Methods for reducing cogging torque in permanent magnet synchronous motors.

R R Bakiev, A F Schevchenko, D Y Babitsky

Novosibirsk State Technical University, 20, Karla Marksa Av., Novosibirsk, 630073, Russia

E-mail: ruslanbakiew@gmail.com

Abstract. The paper presents the results of the study of the cogging torque in synchronous machines with permanent magnets and fractional slot winding. Various methods for optimizing the rotor of a synchronous machine with permanent magnets are considered. The results are shown as a dependence of the cogging torque on magnet opening width. Recommendations for choosing the optimal opening magnet are given.

1. Introduction

The use of permanent magnet synchronous machines (PMSM) began not so long ago. NdFeB and SmCo are high-coercivity rare-earth magnets based on fundamental technologies. These magnets have a high specific magnetic energy, which makes it possible to produce machines with the best mass-dimensional parameters, all other things being equal [1].

In comparison with induction motors, PMSM’s has some advantages:

- Increased efficiency by reducing the overall level of losses in the machine, which is explained by the absence of windings and currents in the rotor, as well as a smaller mass of active materials (copper and steel).
- Increased torque in the same dimensions due to an increase in the pole of the machine, which allows reducing the height of the yoke and due to this increase the diameter of the stator boring.

In Table 1 the technical information of some induction machines with a power of 2.2 kW are presented in the first four columns, as well as information of a synchronous motor with permanent magnets of the same power is presented in the fifth column.

| Engine specification         | Efficiency, % | cos φ | mass, kg |
|------------------------------|--------------|------|---------|
| AIR90L4 universal motor      | 81           | 0.83 | 19.75   |
| 4A90L4Y3 engine series 4A    | 82           | 0.83 | 21      |
| AIPE100S4 single-phase universal motor | 75       | 0.95 | 24.44   |
| RA100L2 induction motor series DIN | 80       | 0.81 | 18.55   |
| DSM synchronous motor with permanent magnet | 90      | 0.84 | 7       |

Table 1. The technical information of some asynchronous machines and PMSM
As it can be seen from this table, the efficiency of a synchronous machine is much greater, and also the mass-dimensions are several times higher than those of analogs among induction machines.

One of the most important problems of PMSM is the cogging torque. The cogging torque arises due to the slotting of the stator and the rotor. They can lead to strong vibrations and noise during the operation of the machine. It should be noted that the cogging torque take place in machines with classical windings. In these machines the slot skewing is used and the fractional slot windings is less than 1. In machines with fractional slot windings, the number of teeth differs little from the number of poles. In this case, the number of the cogging torque is less than in machines with classical windings, but their amplitude is higher. In addition, the cogging torque from the action of permanent magnets occurs also when the stator winding is disconnected. This pulsation is highly undesirable in precise electric drives [1].

The Department of Electromechanics of Novosibirsk State Technical University faced the problem of the cogging torque, during testing a batch of machines for general purpose industrial version. When testing these machines for vibration and noise, the first batch of machines did not performed testing this type of test. The presence of large tooth pulsations of torque, as one of the reasons, led to the fact that the vibration level of the machine does not correspond to National State Standard.

2. Methods for reducing the cogging torque

From the point of view of an electric machine design, methods for reducing the cogging torque can be divided into three groups:

- Choosing the optimal ratio of the numbers of teeth and pairs of poles of a machine.
- Optimization of a rotor design.
- Optimization of geometry of a tooth-slotted stator zone.

The first and third methods are discussed in detail in [2]. The influence of the structural features of the rotor on the cogging torque is a less studied issue.

The ways to reduce pulsations by optimizing a rotor can also be divided into groups:

- Rotor pole shift [3].
- Formation of magnetomotive force by segmentation of the magnets [4].
- Optimization of the pole overlap factor [5].
- The bevel of the poles of the rotor.

As shown by studies at the Department of Electromechanics of Novosibirsk State Technical University, the above-mentioned methods make it possible to obtain comparatively low cogging torque. However, they all lead to a complication of the technology of making the machine, hence, increasing its cost price.

3. Studies of the cogging torque in a rotor with tangential magnetization.

In this paper, the influence of the tooth zone on the pulsation of the electromagnetic torque is investigated. The influence of the tooth zone of the stator has already been studied in the literature, and the tooth zone of the rotor has not been fully investigated.

The model is based on a rotor with tangential magnetization of permanent magnets. In the rotor with tangential magnetization, the influence of opening magnet on the pulsation of the electromagnetic torque was investigated: from a fully open to a completely closed magnet (Figure 1).
In this paper, a machine with fractional slot windings with a number of slots per pole and phase 2/5 was investigated. The number of teeth for this machine is 12, the number of pairs of poles is 5. For the study, a mathematical model of a synchronous motor with permanent magnets was created. The finite element method is based on FEMM software. There were models with various opening of the magnet, which were calculated in the FEMM program in order to obtain the power-angle diagrams of the engine. These diagrams were subsequently decomposed into Fourier’s series to determine the amplitude of the harmonics. Then, a plot was drawn for the cogging torque from the ratio of the width of the opening of the magnet to the pole pitch of the machine. Figure 2 shows the picture of the field distribution of the investigated machine.

For the accuracy of the experiment, the same stator construction is used for all calculation options with a constant volume of magnets. These two criteria give an understanding that any change in the power-angle diagrams is due to a change in the design of the rotor.
4. Results

After calculating the various methods and their approximations, a graph was obtained for the dependence of the cogging torque on the ratio of the width of the opening of the magnet to the pole pitch. Figure 3 shows this relationship.

![Graph showing the dependence of cogging torque on the ratio of the width of the opening of the magnet to the pole pitch.](image)

**Figure 3.** Dependence of the cogging torque on the ratio of the width of the opening of the magnet to the pole pitch.

It is seen from the graph that the smallest pulsations were obtained with a ratio of the opening width to the pole pitch equal to 0.135 and 0.177, and the largest pulsations were obtained at 0.08.

The ordinal number of the harmonics of the cogging torque is defined as the multiplication of the number of pole pairs by the teeth number of machine. The harmonic of the cogging torque having the largest period will be called the fundamental harmonic. In our case, the fundamental harmonic of the tooth pulsations of torque is the 60th harmonic ($\nu = p \cdot Z = 5 \cdot 12 = 60$) and the harmonic is a multiple of it. The torque of tooth pulsations can be represented as the multiplication of the harmonic series of the magnetomotive force of magnets by the harmonic series of permeance. The number of harmonics in magnetomotive force that interact with the permeance harmonics can be very large. But the permeance harmonics for $q = 2/5$ are not so many. They are equal to 5, 10, 15, 20, etc. [2] Accordingly, if it is possible to reduce the 5th harmonic, then the harmonic series of the magnetomotive force of the magnet will not interact with the harmonic series of permeance. This will reduce the cogging torque to a minimum.

Since the 60th harmonic corresponds to the tooth pulsation of torque, with the help of a certain opening of the magnet, we managed to reduce the amplitude of the given harmonic. Theoretically, this can be described by analogy with the shortening of the winding pitch: in order to reduce the amplitude of the higher harmonic, in classical machines this is done for the 5th or 7th harmonic, we make the windings shortening by 1/5 or 1/7, or something average to reduce the amplitude of the higher harmonics. In the case under consideration, one shortens the path by which the magnetic flux closes by an amount that is a multiple of the higher-order harmonic.

After the study, one can make two widths of the opening of the magnet, at which the smallest torque pulsations are obtained: at 0.03 and at 0.178. These opening are recommended to be used for rotors with tangential magnetization and $q = 2/5$. 
5. Conclusion
In this paper the applicability of reducing the cogging torque is considered. Various approaches of reduction the cogging torque were considered. A method for measuring the pulsations of a torque is described. After the study, the dependence of the cogging torque on the ratio of the opening width of the magnet to the pole pitch was revealed. The changes in the pulsations of the torque at various opening are shown. Theoretically, the model explains why the pulsation tooth torque has decreased by analogy with the shortening of the windings pitch, and also recommendations are given for choosing the width of the magnet opening to reduce the cogging torque.

References
[1] Shevchenko A F and Vialcev G B 2010 Part rotor displace method for minimization of cogging torque in permanent-magnet machines *International Forum on Strategic Technology* (Ulsan) pp. 427-429
[2] Pristup A G, Toporkov D M 2017 Comparing of cogging torque reduction methods in permanent magnet machines with fractional slot windings *IOP Conf. Ser.: Earth Environ* 87 032032
[3] Beton C, Bartolome J and Benito J A 2000 Influence of machine symmetry on reduction of cogging torque in permanent-magnet brushless motors *IEEE Trans. Magn.* 36(5) 3819–3823
[4] Lateb R and Tokarabet N 2006 Design technique for reducing the cogging torque in large surface-mounted magnet motors *Recent Developments of Electrical Drives* 59–72
[5] Hwang S M, Eom J B, Jung Y H 2001 Various design techniques to reduce cogging torque by controlling energy variation in permanent magnet motors *IEEE Trans. Magn.* 37(4) 2806–2809