be far from being sinusoidal. For this winding type, the magnetomotive force (MMF) distribution and corresponding space harmonics are shown in figure 2. It is shown from figure 2-b that the 1st, 5th, 7th, 17th and 19th are the dominant space harmonics for this winding type. For the 10-pole machine, however, only the 5th stator space harmonic interacts with the field of the permanent magnets to produce continuous torque. The other MMF space harmonics, in particular the 1st, 7th, 17th, etc., which have relatively large magnitudes, are undesirable and in some cases they limit the usefulness of this winding type in different specific applications.

Using Fourier series function the MMF distribution for the 12-slot/10-poles winding can be described using the following equ. (1).

$$\Theta(x,t) = \sum_{\nu} \frac{m}{2} \cdot \frac{2 \cdot w \cdot {}^{\nu}\xi_w}{\pi\nu} \cdot \hat{i} \cdot \cos\left(\omega t - \nu \frac{\pi}{\tau_p} x + \delta\right) \qquad (1)$$

with

$${}^{\nu}\xi_w = \cos\left(\nu \frac{5}{6}\frac{\pi}{2}\right) \cdot \sin\left(\nu \frac{1}{6}\frac{\pi}{2}\right) \qquad (2)$$

where, ${}^{\nu}\Theta_m$ is the amplitude of the ν-th MMF space harmonic, ${}^{\nu}\xi_w$ is the winding factor, $\hat{i}$ is the phase current amplitude, δ is the load angle, ω is the angular frequency, N is the number of turns per coil, and ν is the space (MMF winding) harmonic.

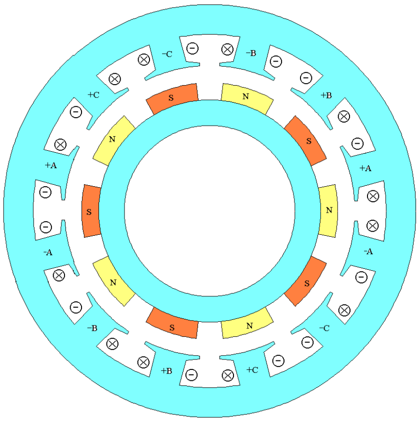


Fig. 1. PM machine with the conventional 12-teeth /10-poles winding topology.

a)

b)

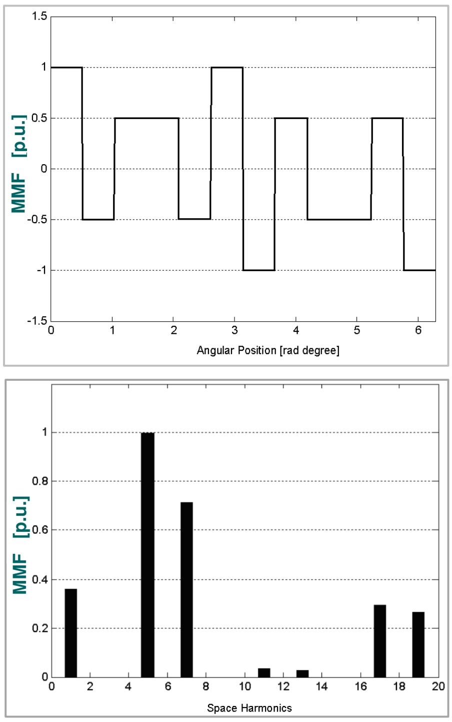


Fig. 2: MMF distribution and the corresponding MMF spectrum for the conventional 12-teeth /10-poles winding topology.

III. A Novel 12-Slots/10-Poles Winding Topology

A new and simple method for reduction of the sub-harmonics for the tooth concentrated windings is developed in [13]. The reduction of sub-harmonics is realized simply by using winding coils with different number of turns per coil side. Figure 3 shows the MMF of one phase, e.g. phase-A, for the conventional and the new 12-teeth/10-poles winding. With n_1 is denoted the number of turns of coil sides in the slots which contain the coils of the same phase, however with n_2 is denoted the number of turns of coil sides in the slots which contain the coils of different phases.

a)

b)

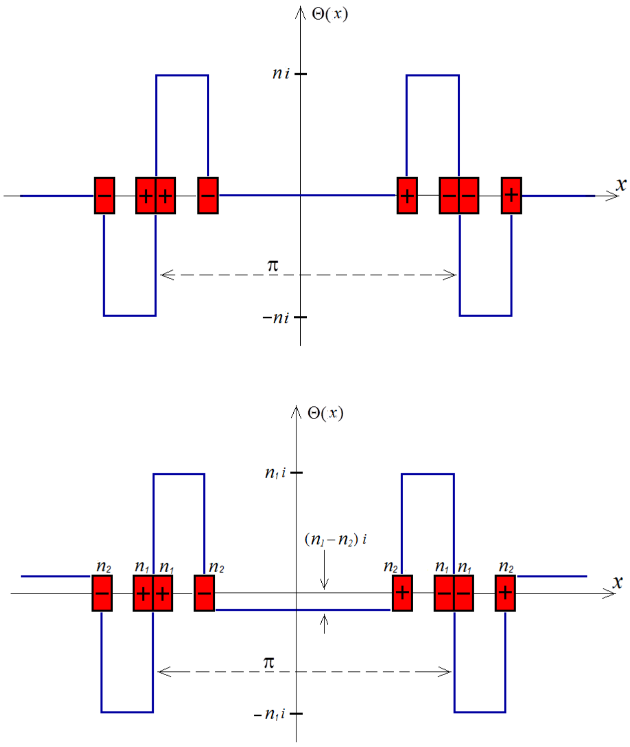


Fig. 3: a). MMF distribution (phase-A) for the 12-teeth /10-poles winding topology; a). Conventional winding, b). New winding with different number of turns per coil side.

From the above figure 3-b, the winding factor for the new 12-slots/10-poles winding with winding coils with different turns per coil side can be described as,

$$ {}^{\nu}\xi_{w,new} = \frac{n_2}{n_2+n_1}\left[\sin\left(\nu\frac{\pi}{2}\right)-\sin\left(\nu\frac{\pi}{3}\right)\right]+\frac{n_2-n_1}{n_2+n_1}\sin\left(\nu\frac{\pi}{3}\right) \tag{3} $$

According to [13], the relation between n_1 and n_2 of the coil windings with different *go-in* and *go-out* turns is,

$$n_1 = n_2 - 1, \qquad \text{and} \qquad 50\% \le n_1 / n_2 < 100\% \qquad (4)$$

Using the above eqs. (3) and (4), the effect of the n_1 / n_2 relation on the windings factor (1st and 5th) for the new winding is presented in the following figure 4, however Table-1 compares the winding factors for different 12-teeth/10-poles winding configurations. It can be shown that using the proposed technique the 1st sub-harmonic is reduced by about 97.5%, however, the working (5th) harmonic remains quasi un-effected (less than 0.45%).

The realization of the new 12-teeth/10-poles winding according to the technique proposed in [13] is illustrated in the following figure 5-a. As well is shown from this sketch, the winding coils with different turns per coil side are realized by non-completely winding the last turn of the coil (the last turn is winded only on one side). Of course, the manufacturing process for the new winding isn't influenced by using the proposed technique. Further, from the figure 4 it is shown that, the reduction of the sub-harmonic down to zero can be achieved for $n_1/n_2 \approx 87\%$. Therefore, for the given relation, e.g. for n_1/n_2=7/8 the comparison of the MMF harmonics for the conventional and the new 12-teeth/10-poles winding is presented in figure 5-b.

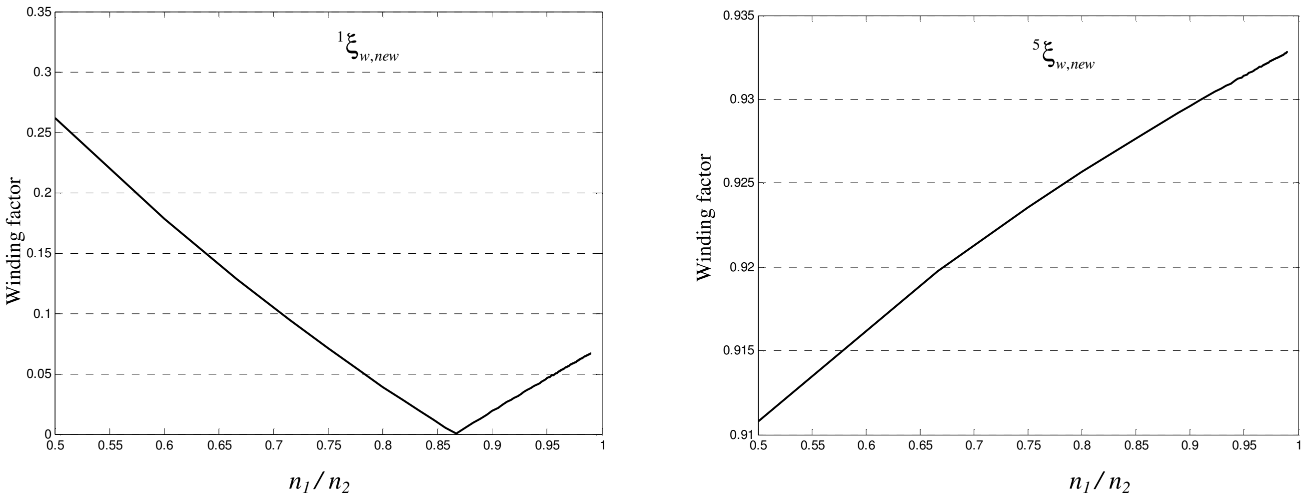
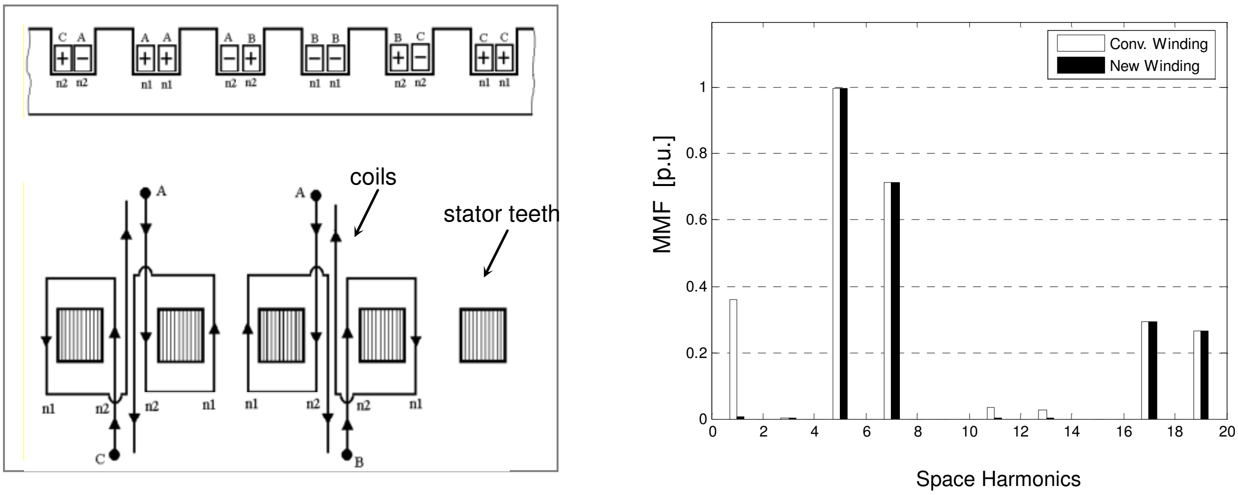


Fig. 4: The 1st and 5th winding factor vs. n_2/n_1.

TABLE I: Winding Factors and Relative Amplitudes of MMF Space Harmonics for Different 12-Teeth/10-Poles Configurations.

ν	Conventional winding		References [8-10]		New winding with $n_1/n_2 = 7/8$	
	${}^{\nu}\xi_w$	%	${}^{\nu}\xi_w$	%	${}^{\nu}\xi_w$	%
1	0.067	35.9	0.0173	9.6	0.0048	2.5
5	0.9331	100	0.9012	100	0.9287	100
7	0.9332	71.4	0.9012	71.4	0.9288	71.4



a) b)

Fig. 5: a). 12-teeth /10-poles winding topology with different number of turns per coil side, b). The corresponding MMF spectrum for n1/n2=0.875.

IV. Rotor Eddy Current Losses

Permanent magnet (PM) synchronous machines are generally considered to have negligible rotor losses, since the rotor rotates in synchronism with the fundamental stator *mmf*. However, the rotor pole pieces and the permanent magnets of PM synchronous machines are exposed to several time and space harmonics in the air-gap field which rotates at different speed with the rotor. This represents a source of losses which can be significant. Moreover, the high conductivity of permanent magnet materials leads to significant eddy current losses and this may cause the thermal demagnetization of magnets.

The eddy-current losses at each rotor region can be calculated by integrating the eddy current loss density over the volume of the region using the following equation,

$$P_{edd,mag} = \frac{1}{T}\int_{0}^{T}\int_{V}\frac{1}{\sigma}J_z^2 \cdot d\mathrm{V}\cdot dt \qquad (5)$$

Using the relation for the induced current density,

$$J_z = -\sigma\frac{\partial A_z}{\partial t} \qquad (6)$$

The eddy current losses can be determined directly from the magnetic vector potential as,

$$P_{edd,mag} = \frac{1}{T}\int_{0}^{T}\int_{V}\sigma\left(\frac{\partial A_z}{\partial t}\right)^2 \cdot dV\cdot dt \qquad (7)$$

However, the above eq. (7) in discrete form is

$$P_{edd,mag} = p\cdot\sigma\cdot f^2\cdot N_{Step}\cdot V\cdot\sum_{k=1}^{N_{Step}}\left(A_{z,k+1}-A_{z,k}\right)^2 \qquad (8)$$

According to the above relation (8), a 2D finite element (FE) model formulated by the magnetic vector potential A_z is used to analyze the eddy current losses of a PM machine.

V. Simulation Results

A PM machine with surface mounted PMs in the rotor for the automotive steering application is considered during the following analysis. Using 2D FE methods the eddy current losses for the conventional and the new 12-teeth/10-poles winding are investigated. Figure 6 shows the geometry and the flux-lines distribution of the investigated PM machine.

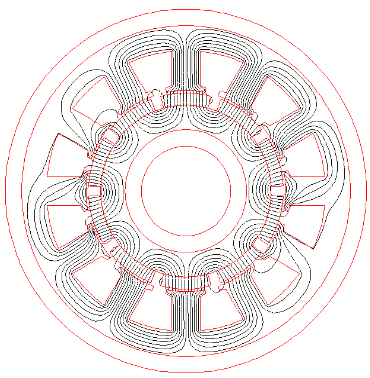


Fig. 6: Investigated PM machine.

During the determination of the PM eddy current losses, the considered PM machine is investigated for the no-load and under load condition. Further, under load condition the PM machine is investigated for the conventional and also for the new 12-teeth/10-poles winding. It is important to underline here that the under-load simulations for the both winding types are performed for the same load (torque) condition, figure 7. Figure 8 shows the obtained PM eddy current losses vs. rotor speed, however the loss distribution under load are shown in the figure 9. It can be deduced from the figure 8 that using the new winding the total eddy current losses are reduced for about 67%, however considering the loss components separately, the eddy current losses due to stator MMF harmonics (armature reaction field) are reduced significantly (about 80%) with the new winding. Furthermore, from the figure 9 it can be shown that for the conventional winding the magnet losses are distributed over the entire magnet region, however for the new winding type the magnet losses are distributed mostly at the rotor surface.

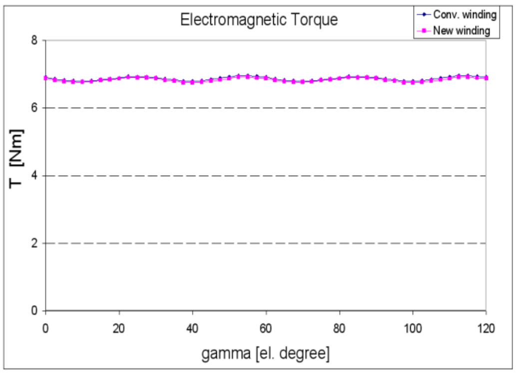


Fig. 7. Electromagnetic torque of the considered PM machine under load condition and for the conventional and the new winding.

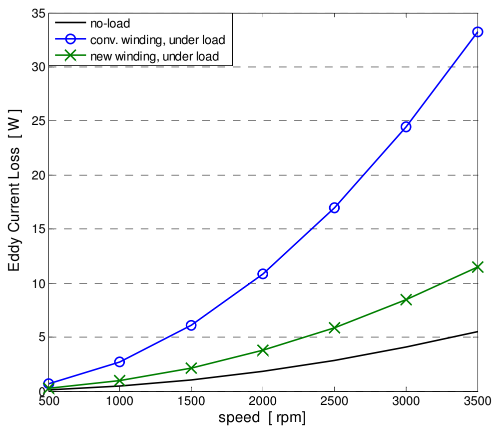


Fig. 8. Comparison of eddy current magnet losses.

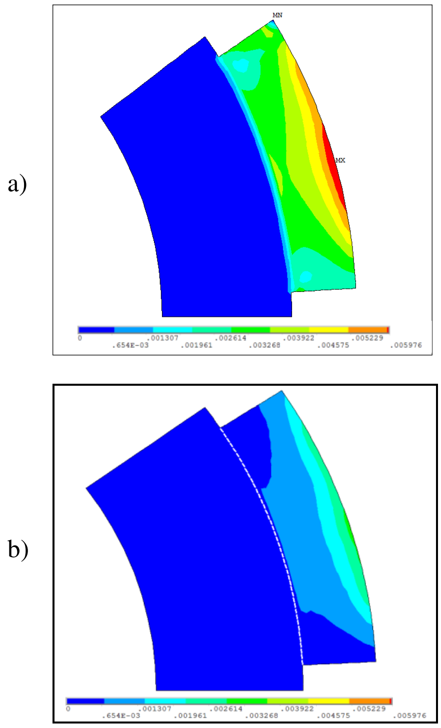


Fig. 9. PM eddy current distribution: a). Conventional winding, b). New winding.

CONCLUSIONS

This paper presents a novel method for reduction of sub-harmonics for the FSCW by using winding coils with different number of turns per coil side. Using the proposed technique the specific sub-harmonics can be reduced without influencing the working harmonic. The presented technique is available for different *m*-phases FSCW and it is easy for implementation, as it doesn't require additional winding coils, such as in [8-10], which complicate the manufacturing process of the winding.

Further, to show the performances of the new winding on the rotor losses, a PM machine for automotive steering application is investigated. The PM eddy current losses are determined for the new and the conventional winding and also for no-load and under load condition. The simulation results show that using the new winding the total eddy current losses are reduced for about 67%, however by considering the loss components separately, the eddy current losses due to stator MMF harmonics (armature reaction field) are reduced significantly (about 80%) with the new winding.

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