Improved design of axial flux permanent magnet generator for small-scale wind turbine

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Abstract: Recently, much attention has been given to axial flux permanent magnet generators due to some advantages such as high efficiency, high power density, and higher torque compared to radial flux generators. In addition, increased number of poles makes them appropriate for low-speed applications such as wind power generators. In this study, an axial flux permanent magnet synchronous generator with unique features such as high power density is designed for small-scale wind turbines. The structure of generator includes a rotor and a stator. The generator is designed and then analyzed by Flux 11.2 software. The analysis includes the effects of air gap distance change with considering wind speed variations. Sinusoidal waveform of induction voltage with the acceptable harmonic characteristics confirms the optimized design of the generator.

Key words: Axial flux permanent magnet generator, finite element method, TORUS structure, wind turbine

1. Introduction

Axial flux permanent magnet (AFPM) machines are very similar to the radial flux machines. Such machines have a stator and a rotor with the disc structure and the magnets are placed in such a way that the manufacturing flux is in line with the common axis of rotor and stator. These generators generally have relatively high power and torque density. Hence, they are suitable for small-scale wind turbines. The reason for more research on axial flux generator with air core is that it provides the requirements for its use in wind turbine application. Three major factors which make these generators suitable for wind energy generation include low cost, reliability, and simplicity of manufacturing process in the noncore generator. The fundamental difference between radial flux permanent magnet (RFPM) and AFPM machines can be found in the power/diameter ratio of the machine. Axial flux machine output power is proportional to the third power of the outer diameter, whereas in radial flux machines, the output power is directly proportional to the square of the diameter. This is one of the basic differences between axial flux and radial flux machines [1].

In recent decades, much research has been done on axial flux machines and the results of such studies provide different structures with unique features for specific applications. In [2], an accurate analytical approach called quasi-3D was used to design surface-mounted AFPM machines. In [3], AFPM machines with different magnet shapes have been investigated to achieve an almost sinusoidal air-gap flux density distribution. A comprehensive review is illustrated in Table 1 [2–18].

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Table 1. Types of axial flux permanent magnet machines.

<table>
<thead>
<tr>
<th>Type of structure</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-stator single-rotor</td>
<td>Compact construction, high torque</td>
</tr>
<tr>
<td>Double-stator single-rotor</td>
<td>Ratio of power to high inertia</td>
</tr>
<tr>
<td>Single-stator double-rotor</td>
<td>Possibility to delete groove and stator iron</td>
</tr>
<tr>
<td>Multistator multirotor</td>
<td>Power density, high speed and power</td>
</tr>
</tbody>
</table>

In the single-stator dual-rotor (SSDR) structure, iron core can be removed. In this case, no ferromagnetic material is used as a core. Therefore, core losses, including eddy current and hysteresis, are removed. Without a core, efficiency of the coreless AFPM machine will be increased. This structure is intended for applications where torque gear and low torque ripple are preferred. The mentioned characteristics of this structure are suitable for small-scale wind turbines. Hence, SSDR structure, also known as TORUS, was selected in this study.

The designer should select the proper machine according to the intended application. The purpose of this study was to design a generator with high power density suitable for small-scale wind turbine according to the intermittent nature of wind speed. Its performance is also evaluated based on possible errors in manufacturing and operating.

2. Design equations of AFPM

The output power of electric machine can be defined by using its dimensions [19]. For an AFPM machine, the following equation is used:

\[ P_{out} = \frac{\pi}{4} k_e k_p k_i A B_g \eta f \left( 1 - \lambda^2 \right) \frac{1 + \lambda}{2} D_o^3, \]  

(1)

where \( P_{out} \) is the output power of an AFPM and \( k_p \) represents the waveform of electrical power. For sine wave, it is equal to 0.5 [20]. \( k_e \) is the EMF coefficient and \( k_i \) is the current waveform coefficient. For sine wave, it is equal to \( \sqrt{2} \). \( B_g \) is the maximum flux density in the air gap, and it is generally referred as magnetic load ability. \( f \) is the frequency, \( p \) is the number of poles, \( D_o \) is the outer diameter of machine, and \( \lambda \) is the inner diameter of machine (\( \lambda = D_i/D_o \)).

Another parameter in the above equation is special electrical loading which is calculated as:

\[ A = \frac{m I_{rms} 2 N_{ph}}{\pi D_m}, \]  

(2)

where \( m \) is the number of phases, \( D_m \) is the average inner and outer diameters of machine, \( N_{ph} \) is the number of rounds in each phase and \( I_{rms} \) is the effective current for each phase.

According to the first equation, the diameter of machine is calculated as:

\[ D_o = \left( \frac{P_{out} \pi}{\frac{\pi}{4} k_e k_p k_i A B_g \eta f \left( 1 - \lambda^2 \right) \frac{1 + \lambda}{2}} \right)^{\frac{1}{3}} \]  

(3)

To achieve the maximum power, the optimal value of \( \lambda \) is equal to \( 1/\sqrt{3} \) [21]. If the goal is to achieve the maximum torque, the value of \( \lambda \) is equal to 0.63 [22].
The axial length of AFPMG shaft with TORUS structure and without core is the thickness of double stator and length of air gap. However, a virtual stator is considered for the simulation of embedding coils. Hence, air gap is divided into two parts. Eq. (4) can be used to calculate the axial length of machine:

\[ L_{ax} = L_s + 2L_r + 2g, \]  

(4)

where \( L_{ax} \) is the axial length of generator; \( L_s \) and \( L_r \) are the thickness of stator and rotor discs, respectively and \( g \) is the air gap. For the air core without groove, the thickness of virtual stator is calculated as follows:

\[ L_s = \frac{B_g \pi \alpha_p D_o (1 + \lambda)}{4pB_{cs}}, \]  

(5)

where \( \alpha_p \) is the ratio of pole bow to pole step and \( B_{cs} \) is the maximum density of the magnetic flux through the stator in accordance with Eq. (6):

\[ B_{cs} = \begin{cases} 5.47 f^{-0.32} & f > 40 \text{Hz} \\ 1.7 - 1.8 & f \leq 40 \text{Hz} \end{cases}. \]  

(6)

The axial length of rotor can also be calculated by:

\[ L_r = \frac{B_g \pi D_o (1 + \lambda)}{8pB_{cr}}, \]  

(7)

where \( B_{cr} \) is between 1.6 and 1.8 Tesla for axial flux machines with TORUS structure.

3. The induced voltage equation

In AFPM machine, the distribution of magnetic flux in the air gap is approximately pure sinusoidal, leading to an EMF with a sinusoidal waveform. In the design of electrical machine, the main part, or the base of the distribution of flux, is an important part. For a sinusoidal distribution of the magnetic flux density at the air distance, the base flux at each pole is obtained from the following equation:

\[ \Phi_p = \int_{-\frac{\pi}{p}}^{\frac{\pi}{p}} \int_{r_i}^{r_o} B_{m1} \cos \frac{p}{2} \theta r \, dr \, d\theta = \frac{2}{p} B_{m1} (r_o^2 - r_i^2), \]  

(8)

where \( p \) is the number of poles, \( B_{m1} \) is the amplitude of the base magnetic flux density, and \( r_o \) and \( r_i \) are, respectively, the external and internal radius of the rotor disk. The flux induced on each pole is expressed in terms of the density of the magnetic flux of the air gap \( B_g \):

\[ \Phi_p = \frac{2.22 B_g (r_o^2 - r_i^2)}{p}, \]  

(9)

where \( B_g \) is calculated by the magnetic field of the machine and the point of operation on the permanent magneto magnetization curve. For an AFPM machine with \( N_{ph} \) rounds in each series phase, the effective value of the base EMF is obtained from the following equation:

\[ E_{ph} = \sqrt{2} \pi f N_{ph} \Phi_p k_w, \]  

(10)
where $k_{w1}$ is the coefficient of distribution of the winding and is obtained from the following equation:

$$k_{w1} = \frac{\sin \frac{\alpha}{q} \sin \frac{\pi}{2}}{q \sin \frac{\pi}{2}}.$$ (11)

In the last relationship, $q$ is the number of slots in each pole in each phase and $\alpha$ is the step of winding.

4. Electromagnetic design of generator

Because the selected magnets are circular, the air gap flux density generated by them can move in all directions. In fact, sinusoidal flux density is distributed around the generator. The flux distribution around the poles of the generator is shown in Figure 1.

Laplace equation in two-dimensional space and Cartesian coordinates are used. Figure 2 shows two-dimensional axial flux generator type based on TORUS structure. Because the generator is symmetrical, it is symmetrically divided into two parts by the boundary line to facilitate the analysis.

![Figure 1. Flux distribution around the poles of the generator.](image)

![Figure 2. Two-dimensional axial flux generator.](image)
The issue can be solved as suggested in [23]. By using this model, the magnetic vector potential and flux density between magnets and symmetry boundary are obtained as:

\[ A_{zn}(x) = -\frac{J_n \mu_0}{u_n} \sinh u_n \frac{t_m}{2} \cosh u_n \left( \frac{g}{2} - y \right) \sin u_n x, \]  
\[ B_{yn}(x) = \frac{J_n \mu_0}{u_n} \sinh u_n \frac{t_m}{2} \cosh u_n \left( \frac{g}{2} - y \right) \cos u_n x \]  

(12) \hspace{1cm} (13)

In the above equations: \( u_n = \frac{n}{r} \).

Flux density in the boundary line can be calculated by using \( y = \frac{g}{2} \):

\[ B_{yn}(x) = \left[ \frac{J_n \mu_0}{u_n} \sinh u_n \frac{t_m}{2} \right] \cos u_n x = \hat{B}_n \cos u_n x \]  

(14)

5. Analysis and optimization method

In this paper, an AFPM machine equipped with cylindrical magnets was investigated, and a semianalytical method called quasi-3D approach was used for the fast design of the machine. Effectiveness and accuracy of quasi-3D method was assessed on different AFPM machines. For increasing the accuracy of computations, ferromagnetic rotor core material was not considered to be ideal. Instead, B-H curves were used for magnetic materials and the effects of the magnetic potential drop at iron parts of the machine were taken into account by using a saturation coefficient. In quasi-3D computation, the average diameter of a particular computation plane starts from the external diameter of the machine [2].

The minimal cost design of an axial flux permanent magnet generator was searched by using a genetic algorithm with consideration of practical and performance constraints. Improved design procedure of AFPM using GA is shown in Figure 3 [24].

6. Features of the designed model

According to the equations and considerations, an AFPMG with TORUS structure and N-S placement of magnets was designed according to the features in Table 2.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal power</td>
<td>P</td>
<td>1000</td>
<td>W</td>
</tr>
<tr>
<td>Number of phase</td>
<td>m</td>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Frequency</td>
<td>f</td>
<td>10</td>
<td>Hz</td>
</tr>
<tr>
<td>Nominal speed</td>
<td>n</td>
<td>150</td>
<td>rpm</td>
</tr>
</tbody>
</table>

The suitable slot-pole number was chosen according to the result obtained in [25]. The selection was partly based on the results of 3D finite element analysis (FEA), which was performed for the reported machine configurations. Table 3 shows the considerations for the generator design.

Table 4 provides the physical dimensions and output results obtained from the direct algorithm of the electrical machine design.
Determination of initial design parameters

Using genetic algorithm to obtain the optimum design variables (Minimize the object function subjected to constraints)

Calculation of main dimension based on sizing equation for AFPM machines

Electromagnetic design of stator and rotor cores and windings characteristic

Calculation of machine losses and efficiency

If the required accuracy is reached, save the design variables

If required accuracy is not reached

Figure 3. Improved design procedure of AFPM using GA [24].

Table 3. Constraints and considerations of the design.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric load density</td>
<td>A</td>
<td>10500</td>
<td>A/m</td>
</tr>
<tr>
<td>Maximum flux density in the air gap</td>
<td>$B_g$</td>
<td>0.74</td>
<td>T</td>
</tr>
<tr>
<td>Form factor of power wave</td>
<td>$k_p$</td>
<td>0.777</td>
<td>-</td>
</tr>
<tr>
<td>Coefficient of current waveform</td>
<td>$k_i$</td>
<td>0.134</td>
<td>-</td>
</tr>
<tr>
<td>EMF coefficient</td>
<td>$k_e$</td>
<td>$\pi$</td>
<td>-</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>$B_r$</td>
<td>1.2</td>
<td>T</td>
</tr>
</tbody>
</table>

Table 4. Dimensional physical parameters for the designed machine.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of poles</td>
<td>$p$</td>
<td>8</td>
<td>-</td>
</tr>
<tr>
<td>Ratio of internal diameter to external diameter</td>
<td>$\lambda$</td>
<td>0.574</td>
<td>-</td>
</tr>
<tr>
<td>Outer Diameter</td>
<td>$D_o$</td>
<td>230</td>
<td>mm</td>
</tr>
<tr>
<td>Inner diameter</td>
<td>$D_i$</td>
<td>130</td>
<td>mm</td>
</tr>
<tr>
<td>Axial length of generator</td>
<td>$L_{ax}$</td>
<td>60</td>
<td>mm</td>
</tr>
<tr>
<td>Total length of the air gap</td>
<td>$2g$</td>
<td>20</td>
<td>mm</td>
</tr>
<tr>
<td>Radius of the permanent magnet</td>
<td>$R_{pm}$</td>
<td>25</td>
<td>mm</td>
</tr>
<tr>
<td>Thickness of the rotor disc</td>
<td>$L_r$</td>
<td>10</td>
<td>mm</td>
</tr>
</tbody>
</table>
7. Finite element simulation and analysis of AFPMG

The finite element method is the most common solution of the vector field problems. Investigating the magnetic field distribution, especially in electromagnetic issues, has several benefits. It enables detailed local analysis. The significant parts of results include gradient field, magnetic field intensity, and saturation. However, this method also has some drawbacks. Due to its numerical nature, the obtained response is necessarily approximate. Incorrect use of this method may lead to incorrect results. Since the calculated quantities have spatial distribution, the calculation time is long.

The studied AFPMG was three-dimensionally simulated by Flux 11.2 Cedrat. According to the three-dimensional finite element, the electromagnetic field was calculated by using A-V-A formulations for analyzing the electromagnetic AFPM generator [26]. By using Maxwell’s equations to calculate the magnetic field on the basis of A-V-A formulations, Eqs. (15) and (16) were obtained [27]:

\[ \nabla \times ([v] \nabla \times \hat{A}) - \nabla v_e \nabla \hat{A} = \hat{J}, \]  

(15)

\[ -\nabla [\sigma] \left( \frac{\partial \hat{A}}{\partial t} + \nabla V \right) = \nabla . J = 0. \]  

(16)

Eq. (17) states the permanent magnet surface as follows:

\[ \nabla \times ([v] \nabla \times \hat{A}) - \nabla v_e \nabla \hat{A} = \nabla \times \left( [v] \frac{[M_0]}{v_0} \right) \]  

(17)

\( \hat{A} \) and \( V \) are the magnetic vector potential and the electric potential, respectively. \([v]\) is the reluctivity matrix and \([\sigma]\) is the electrical conductivity matrix. \(v_e\) is one-third reluctivity matrix. \(\hat{J}\) is the current density vector, \(M_0\) is inherent hysteresis, and \(v_0\) is the air reluctivity.

The AFPMG used in this study had TORUS structure and there were 8 circular magnets on each rotor. Figure 4 shows the 3D structure of AFPMG and flux density distribution in rotor yoke and the permanent magnet rotor disk, respectively. According to this figure, flux density of rotor is up to 1.2 Tesla.

Figure 5 shows the direction of magnetic field lines related to phase voltage in the TORUS machine with N-S Magnets under no-load conditions. According to Figure 6, the maximum voltage of each phase is 124.5 V. In addition to the electrical parameters such as EMF, it is possible to draw the parameters of the mechanical part.

Figure 8 shows the harmonic spectrum of the first phase voltage. According to this figure, the main harmonic amplitude is higher than those of other harmonics.

8. Impact of change of air gap on generator performance

A problem which may occur in many axial flux electrical machines is the air gap displacement. Under such conditions and in the generators with TORUS structure, the deviation in air gap means increasing the gap between two rotors. Figure 9 shows the displacement of rotor axis [28].

Here, \( \hat{g}_1 \) is length of the gap generated under fault conditions, \( g_1 \) is length of the air gap under normal conditions, and \( r \) is [28]:

\[ r = g_1 - \hat{g}_1 \]  

(18)
Figure 4. The 3D structure of AFPMG and flux density distribution in rotor yoke.
Moreover, air gap displacement factor (AFD) is defined as:

\[ ADF = \frac{r}{\frac{r}{g_1}} \times 100. \]  

(19)
A displacement factor higher than 50% will lead to the break-up of the machine. For a proper analysis of the designed generators, the condition due to the fault of increasing the air gap was applied on the generator taking into account the displacement factor of 25%. Figure 10 shows the mentioned conditions. The normal operation was then compared with the condition where the air gap was displaced. The analysis was done in no-load mode. According to the winding flux in Figure 11, the flux amplitude reduced under fault conditions. The reason is that the reluctance of air gap was increased by changing the size of air gap.

The torque diagram of Figure 12 indicates that increasing the air gap significantly reduces the torque of the system. Reducing the electromagnetic torque and the magnetic flux decreases the system efficiency.

9. Impact of N-S opposite poles deviation on generator performance

When the generator has a grooved core, deviation from the opposite poles can be used as an effective method to reduce the torque of gear. Therefore, it is not important in the current research because the air core was used in this study. However, its impact on the designed generator was investigated. Considering that the pole step in the designed machine is 40°, the impact of diversion in two modes of 2.5° and 5°, as shown in Figures 13 and 14, was investigated.

The graph of the induced EMF is shown in Figure 15. When the deviation of 2.5° is increased to 5°, the
peak of the EMF reduces. This can be due to the weakening of the resultant flux density passing through the coils.

According to the torque graph shown in Figure 16, increasing the deviation to 2.5° reduces the torque ripple. However, increasing the diversion up to 5° increases the torque oscillations.

10. Impact of changing wind speed on generator performance
One of the essential characteristics of wind is its intermittent nature and variable speed. Therefore, a wind turbine generator must have certain characteristics. Compatibility of the generator at different wind speeds is very crucial. In fact, the generator must be capable of maintaining the desired output characteristics when the wind speed changes. The most important features of axial flux generator for wind turbines include reduced torque ripple and voltage and destructive harmonic spectra. For comparing the effects of changes in wind speed
in no-load and nominal modes, the generator is exposed to a range of wind speeds. Figure 17 shows the induced EMF in such two modes.

According to Figure 18, the parameters are directly and indirectly affected by the wind speed. Induced EMF range is the parameter which is the most obviously influenced. The wind speed is considered to be increasing gradually. The induced EMF also increases according to the increased wind speed. In the axial flux machines, frequency depends on the speed and number of poles. Hence, reducing the wind speed, for a fixed number of poles, increases the frequency and vice versa. Wind speed variations lead to change in the axial flux generator torque. The difference and heterogeneity of the torque amplitude at different moments create distortion and noise in generators. However, high number of poles in axial flux machines leads to compatibility of the generator at wide range of speeds.

Figure 19 shows the EMF harmonic spectrum at both nominal and variable speeds.

There is another mode where the turbines are working at the nominal speed. Therefore, a sudden speed change was applied to the system to assess its performance. In this simulation, at the time of 0.15 s, the speed changes. Increasing the wind speed to 9 m/s increases the frequency and the current amplitude, as shown in Figure 20. Increasing the current amplitude and frequency will increase the losses of the machine, reducing the power output at speed of 9 m/s compared to 7 m/s. The graph of losses at different wind speeds is shown in Figure 21.

11. Comparing generator performance under no-load and full-load conditions
In order to compare the function of the generator in no-load and full-load states, it was connected, in simulation of a resistor, to the generator windings, which for no-load state, applied a negligible value of $8 \times 10^8 \Omega$, and for full-load state, the resistance value equal to 8 $\Omega$. By changing the resistance, no-load and full-load conditions were obtained in the software. Figure 22 shows the induced EMF in no-load and full-load modes. As expected, by increasing the current in the coil terminals, the voltage drop of 50% appears in the peak of induction voltage.
The performance of the generator for inductive and capacitive loads was also simulated and investigated. Figure 23 shows the induction voltage in no-load state and currents for resistor load and resistor inductive and resistor capacitive load. The phase difference between the resistive current and inductive and capacitive loads is quite evident.

Figure 24 shows the torque in no-load and full-load. According to this figure, the generator shows a full behavior in full-load mode.

Figure 25 shows the harmonic spectrum in no-load and full-load. Under no-load condition, the third harmonic has higher amplitude than those of other harmonics and in full-load, the harmonic spectrum is reduced.
12. Conclusion

In this study, axial flux permanent magnet generator with air core and without groove is proposed which is suitable for low-speed wind turbines. The proposed generator has some features including enough number of poles, optimal number of coils and poles, and the appropriate air gap to produce induction propulsion with good quality at low speeds. When the TORUS structure with air core is used, the stator has no ferromagnetic material. It has several advantages including light generator structure and low losses and costs. In fact, the absence of ferromagnetic layers in the stator core leads to the removal of the eddy current and hysteresis losses of the core. In this case, the gear torque is also low. During operation, the generator produces noise. The results of the finite element analysis would be a great help for analyzing the designed generator. The current, voltage, torque, and other electrical and electromagnetic parameters are confirmed by the finite element analysis. The waveform of the induced EMF with harmonic characteristics shows that the designed generator has the desired
characteristics. The designed generator has a simple structure. Replacement of the opposite poles up to 5% can reduce gear torque and ripple, and a further increase of this amount results in unfavorable effects on generator performance and its output characteristics. Error caused by the air gap deviations also has adverse influence on torque and induced EMF due to decreasing the flux and weakening the induction field in the coil.

The effect of wind speed variations on the performance of axial flux generator was also discussed. Since most of the simulations were at the constant and nominal speed, influence of changing wind speed was investigated in the present study. The results indicate that the designed generator operates with the desired characteristics in a wide range of wind speeds.

References