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*PHYSICAL AND TECHNICAL ENERGY PROBLEMS*

# ACTIVE ZONE OF PERMANENT MAGNET SYNCHRONOUS MACHINE WITH A NON-OVERLAPPING CONCENTRATED WINDING

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The research is devoted to the investigation of NdFeB permanent magnet (PM) based synchronous generators with non-overlapping concentrated windings. The rotor of such a generator has 10 pole pairs (PMs), which is dictated by the nominal voltage frequency ($f$=50 Hz) and the rotational speed ($n$=300 RPM). Comparison is made for four generators with three-phase winding coils and stator tooth numbers 18, 21, 24 and 27.

***Keywords:*** *active zone, permanent magnet synchronous generator, torque*

## 1. INTRODUCTION

Nowadays, in the power range of 0.1–20 kW more than 90 % of wind turbines have synchronous generators with NdFeB permanent magnets (PMs). The absolute majority of such generators are gearless, being driven directly from a wind turbine. Low-speed generators of these wind turbines have a sufficiently high number of poles (i.e., of PMs) on the rotor, which causes certain technological problems for manufacturers of stators and for automatic stacking of multiphase distributed windings.

The PM generators have a variety of advantages as compared with the traditional designs of electromagnetically excited generators. These advantages are:

- Better weight-size relationships; their PMs have lower weight and volume than the excitation windings;
- Possibility to manufacture multipolar generators of smaller weight and size;
- Higher efficiency, since there is no need to spend 10 % of the nominal power on the excitation;

- Increased reliability thanks to the brushless and contactless design as well as to the absence of excitation winding whose characteristic features are accelerated ageing and frequent insulation damage;
- Absence of the brushes and contact rings, which reduces the maintenance expenses;
- Their demagnetizing armature reaction is less expressed, which ensures a high operational stability of the generator;
- The PM generators are highly efficient as well as practically have no losses on the rotor.

At the same time, the PM generators have certain disadvantages. One of them is the uncontrollable magnetic field strength. Therefore, it is complicated to use the wind energy at low rotational speeds of their rotors when the turbine rotational speed is also low. However, the wind speed higher than nominal can also cause a dangerously high output voltage. It should be noted that in the PM generators the magnetic field is constant, even when standing still.

One of the disadvantages of the NdFeB based PM generators is relatively high values of the cogging torque at a cut-in of the wind turbine. This means that there are also relatively high values of the required initial wind speeds, which leads to a significantly reduced operational range for winds in general. In order to reduce the cogging torques of such generators, several solutions are implemented, beginning with skewing the PM teeth and then choosing the optimum relationship between the tooth number on the stator and the number of pole pairs [1], [2]. The present paper considers the conditions that provide selection of the optimum relationship between these numbers in the generator tooth zones, so that it would be possible to gain the maximum values for electromagnetic power of the generator and the minimum value for its cogging torque. A high price of rare-earth magnets is also one of the disadvantages of these generators.

## 2. ANALYTICAL TREATMENT OF ACTIVE ZONES

In our experiments, we chose the traditional design circuit of a synchronous generator equipped with permanent magnets on the rotor and non-overlapping concentrated winding on the stator. In order to simplify the manufacturing technology and reduce the cogging torque, the connection between the stator tooth number $Z_1$ and the number $p$ of PM pairs is determined using the expression:

$Z_1 = 2p \pm k$, where $k$ is a whole number *(1, 2, 3, ....)*. (1)

Assuming that the nominal frequency $f$=50Hz of the voltage across the stator winding and the rotational frequency $n$=300RPM of the wind turbine and the generator rotor prescribed by technical specifications for a given wind turbine, the main design of generator was chosen in which $p$=60$f$/$n$=10 pairs of PMs were located on its rotor ($N_m$=20 radial magnetized magnets). Having regard to expression (1) and considering $Z_1$ as a multiple of the phase number ($m$=3), comparison and analysis of four generators have been carried out (see Table 1), each with its own number of stator teeth.

*Table 1*

**Configurations of the Machine**

| | | | | |
|---|---|---|---|---|
| Stator tooth number | 18 | 21 | 24 | 27 |
| Pole pair number | 10 | 10 | 10 | 10 |
| *k* | -2 | +1 | +4 | +7 |
| Number of teeth per phase | 6 | 7 | 8 | 9 |

The tooth number $Z_1$ in synchronous generators with coils on stator is chosen as a multiple of the double phase number *2m*. The former number can be $Z_1$=18 or $Z_1$=24 for a three-phase generator (*m*=3). In our case, numerator $Z_1$ in the ratio $Z_1/2p$ and its denominator *2p* are even numbers with multiplier 2. Such geometry of a tooth zone affects positively the shape and symmetry of phase voltage in synchronous machines with the electromagnetic excitation or the excitation from PMs with distributed windings and a large number of teeth on the stator.

Within PM generators of the type a significant cogging torque arises, which leads to appearance of salient teeth on the stator. To overcome this, stronger winds are needed to start up the wind turbine, which would significantly reduce the range of operating winds in general. As research [3] has shown, one of the methods to reduce the cogging torques is to design an active zone with $Z_1$ and *2p*, i.e., the stator tooth number and the rotor pole number that do not have a common multiplier. Due to the fact that the rotor PM number is always a multiple of 2, it is proposed to choose the stator tooth number $Z_1$ as a multiple of the phase number *m=3*. This would determine (also taking into account expression (1)) the choice of variants for further research into the operation of generators depending on the stator tooth numbers $Z_1$=21 and $Z_1$=27.

In Fig. 1, the cross-section is shown for a PM synchronous generator (PMSG) with $Z_1$=18 and *p*=10, a stator with teeth and three-phase armature winding coils. On the rotor, NdFeB permanent magnets are situated.

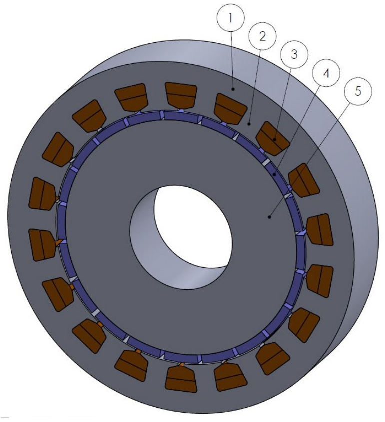


*Fig. 1.* Cross-section of a PM generator with $Z_1/2p$ = 18/20:
1 – stator, 2 – stator teeth, 3 – three-phase armature winding coils,
4 – rotor, 5 – NdFeB permanent magnets.

## 3. NUMERICAL MODELLING OF PMSG AND DETERMINATION OF TORQUES

The mathematical modelling experiments were performed with the aim to improve the PMSG design and determine the electromagnetic and cogging torques. The generator under investigation was designed based on calculation of the magnetic field in PMSG cross-section. Using numerical methods for the calculation allows for a detailed analysis of the field distribution in PMSG separate elements. In this study, software based on the finite element method (FEM) was employed for the numerical modelling, taking into account PMSG design elements and material properties. In Fig. 2, the picture of magnetic field in the generator cross-section is presented.

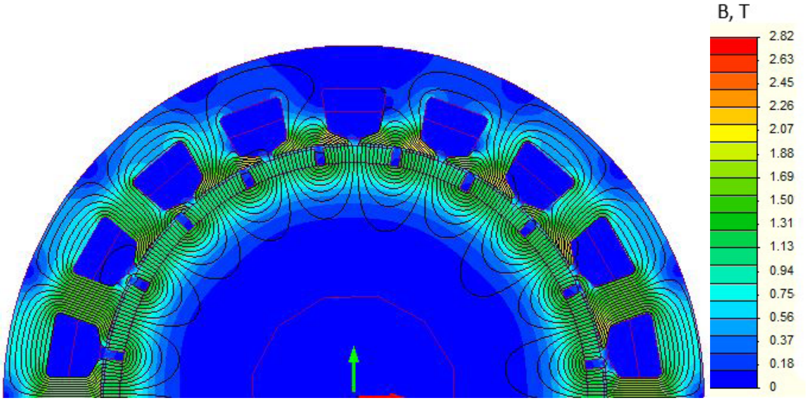


*Fig. 2.* Magnetic field in the PMSG cross-section.

The electromotive forces of neighbouring coils are shifted in the magnetic field with regard to each other by the angle [4], [5]:

$$\alpha_z = \frac{2\pi p}{Z_1}, \tag{2}$$

which is very close but not equal to 180 el. degrees.

The angle between the electromotive forces of two coils situated on the neighbouring teeth of the armature is:

$$\alpha_c = \begin{cases} \alpha_Z + \pi, \, when \, Z_1 < 2p \\ \pi - \alpha_Z, \, when \, Z_1 > 2p \end{cases}. \tag{3}$$

Fundamental winding factor $k_w$ is defined in accordance with the following formula:

$$k_w = k_p \cdot k_d, \tag{4}$$

where $k_p$ is the pitch factor,

$$k_p = \sin\left(\frac{\pi p}{Z_1}\right) \tag{5}$$

and $k_d$ is the distribution factor.

In turn, the distribution factor will be

$$k_d = \begin{cases} \dfrac{\sin\left(\dfrac{2p}{Z_1}-1\right)\cdot\dfrac{\pi}{2}}{a\cdot\sin\left(\dfrac{2p}{Z_1}-1\right)\cdot\dfrac{\pi}{2}}, \ when \quad Z_1 < 2p. \\ \dfrac{\sin\left(1-\dfrac{2p}{Z_1}\right)\cdot\dfrac{\pi}{2}}{a\cdot\sin\left(1-\dfrac{2p}{Z_1}\right)\cdot\dfrac{\pi}{2}}, \ when \quad Z_1 > 2p. \end{cases} \tag{6}$$

Taking into account expressions (1) and (3), formula (7) will be transformed to the following:

$$k_d = \frac{\sin\dfrac{\pi}{2m}}{a\cdot\sin\dfrac{\pi}{2ma}}. \tag{7}$$

This can be exemplified by the vector diagram of electromotive forces and by the circuit of coil connection into a three-phase armature winding for an inductor machine with the number of stator teeth $Z_1$=18 and the number of permanent magnets on the rotor $N_m$=2.

To form a three-phase winding, the following variants of coil connection are possible:

phase A: +1, -2; +3; +10; -11; +12;
phase B: +7; -8;+9;+16;-17;-18;
phase C: +4; -5; +6; +13; -14; +15.

Sign «+» corresponds to the series connection of coils, and sign «-» − to the back-to-back connection.

Figure 3 presents a vector diagram for a PMSG having the stator tooth number $Z_1$=18 and the rotor pole pair number $p$=10.

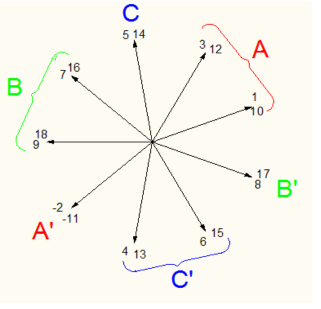


*Fig. 3.* Vector diagram of PMSG electromotive forces.

In Table 2 the values are given for various parameters:the angle of electromotive forces between neighbouring coils ($\alpha_Z$), the angle betwen electromotive forces of two coils situated on the neighbouring teeth of armature ($\alpha$), the fundamental winding factor ($k_w$), the cogging torque ($M_{cogging}$), the least common multiple (*LCM*), and the greatest common divisor (*GCD*).

*Table 2*

**Parameters of Different Generators**

| | 18/10 | 21/10 | 24/10 | 27/10 |
|---|---|---|---|---|
| $\alpha_z$ | $200^0$ | $171.43^0$ | $150^0$ | $133.33^0$ |
| $\alpha_c$ | $20^0$ | $8.57^0$ | $30^0$ | $46.67^0$ |
| $k_d$ | 0.96 | 0.95 | 0.97 | - |
| $k_p$ | 0.985 | 0.99 | 0.966 | - |
| $k_w$ | 0.945 | 0.953 | 0.945 | 0.877 |
| $M_{cogging,}$ *Nm* | 0.011 | 0.00186 | 0.011 | 0.004024 |
| *LCM* | 180 | 420 | 120 | 540 |
| *GCD* | 2 | 1 | 2 | 1 |

In the case of a generator with the 27/10 tooth zone design the condition for the coil windings on neighbouring teeth is not met. In compliance with expression (1), the $k$ value must be minimal (close to 1); then the angle between the neighbouring teeth will be close to 180 degrees.

As seen from Table 2, the least cogging torque value is when there are $Z_1$=21; $p$=10 and $Z_1$=27; $p$=10. In [3], recommendations are given as to the choice of combinations with the least cogging torque. A very low value of this torque can be obtained if the slot and pole numbers are chosen so that the least common multiple (*LCM*) between them is large. The closer the number of slots to the number of poles, the higher their *LCM*.

One of the problems of electric machines is vibrations and noises depending on the combinations of stator tooth and pole numbers. Such type vibration and noise are caused by radial magnetic forces in the airgap, while tangential ones act on the rotor thus creating torque. If the distribution of radial magnetic forces along the airgap is non-uniform, their sum creates one-direction pull force that with time begins to rotate causing the above-mentioned vibration and noise in the machine. This gives rise to the so-called unbalanced magnetic pull force, which might be related to asymmetry in windings. For combinations of stator tooth and pole numbers with $2p=Z_1\pm1$ and some combinations with odd tooth numbers there could be the greatest common divisor (*GCD*) when these numbers are equal to *1*. Such type designs are not recommended, since they might provide unbalanced magnetic pull forces.

Figure 4 shows dependence of the generator maximum electromagnetic torque on the rotor rotational angle for different numbers of stator teeth, i.e., for different combinations of PMSG active zones.

The maximum electromagnetic torque is 53 Nm for the stator tooth numbers $Z_1$=18 and $Z_1$=21, with the least *k* values in equation (1).

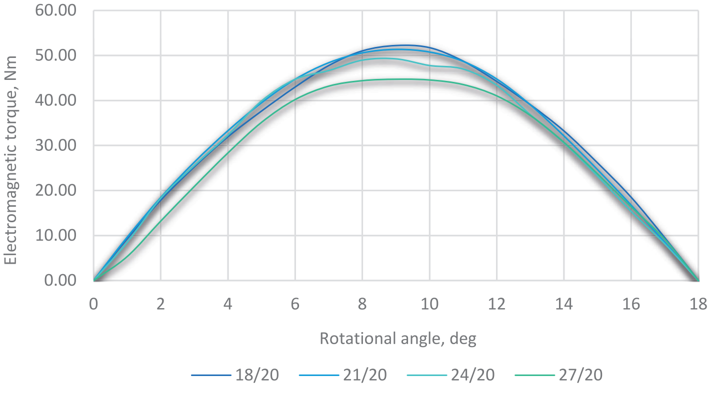


*Fig. 4*. Electromagnetic torque *vs.* rotational angle for different PMSG active zone combinations.

The dependence of PMSG maximum electromagnetic values on the PM width (in degrees) is shown in Fig. 5 for different stator tooth numbers. From the curve it can be seen that the NdFeB PM width increases up to the point when the pole pitch becomes optimal for the generator electromagnetic torque.

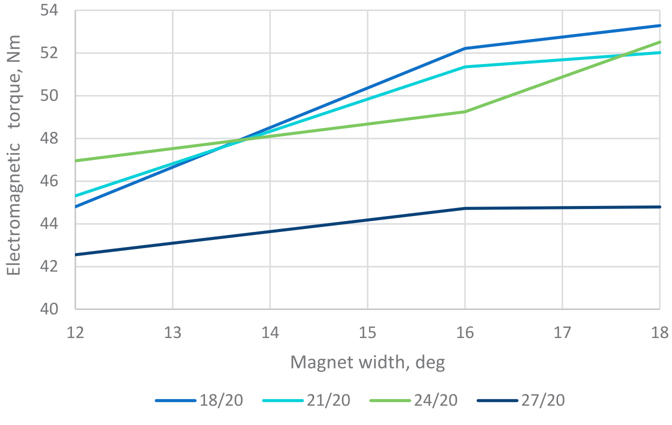


*Fig. 5*. Electromagnetic torque *vs.* PM width for different PMSG active zone combinations.

Figure 6 presents the dependence of cogging torque on the PM width in degrees. It is seen that at 16 degrees the cogging torque has a lower indicator. This can be explained by close values of the slot opening angular sizes and the interpolar distance. As also discussed in 1, if the interpolar distance is equal to the angular size of the slot opening, pulsation of the torque becomes smoothed, which is due to the constancy of mutually overlapped areas of stator teeth and rotor poles. Therefore, the irregularity of pulsation due to changes in the magnetic field is mainly concentrated in the airgap at the rotor rotation.

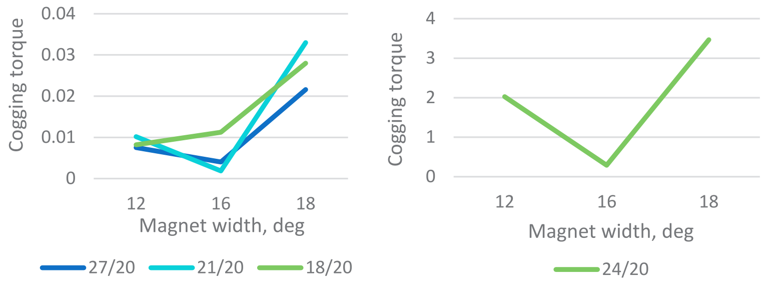


*Fig. 6*. Cogging torque *vs*. magnet width for different PMSG active zone combinations.

In Figs.7 and 8 the curves of no-load and load characteristics are shown. It can be seen that all the generator designs are close to each other, still a better variant is at $Z_1$=18 and $p$=10.

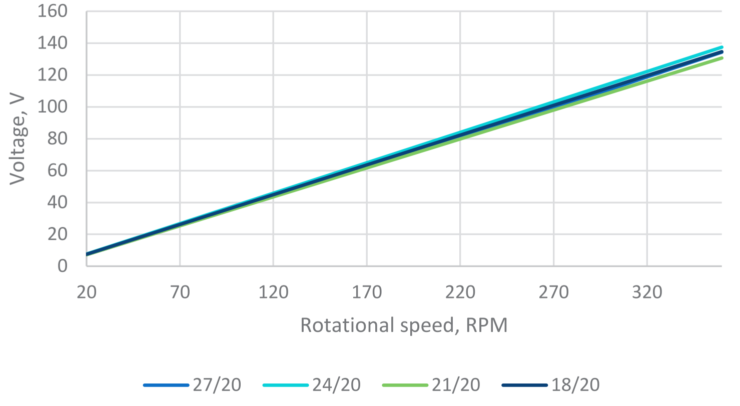


*Fig. 7*. Phase voltage *vs*. rotational speed for different active zone combinations.

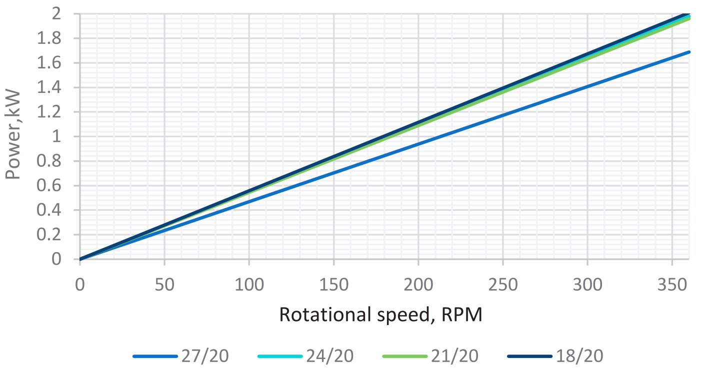


*Fig. 8*. Power *vs*. rotational speed for different active zone combinations.

As seen in Fig. 8, all combinations are close to each other, while under load the generator with $Z_1$=27 has a lower indicator.

## 4. CONCLUSIONS

In the research presented, investigation and comparison have been carried out for the NdFeB PMSGs with non-overlapping concentrated windings in which the coupling between the number of teeth $Z_1$ and the number of permanent magnets 2p on the rotor is determined by the relationship $Z_1 = 2p \pm k$.

To the investigation four generators were subjected, with the stator tooth numbers $Z_1$ = 18, 21, 24, 27, and with 20 PMs on the rotor. To improve the design of PM synchronous generators, mathematical modelling experiments have been performed. As a result, the values of maximum and cogging torques have been determined and compared. It is shown that a decrease in parameter k leads to an increase in the electromagnetic moment of generator and a decrease in its breaking torque at the start-up. However, at the minimum *k* values (e.g., at *k* = 1) the winding of each phase is concentrated on *Z/m* neighbouring teeth that occupy 1/3 of the stator recess. This leads to one-sided magnetic attraction of the rotor, which is responsible for elevated vibrations, noise, wear of bearings, etc.

## *ACKNOWLEDGEMENTS*

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PASTĀVĪGO MAGNĒTU SINHRONĀS MAŠĪNAS AR VIENZOBSPOĻU KONCENTRĒTU TINUMU AKTĪVĀ ZONĀ

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K o p s a v i l k u m s

Darbs ir veltīts sinhrono ģeneratoru ar NdFeB pastāvīgajiem magnētiem (PM) un koncentrētu vienzobspoļu tinumiem izpētei. Šāda tipa ģeneratora rotoram polu pāru skaits (PM) ir 10, kuru nosaka nominālā sprieguma frekvence ($f$=50 Hz) un rotācijas ātrums ($n$=300 RPM). Tiek salīdzināti četri ģeneratori ar trīsfāžu tinumu un statora zobu skaitu 18, 21, 24 un 27.

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