Design and analysis of a new axial flux permanent magnet synchronous generator for wind

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Abstract. The paper deals with a new design of a low-speed disk permanent magnet axial flux synchronous machine for decentralized power generation, which has improved weight-size parameters. In the new design the value of the air gap value is reduced by removing all inter-coil connections from the gap and also a concentrated winding with a high winding coefficient is applied. A two-rotor prototype of this design is created (150 W, 83 V, 250 rpm) and its magnetic circuit and the concentrated windings arrangement are described, as well as the results of the machine experimental study. The 2D finite element analysis is used to determine the effect of the air gap value effect on the disk slotless generator parameters. The method of rational choice of the machine main dimensions and the parameters of its winding according to nominal data and electromagnetic loads limitations are presented. Comparison of parameters and characteristics of a 20-pole-pair 5 kW synchronous wind generator with the new design and cylindrical one with tangential magnetization is performed. The proposed slotless design exceeds the cylindrical one in efficiency and requires less material costs. The limitations are the higher value of the outer machine diameter and the required large magnets mass.

1. Introduction
Wind power occupies an increasing share in the total balance of renewable energy sources – its annual world input capacity in recent years exceeds 50.0 GW. Russia is not the world wind energy leader, but in 2017, significant steps have been taken in the wind energy development. In the northern regions of Russia, there is a huge wind potential, but the main source of energy there is a diesel generator. The work of the wind turbine in combination with the diesel generator will not only increase energy saving, but also will reduce the fuel delivery cost for hard-to-reach areas. Low-power plants should provide energy to individual objects, and such installations have already been proposed [1, 2]. Permanent magnet synchronous machines are widely used in wind power generation due to their known advantages. Direct-drive multi-pole designs [3] are preferred for them. It can be created by three different ways: with tangential flux [4, 5], with axial flux [6-10] and with transverse flux [11, 12]. Several design versions are proposed for each of these three ways. The choice of machine topology determines its dimensions and parameters, the optimization of which is also proposed [5, 13-15]. The main dimensions for the axial flux generator are the outer and inner rotor diameters.
2. A new design machine structure
The paper presents the investigation results of a new design of an axial flux slotless permanent magnet (PM) synchronous generator for decentralized power generation. A new design has improved mass-dimensional parameters due to a concentrated winding with a high winding coefficient and a small air gap owing to the removal of all intercoil connections [16]. The new design (figure 1) is implemented in the prototype of three-phase synchronous generator SGPM-0.15-250A (150 W, 83 V, 250 rpm), which has the following dimensions, winding data and electromagnetic loads:

| Parameter                        | Value  |
|----------------------------------|--------|
| Inner diameter $D_{1i}$, mm      | 110.0  |
| Outer diameter $D_{1o}$, mm      | 200.0  |
| Air gap $\delta$, mm             | 4.0    |
| Slots number of per pole and phase $q$ | 0.375  |
| Number of turns per phase $w$     | 360    |
| PM length $l_{pm}$, mm           | 47.5   |
| PM width $b_{pm}$, mm            | 15.0   |
| PM height $h_{pm}$, mm           | 5.0    |
| PM residual flux density $B_r$, T | 1.12   |
| PM coercive force $H_c$, kA/m     | 800.0  |
| Air gap flux density $B_\delta$, T| 0.46   |
| Ampere density $A_1$, A/cm        | 63.0   |
| Current density $j_1$, A/mm$^2$   | 4.2    |

Figure 1. The electric machine design (a) and the stator magnetic core shape (b): 1 – stator, 2 – magnetic core, 3 – concentrated winding, 4 – two rotors, 5 – permanent magnets, 6 – technological grooves, 7 – ring groove.

The prototype is designed and manufactured on the basis of DC motor DPU 240-1100-3-D41-09. Housing, bearing shields, shaft and bearings are used. Two disk rotors with permanent magnets (Figure 2, a) instead of a disk stamped anchor with a printed winding are placed on the shaft. Instead of the motor excitation system, a stator with a 3-phase winding is fixed on the frame (Figure 2, b). The choice of the phases, the stator teeth and the rotor poles number made it possible to perform a concentrated winding with the slots number per pole and phase $q=Z/(2pm)=3/8$ and a high winding coefficient $k_w=0.945$ (Figure 2, b). The winding of each phase is the same. For example, phase $U$ consists of three coils groups arranged in three groups of technological grooves: 1, 2, 3, 4; 10, 11, 12, 13; 19, 20, 21, 22 (Figure 2, b), where grooves 2,3; 11,12; 20,21 are completely occupied by conductors of phase $U$, and grooves 1, 4; 10, 13; 19, 22 only by half, and the second half belongs to conductors of neighboring phases $V$ and $W$. In order to reduce the air gap value in which the winding conductors are located, the magnetic circuit provides for the implementation of the ring groove 7 due
to the fact that the inner sheets of the magnetic circuit are of a smaller diameter than the outer ones. In the formed ring groove 7 (Figure 1, b) connections between coils groups are located (for example, for phase $U$ transitions from technological groove 7 to 13, from 16 to 22, from 25 to 1). Thus, the air gap value is determined only by the active winding conductors, which improves the weight and size of the machine.

![Figure 2. The rotor (a) and the stator with concentrated winding (b) of a prototype.](image)

### 3. Simulation and results

For the slotless stator design, the parameter that determines the effectiveness of the machine is the air gap value, the effect of which on the fluxes is studied by the prototype 2D finite element analysis of 2-pole pitch. The distribution of the vector magnetic potential at no-load over 2-pole pitch an air gap of 4 mm and 8 mm is presented in Figure 3.

![Figure 3. The vector magnetic potential distribution over 2-pole pitch at no-load for an air gap of 4 mm (a) and 8 mm (b).](image)

When the air gap growth, the leakage factor increases significantly (Figure 4, a), and at gap values up to 4 mm the 2D finite element analysis and electromagnetic calculation give the same assessment, at large gaps on electromagnetic calculation the underestimated value of the leakage factor will be received and the calculated open circuit value of EMF will be higher than the real one (Figure 4, b).

![Figure 4. The dependences of flux leakage factor (a) and open circuit EMF (b) on the air gap value.](image)
The prototype investigation was carried out on the test bench (Figure 5) at open circuit and different loads, when only one rotor or a set of two rotors has been installed. The maximum current load of the stator winding has been determined by thermal tests: overheating Δθ=100°C corresponds to a load of 1.75 A and a current density of 4.2 A/mm², which allows increasing the power of the prototype up to 200 W.

\[ \text{Figure 5. The prototype on the test bench (a) and its output voltage oscillogram (b).} \]

No-load characteristics (a) and external characteristics defined for different air gaps (Figure 6) confirm the decisive air gap role for the proposed design. The machine phase voltage is almost sinusoidal.

\[ \text{Figure 6. Open-circuit loading (a) and external generator characteristics (b) at different air gaps (δ₁>δ₂).} \]

### 4. Parameters choice technique

The technique of the main dimensions and winding data choice is proposed for the new design. It is necessary to place two coils with the turns number \( w_k \) which can be divided by height into \( n_l \) layers, and each turn can contain \( n_c \) conductors with a diameter \( d_{1w} \) in the technological groove on the inner stator diameter \( D_i \).

Assuming that the technological factor for laying is \( k_l=1.1 \), and the technological width of the groove is \( b_z \), we obtain the equation

\[ d_{1w} n_c w_k n_l = \frac{\pi D_i}{Z} b_z \]

(1)

On the other hand, the current density should not exceed the permissible value

\[ j_p = I \left( 0.25 \pi d_{1w}^2 n_c \right)^{-1} \]

(2)

The inner diameter is determined from the expressions (1) and (2), which linearly depends on the coil turns number \( w_k \) for the accepted value of the permissible current density \( j_p \).
The air gap flux $\Phi_\delta$ is determined by the total permanent magnets flux and the magnetic resistance of the gap $\lambda_\delta$, of the permanent magnets $\lambda_m$ and of the permanent magnets leakage $\lambda_{sm}$:

$$\Phi_\delta = \frac{\lambda_\delta}{\lambda_m + \lambda_{sm}} \Phi_m = K_p \Phi_m = K_p B_s S_m$$

The coefficient $K_p$ actually depends on the PM height $h_m$ and the air gap value $\delta$. If we assume that $\lambda_{sm}=0.4\lambda_m$, then for $K_p$ we get the expression.

$$K_p = \frac{h_m}{h_m + 1.4\delta}$$

and for the coil turns number

$$w_i = \frac{U_f a m}{8.88 f K_p B_s S_m Z_k}$$

The coil turns number according to the expression (6) depends on the machine rated data ($U_f, m, a, f$) and on the selected PM data ($B_s, S_m, h_m$). It should be noted that the choice of the magnet area $S_m$ and the coefficient of the pole arc $\alpha$ unambiguously leads to the following definition of the outer diameter of the disk

$$D_o = D_i + 2l_m = D_i + 2S_m (\alpha \tau)^{-1}$$

where $\tau$ is the polar pitch value.

The electromagnetic calculation of the new design three-phase synchronous generator SGPM-5-150A ($P=5$ kW, $U=400$ V, $I=8$ A, $n=150$ rpm) is compared in Table 1 with the characteristics of the wind generator with tangential magnetization (SGPM-5-150T) [5]. Generators have the same rated data and concentrated winding at $m=3$, $Z=42$, $2p=40$, $q=0.35$.

**Table 1.** Comparison of the characteristics of a wind turbine generator with a tangential and axial flow.

| Design          | Tangential (SGPM-5-150T) | Axial (SGPM-5-150A) |
|-----------------|--------------------------|---------------------|
| Inner diameter, mm | 550                      | 550                 |
| Outer diameter, mm | 640                      | 680                 |
| Active length, mm | 56                       | 65                  |
| Air gap, mm     | 4.0                      | 4.0                 |
| Number of turns per phase | 560                 | 357                 |
| PM length, mm   | 56                       | 59                  |
| PM width, mm    | 21.7                     | 40.0                |
| PM height, mm   | 6.0                      | 5.0                 |
| Air gap flux density, T | 0.86               | 0.582               |
| PM leakage factor | 1.62                     | 1.16                |
| Ampere density, A/cm | 156                 | 88.9                |
| Current density, A/mm² | 3.45                | 2.93                |
| Heat factor, A²/mm³ | 538                   | 260                |
| PM stock ratio | 1.23                     | 1.15                |
| Copper loss, W  | 271                      | 92                  |
| Iron loss, W    | 51                       | 97                  |
| Total loss, W   | 380                      | 262                 |
| Efficiency, %   | 92.9                     | 95.0                |
Comparison of characteristics of electric machines with different flux topology presented in Table 1. It shows that the axial magnetization rated data are realized at lower values of electromagnetic loads, which gives an increase in efficiency by 2.1% and at the same time saving copper 2.2 times. The volume of two rotors of the machine with axial flux is 1.5 times less than the volume of the machine rotor with tangential magnetization, but the required mass of magnets is more than 3 times higher than with tangential magnetization. Taking into account the existing prices for winding copper and permanent magnets, the cost of these materials for the axial flux machine will be less.

5. Conclusions

The new design of the axial flux slotless three-phase synchronous generator for decentralized power generation is proposed, which has improved mass-dimensional parameters due to the use of a concentrated winding with a high winding coefficient and a reduction of the air gap owing to the removal of all inter-coil connections.

The original technique of rational choice of the machine main dimensions and the parameters of its winding according to the rated data and limitations of electromagnetic loads is developed. The use of the proposed axial flux synchronous machine design as a wind generator instead of the traditional cylindrical design with tangential magnetization permits to decrease the total materials cost and to increase efficiency by 2%.

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