Investigation and improvement of flux density harmonic content in electrical machines with fractional slot tooth concentrated windings

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***Abstract*—The fractional slots tooth concentrated windings are characterized by high number of a magnetic field spatial harmonics. It leads to undesirable effects on an electrical machine, such as eddy current loss in the rotor, localized core saturation, vibration and noises. This paper compares three electrical machines with different fractional slots tooth concentrated windings but designed for the same power with the same active volume. The compared machines' performances and harmonic content of the created magnetic field are presented. In particular, the winding which allows to improve the harmonic content of the magnetic field with the improved topology is presented.**

***Keywords*—permanent magnet synchronous machines, fractional slot tooth concentrated winding, flux density, spatial harmonics, finite element analysis**

I. Introduction

Wide industry usage of permanent magnet synchronous machines (PMSM) began not so long ago. Market appearance of the consumer grade high coercive rare-earth magnet made it possible. These magnets have a high specific magnetic energy. It allows with all other things being equal to produce machines with the best mass-dimensional parameters [1].

However, PMSM also have disadvantages. One of them is a torque ripple. The torque ripple arises due to the slotting effect of the stator and the rotor. It can leads to strong vibrations and noise during the machine operation. In addition, the torque ripple based on permanent magnets also occurs when the stator winding is disconnected [1].

PMSM with fractional slot tooth concentrated windings (FSCW) are becoming more and more attractive solutions for the different industry applications. The concentrated winding machines have potentially more compact design compared to the conventional machines with distributed windings due to shorter and less complex end-windings. The volume of copper used in the end-windings can be reduced in significant proportions with such windings. Also it leads to lower loss level in these machines. FSCW arrangement with number of slots per phase and per pole less than one ($q<1$) have become an attractive alternative for traditional solutions in modern applications. It generally presents higher performances and is widely used in many industry applications [2] - [4].

However, the magnetic field of these windings has many space harmonics. These unacceptable harmonics lead to undesirable effects such as localized core saturation, eddy current loss in the magnets [5] - [6], noises and vibration [7] - [10], which are the main disadvantages of these winding.

One of the main design stages is selection of the winding topology. There are a lot of different combinations of numbers of poles and numbers of teeth for FSCW. The correct choice of the winding topology allows to satisfy requirements for the operation of the electrical machine.

This paper compares three electrical machines with different fractional slots tooth concentrated windings but designed for the same power with the same active volume.

II. Task Description

The engineering task is to design a generator of 16 kW power. Rotation speed is 1500 *rpm*. Output Voltage is 250 *V*. Voltage frequency is no more than 300 *Hz*. Also there is a limitation of the active volume dimensions: external diameter is no more than 250 *mm*, length is no more than 200 *mm*.

PMSM was chosen as the task solution The rotor has a design with a tangential arrangement of magnets.

A. Active volume dimensions

The main active volume dimensions were chosen: bore diameter D = 180 *mm*; length l_δ = 200 *mm i*n the course of design calculations. The outer diameter D_a was chosen 245 *mm* whereas this diameter is the normalized size for manufacturing of electrical machines.

The air gap was the same for the all compared machines.

B. Winding data

Since there is a limit on the frequency of the output voltage of 300 *Hz*, the following types of FSCW were used:

- number of slots per phase and per pole $q=4/11$. Pole pairs $p=11$. Number of slots $Z_1=24$. Frequency of the output voltage for this winding type is 275 *Hz*.
- number of slots per phase and per pole $q=2/5$. Pole pairs $p=10$. Number of slots $Z_1=24$. Frequency of the output voltage for this winding type is 250 *Hz*.
- number of slots per phase and per pole $q=2/5$. Pole pairs $p=10$. This winding has improved topology. Number of slots for this winding is doubled $Z_1=48$.

These winding types produce similar output voltage in frequency that satisfies the requirements.

It should be noted that the same electric loading is used for all types of windings during the comparison. Also the working harmonic magnitude of the magnetic field flux density in the air gap has the same value.

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III. Windings Investigation

The windings are not sinusoidal distributed in machines with FSCW. As a result, magnetic field in the air gap may be far from being sinusoidal. Analyze the stator winding magnetic field and its space harmonics gives the main information about the electrical machine characteristics. As well known, the air gap flux density, electromagnetic torque, torque ripple, magnetic radial forces, and etc. are directly related to the stator magnetic field characteristics.

A finite element analysis is used for investigation the distribution of flux density in the air gap. In order to eliminate permanent magnet flux density component and to obtain only the stator winding flux density, the rotor is replaced by a solid steel cylinder during calculation. Basically such an assumption is acceptable only for linear systems, and the saturation effect makes some modifying of magnetic flux distribution. By using of solid steel cylinder rotor without magnets the air gap permeability is constant and the magnetic flux density curve has the same form like magnetomotive force curve. The resulting flux density function is expanded in a Fourier series.

A. *q=4/11 winding*

The spatial harmonics magnitudes of the flux density for FSCW with number of slots per phase and per pole *q=4/11* is presented on Fig. 1. The 11th is the working harmonic for this winding. Obviously, this harmonic has maximum magnitude. However, there are a number of other spatial harmonics. In particular: 1st, 5th, 7th, 13th, 17th, 19th. The 13th harmonic has the largest magnitude among them.

B. *q=2/5 winding*

Fig. 2 presents the spatial harmonics magnitudes of the flux density for FSCW with number of slots per phase and per pole *q=2/5*. The 5th is the working harmonic for this winding. Obviously, this harmonic has maximum magnitude. However, there are a number of other spatial harmonics. In particular: 1st, 7th, 17th, 19th. The 7th harmonic has the largest magnitude among them.

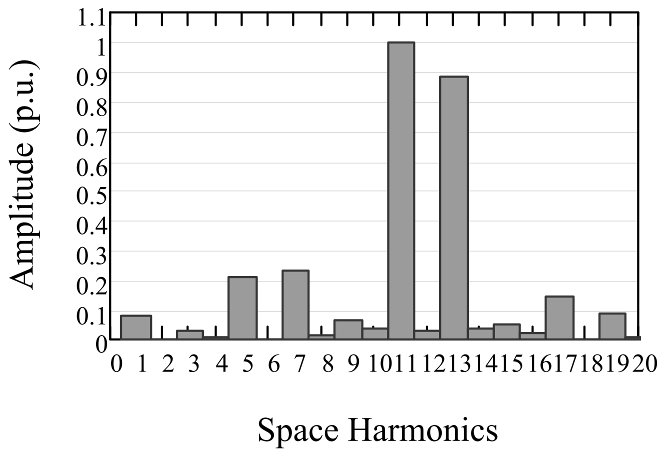

Fig. 1. The spatial harmonic content of the flux density for *q=4/11* winding.

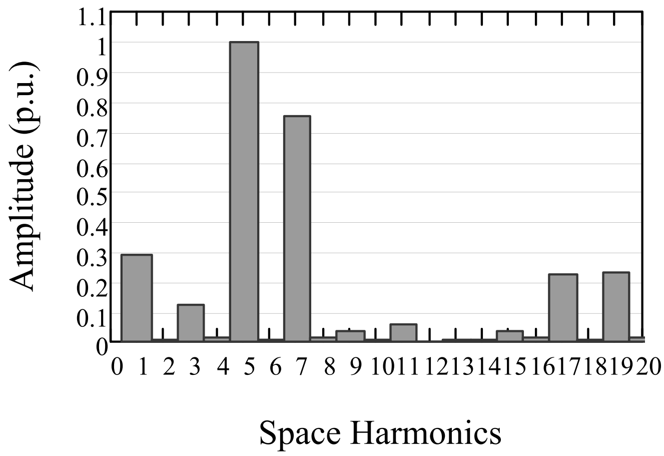

Fig. 2. The spatial harmonic content of the flux density for *q=2/5* winding.

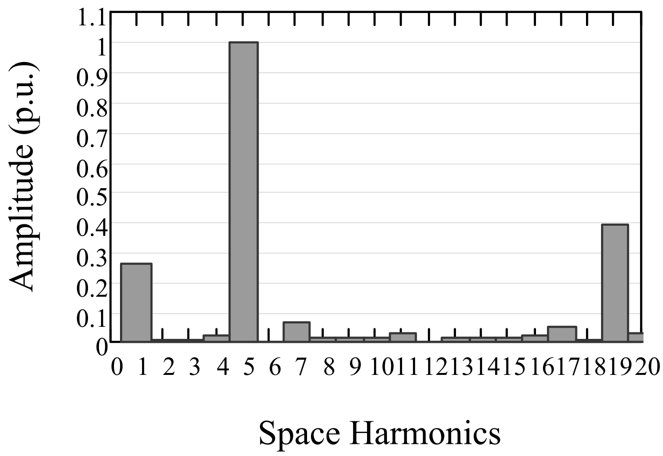

Fig. 3. The spatial harmonic content of the flux density for *q=2/5* improved winding.

C. *q=2/5 improved winding*

Spatial harmonics magnitudes of the flux density for FSCW with number of slots per phase and per pole *q=2/5* with the improved topology presented on Fig. 3. This winding differs from the previous in that it has doubled number of slots. The conventional concentrated winding is divided into two separate winding systems. Both windings are identical, are connected in series, and are supplied by the same inverter. The second winding is shifted mechanically for a specific angle referred to the first winding [11], [12]. The distribution of the winding allows to improve the spatial harmonic content of the magnetic field in the air gap. In this case, the 5th working harmonic remains at the same level. However, magnitudes of the 1st, 7th, 17th spatial harmonics are decreased. The magnitude of the most undesirable 7th harmonic is minimized. It should be noted that the reduction of sub- and higher harmonics leads to the differential flux leakage decreasing.

IV. Analyzing of Resuls

As was shown above, the classic FSCW has a large number of the magnetic field spatial harmonics. Its presence causes the previously described undesirable effects. The third winding has the best harmonic composition among all three presented. The third winding with number of slots per phase and per pole *q=2/5* with the improved topology has the best harmonic content among the presented. In particular, the reduction of the 7th harmonic leads to reduction of magnetic radial forces [7]. Also as a consequence, it causes decreasing of vibration and noise level.

Fig. 4 shows the torque vs. rotor position characteristics of the compared machines. The winding with *q=2/5* has the highest maximum moment. However, this winding has the biggest value of torque ripple that is shown on Fig. 5, and the form of the torque graph is far from being sinusoidal. The winding with *q=4/11* has distinct better performance. The winding with *q=2/5* with the improved topology has the lowest level of ripple, and the graph shape is close to sinusoidal. A significant reduction of torque ripple leads to improvement of the machine noise-vibration-harshness behavior.

The Table 1 presents some characteristics of the compared machines. All windings have similar coil resistance. The improved winding with *q=2/5* has slightly higher coil resistance than the convention winding due to slight increase of the end-windings total length. As was noted above, the improved winding with *q=2/5* has the reduced value differential flux leakage. This leads to decreasing of inductance from differential leakage, and, as a result, decreasing of the total winding inductance. So, this winding has the lowest inductance.

Since the designing electrical machine is a generator, its external characteristic external characteristic plays a big part. External characteristics of the compared machines are presented on Fig. 6. Obviously, the improved winding with *q=2/5* has shunt characteristic due to the lowest value of the inductance. This is the most favorable generator performance. Also, machine with this winding has a minimum voltage decrease at rated current.

The machine with the improved winding topology with *q=2/5* shows conspicuous better performance in comparison with the convention FSCW due to the combination of the presented above characteristics.

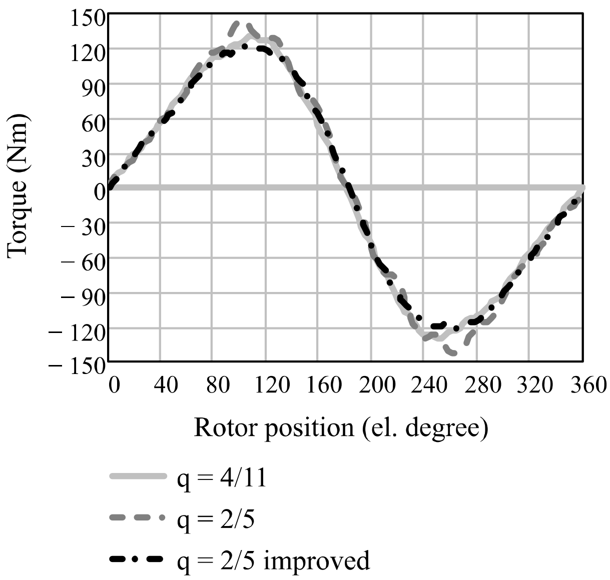

Fig. 4. Torque vs. rotor position characteristics for the compared machines.

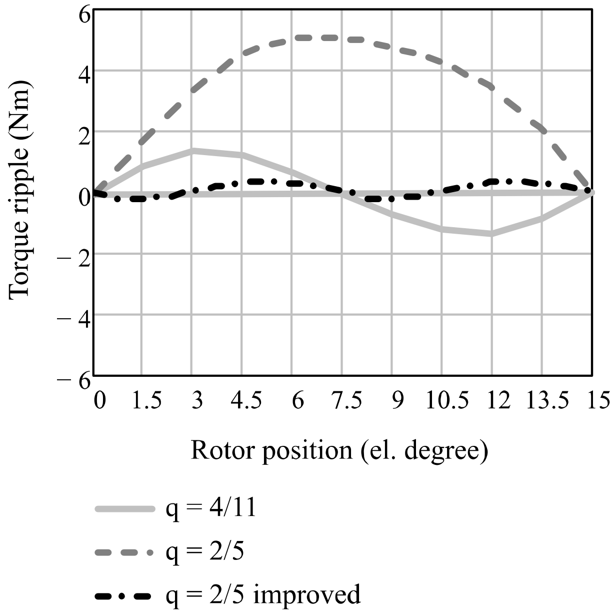

Fig. 5. Torque ripple vs. rotor position characteristics for the compared machines.

TABLE I. CHARACTERISTICS OF THE COMPARED MACHINES

Char-acter-istic	**Winding type**		
	q=4/11; Z_1=24	***q=2/5; Z_1=24***	***q=2/5; Z_1=48***
M_{max}, N·m	131	143	121
Torque ripple, N·m	1.327	5.103	0.347
E_0, V	247.5	256.6	248.5
R_1, Ω	0.191	0.19	0.196
L_d, mH	2.44	2.87	2.04
L_q, mH	5.15	5.43	3.60

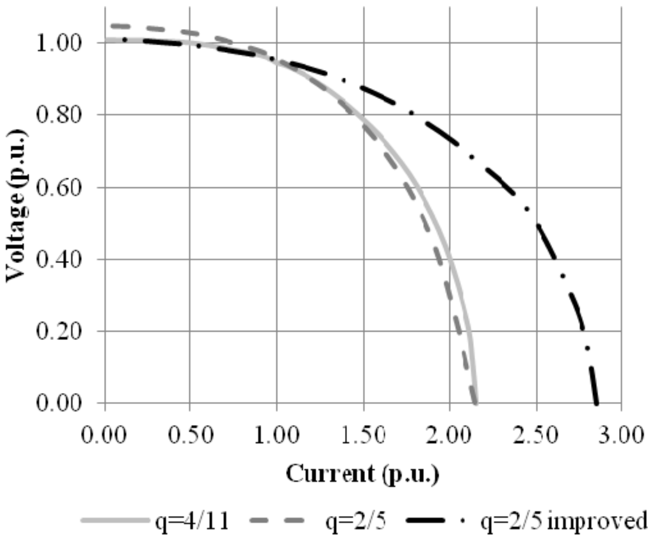

Fig. 6. External characteristics of the compared machines.

V. CONCLUSION

The fractional slot tooth concentrated windings have a large number of the magnetic field spatial harmonics, which leads to undesirable effects. Comparison of three electrical machines with different FSCW is presented. Two windings have the convention topology with number of slots per phase and per pole $q=4/11$ and $q=2/5$. The third winding has number of slots per phase and per pole $q=2/5$ with the improved topology.

The harmonic content of the magnetic field for each winding is presented. Also the external characteristics are presented. The machine with the improved winding topology with $q=2/5$ shows conspicuous better performance in comparison with the convention FSCW due to the combination of the presented above characteristics.

The magnetic field harmonic content improvement is presented only for FSCW with $q=2/5$, but this improvement method can be used for FSCW with different q.

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