Design Analysis of High-Speed Axial-Flux Generator

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Abstract: Problem Statement: Axial flux permanent magnet machines are regarded as compact high efficiency generators for micro-turbines employed in the distributed power generation systems. High-speed rotor of the generator causes some designing and modeling problems. Sensitivity analysis tasks of the machine parameters are difficult and completely different in comparison with the problems associated with conventional machines. **Approach:** This article presents a modeling procedure with some details for performance predictions of High-Speed Axial Flux Generator (HSAFG). The FEM results are employed to validate the proposed model. Proper values of inner diameter to outer diameter ratio, plus back iron thickness of two rotor discs located in two ends are serious design problem for a HSAFG. **Results:** Impacts of these two parameters on the performance characteristics of a HSAFG are investigated in this paper. Their optimum values are determined for the machine by somewhat precise considerations of the output voltage and efficiency. **Conclusions/Recommendations:** It has been found out that the optimum performance of HSAFG regarding the voltage and efficiency is achieved by the value of inner to outer diameter ratio sited between 0.5-0.65. Moreover, the thickness of the rotor back iron can be designed by trial method to produce sufficient air gap flux and resultant terminal voltage. Adding extra back iron would just increase the rotor inertia with no benefit.

Key words: Generator, high speed, axial flux, modeling, design

INTRODUCTION

Recently more attentions are paid for development of high speed PM generators driven by micro turbines[1-4]. Axial flux permanent magnet machines have been used increasingly using high-energy magnets for various applications. These machines are regarded as high-efficiency and high power density for distributed power generation system[5-10]. Axial flux design or disk type geometry provides a better cooling facility because of higher surface areas of the stator and rotor. Due to better heat transferring, total electrical loss of an axial machine can be low compared with that of similar rating other structure machine.

In this study, the modeling and designing of a permanent magnet synchronous alternator with axial flux structure are investigated. Modeling details are given and impacts of two important feature parameters of the machine on the operational characteristics are discussed. These two are ratio of the inner diameter to outer diameter (λ) of the machine[4] and thickness of the back iron used in the rotors of two ends. The machine is somewhat coreless and there is no iron in the machine except in two ends.

MATERIALS AND METHODS

Rotor and stator features: Figure 1 shows a schematic view of a high speed axial flux machine. Due to the high rotor speed and high frequency of the stator flux variation, the design of a high-speed machine is quite different from designing a conventional machine with low speed and low frequency[11-13].
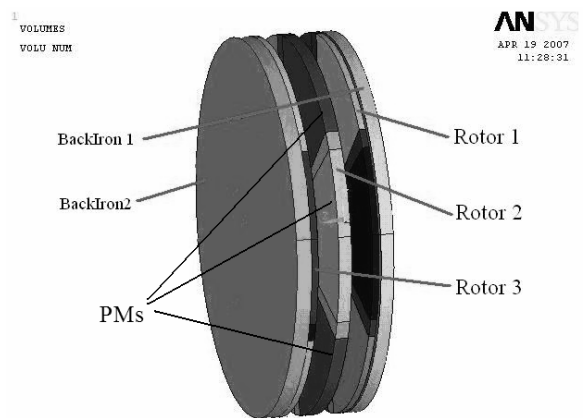

Fig. 1: View of a high speed axial flux generators

Many simulations show that sintered Nd-Fe-B material is the best candidate for the permanent magnets[14]. High frequency stator current and flux, strictly suggest designing a coreless stator[15-20] instead of employing common stator core with slots. The skin

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effect has to be decreased using Litz wire, the wire is divided into individually insulated strands of small diameter wires.

Loss calculation: One limiting parameter in high-speed axial-flux PM generator is the magnet temperature. The temperature in the magnet must be kept low and cooling must be efficient. Loss calculation is only briefly described here[21].

- Rotation losses are the main losses in high speed machines. Air friction losses (Windage losses) are depended to g (air gap) and Do (Outer diameter). Calculations of this power loss have been investigated in many papers. Here Windage losses are calculated using equation found in[22,23]. The power to overcome drag resistance of the rotating disc is:

$$P_{mech} = 0.0311 \times \left(\frac{2 \times g \times 10^{-3}}{D_o} \right)^{-0.25} \times \mu^{-0.25}$$
$$\times \rho^{0.75} \times \left(f \times \frac{2}{p} \right)^{\frac{11}{4}} \times \left(\frac{D_o}{2} \right)^{4.5}$$

(1)

- Stator winding losses will be obtained by the simple equation:

$$P_{cu} = R_s \left| I_{load} \right|^2$$

(2)

- Eddy current losses:
  High frequency of magnetic filed cause additional losses in stator (eddy current losses)[23]:

$$P_{eddy\_cu} = \frac{(B_g \times 2 \times \pi \times f \times D_{strand} \times 10^{-3})}{32 \times \rho} \times V_{cu}$$

(3)

Modeling: The simple model of HSAEG can be obtained by collecting all electromagnetic models (Reluctances) of elements of machine together (Fig. 2). In this model the accuracy of the model is increased by leakage flux (R_{l1} and R_{l2}) and fringing flux (R_g) consideration. (Air gap flux density with these considerations is 0.462 Tesla and without them is 0.496 Tesla)

By modeling and solving the machine in ANSYS software, the following result (Fig. 3) will be obtained. The flux density is near the result of our model (air gap flux density calculated by this model is 0.462 Tesla and by FEM is 0.427 Tesla).

According to magnetic model, the inductances of machine can be accurately calculated as below

$$L_{asas} = \frac{\lambda_{as}}{i_{as}} \text{ (When } i_{bs} = i_{cs} = 0 \text{)}$$

(4)

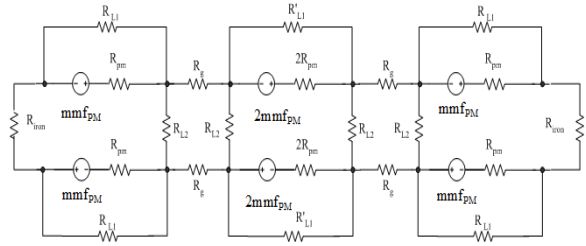$$\lambda_{as} = N_s \times \varphi_{as}$$
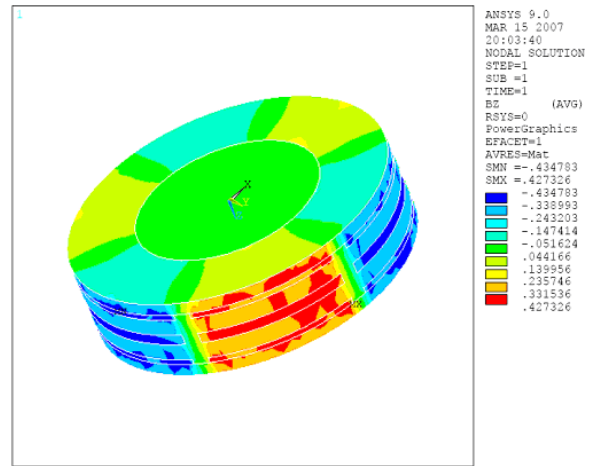
(5)

Fig. 2: Electromagnetic model

Fig. 3: Result of FEM (PM of rotor)

MMF of rotor (PM) flux is calculated according to the magnetic model of the machine.

For stator modeling, the mutual inductance between first and second stacks can be obtained in the similar way. At last, the inductance matrix of the machine can be found as below:

$$Ls = 10^{-4} \times \begin{bmatrix} 0.1322 & -0.0441 & -0.0441 & 0.1255 \\ -0.0441 & 0.1322 & -0.0441 & -0.0418 \\ -0.0441 & -0.0441 & 0.1322 & -0.0418 \\ 0.1255 & -0.0418 & -0.0418 & 0.1322 \\ -0.0418 & 0.1255 & -0.0418 & -0.0441 \\ -0.0418 & -0.0418 & 0.1255 & -0.0441 \\ & & -0.0418 & -0.0418 \\ & & 0.1255 & -0.0418 \\ & & -0.0418 & 0.1255 \\ & & -0.0441 & -0.0441 \\ & & 0.1322 & -0.0441 \\ & & -0.0441 & 0.1322 \end{bmatrix}$$
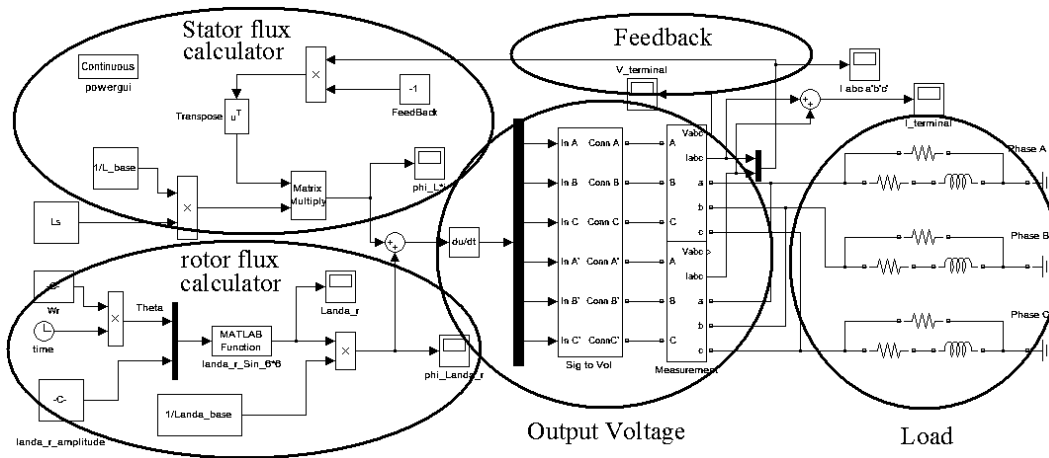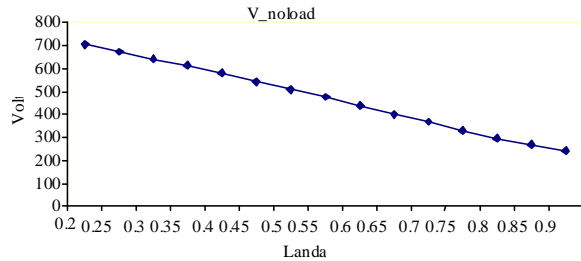
(6)

Fig. 4: Electrical model of a coreless HSAFG

Fig. 5: Voltage (volt) vs. λ

For modeling the resistance of stator (Copper Litz wire), the below formula was used[24]:

$$R_s = \frac{\rho_{cu} \times N_s \times (2 \times (\pi \times \frac{D_o + D_i}{2}) \times \frac{1}{P} + 2 \times (\frac{D_o - D_i}{2}))}{a \times N_{strand} \times A_{strand}}$$

RESULTS AND DISCUSSION

Simulation: By connecting the above mentioned models together, the electrical model of the machine is obtained (Fig. 4).

The performance analysis is based on the design study of a 50,000-rpm, 50KW and 400V generator. The results of lambda ($\lambda = \frac{D_i}{Do}$) and Back-iron sensitivity analysis are presented in this research.

Figure 5 how curves for voltage due to increasing lambda (λ) from 0.2-0.9. In analysis these parameters are given constant values:

D_o = Outer diameter
L_s = Length of stator
L_{pm} = Length of PM
L_{bi} = Length of back iron
D_{starnd} = Diameter of each wire of conductor
B_r = Residual flux density of PM
Z_L = Load impedance

During the increasing lambda, the air-gap flux density (B_g) and the back-iron flux density ($B_{backiron}$) are decreased (B_g from 0.56-0.45 Tesla and $B_{backiron}$ from 1.66-1.33 Tesla), because of reluctance of air gap and therefore total reluctance increasing.

According to B_g, voltage of machine is decreased from 704-240 Volts. It shows the lambda intensive influence on output voltage of generator.

In the other hand, increasing of λ is equal to decreasing area of rotors (PMs):

$$\lambda = \frac{D_i}{D_o}$$

$$A_g = \pi((\frac{D_o}{2})^2 - (\frac{D_i}{2})^2) \times \frac{1}{P}$$

By increasing λ, the PMs become smaller and the price of machine is decreased. So this mention leads designing to select high value for lambda.

Hence, the best range for lambda is obtained about 0.5-0.65.

To enlarge this study, the efficiency vs. lambda for some loads (100, 75,50 and 25%) is considered (Fig. 6).

Fig. 6 shows the satisfied point for lambda is decreased by decreasing the load power. Also it declaims the influence of this parameter heightens by decreasing load of machine (% 30 variations in efficiency for increasing lambda from 0.4 to 0.75 at Load = 25%).

Other important parameter of multi layer axial flux machine is the thickness of the back iron employed in the rotors located in two ends. In these graph, thickness of the back-iron is varied between 1-3 cm.
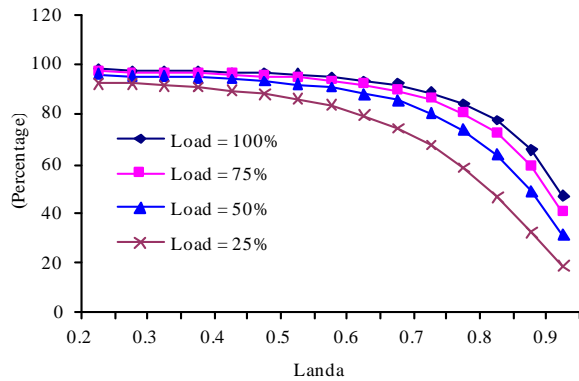
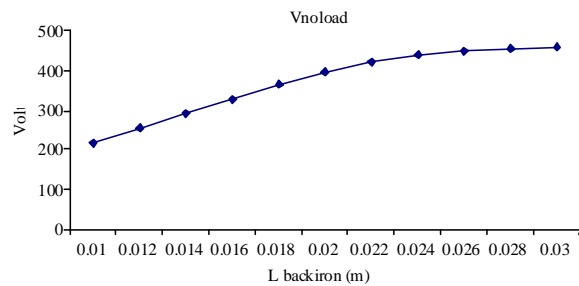

Fig. 6: Efficiency (%) vs. λ

Fig. 7: No-load voltage (V) vs. L_{bi}(m)

while the rotor speed, load impedance and the value of λ are remained constants. The values of these parameters are N = 50,000rpm, R_{load} = 0.8pu and X_{load} = 0.6pu and $\lambda = \dfrac{D_i}{D_o} = \dfrac{1}{\sqrt{3}}$ respectively. Variation of the no-load voltage versus length of the back-iron is shown in Fig. 7.

During the increasing back-iron, the air-gap flux density (B_g) is increased from 0.23- 0.49 Tesla (because reluctance of back-iron and therefore total reluctance decreasing). But because of increasing cross section of back-iron, the back-iron flux density ($B_{backiron}$) is decreased from 1.81-1.35 Tesla (opposite to B_g).

According to B_g, voltage of machine is raised from 221-459 Volts. (So because of low output voltage, low values of $L_{backiron}$ are not acceptable). In the same way, the loaded output voltage is enlarged from 216-450 Volts.
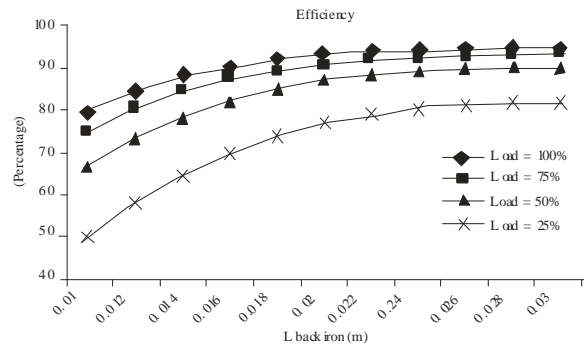

Fig. 8: Efficiency (%) vs. L_{bi}(m)

In the last, sensitivity analysis and variations of the efficiency versus variation of the back-iron thickness for a few typical loads i.e., 100, 75, 50 and 25 % of full load are shown in Fig. 8.

The suitable thickness value of the back-iron is decreased by increasing the load. Also this figure illustrate the influence of this parameter heightens by decreasing load of machine (30% variations in efficiency for increasing length of back-iron from 0.01 to 0.03m at Load = 25%). Briefly this graph illustrates that a very small thickness of the rotor yoke reduces the terminal voltage and efficiency but a large value of it increases cost of the machine and rotor inertia with no significant improvement in the performance characteristics while a big inertia may cause the mechanical problems too.

CONCLUSION

A design methodology and modeling of a modular high-speed axial-flux PM generator have been proposed in this study. Electric model is presented taking the leakage and fringing effects into account.

Variations of the main output parameters like efficiency and output voltage with respect to λ are illustrated. Simulation results show how the output parameters are varied by variation of λ. In conventional or radial flux machine, the ratio of inner diameter to outer diameter has been already considered. In this study the influences of λ in HSAFG lambda is discussed. The best range of λ obtained by simulation of this study is about 0.5-0.65.

The efficiency vs. length of back-iron for some loads is described. In spite of conventional or radial

flux machine, the length of back-iron in the HSAFG has no significant effect on the iron losses of the axial flux machine. The back-irons of two end rotors rotate along with fundamental rotating flux, so iron losses in the back-iron can be ignored if the higher order harmonics are negligible. For a given size and output power of the machine, the air gap flux is strictly related to the length 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.

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