RESEARCH ON REDUCING COGGING TORQUE IN PERMANENT MAGNET SYNCHRONOUS GENERATORS

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This paper presents different cogging torque reduction methods. The numerical methods used were experimentally validated using a permanent magnet synchronous generator.

Keywords: permanent magnet synchronous machine, finite element analysis, cogging torque reduction methods

1. Introduction

One of the electrical generators used in wind systems are synchronous generators with permanent magnets. This type of machines have an important disadvantage which is cogging torque that result due attraction of stator slots and excitation magnetic field of permanent magnets [1],[2]. Cogging torque generate vibrations an whear of the bearings and in case of eolian sistems prevent the tubine to start at small wind speeds [2]. This paper present several methods to reduce cogging torque on a permanent magnet synchronous generator by adjusting some of its geometrical parameters.

2. Generator description

The studied generator presented in Fig. 1, have rated power equal with $S_n = 105$ VA, rated voltage $U_n = 32$ V, $2p = 4$ poles and $Z_t = 24$ stator slots.

The rated torque of generator is $M_n = 0.96$ Nm. The permanent magnets are made of Koerdym 70P with remnant flux density $B_r = 0.676$ T and relative permeability $\mu_r = 1.353$ and stator/rotor core is made of Stabolec 150-50. Cogging torque value is $T_{cog} \approx 0.04$ Nm that represent approximately 4% of the nominal torque value.
3. FEM analysis of the PM synchronous generator

For numerical analysis of the machine was used professional software package FLUX from CEDRAT. All the calculation is based on a 2D magnetostatic field model of the studied generator, presented in paragraph 2.

Computation domain, is represented in Fig. 2, composed of several distinct regions: turquoise – magnetic cores, magenta – permanent magnet (north pole), blue – permanent magnet (south pole), green – air, yellow – stator wedges, red – negative sense of current through coil, black – positive sense of current through coil.

Further were presented numerical results of the simulations of the PM generator for no-load and load operating regimes. In Fig. 3. was represented spectrum of magnetic field lines and chart of magnetic flux density through a cross-section through the machine.

Preliminary results, obtained from numerical analysis of the PM generator, was compared with experimental data, determined in the laboratory, to validate
the numerical model. The test bench used to measure values of cogging torque was represented in Fig. 4, and the test bench used to measure no-load and load voltage and currents was represented in Fig. 5.

Fig. 3. Spectrum of the PM synchronous generator magnetic field lines and chart of magnetic flux density.

Fig. 4. Test bench used to measure cogging torque [3]
In Fig. 6. was compared the calculated and measured values of cogging torque $T_{cog}$ which shows a good approximation of $T_{cog}$ value through FEM analysis.

Comparing the results obtained by experimental and numerical determination of no-load voltage, represented in Fig. 7, can be observed a good approximation of no-load voltage using numerical methods FEM.

In Fig. 8. was represented, the operation of PM generator on a resistive load, instantaneous values over a period, of measured and calculated values of current and voltage of the PM generator. As well as in no-load case can be seen a good agreement between measured and calculated values.
4. Cogging torque reduction methods

4.1. Asymmetrical arrangement of magnets

One of the cogging torque reduction methods is represented by asymmetrical arrangement of permanent magnets on rotor [4],[6]. To asymmetrical arrangement the permanent magnets, the axes of PM can be rotated (around the center of symmetry of the rotor section of the machine) with different angles in relation with equidistant axes corresponding of the symmetrical machine. From example, in Fig. 9, was presented a cross section through the PM generator in which the upper magnetic pole has the symmetry axis identical with equidistant axis, and the other three magnetic poles axes are rotated with angles P1, P2 respectively P3, in relation with corresponding
equidistant axes.

In Fig. 10, was represented variation of cogging torque over a 15 geometrical rotation degrees, as it is noted the peak value of cogging torque drops by 85%, from \( T_{cog} = 0.0403 \text{ Nm} \) for symmetrical arrangement of PM to \( T_{cog} = 0.0065 \text{ Nm} \) for asymmetrical arrangement of PM.

As a result of asymmetric arrangement of magnets in optimal configuration with displacement angles \( (0; 2.25; -6.66; -9.63) \), the peak value of phase voltage \( U_f \) decrease with approximately 4.5%. For the PM asymmetrical configuration the waveform of phase voltage \( U_f \) is closer to a sinusoid compared with the one obtained from PM symmetrical configuration.

After asymmetric arrangement of PM’s in optimal configuration \( (0; 2.25; -6.66; -9.63) \), the peak values of radial forces (Fig. 11) are increased significantly. Thus, the maximum calculated peak value of radial force is \( F_{r,m} = 0.485 \text{ N} \), for asymmetrical arrangement of magnets which is 17 times greater than value of radial force \( F_{r,o} = 0.029 \text{ N} \) obtained for the case when the generator has the PM symmetrical arranged.

4.2. Stator skew

A well-known cogging torque reduction method consists in inclination of the stator slots of the machine [4]-[7], the stator of the machine with skewed slots can be seen in Fig. 12. A way to calculate the optimum inclination angle of stator slots \( \alpha_{sk} \) that lead to maximum minimization of cogging torque can be achieved by using equation (1) given in [6].

\[
\alpha_{sk-s} = \frac{1}{N_p} \frac{360}{Z_1} = 15^\circ
\]
where \( N_p = 1 \) is periodicity of \( T_{cog} \) curve on a slot pitch, and \( Z_p = 24 \) stator slots.

As a result of inclination of stator slots with angle \( \alpha_{sk-s} = 15^\circ \) as in Fig. 12, the calculated value of cogging torque by FEM analysis is \( T_{cog-sk} = 0.00068 \) Nm, value which is 59 times smaller than cogging torque of the machine without modification \( T_{cog} = 0.0403 \) Nm.

From external characteristic, represented in Fig. 14, can be observed that with inclination of stator slots the phase voltage \( U_f \) decrease, this drop was felt especially at lower values of load relative to rated load.

4.3. Rotor skew

As the cogging torque reduction method by skewing the stator slots presented in paragraph 4.2, this method refer to inclination of rotor permanent magnets to reduce cogging torque [8],[9]. The rotor with tilted permanent magnets
can be seen in Fig. 15. By using this method the machine manufacturers must also
consider that the inclination of permanent magnets is a difficult manufacturing
process leading to a high production costs and the difficulty to magnetize the PM
[6].

Further we represented in Fig. 16, cogging torque curves obtained for
original configuration of the machine and for tilted permanent magnets with an
inclination angle equal with $\alpha_{sk-r} = 17.5^\circ$. As can be seen in Fig. 16, the peak value
of cogging torque $T_{cog} = 0.0055$ [Nm], obtained by inclination of PM with $\alpha_{sk-r} =
17.5^\circ$, has sa value 7.3 times lower than the values of cogging torque obtained for
original configuration of the machine $T_{cog} = 0.0403$ [Nm].

As can be seen in Fig. 17. with the inclination of the permanent magnets it
is noted that the phase voltage decreases.

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**Fig. 15.** PM machine with skewed rotor

**Fig. 16.** Comparison of cogging torque curves obtained for skewed rotor and for original configuration of the machine

**Fig. 17.** External characteristics $U_f(I_f)$ obtained for skewed rotor and for original configuration of the machine
5. Conclusions

This paper studies the influence of geometrical parameters of a PM synchronous generator on cogging torque in order to reduce its value. From the point of view of cogging torque reduction, the most efficient method is stator skewing the lead to a drastically decrease of $T_{cog}$ by 59 times followed by rotor skewing that decrease cogging torque by 7.5 times and the less efficient $T_{cog}$ reduction method for this machine configuration is when the permanent magnets of the rotor are disposed asymmetrically when cogging torque was decreased by 6.2 times. Other differences between the three methods are that asymmetrical displacement of magnets lead to an increase of radial forces about 17 times but the advantage of this method is that can be applied on an already existing machine if magnets can be removed from rotor.

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REFERENCES

