Back-iron Consideration in High-Speed Axial-Flux Machine

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Introduction

Recently more attention is paid to the development of high speed PM generators driven by micro turbines [1–5]. Nevertheless, the high-speed operation imposes stringent engineering design constrains which are not considered in conventional machine [6, 7].

This paper is devoted to modeling and designing of a permanent magnet synchronous alternator with axial flux structure. The back iron used in the rotors of two ends is the main subject investigated in the paper.

In the axial flux machine, back iron of the rotor dose the same job that in conventional machine with some differences. The yoke of the stator of the conventional machine presents some iron loss increasing with frequency but in the axial flux machine, the back iron rotates with the rotors. This paper presents a full consideration and impact of the back iron of high speed axial flux generator (HSAFG) on the performance characteristics including voltage, output power and efficiency.

Design

Fig. 1 shows a schematic view of an axial flux machine with three rotors and two stators.

Due to the high speed of the rotor and high frequency of the stator flux variation, the design of a high-speed machine is quite different from designing a conventional low speed and low frequency machine [8–10].

Sintered Nd-Fe-B material is generally the best candidate for use in the rotor of the PM machines [11]. In addition, coreless stator is a common suggestion for axial flux machine due to high frequency stator current and flux [12–16].

For the modeling purposes, the magnetic circuit of the machine with all details is required. Simple magnetic circuit of the HSAEG machine comprising all reluctances is shown in Fig. 2. The leakage reluctances $R_{l1}$ and $R_{l2}$ and fringing reluctance $R_f$ are taking into account for most accuracy of the model. As an example, the air gap flux densities are 0.488 and 0.5617 Tesla when these parameters are taken into account or ignored respectively.

All the parameters of the magnetic circuit are calculated by design-based equations given in [17]. $R_{l1}$ is the PM leakage reluctance and is equal to:

$$ R_{l1} = R_A \left| R_g \right. $$

(1)

$$ R_A = \frac{2P}{\mu_0 B A L R_{PM}^{\frac{1}{2}}} $$

(2)

$$ R_g = \frac{a P}{\mu_0 \delta (3D_c + 2L_{PM}) L_{PM} L_{PM} + 3g - 6g} $$

(3)

The reluctance for leakage flux occurred between two PMs is:

$$ R_{l2} = \frac{1}{\mu_0 Per_{l}} $$

(4)

$$ Per_{l} \text{ (permeance)} = \frac{L_{PM} \times P}{2\pi (1 - \delta)} Ln \frac{R_s}{R_{l}} $$

(5)

Reluctance of the PM

$$ R_{PM} = \frac{L_{PM}}{\mu_0 A_{PM}} $$

(6)

The reluctance of the air gap including the stator can be written as:

$$ R_{L1} = \frac{(L_1 + 2g)}{\mu_0 A_s} $$

(7)

Then the fringing effect is evaluated and total value for $R_f$ is obtained using $R_{g1}$. 

87
For checking this design, the FEM is used. The 2-D FE modeling of this machine can be carried out by introducing a radial cutting plane at the average radius, which is then developed into a 2-D flat model. The Neumann boundary condition is assigned to the top and bottom boundary. Result of 2D FEM (Magnetic Flux Density) is shown in Fig. 3.

List of symbols used in (1–7) and Fig. 1, 2: 

- \( \mu_{\text{eff}} \) – air viscosity coefficient (kg/ms); 
- \( \rho \) – air density (kg/m³); 
- \( g \) – air gap (m); 
- \( L_{\text{bi}} \) – thickness of the back iron (m); 
- \( L_{\text{PM}} \) – thickness of PM (m); 
- \( L_{\text{s}} \) – thickness of stator (m); 
- \( \mu_0 \) – air magnetic permeability; 
- \( \mu_r \) – PM relative permeability; 
- \( P \) – number of poles; 
- \( \delta \) – ratio of width of PM to pole pitch; 
- \( \rho_{\text{Cu}} \) – electrical resistivity (Ω·m); 
- \( N_{\text{s}} \) – number of series coil per phase; 
- \( D_{\text{o}} \) – outer diameter (m); 
- \( D_{\text{i}} \) – inner diameter (m); 
- \( D_{\text{sh}} \) – shaft diameter (m); 
- \( D_{\text{starnd}} \) – diameter of each conductor (m); 
- \( A_g \) – area of air gap (m²); 
- \( \lambda \) – ratio of \( D_1 \) to \( D_6 \) (\( \lambda = \frac{1}{\sqrt{3}} \)).

**Loss calculation**

In general heating is a main limitation of electrical machines but since the high temperature reduces magnetic quality of the permanent magnets therefore heating and high temperature relatively is much problematical in the PM machines. For this reason, loss calculation is important in the PM machines:

a. Rotation losses were calculated using equation found in [18]. The power to overcome drag resistance of rotating disc is:

\[
P_{\text{mech}} = \frac{1}{2} C_f \rho (2\pi N_m)^3 (R_s^5 - R_m^5).
\]

That \( C_f \) the coefficient of drag for turbulent flow can be found as

\[
C_f = \frac{3.87}{\sqrt{Re}}.
\]

That \( Re \) the Reynolds number for a rotating disk with its outer radius is

\[
Re = \frac{R_s \nu}{\mu_{\text{air}}} = \frac{2\pi N_m \rho R_s^2}{\mu_{\text{air}}}
\]

It is seen rotational (mechanical) loss is not relation to back iron.

b. Stator winding loss will be obtained by the simple equation:

\[
P_{\text{cu}} = \frac{R_s V_{\text{load}}^2}{\rho_{\text{Cu}}}
\]

c. High frequency content of magnetic filed causes additional loss (eddy current loss) in the stator winding [19]:

\[
P_{\text{eddy,cu}} = \frac{(B_x^2 + x^2 \times f \times D_{\text{starnd}} \times 10^{-9})^2}{32 \times \rho_{\text{Cu}}} \times V_{\text{cu}}.
\]

**Simulation**

Linking all subsystems of HSAFG model in a Matlab/Simulink environment, the computer model of the machine is obtained.

Simulation machine is a 30 kW, 400 Volts and 30000 rpm axial flux generator with two stators and three rotors.

An increment of thickness of back iron from 1 to 10
millimeters yields to reductions of the back-iron flux density (Fig. 4) and significant increase of the air-gap flux density (Fig. 5) for all numbers of pole. Air gap flux density configures the induce voltage and as seen in Fig. 6. As a conclusion, for providing sufficient voltage it is vital that the thickness of back iron for this machine be at least 3 millimeters.

According to the formula given in the previous section, mechanical loss (windage loss) is not related to $L_B$ and it is $3,286\,\text{W}$ for the simulation machine. Therefore, total power loss (Fig. 7) is depended on the copper and eddy current losses, so the power loss is increased. However output power (Fig. 8) is increased whilst the efficiency (Fig. 9) is changed accordingly by back iron variations. All these figures and discussion indicate that the thickness of back iron is a vital parameter in the axial flux machine and its optimum value can be determined individually by full simulation of the machine.

**Conclusion**

Modeling of a modular high-speed axial-flux PM generator were discussed in this paper.

For a given size and output power of the machine, the air gap flux is strictly related to the thickness of back-iron. Therefore, for producing sufficient air gap flux and resultant terminal voltage, adequate thickness of the rotor back-iron would be obligatory. Mass of the rotation parts including back-iron and cost of the machine are the main restrictions of an excessive large value of the back iron. Simulation of the machine with some details, would recommend an optimized values of the back-iron for a wide range of the output powers. For a given example machine it was illustrated, that an insufficient value of thickness of the rotor back iron reduces somewhat the terminal voltage and efficiency. Inversely if a large value of thickness is chosen the rotor inertia will increase and this may cause some mechanical problems with no significant improvement of the machine performance characteristics.
References


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High-Speed Axial Flux Generator (HASFG) has come into attention because of its some advantages such as high power density and efficiency. This paper presents a modeling and designing procedure of HASFG with some details. The optimized thickness of the back-iron used in the rotor of two ends is determined for a HASFG by carefully considerations of the terminal voltage, output power and efficiency. It is illustrated that a very small thickness of the rotor yoke reduces the terminal voltage and efficiency and a very large value of it increases the rotor inertia, mechanical problems and cost of the machine with no significant improvement of the machine performance characteristics. III. 9, bibl. 19 (in English; summaries in English, Russian and Lithuanian).


Bystrodejivuem gneratorem osesov magnitnog potoka (HASFG) popularen svoimi prednosti, takimi kak vysoka plontnost mocesti i effektivnosti. Predstavlja se procedura modeliranja i proektorvanja HASFG. Konstrukcija ritora za HASFG opredeljava:i takt seljavano predelno vno napajanje, vnovodnu mocest i effektivnost. Pokazano, da je vcel majhen takstni tolika komuta ritora umenja predelno napajanje i effektivnost, a vcelo ve olja uravnotejava mehanike probleme i cenu masina z budnosti usovremenovanja characteristic work for. Il. 9, bibl. 19 (na anglistikom jaz; referati na anglistikom, ruskim i litovskim jaz.).


Didelio grižio ašinio srauto generatoriusto (HASFG) sulaukia dėmesio dėl tam tikrų savo pranašumų, tokių kaip didelis galios tankis ir efektyvumas. Pristatytas HASFG modeliavimo ir projektavimo procedūra. Optimizuojant rotoriaus konstrukciją svertinama išimtini sūnë, išimtini galia ir efektyvumas. Parodytų, kad labai mažas rotoriaus jungo storis sumažina gnybų šimtą ir efektyvumą, o labai didelis storis didina rotoriaus inerciją, sukelta mekaninių problemų ir didina įranga kinin, bet jo naudo charakteristikos nepagerėja. Il. 9, bibl. 19 (anglų kalba; santraukas anglų, rusų ir lietuvių k.).