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Efficiency Improvements of Electric Machines for Automotive Application

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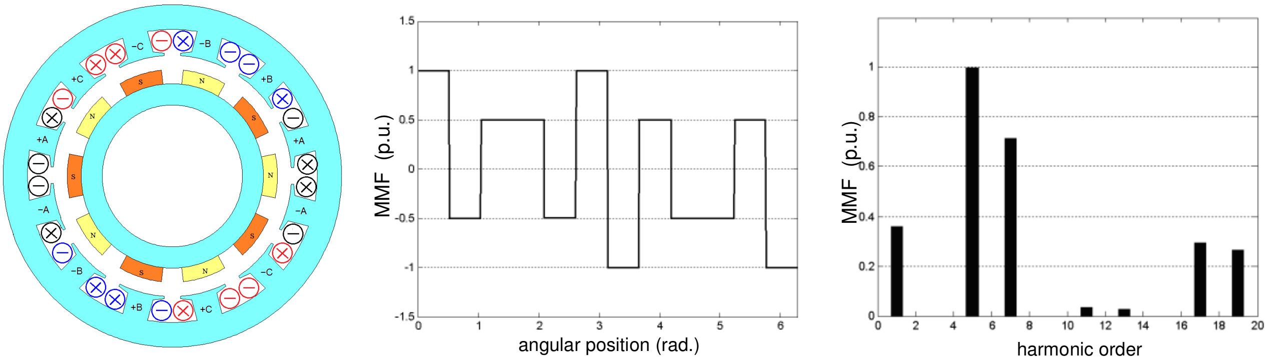
Abstract

Different costs effective and high efficiency methods for improving the main performances of tooth concentrated windings are presented. Using these simple techniques, the sub- and high winding space harmonics clearly can be reduced. Different PM machines for steering and also for hybrid electric vehicle and battery electric vehicle applications are designed and analysed. The investigated PM machines show good performances.

Keywords: Concentrated winding, efficiency, PM machines

1 Introduction

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]. 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 [2, 3], and noise and vibration [4, 5], which are the main disadvantages of these winding types.
A PM machine with 12-teeth and 10-poles is illustrated in the following figure 1-a. 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, so that the phase windings do not overlap. For this winding type, the magneto motive force (MMF) distribution and corresponding space harmonics are shown in figures 1-b and 1-c. It is shown from figure 1-c 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.
There have been several works in the last time devoted to improve the performances of the FSCW regarding to reduction of winding harmonics [6 to 11]. In this paper, different novel solutions for improving the concentrated winding performances are presented. The proposed techniques are used for reduction of unwanted harmonics of the 12-teeth/10-poles winding, however, of course these techniques are useful also to any other concentrated winding topology. According to the presented new techniques different electric machines for automotive application are designed and investigated.



a) b) c)

Fig. 1: a). PM machine with 12-teeth /10-poles winding topology, b). Winding MMF distribution, c). Corresponding MMF spectrum.

2 Concentrated Winding with Different Turns per Coil-side

A novel solution for reduction of sub-harmonics for the FSCW by using winding coils with different number of turns per coil side is presented in [7]. Using the proposed technique the specific sub-harmonics can be reduced without influencing the working harmonic. The realization of the new 12-teeth/10-poles winding according to this technique is illustrated in the following figure 2, however, the comparison of the MMF harmonics for the conventional and the new 12-teeth/10-poles winding is presented in figure 3. 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. For n_1/n_2=7/8, the 1st sub-harmonic of the considered winding type is reduced down to zero.

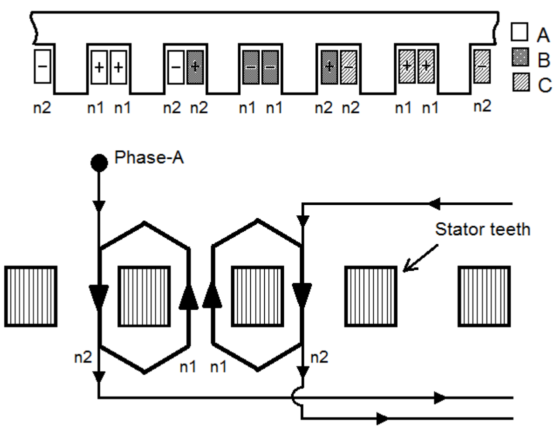


Fig. 2: New 12-teeth /10-poles winding topology with different turn per coil side.

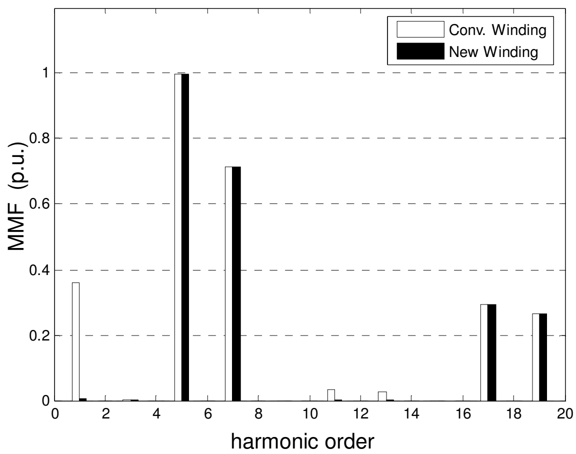


Fig. 3: Comparison of MMF winding harmonics.

The following figure 4 compares the eddy current losses in rotor magnets for a PM machine with the conventional and the new 12-teeth/10-poles winding and also for two different rotor types (surface magnet rotor – SPM, and inset magnet rotor – IPM). The investigated machine is designed for automotive application and is characterized with an outer diameter of 76 mm, axial length of 25 mm and maximal power of 600 W. Further, finite element methods (FEM) are used to derive the the magnet losses, and for all considered machine cases the simulations are perforemed under the same load conditions (torque and speed). As well is shown, depending on the rotor type the rotor magnet losses are different, however, using the new winding topology the magnet losses can be reduced more than 50%. The magnet losses distribution for the SPM machine type are presented in figure 5. From the obtained results it can be concluded that for the conventional winding type as results of the first winding sub-harmonic the magnet losses are induced over the complete magnet region, however, using the new winding the magnet losses are distibuted only on the magnet surface. These losses are induced from the air-gap flux density high harmonics.

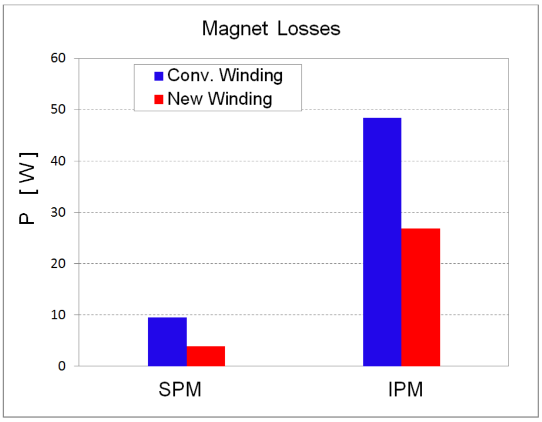


Fig. 4: Comparison of rotor magnet losses.

a)

b)

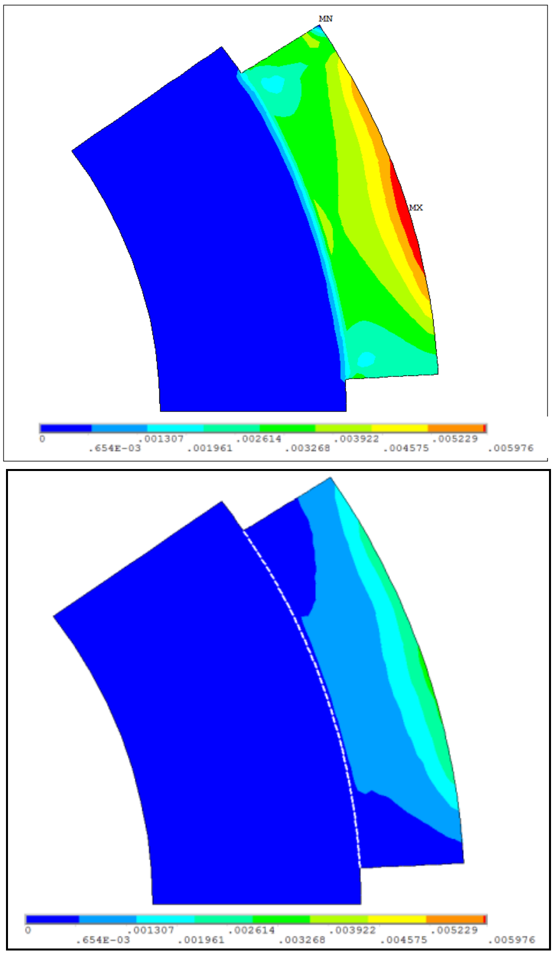


Fig. 5. PM eddy current distribution: a). Conventional winding, b). New winding.

3 Flux Barriers in Stator Yoke

Different from the previous solution where the reduction of winding sub-harmonics is performed by modification of the coil construction, another new technique proposed in [8] solves the same problem by modifying the stator yoke in specific locations. Of course, it is true that for influencing the winding harmonics it is required to modify something in the winding layout or construction, however, the method presented in [8] reduces the effect of winding sub-harmonics indirectly by using flux-barriers in stator yoke. Using this simple solution the air-gap flux density sub-harmonics can be reduced down to zero. Furthermore, this technique is related also with additional advantages for the electric machine such as available high efficiency cooling, solving the noise problems and so on [8].

Figure 6 shows a 12-teeth/10-poles PM machine with the new stator structure, however, figure 7 shows the air-gap flux density harmonics due to stator current for the presented solution. In the presented example the flux barriers are realized by building deeper slots in radial direction in the stator slots which contain the coil sides of the same phase. As well is shown, using the new stator topology the air-gap flux density sub-harmonics completely can be reduced.

It is important to underline here that the presented technique is used for improving the performances of a 12-teeth/10-poles concentrated winding, however, it is applicable to any tooth concentrated winding.

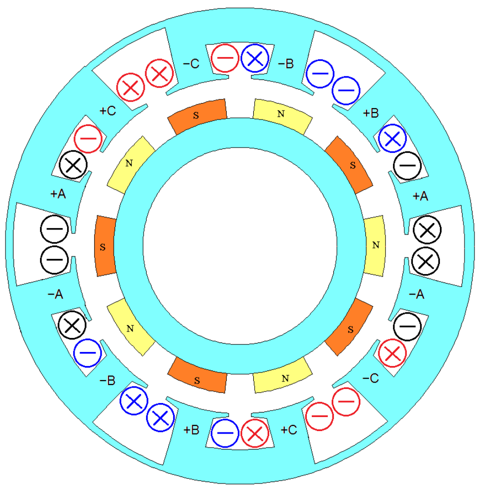


Fig. 6: 12-teeth /10-poles PM machine with flux-barriers in the stator yoke.

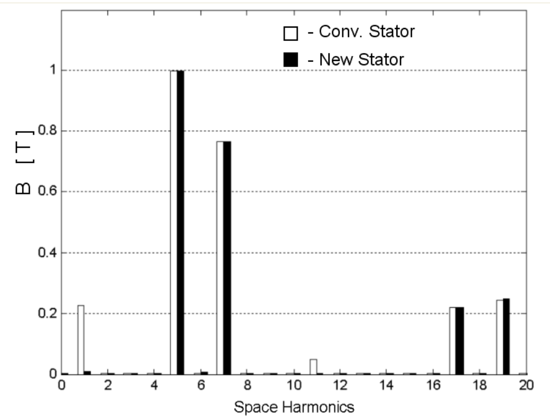


Fig. 7: Comparison of air-gap flux density harmonics due to stator currents.

Using the new stator structure a low cost (LC) 12-teeth/10-poles PM machine with inset magnets in rotor is designed and the first prototype is built, figures 8 and 9. The stator core consists of twelve simple tooth/yoke stator segments of iron core material and of six additional stator yoke components of non-magnetic material which are used as flux-barriers and also for fixing (mounting) the complete stator structure.

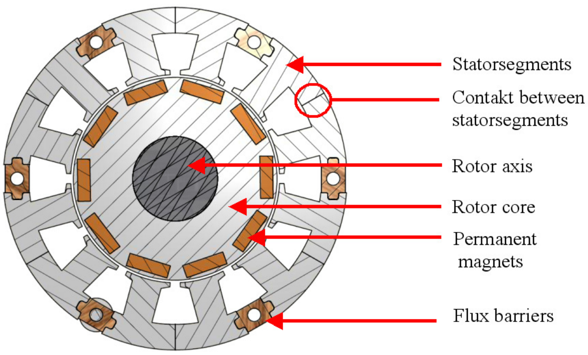


Fig. 8: Geometry of the designed LC PM machine.

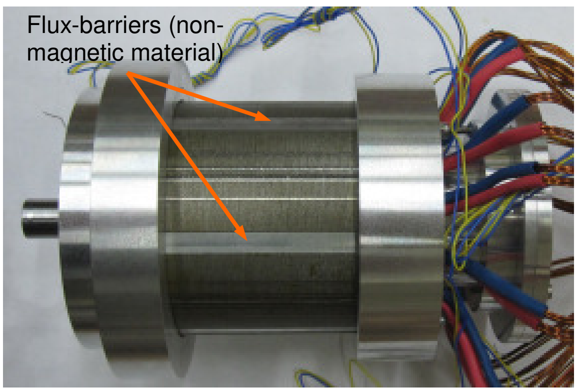


Fig. 9: Designed LC PM machine prototype.

The simulation and the first measurement results for the no-load induced voltage are shown in following figures 10 and 11.

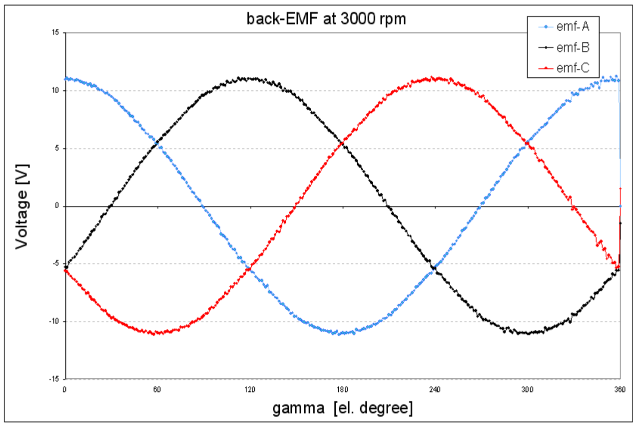


Fig. 10: FEM results: Induced no-load voltage at 3000 rpm.

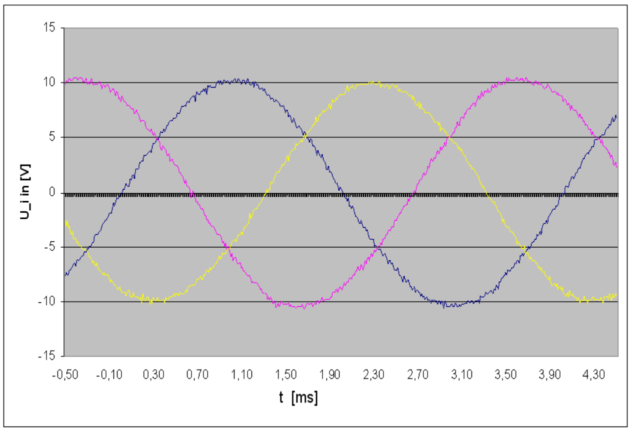


Fig. 11: Measurement results: Induced no-load voltage at 3000 rpm.

4 A Novel 18-teeth/10-Poles Tooth Concentrated Winding

A novel method for reducing simultaneously the sub- and the high MMF-harmonics using tooth concentrated winding is proposed in [9]. The new method is based on increasing the number of stator slots, using two winding systems shifted to each other for a specific angle, and using different turns per coil for the neighbouring phase coils or using coils with different turns per coil-side. In the following figure 12 this technique is applied to the 12-teeth/10-poles winding for obtaining a novel 18-slot/10-pole tooth concentrated winding. From the MMF spectrum given in figure 13 it is shown that using this method the sub- and high MMF harmonics are mostly reduced down to zero. Therefore using this new winding the main machine performances, such as efficiency and noise and vibrations clearly can be improved compared with the conventional concentrated windings.

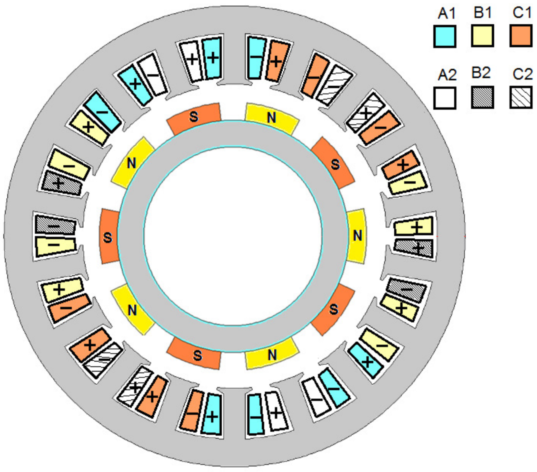


Fig. 12: New 18-slot /10-poles winding topology.

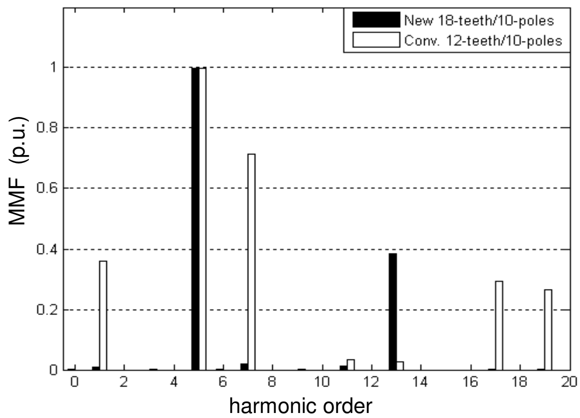


Fig. 13: MMF winding harmonics.

Table-I	18-Slot/10-Poles	24-Slot/10-Poles
U_{DC} (max)	600 V	300V
T_{max} @ n=4700rpm	300 Nm	250 Nm
n_{max}	12000 rpm	12000 rpm
Outer Diameter	230 mm	220 mm
Active axial length	150 mm	130 mm

Using the new 18-teeth/10-poles winding type a PM machine for HEV or BEV application is designed. The main specifications of the considered PM machine are presented in Table-I, however, figures 14 and 15 show the electromagnetic torque and the efficiency map obtained with FEM. As well is shown the designed PM machine with the new winding is characterised with low torque ripple and high efficiency.

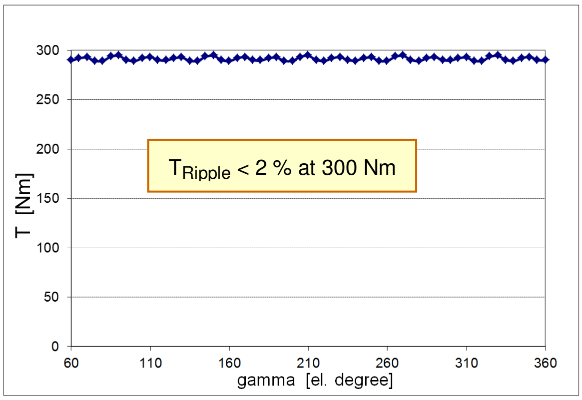


Fig. 14: Torque vs. rotor position characteristics for the 18-teeth/10-poles PM machine.

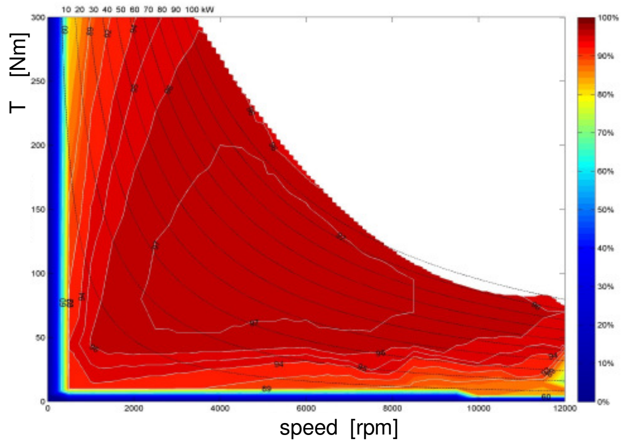


Fig. 15: Efficiency versus torque and speed of the new motor.

5 The 24-teeth/10-Poles Winding Topology

Another new solution for improving the concentrated winding performances is proposed in [10, 11]. Different from the previous solution, this method is based on doubling the number of stator slots, using two identical winding systems connected in series and shifted to each other for a specific angle, using stator core with different tooth width and using different turns per coil for the neighbouring phase coils. Figure 16 shows the new winding distribution. For sake of simplicity only the phase-A is illustrated. With n1 and n2 are denoted the turns per coil for the first and the second coil, respectively (neighbouring coils of one phase). Further, A1 and A2 represent the coils of phase-A for the first and the second winding system, respectively. The corresponding MMF spectrum for the new winding topology is presented in figure 17. As well is shown, using the new techniques the main unwanted harmonics such as the 1st and 7th are completely canceled. Further, it is shown that the 17th harmonic is also reduced by more than 50%. Therefore, having such improvements in the MMF spectrum leads to huge improvements of the PM machine performances, and makes the new winding type attractive for designing also other AC machines such as induction machines or electrically excited synchronous machines.

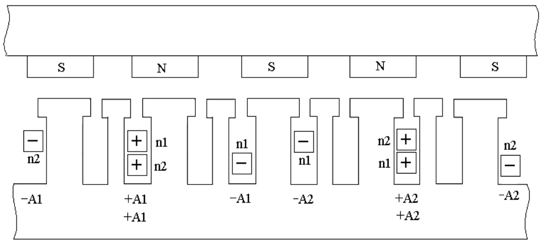


Fig. 16: New 24-teeth/10-poles winding topology (phase-A).

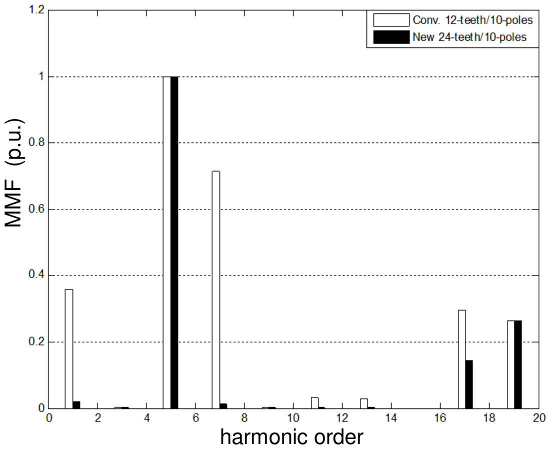


Fig. 17: MMF winding harmonics.

According to the new 24-teeth/10-poles winding different electric machines are designed and corresponding prototypes are built. The following figure 18 shows the stator prototype designed to operate with two different rotor types: permanent magnet rotor and squirrel-cage rotor. The main specifications of the designed electric machine are given in Table-I (the given value for torque corresponds to PM rotor).
Figure 19 compares the electromagnetic torque characteristics of the new 24-teeth/10-poles PM machine with an 8-poles PM machine with conventional distributed winding (q=2). Regarding to the torque ripple, the new motor design is very advantageous compared with the standard design; the new motor design delivers a very smooth torque. Therefore, skewing is not necessary applying this design. Further, the efficiency map for the new PM machines is presented in figure 20.

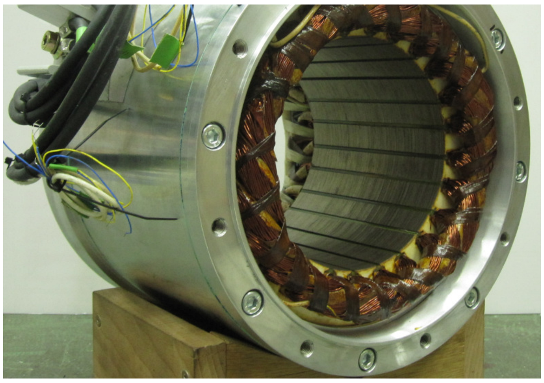


Fig. 18: Stator prototype according to the new 24-teeth/10-poles winding topology.

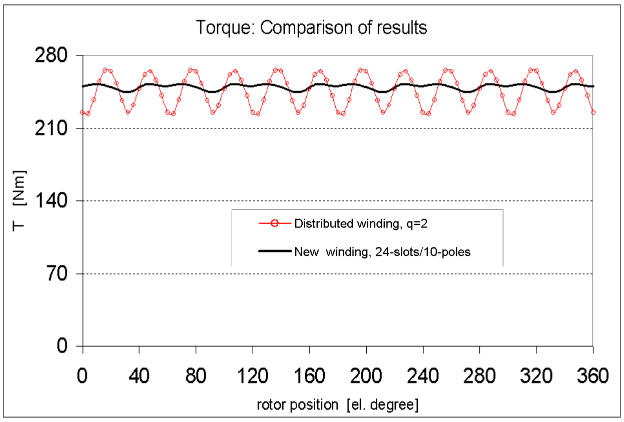


Fig. 19: Torque vs. rotor position characteristics for the standard and the new design (FEM results).

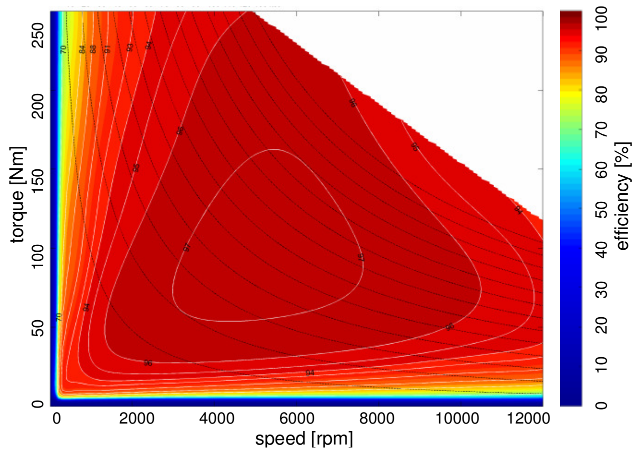


Fig. 20: Efficiency versus torque and speed of the new PM motor (FEM results).

6 Conclusions

Fractional slot tooth concentrated windings are characterized by high space harmonics which result in undesirable effects on electric machine, such as localized core saturation, additional losses in stator, rotor, magnets, and noise and vibration. In this paper different cost effective and high efficiency solutions for improving the performances of concentrated windings are presented;

1). Reduction of sub-harmonics:

- Using coils with different turns per coil side,
- Using flux barriers in the stator core (yoke).

2). Reduction of sub- and high harmonics simultaneously:

- Increasing the number of stator slots, using two winding systems shifted to each other for a specific angle, using stator core with different tooth width and using different turns per coil for the neighbouring phase coils.

According to the proposed new techniques different electric machines for automotive application are designed and prototype machines are built. It is important to underline here that the presented techniques are applied to the 12-teeth/10-poles winding, however, of course these techniques are also applicable to any concentrated winding topology. Further, the new presented windings are applicable also to other machine topologies, like induction machines and electrically excited synchronous machines.

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