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Methods to Reduce Cogging Torque of Permanent Magnet Synchronous Generator Used In Wind Power Plants

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***Abstract*—This paper presents five latest methods and explains the last- new one with intention to reduce the cogging torque of permanent magnet synchronous generators (PMSG). The PMSGs are widely used in wind power plants (WPP) as one of the renewable power generation. One of the international goals is to expand the use of renewable energy sources. The main disadvantage of PMSG is the influence of magnetic interaction between the magnets and the teeth on the operation of PMSG, thus many scientists have been researching the possibilities to reduce the cogging torque. The magnetic field modelling software is used to obtain the values of PMSG cogging torque. The calculations in this software are based on finite element analysis. A methodology is created to obtain the 3D results from the 2D modelled magnetic field. The achieved results allowed to submit a patent. The new proposed method is researched allowing to receive the first results of PMSG optimal design, thus expanding the lower boundary of operating wind speed for WPP.**

***Index Terms*—Electromagnetic fields, finite element analysis, permanent magnet machines, torque measurement, wind power generation.**

I. INTRODUCTION

In the last decades, the use of renewable power generation is emerging to decrease the greenhouse gas emission. To ensure the tomorrow's energy needs the wind power generation is considered to have the best potential for tackling this challenge [1]–[3]. The goal is that, by 2035, the renewables will be generating more than 25 % of world's electricity [3]–[5]. A quarter from these 25 % will be coming from wind, being the second largest renewable energy source after hydropower [4].

Recently the permanent magnet synchronous generators (PMSG) are widely used in wind power plants (WPP) in the low and middle power range (till 50 kW), and mostly these generators are directly connected with the wind turbine without any reduction gear system as the gearbox failure rate is high (Fig. 1) [3], [6]–[13]. Another popular generator used in WPPs is the doubly fed induction generator [14]–[19], but it will not be overviewed in this article.

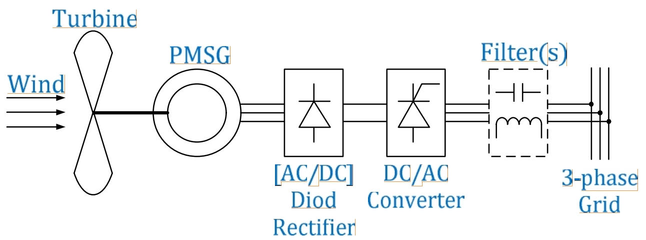

Fig. 1. PMSG in the circuit of WPP.

Thus the research object is the PMSG that is directly connected with the turbine. The PMSG (Fig. 2) has the following main parts: stator 1, teeth 2, slots 3, rotor 4 and permanent magnets (PM) 5.

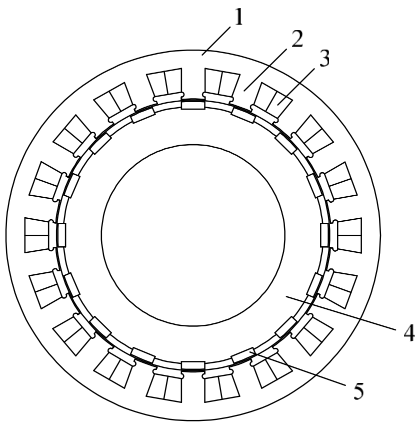

Fig. 2. PMSG in cross section ($Z_1 = 18$, $2p = 16$).

The main disadvantage of PMSG is the influence of magnetic interaction between the rotor magnets and the stator teeth – called cogging torque T_C. The generator's start-up torque must be greater than the cogging torque induced by PMs to start to rotate. To overcome the high cogging torque the initial wind speed must be higher, which, in turn, significantly shortens the diapason of operating wind speed, and thus lowers the operation effectiveness of the whole WPP. Many scientists have been researching the possibilities to reduce the cogging torque [20]–[24].

Thus, the research subject is the cogging torque T_C of PMSG (with intention to reduce it).

Latest trend is to use the PMSG with non-overlapping

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concentrated windings [10], [21], [25]–[30]. The production technology of non-overlapping concentrated windings' insertion in stator (armature) teeth with opened or half-opened slots is comparatively simple. This production technology allows obtaining generators with high technical-economical indicators. However, these generators have the pronounced salient-form stator teeth, which with the interaction with the rotor's permanent magnets also lead to high cogging torques T_C. The PMSG with these windings are further researched.

The base parameters of the researched PMSG are given in Table I and Fig. 3.

TABLE I. BASE PARAMETERS OF PMSG.

Parameter	Symbol	Size	Unit
Axial length	l	36	mm
Stator teeth number	Z_1	18	-
Stator slot opening	opened/ half-opened		-
Pole pair number	p	5 … 12	-
Rotor PM width	b_m	*var*	mm
Rotor PM height	h_{PM}	3	mm
Rotor inner radius	R_1	37.24	mm
Rotor outer radius	R_2	52.77	mm
Air gap	δ	1	mm
Air gap radius	R_δ	55.45	mm
Windings height	h_w	9.55	mm
Stator inner radius	R_3	55.95	mm
Stator outer radius	R_4	76	mm
Steel grade (yokes, teeth)	M530-50A5		-
PM material	NdFeB		-
PM coercive force	H_c	900 000	A/m
PM residual induction	B_r	1.2	T
PM relative magnetic permeability	μ_*	1.061	-

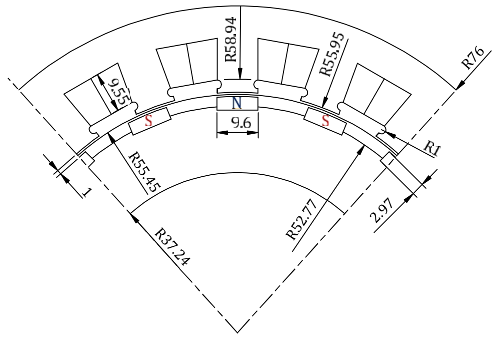

Fig. 3. Base dimensions of PMSG in cross section (Z_1 = 18, $2p$ = 16). Except the slot opening and PM's pole pair number p and width w_{PM}, which are variable. Sizes in mm.

Magnetization curve for steel grade M530-50A5 is given in Appendix A.

II. METHODOLOGY OF TORQUE AND FLUX CALCULATION

The PMSG cogging torque and the magnetic flux in a tooth is calculated by its two dimensional (2D) magnetic field. The magnetic field is modelled in application software *QuickField*® (QF), which is based on the finite element analysis (FEA) [31].

The methodology of obtaining the electromechanical torque and magnetic flux is following:

1. Set experiment plan;
2. Prepare blueprints;
3. Define mathematical models;
4. Model magnetic field;
5. Read the necessary physical parameters.

First always is set the experiment plan according to the research interests.

After knowing all design variants of PMSG, its cross section blueprints can be prepared. We are using the drawing application software *AutoCad*® to make the .dxf files, which later are imported in QF.

The third step includes the definition of mathematical model for every uploaded .dxf file variant. The materials and energy sources are defined in the mathematical model:

– The air gap is defined with air relative magnetic permeability $\mu_{0*} = 1$.

– The PM material is defined with its relative magnetic permeability μ_* (value given in Table I).

– The PM field source is given by magnets edges with according (positive and negative) coercive force H_c (Table I).

– The stator and rotor yokes are defined as electro technical steel with grade M530-50A5, its magnetization curve $B = f(H)$ is input (Appendix A).

– As the electromechanical torque is calculated in interest to obtain the cogging torque's value, then the mathematical model is defined without excitation from windings. Thus the stator windings are defined with j = 0 A/m². Only the permanent magnets induce the forces, and with interaction to salient teeth of stator they lead to cogging torque.

The fourth step is the modelling of magnetic field for the overviewed variant (Fig. 4). From the modelled magnetic field the mechanical torque T and magnetic flux in a tooth, Φ_{Z1} is calculated. The torque is calculated by the circle made by air gap radius R_δ.

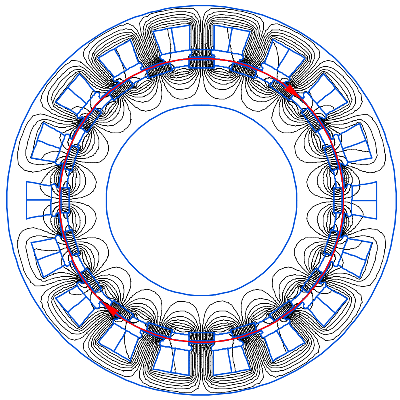

Fig. 4. Modelled magnetic field in PMSG cross section (Z_1 = 18, $2p$ = 20).

Therefore, the last step is to read and note the necessary physical parameters.

III. COGGING TORQUE REDUCTION METHODS

Nowadays there are proposed different solutions for the start-up torque's reduction possibilities for PMSG with non-overlapping concentrated windings.

A. *Slot Opening Design*

First can be mentioned the cogging torque reduction method by an appropriate choice of slot opening design [27], [32]. The opened or half-opened slots must be chosen. The half-opened slots are an acceptable opportunity only for generators with small pole pair number $p \leq 6$ [27]. For greater pole pair numbers there is no effectiveness of applying this method for cogging torque minimization, and the opened slots should be chosen. Further will be researched PMSG with opened slots.

B. Stator Teeth and Rotor Poles Ratio

The next significant cogging torque reduction method is the rational choice of ratio between the stator teeth number Z_1 and number of permanent magnets $2p$ [8], [27]. The previous results [27] confirm that the cogging torques are smaller for PMSG with the nearest ratio $Z_1/2p = 1$ or mathematically (1), thus for the given case $Z_1 = 18$ the PM pole pair number should be $p = 8$ or 10, i.e., $Z_1/2p = 18/16$ or 18/20 (Fig. 5).

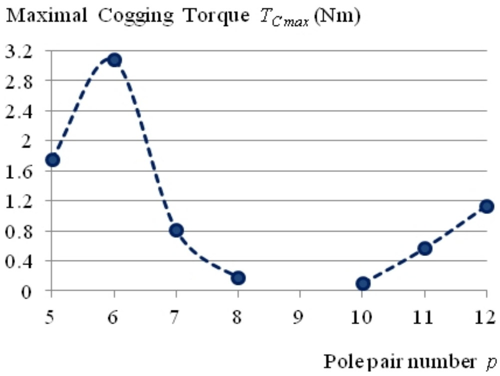

Fig. 5. Maximal values of cogging torque T_C for PMSG with $Z_1 = 18$ at different pole pair numbers p (slot design – opened).

$$\lim_{p \to \frac{Z_1}{2}} Z_1/2p = 1. \quad (1)$$

The $Z_1/2p = 18/18$ or p = 9 cannot be taken as we need to ensure that the PMSG works as an electrical machine.

C. Stator Teeth or Rotor Magnets Skewing

Another well-known cogging torque reduction method is the skewing of the stator teeth or the rotor magnets [10], [12], [22], [23], [32], and [33].

D. Use of Non-Radially Mounted PMs

Comparing new method used and closer described by authors in [34]. The rectangular (prismatic) PMs are mounted not through whole axial length, but in a part of it, thus used less magnet material, reducing also the costs of raw materials.

This method allows the cogging torque reduction on the fact that there are used less PMs thus reducing the influencing force induces by magnets through the stator teeth. However, this method is less researched and here cannot be given certain data at the moment – if is the cogging torque reduction that great that other generator operation parameters stay in the necessary diapason.

There are other types of non-radially used magnets field, e.g., [35].

The previously mentioned methods for cogging torque minimization are effective in a certain conditions, and each of them has a smaller or greater disadvantage, e.g., more complicated technology of generator manufacturing, lowered parameters at nominal operational mode or at mode close to the nominal, etc.

E. Permanent Magnets Shifting in Rotor Pole

The proposed PMSG has on the rotor placed sequent N and S polarization permanent magnets [36], [37]; every such magnets polarization forms a pole. The pole consists of n magnets every which is equally made by form, angle and sizes accordingly to the stator's inner surface ($n = 4$ in Fig. 6). Figure7 gives the insight of this geometric placement in axial length l, given for two stator tooth pitches ($2t$).

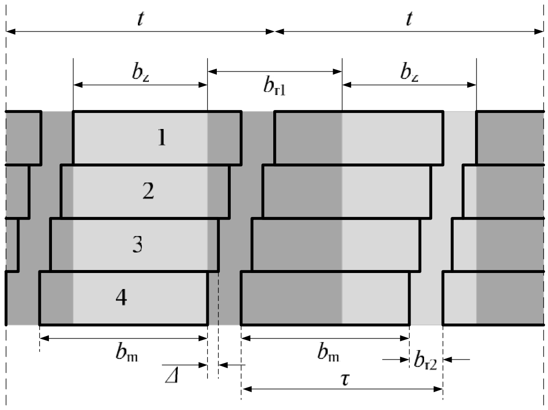

Fig. 6. Principal placement of rotor permanent magnets in axial length l according to stator teeth (for 2 stator poles t).

All n magnets are shifted by an angle Δ so that they all fit within the generators pole pitch τ.

The relations between the geometrical parameters of PMSG active zone are given from (2) till (7).

Tooth pitch of stator

$$t = \frac{360}{Z_1} = b_z + b_{r1}. \quad (2)$$

As the PMSG has opened slots, then for simplified research condition the slot's width b_{r1} is taken equal to the tooth width b_z

$$b_z = b_{r1} = \frac{t}{2}. \quad (3)$$

Pole pitch of rotor

$$\tau = \frac{360}{2p}. \quad (4)$$

Permanent magnet's width

$$b_m = \frac{\tau + b_z}{2}. \quad (5)$$

The groove's width between two sequent permanent magnets

$$b_{r2} = \frac{\tau - b_z}{2}. \quad (6)$$

The maximal angle by which the n magnets are shifted from each other (in one rotor pole)

$$\Delta_{\max} = \frac{\tau - b_z}{2\times(n-1)}. \tag{7}$$

For the example of the overviewed method for cogging torque reduction is taken opened slot PMSG with stator teeth number Z_1 = 18 and the magnets pole pair number p = 12 (total magnets number is $2p$ = 24). The variable design and electrical parameters for this PMSG are given in Table II accordingly to (2)–(7), the rest design parameters are the same as given in Table I.

TABLE II. DESIGN AND ELECTRICAL PARAMETERS FOR GIVEN EXAMPLE.

Parameter	Symbol	Size	Unite
Stator tooth pitch	t	20	° (geom..)
Tooth width	b_z	10	° (geom..)
Stator groove width	b_{r1}	10	° (geom..)
Rotor pole pitch	τ	15	° (geom..)
PM width	b_m	12.5	° (geom..)
Groove between two sequent rotor poles	b_{r2}	2.5	° (geom..)
PM number in a pole	n	4	-
Maximal shifting angle	Δ_{max}	0.833	° (geom..)

To this example, we will return after discussion of developed methodology for the calculation of magnetic field, obtaining three-dimensional (3D) results from two-dimensional (2D) ones.

IV. Field Modelling Methodology from 2D to 3D

In classical design of PMSG, where PMs are straight throughout the axial length, the generator cross section is identical at any level of axial length. Thus, the simple 2D magnetic field can be modelled. With skewed or shifted magnets in a pole it is a bit more complicated and the real results can be taken from 3D modelled field.

However applying appropriate methodology the results can be taken from 2D magnetic field as from 3D one. Thus, the following magnetic field modelling methodology is developed and used:

1. Know Z_1, p, l etc.;
2. Choose n and the turning angle α step;
3. Calculate the parameters as given in Table II and the length l_i;
4. Model magnetic field for every i-th magnets position (shifting angle Δ) at certain stator position (turning angle α);
5. Summarize torques by (9) – this is obtained T_C at certain turning angle α.

Repeat the 4., 5. step as many times as necessary.

The generator axial length l is divided in n equal parts (because of n magnets in a pole) thus the i-th length is

$$l_i = \frac{l}{n} = \frac{36}{4} = 8(\text{mm}). \tag{8}$$

The cross section drawing is prepared according to design dimensions given in Table I and Table II.

To obtain the torque value at certain turning angle α the stator is turned by this angle. Thus at turning angle α = 0° (geom.) only the rotor will be turned by shifting angle Δ (in example case $\Delta = \Delta_{max}$). At one turning [point] angle α we calculate the torque by (9).

$$T_C = \sum_{i=1}^{n} T_i, \tag{9}$$

where T_i is the mechanical torque of the generator for i-th magnet position in the rotor pole.

As an example, the i-th calculated torque's values are given for a PMSG with shifted PMs at turning angle α = 12° (el.) (Table III). This position is also easy to be found in Fig. 7.

TABLE III. TORQUE AT ANGLE α = 12° (EL.).

i	Length l_i (mm)	Torque T_i (Nm)
1	8	0.047
2	8	0.220
3	8	0.132
4	8	-0.041
Σ	36	0.36

For the overviewed example the developed methodology was used. The cogging torque of standard design PMSG (straight magnets in the rotor pole) is compared with the cogging torque of new design PMSG (the magnets are shifted from each other within the rotor pole) depending from the turning angle α, i.e., $T_C = f(\alpha)$ (Fig. 7).

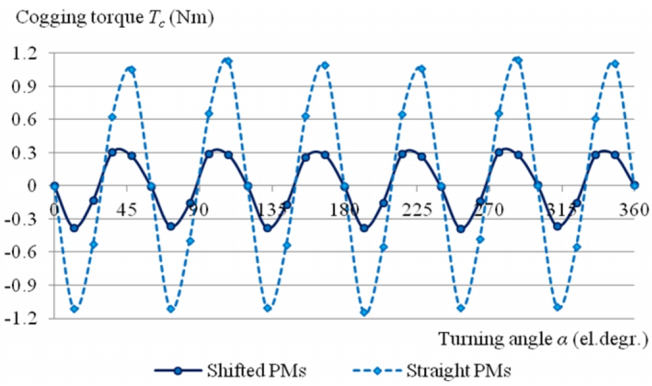

Fig. 7. Methodology for obtaining 3D results from 2D magnetic field.

The magnets shifting gives good result – the maximal value of the cogging torque T_C is for about 3 times lower than the PMSG with the straight magnets has.

V. Optimization

The magnets shifting method gives good results in cogging torque reduction, thus the possibility to optimize such a PMSG is researched taking into account the influence from two parameters: shifting angle Δ and magnets number n in a rotor pole.

A. Shifting Angle Δ

In general, the angle Δ by which the n magnets in a rotor pole are shifted from each other is calculated so

$$\Delta = \beta \times \Delta_{\max}. \tag{10}$$

The coefficient β can be freely chosen in a condition $\beta \leq 1$.

The chosen coefficients β and corresponding shifting angle Δ values, as well as the maximal values of the T_C are given in Table IV. Overviewed the example case with $n = 4$.

TABLE IV. MAXIMAL T_C AT DIFFERENT COEFFICIENTS β.

	β	Δ (°geom.)	T_C (Nm)
A	1	0.833	0.39
B	0.9	0.750	0.43
C	0.8	0.667	0.50
D	0.7	0.583	0.55

For these variants (A-D) the corresponding curves of cogging torque T_C are given (Fig. 8).

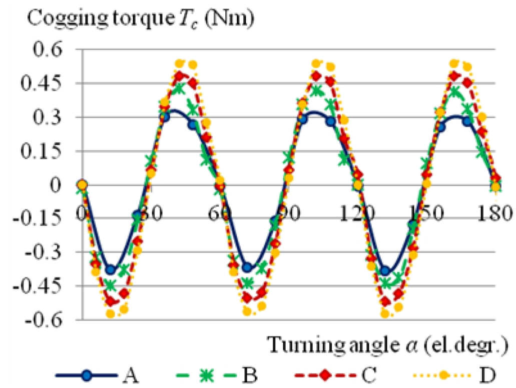

Fig. 8. Curves of cogging torque for different coefficients β ($n = 4$).

The results show that the optimum is in case A ($\beta = 1$), when the value of shifting angle Δ is the maximal, i.e., $\Delta = \Delta_{max}$.

B. *Magnets Number n in a Rotor Pole*

To research the influence of different magnet number n in a rotor pole a constant value of shifting angle Δ is taken the maximal one $\Delta = \Delta_{max}$.

It is chosen to test two more values of magnets number n in a rotor pole: $n = 3$ and $n = 5$ (Fig. 9).

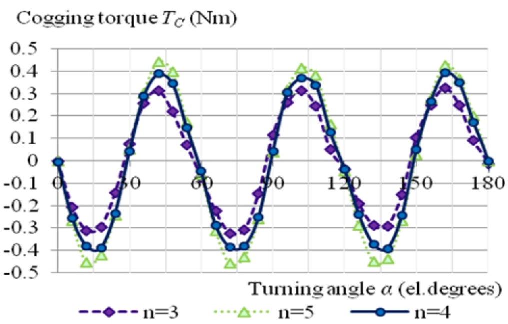

Fig. 9. Curves of cogging torque for different coefficients β ($n = 4$).

The results show that with magnets number $n = 3$ in a rotor pole there can be reduced the cogging torque a bit more than with $n = 4$.

VI. FURTHER RESEARCH PLANS

A. *Optimization Variants*

The next researched will be intended to analyse other influencing parameters which could significantly minimize the cogging torque for PMSG with shifted magnets in a pole.

B. *Forecasting*

It is planned to prepare the forecasting tool to predict the cogging torque values for PMSG used in WPP, similar to [21], [38].

The multivariate data analysis method – regression models – will be used to synthesize mathematical models for the forecasting of the cogging torque values as it was done for the magnetic coupler [39] and synchronous reluctance motor [40].

VII. CONCLUSIONS

PMSGs have cogging torques, which depend on the number of magnets on the rotor $2p$, and there are different methods used in the world to reduce the cogging torque. Some of these methods are given in this paper.

The magnets shifting method is proposed. This method use n magnets which are equally shifted from each other by an angle Δ in a rotor pole. The research confirmed that this method can be used for cogging torque T_C reduction in PMSGs.

A small optimization was made. The best results in cogging torque's reduction is at maximal possible shifting angle Δ, i.e., $\Delta = \Delta_{max}$. The cogging torque can be minimized also reducing the number of magnets in a pole. The smaller is the number n of magnets in a rotor pole, the smaller is the cogging torque T_C.

APPENDIX A

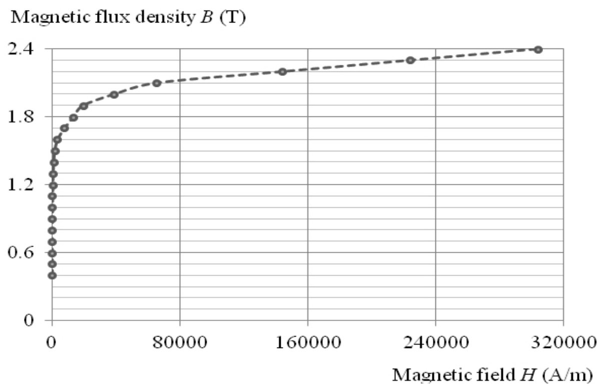

Fig. A-1. Magnetization curve for steel grade M530-50A5.

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