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Methods to Reduce the Cogging Torque in Permanent Magnet Synchronous Machines

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***Abstract*—The phenomenon of cogging torque in permanent magnet synchronous generators with concentrated windings is considered in this work. Dependence of fluctuation amplitude of the torque on width of stator slot opening is researched. The method to reduce the cogging torque by skewing of stator slot and opening of stator slot width equal distance between magnet and tooth on the rotor is described. The construction of this generator is obtained on the basis of numerical simulation results**

***Index Terms*—Torque, finite element method, permanent magnet machines.**

I. INTRODUCTION

Permanent magnet synchronous generators (PMSG) are used in low power wind turbines because of advantages of generators, such as high efficiency, simplicity and reliability of construction. Synchronous generators of modern wind turbines are directly connected to wind turbines. One of main disadvantages of PMSG is the cogging torque. Cogging torque is expressed in change of the torque on rotor in interaction of magnet flux and stator teeth. Additional vibrations, acoustic noise and more complicated starting conditions appeared in this case, exploitation become more difficult.

Nowadays there are many actions how to reduce pulsations of the cogging torque [1]–[4]:

1) To use fractional number of slot per pole and phase;
2) To optimize sizes of magnet;
3) To use skewing of stator slots or magnets;
4) To change width of opening stator slot.

It should be noted that the cogging torque is depend on geometrical parameters of machine. Therefore, reduction of torque is the main task in design of machine.

II. THE ANALYZED MACHINE

The object of this research is the generator with impulse of high-energy magnets Nd-Fe-B. Basic sizes of the generator in cross section are presented in Fig. 1. As you can see in Fig. 1, permanent magnets alternate with teeth. Magnets form poles of one polarity, and teeth form poles of opposite polarity, but with the same nominal flux (Fig. 2). This construction of generator allows to reduce costs of production and to simplify connection of magnets on the rotor.

The finite element method is used to determine torque of the generator. Basic geometric data presented in Table I.

The advantage of this method: it allows solving problems in complicated geometry of tooth zone, taking into account non-linearity of environments.

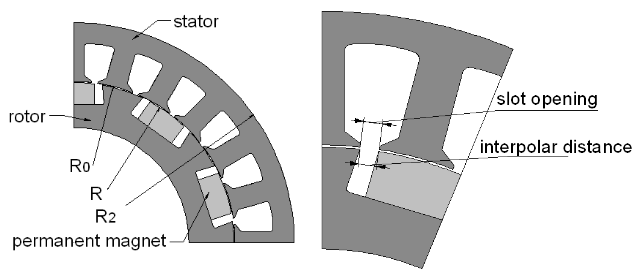

Fig. 1. Cross section of the PMSG.

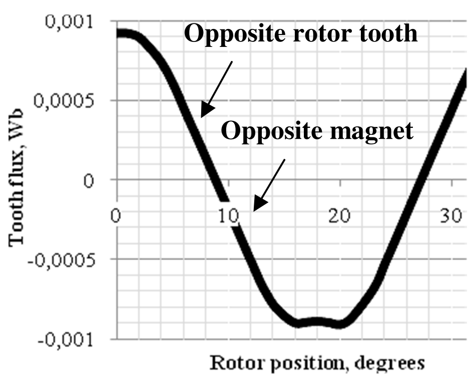

Fig. 2. Change of flux in stator tooth vs. rotor position.

Distribution of magnetic flux in the cross section of machine is shown in Fig. 3. Fluctuation curve of cogging torque is shown as function of turning angle of the rotor in Fig. 4. Cogging torque is calculated by simulating the machine at no-load (no current in the armature winding).

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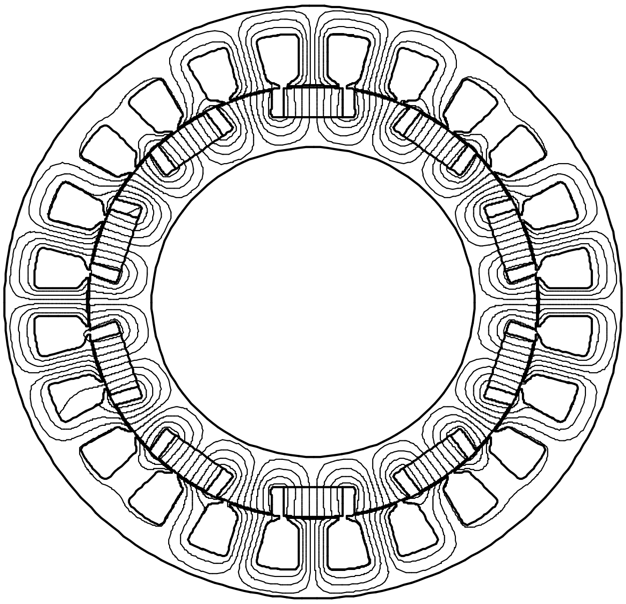

Fig. 3. The distribution of magnetic flux in machine cross-section

The presence of uneven rippling of the cogging torque should be noted, maximal value of cogging torque is M = 1.4 Nm. This generator is designed for wind power plant, that is why the cogging torque of generator has to be low enough at start-up moment and aerodynamic power of wind turbine will be able to overcome it. Otherwise, at large values of cogging torque, the turbine will be able to start work only in conditions of strong wind. Therefore, the main purpose of this research is to find opportunities for alignment of pulsations and to decrease the cogging torque to minimum.

TABLE I. BASIC SIZES OF GENERATOR WITH NUMBER OF STATOR TOOTH Z_1=24 AND NUMBER OF POLES 2P=20.

Diameter of stator bore	D	190	mm
Outside diameter	D_2	260	mm
Inner diameter	D_0	140	mm
Core length	l	50.8	mm
Magnet width	b_m	25.4	mm
Stator tooth width	b_{z1}	22	mm
Stator slot opening width	b_s	3.6	mm
Rotor slot width	b_{z2}	25.5	mm
Interpolar distance	b_w	5	mm
Air gap	δ	0.6	mm

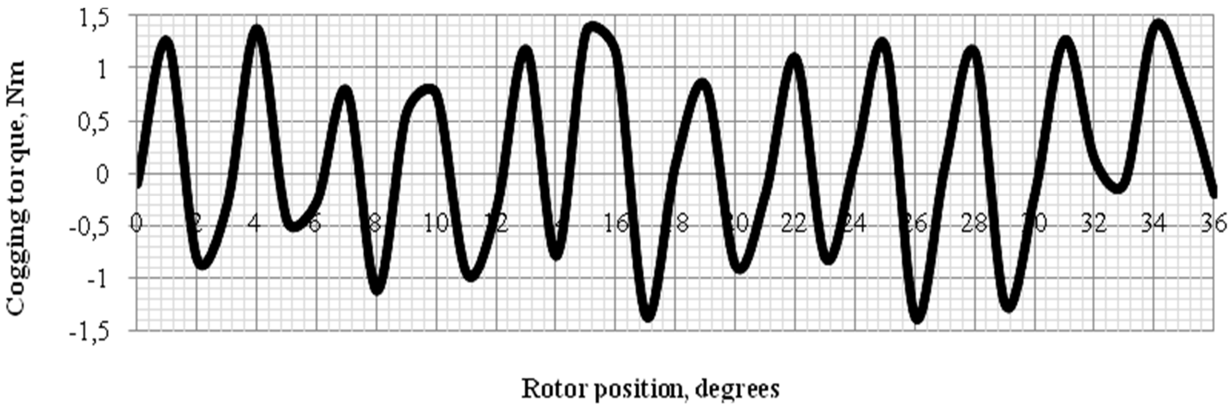

Fig. 4. Dependence of cogging torque vs. rotor angle.

III. INFLUENCE OF SLOT OPENING WIDTH ON COGGING TORQUE VALUE

The influence of opening slot width on pulsations of cogging torque is investigated in this work. Changes of width varied from 3.5 to 5.5 mm. Curve in Fig. 5 shows how maximal cogging torque depends on slot opening width.

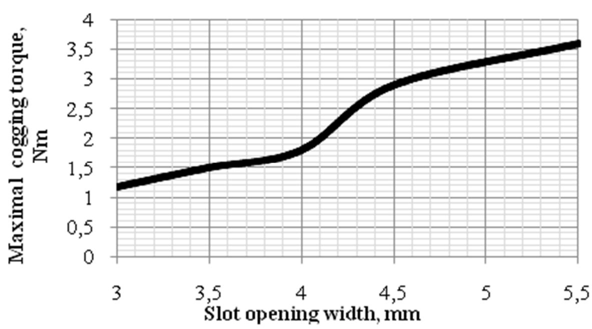

Fig. 5. Dependence of maximal cogging torque vs. slot opening width.

The conclusion is - the wider opening of slot, the greater value of cogging torque. However, it should be noted that value of slot opening width is determined by technological requirements and it depends on cross section of armature conductors. Therefore, designer has to calculate the minimal possible value of slot opening width according to generator power.

Based on these results, it should be noted that irregularity of pulsations due to changes of magnetic field is mainly concentrated in air gap by rotating the rotor. To align torque pulsations is possible by ensuring the equality of angular sizes of slot opening and interpolar distance

$$b_s = b_w. \tag{1}$$

Curves of the cogging torque for two cases are presented in Fig. 6: case of equality $b_s = b_w$ and case of different values of slot opening width and interpolar distance $b_s \neq b_w$. If the interpolar distance is equal to angular size of the slot opening, pulsations of torque become aligned; it is done because of constancy of mutual covering areas of stator teeth and rotor poles.

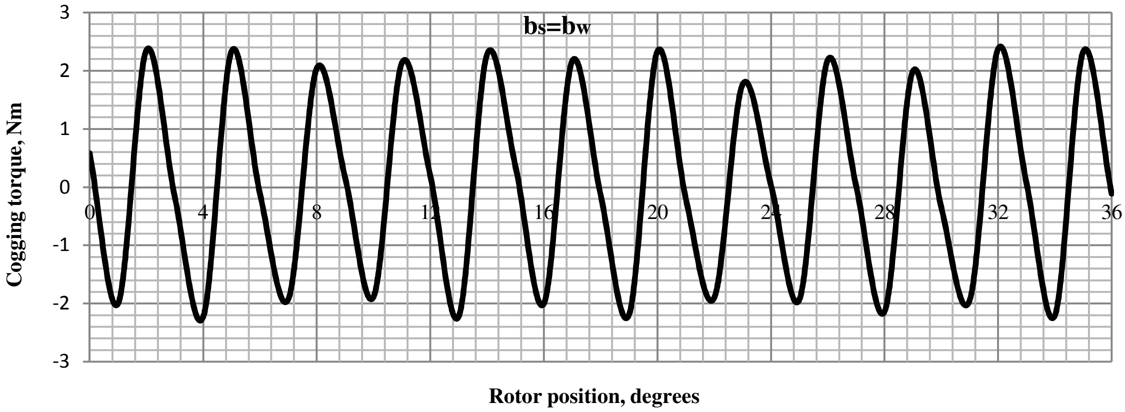

Fig. 6. Dependence of cogging torque on rotor angle.

IV. Stator Slots Skewing

The most effective way to reduce cogging torque is skewing of stator slots or rotor poles. It means skewing of one side of stator (rotor) core by few degrees in according to the other side of core (Fig. 7). The skewing allows to eliminate the cogging torque or to reduce it to minimum.

However, the skewing complicates process of production, it increases final price of product.

Skewing of slots may also complicate set of armature winding, reduce effective area of slot and increase the length of conductor. To skew poles of rotor we need complicated form magnets, so it will increase price of construction significantly. Further we will consider possibilities to reduce pulsations of cogging torque by skewing of stator slots, if slot opening width is equal to interpolar distance ($b_s = b_w$).

To skew stator slots effectively the following equalities should be done:

$$b_{z1} + b_s = \frac{360}{Z_1}, \quad (2)$$

$$b_m + b_w = \frac{360}{2p}, \quad (3)$$

$$b_m = b_{z1} \pm b_s. \quad (4)$$

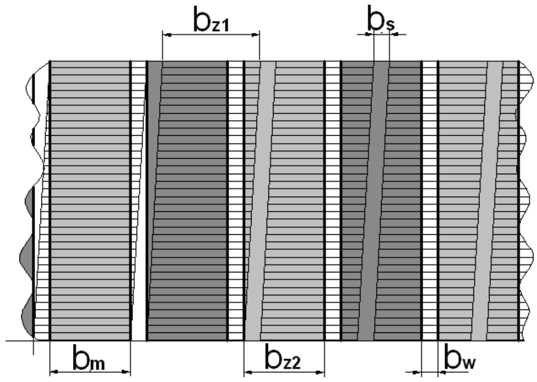

Fig. 7. Slots skewing.

Slots skewing angle and equal values: slot opening and interpolar width – have to be equal to the period (Δα) of irregular moment changes between near positions of rotor stable balance

$$\Delta\alpha = |\alpha_1 - \alpha_2| = \left|\frac{360}{2p} - \frac{360}{Z_1}\right|. \quad (5)$$

If Z_1=24; 2p=20 then

$$\Delta\alpha = \alpha_1 - \alpha_2 = \frac{360}{20} - \frac{360}{24} = 3^0;\ b_s = b_w = 3^0. \quad (6)$$

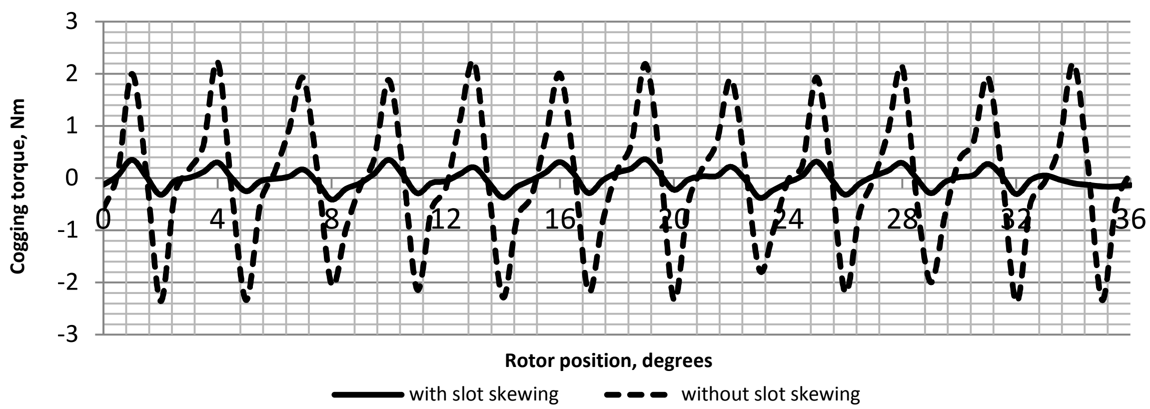

Fig. 8. Curves of change of the cogging torque at rotational rotor with stator slot skewing and without.

Effective skewing angle for this construction of generator is $\alpha_{sk}=3^0$. In this case, it should be noted that the stator slot skewing makes easier transition of stator teeth in zone of near pole by value of stator slot opening.

Torque fluctuation curves of rotor turning are shown in Fig. 8 in case if slots have been skew or not.

Implementation of optimal skewing reduced the amplitude of torque pulsations to 0,3 ÷ 0,4 Nm.

It should be noted that width of magnet has to be equal to width of rotor teeth. If equality $b_m = b_{z2}$ does not exist, the flux through the stator tooth increases, value of maximal cogging torque increases also, so you should choose magnet width equal to rotor teeth width.

V. CONCLUSIONS

The possibilities to reduce cogging torque are considered in this work. It will be done if to change width of stator slot opening and to skew stator slots. Decreasing of slot opening width leads to reduction of the cogging torque pulsations. Reduction of width opening is limited by normal set of winding in stator slots. Using the stator slots skewing, if slot opening is equal to interpolar distance, is the most effective way to deal with cogging torque and it allows to reduce pulsations by 80%.

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