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Air Gap Optimization of High-Speed Axial-Flux PM Generator

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Abstract: The aim of this research is an air gap (between stator and rotor) sensitivity study in the special High-Speed Axial Flux Generators (HSAFG). This study firstly presents designing and modeling of this machine. Then air gap impacts on the machine performance including three main performance indexes of the machine i.e., efficiency, induced voltage and THD are considered using a Matalab/Simulink program supported by finite elements field analysis. At the end, according to this sensitivity analysis the lowest value of the air gap is recommended for HSAFGs.

Key words: Electrical machine, PM generator, design, air gap sensitivity, harmonic study

INTRODUCTION

A micro-turbine (as its name implies) is a small size gas turbine. Generally, anything below 500 kW can be considered a micro-turbine. Some are used for model jet fighters; some are being developed for use in very small spy drones and others are used to produce electricity. Micro-turbines have been used in many different applications since the mid to late 1960's. They play an important role as strategic power sources remote and disastrous zones where grid power is unavailable, the security and economy of the grid power would be enhanced with the connection of a multiple of these micro-turbines (with high speed generators) in distributed generation.

Axial-flux type machines have been considered for a number of applications such as fans, wind turbine generator (Mueller *et al*., 2005) and some electric vehicles (Lovatt *et al*., 1998; Benoudjit *et al*., 2000). This machine commonly used as a PM synchronous machine for some benefit such as lower moment of inertia (Kuang-Cheng *et al*., 2008). Lightness, low cost and high efficiency features of these type machines (Azzouzi *et al*., 2005; Rong-Jie *et al*., 2005; Profumo *et al*., 2000) make it suitable as micro-turbines. This type machine is used in high speed for more benefits (Sundaram *et al*., 2005; Holmes *et al*., 2005). This high-speed generator offers large power-to-weight ratio and compact structure in comparison with lower speed counterparts. Although the high-speed operation imposes stringent engineering design constrains (Parviainen *et al*., 2005; Luk and El-Hasan, 2005).

In the common electrical machines, any increases in the air gap, causes some decreases in the air gap flux density (B_g) and resultant induced voltage in the terminal of the machine. This happens in the high-speed axial flux machine of course with some differences. In this study, a 30,000 rpm, 400 volts, 30 kW high-speed axial flux generator is designed. The electrical model of machine is obtained in Simulink (Matlab software). For inductances calculation, magnetic model with leakage flux, fringing effect, nonlinear back iron and curve of PMs considerations are used. This model checked by FEM software (ANSYS). Finally, the air gap sensitivity and its function on flux density, induced voltage, efficiency and THD of the machine are discussed.

ELECTRICAL MODELING

Figure 1 shows a schematic view of intended machines. Three rotors and two stators can be fined in Fig. 1. Two back irons are arranged in two ends of machine.

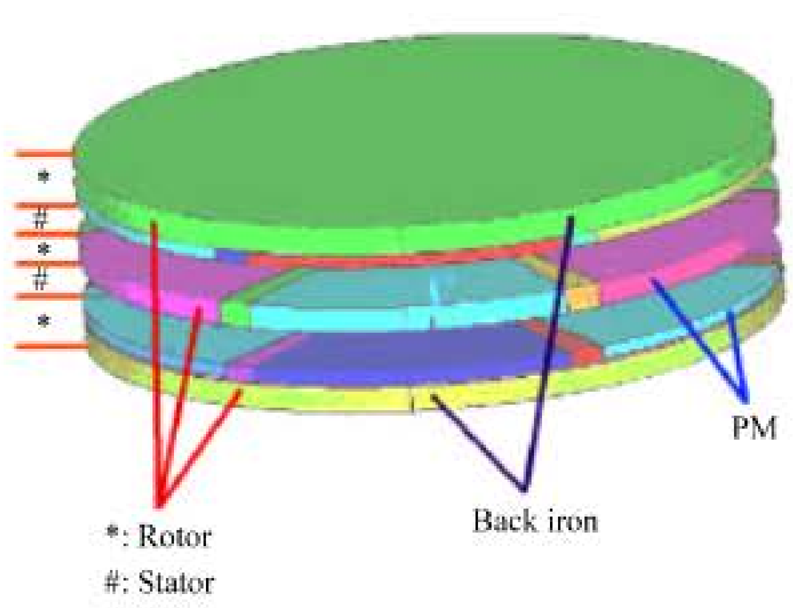

Fig. 1: View of a high-speed axial flux generator

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For the modeling purposes, the magnetic circuit of the machine with all details is required. The magnetic circuit can be used to calculate the self and mutual inductances of the stator coils. Simple magnetic circuit of the HSAEG machine comprising all reluctances is described in references (Sadeghierad *et al*., 2007, 2008). The leakage reluctances R_{l1} and R_{l2} and fringing reluctance in R_g are taken into account for most accuracy of the model. As an example, the air gap flux densities are 0.485 and 0.493 Tesla when these parameters are taken into account or ignored, respectively.

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

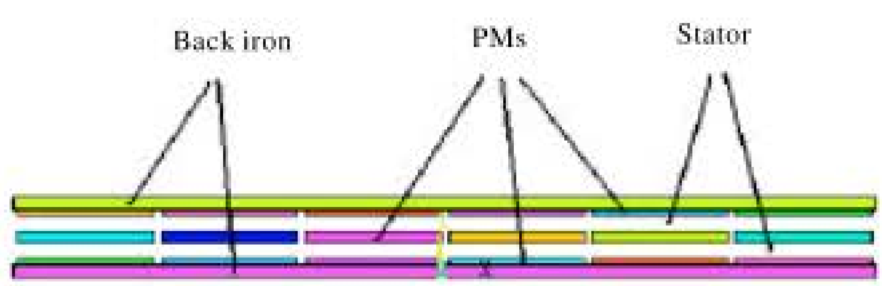


Fig. 2: 2-D FE modeling

In this study, harmonic calculation is studied in no-load condition. It is the worst case, because the windings at loaded condition roles as a damper of harmonics. Result of 2D FEM (magnetic flux density) is shown in Fig. 3. This figure shows the flux density is 0.462 (the flux density of model is 0.485).

The main part of the stator is a few turns, concentric two layer windings occupying a very small space. Linking all subsystems of HSAFG model in a Matlab/Simulink environment, the computer model of the machine as shown in Fig. 4 is obtained.

Design consideration and Loss calculation: In rotor designing process, after combining the considerations, the sintered Nd-Fe-B material would be the best candidate for PM (Gieras *et al*., 2005). In the stator designing, the main problem is the high frequency of stator current and flux; it is suggested to use a coreless stator (Rong-Jie *et al*., 2005; Eastham *et al*., 2002; Rong-Jie and Kamper, 2004). The skin effect in this machine is high (because of high speed and very high frequency of machine). Also winding's eddy current losses are not considered in conventional machine but in HSAFG, it is important and should be considered with using Litz wire (the wire is divided into individually insulted strands with small size).

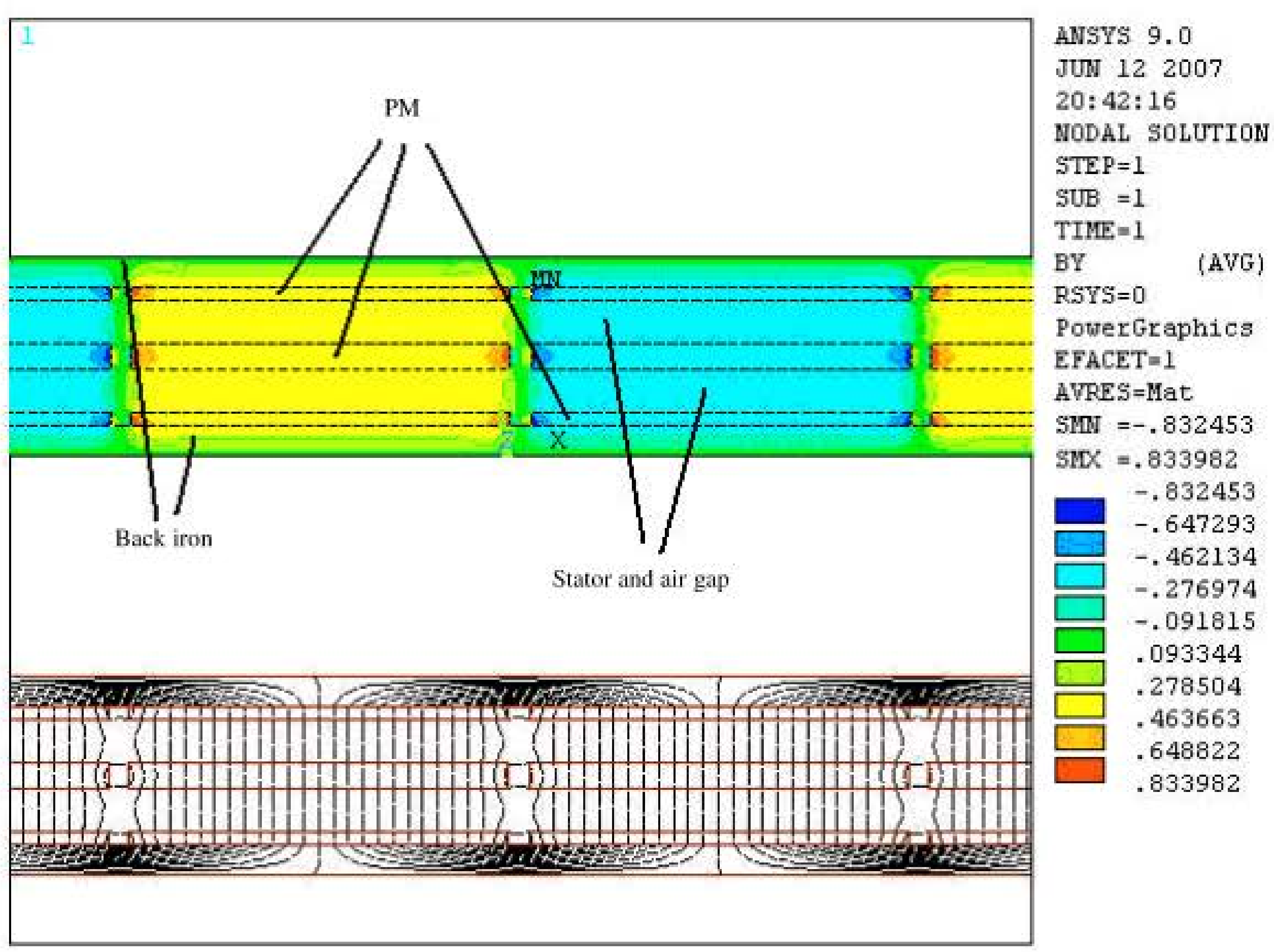


Fig. 3: Result of FEM (magnetic flux density)

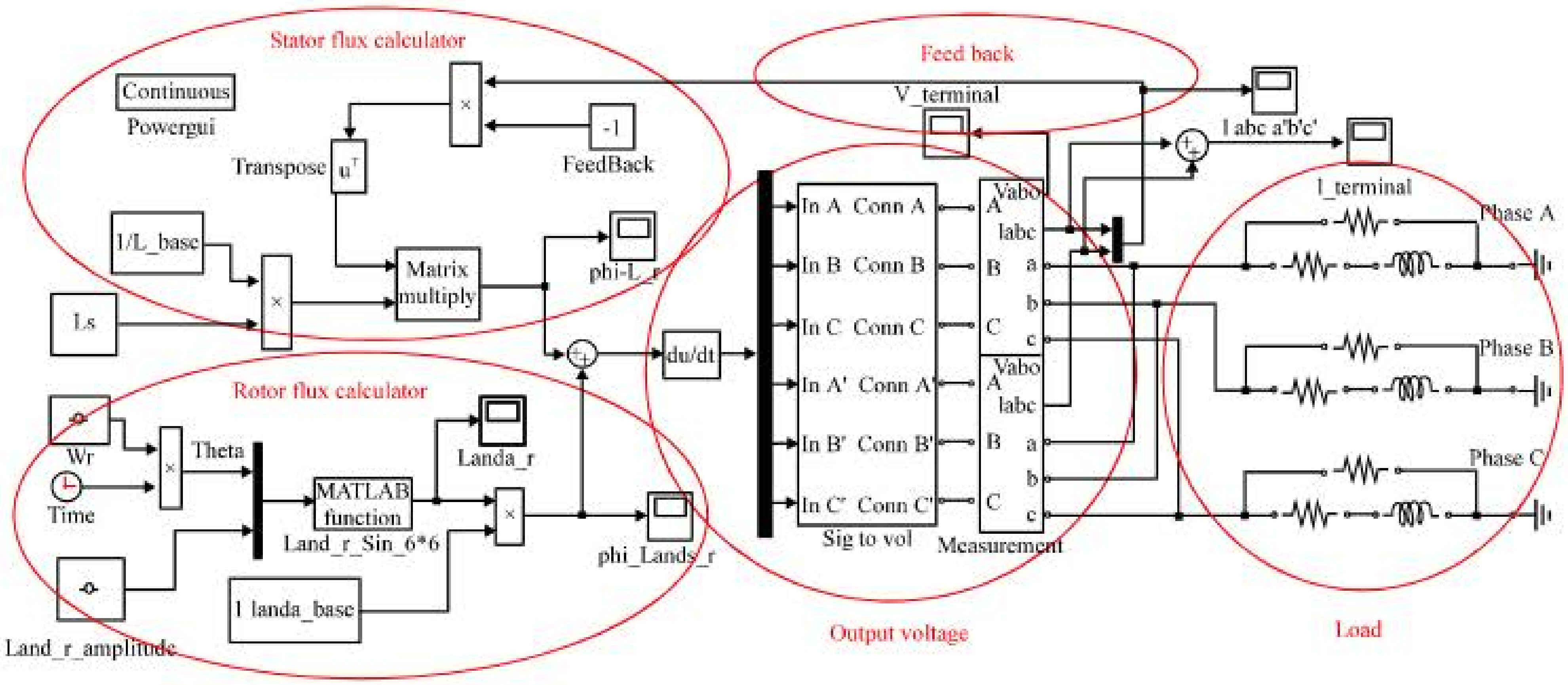


Fig. 4: Electrical model of a coreless HSAFG

One of main limitations in PM machine designing is the magnet temperature, so the losses in the machine must be kept low. Loss calculation is only briefly described here:

- Rotation losses were calculated using equation found in Gieras *et al*. (2005). The power to overcome drag resistance of rotating disc is:

$$P_{mech} = \frac{1}{2} c_f \rho (2\pi N_m)^3 (R_o^5 - R_{sh}^5) \tag{1}$$

In which the drag constant (c_f) for turbulent flow can be found as:

$$c_f = \frac{3.87}{\sqrt{Re}} \tag{2}$$

where, Re is the Reynolds number and it can be written versus outer radius of a rotating disk as:

$$Re = \rho \frac{R_o v}{\mu_{air}} = \frac{2\pi N_m \rho R_o^2}{\mu_{air}} \tag{3}$$

It is seen rotational (mechanical) loss is related to the air gap (inverse relation).

- Stator winding losses are obtained by the simple equation as:

$$P_{cu} = R_s \times |I_{load}|^2 \tag{4}$$

This power loss is related to the load current.

- Eddy current losses

Due to high frequency stator current and magnetic filed we would have some additional losses (eddy current losses) given by:

$$P_{eddy\_cu} = \frac{(B_g \times 2 \times \pi \times f \times D_{strand} \times 10^{-3})^2}{32 \times \rho_{cu}} \times V_{cu} \tag{5}$$

This loss is important in this machine (because of high frequency especially at high pole number).

So, the efficiency is calculated by a formula given as below:

$$\eta = \frac{P_{out}}{P_{out} + P_{loss}} \times 100 \tag{6}$$

where, P_{loss} is equal to:

$$P_{loss} = P_{mech} + P_{cu} + P_{eddy\_u} \tag{7}$$

Simulation results: Using the model of HSAFG, a high-speed machine is designed. The outer diameter is obtained using the main input parameters (V, P_{out}, Nm) and other essential parameters like N_{stack}, D_{strand} and J. After that, the thickness of stator, thickness of PM and thickness of back iron are estimated. Air gap with fringing and leakages are analyzed and then the model is solved by a nonlinear method. Knowing resistance and inductance of stator, the stator flux is computed by use of Simulink/Matlab software. The model of the machine is connected to the load, so the output voltage and power are calculated. Using loss calculation formulas, total

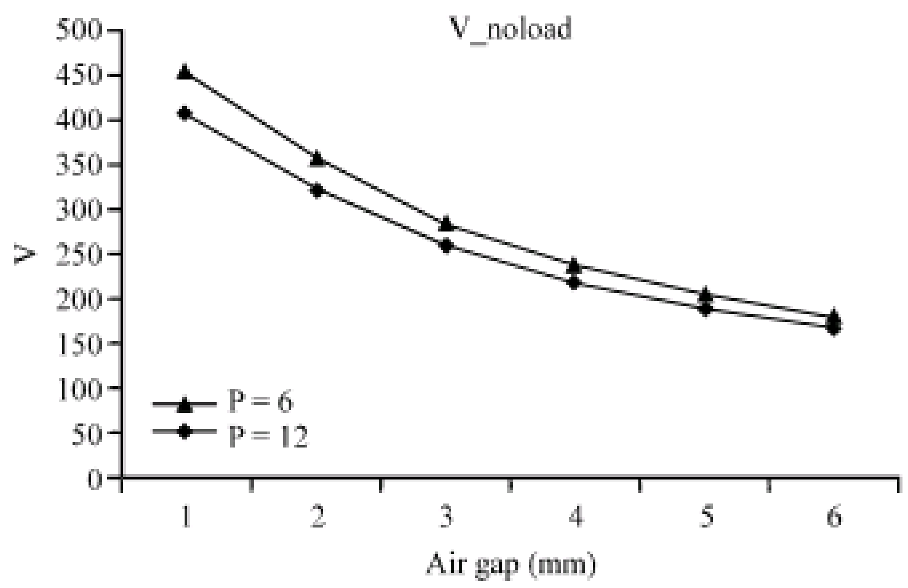


Fig. 5: Output voltage (no-load) (V) vs. air gap (m)

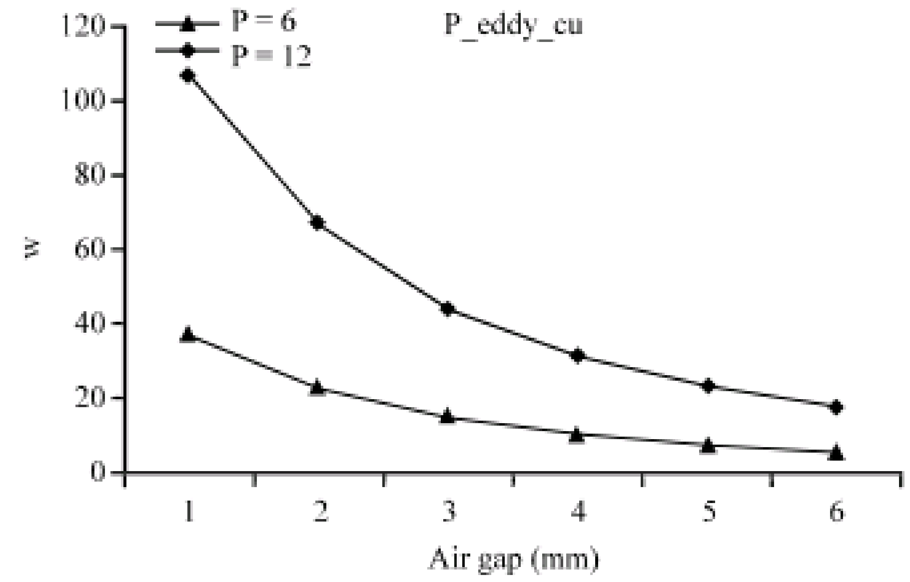


Fig. 7: Eddy current losses (W) vs. air gap (m)

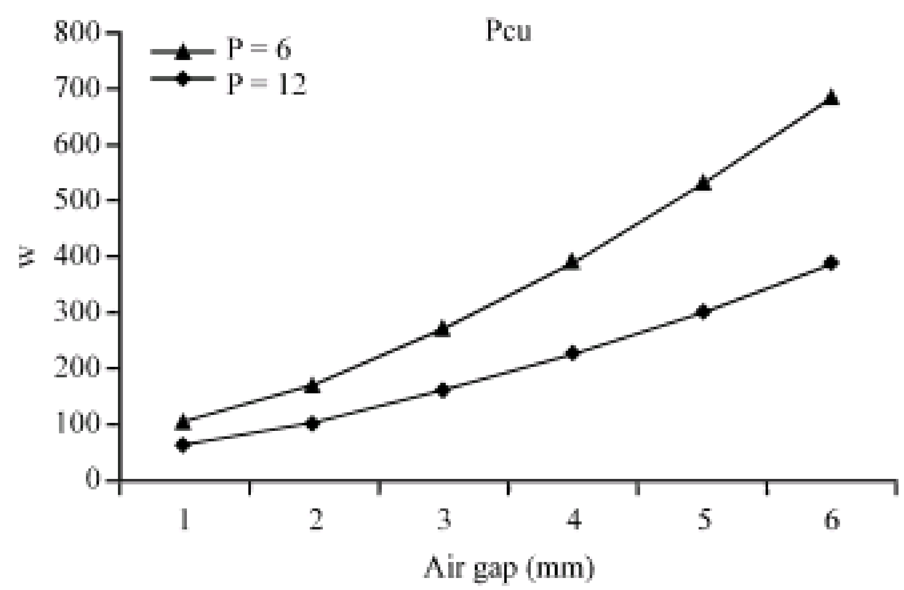


Fig. 6: Copper losses (W) vs. air gap (m)

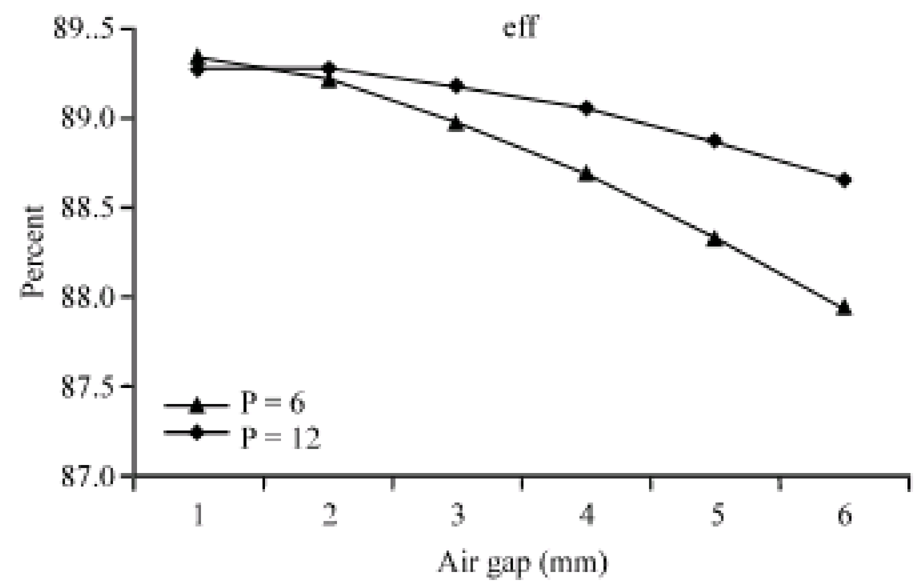


Fig. 8: Efficiency vs. air gap (m)

power losses and efficiency are worked out. Briefly, a HSAFG is designed according to design algorithm that presented in the Appendix. This designed machine is used for the air gap sensitivity analysis.

Air gap is an important design parameter in the electric machine design. Air gap sensitivity is shown in Fig. 5-8 (by increasing from 1 to 8 mm).

Because of specific driver (micro-turbine), the speed of the machine is assumed constant (30,000 rpm). Nevertheless, since the terminals of generator are connected to power electronic devices its tolerance would be acceptable. The output power is defined as 30 kW, so with output voltage reduction more output current is needed.

These analyses are done for two different machines, six-pole machine as a low pole number and 12-pole machine as a high pole number. Other parameters are kept constant values:

D_o : Outer diameter
D_i : Inner diameter
L_s : Length of stator
L_{pm} : Length of PM
L_{bi} : Length of back iron
D_{stand} : Diameter of each wire of conductor
B_r : Residual flux density of PM

Figure 5 shows peak values of the output voltages versus the air gap of both machines. As seen in this Fig. 5 the output voltage is inversely decreasing with the air gap variation for these two different machines. For a large value of the air gap, the PMs cannot produce enough flux density, so in this regard the low air gap is recommend.

Copper losses versus the air gap having a relation with air gap proportionally (Fig. 6). For providing a predetermined constant power when the air gap is increased, the current and consequently the copper losses have to increase. In contrary with copper loss, eddy current loss in the conductors has inverse relation with the air gap. This loss intensively rises by increasing the pole numbers. But similar to copper loss, for higher number of poles, the variation of the eddy current loss will be greater (Fig. 7). However, total power loss has approximately a direct relation with air gap variation. It is due to more effectiveness of the copper losses. Figure 8 shows that in the HSAFG the efficiency smoothly decreases by increasing air gap, while this reduction in the conventional machine is much greater. It is due to presence of high value rotation losses in the high-speed machine that independent to the air gap (In this machine, the power is equal to 3286 W). This variation is greater for the machine with less pole number.

HARMONIC STUDY

Another air-gap sensitivity analysis that presented here is about harmonics. For a few values of the air gap (g) a FE analysis described before are performed and flux densities in the middle closed path of the stator winding are evaluated. The air gap is increased from 2 to 6 mm by step 1 mm. The THD spectrums of the flux densities for a few air gaps are shown in Fig. 9. THD is varied from 33.76 to 31.05% by variation of the air gap from 2 to 6 mm. The third and fifth harmonic are varied somewhat similarly as shown in Table 1. As seen in this Table 1 the harmonic content of the flux density does not vary significantly by the air gap variation. This is because stator itself is a part of the air gap in the coreless machine particularly in the no load operating condition. Therefore, the air gap is naturally too large and being larger does not affect the harmonic content extensively.

Table 1: Third and fifth harmonics of MMF vs. air gap

g (mm)	3rd harmonic percentage (to first harmonic)	5th harmonic percentage (to first harmonic)
2	29.67	14.06
3	29.14	13.33
4	28.67	12.74
5	28.31	12.31
6	28.05	12.02

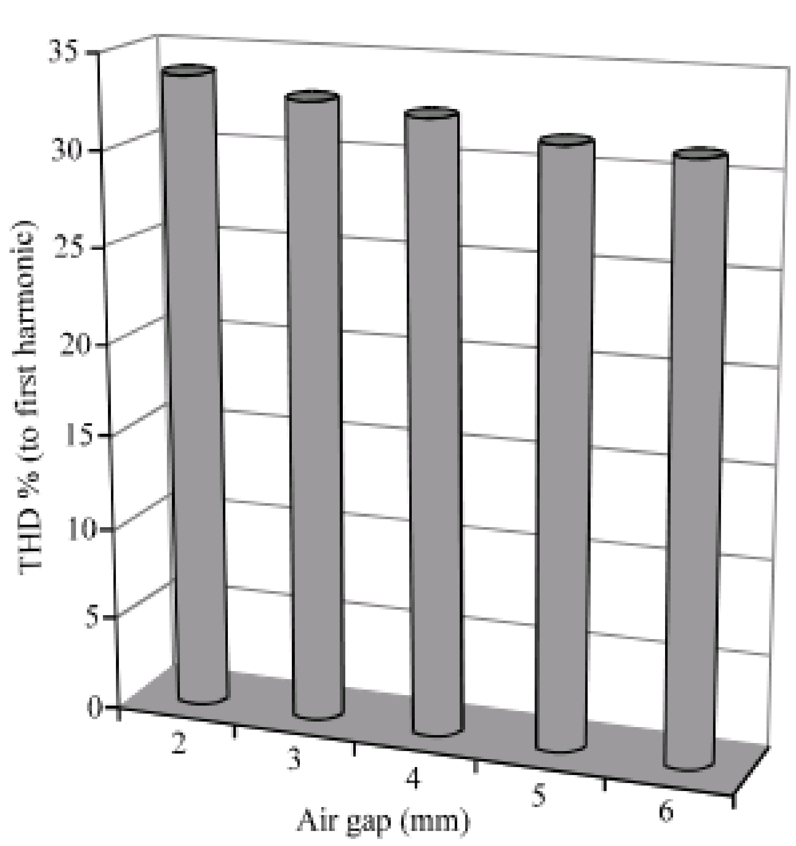


Fig. 9: THD of MMF vs. air gap

CONCLUSION

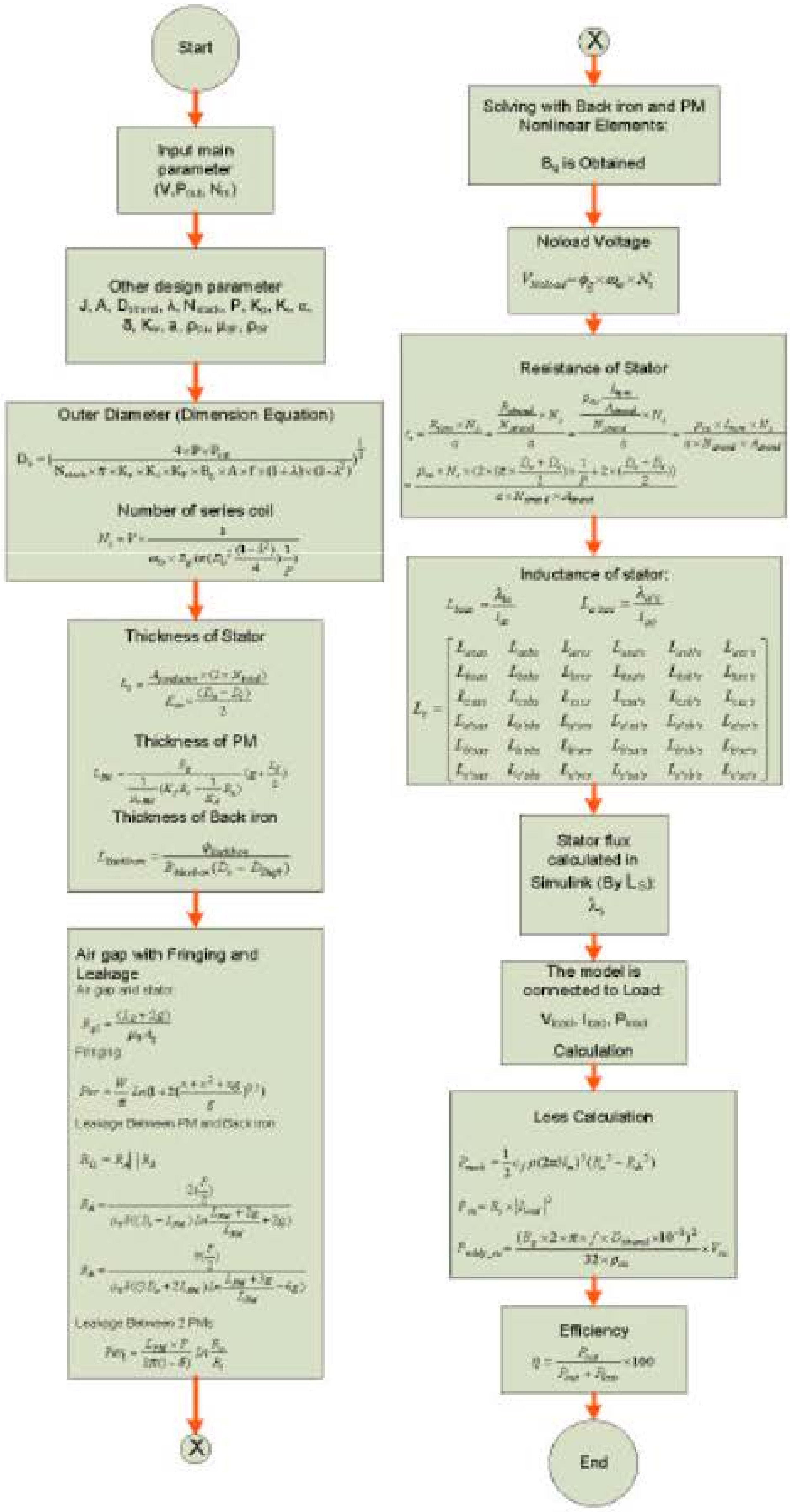
Modeling of a modular high-speed axial-flux PM generator has been proposed with some details. FEM analysis was presented for validation of the magnetic circuit model and for field analysis purpose.

The influences of the air gap on main performance characteristics of the HSAFG machine were simulated and discussed. It was shown that increasing the air gap causes some reductions in the output voltage, efficiency and THD. The efficiency of the HSAFG is determined by the rotational loss and this does not change greatly by air gap variation (different to conventional machines). Therefore regarding all performance characteristics except THD, lowest value of the air gap is recommended. Of course, this small value for the air gap is chosen regarding the mechanical and manufacturing limitations. However, regarding the THD some large value of the air gap is required. Fortunately, in the coreless machine, the air gap inherently is large and any intentionally barging the air gap does not affect the THD. As a conclusion, it can be mentioned the smallest possible value of the air gap for the HSAFG machine can be applied as an optimistic value with some confidences if the small improvement in the THD by using a larger air gap is not greatly a matter.

NOTATIONS

P	:	Number of poles
N_m	:	Speed of rotor (rpm)
N_s	:	Number of series coil per phase
g	:	Air gap (m)
D_o	:	Outer diameter - R_o : Outer radial (m)
D_i	:	Inner diameter - R_i : Inner radial (m)
D_{sh}	:	Shaft diameter - R_{sh} : Shaft radius (m)
D_{stamd}	:	Diameter of each wire of conductor (litz wire) (m^2)
a	:	Number of parallel coil of each branch
μ_{air}	:	Air viscosity coefficient (kg $msec^{-1}$)
ρ	:	Air density (kg m^{-3})
V_{cu}	:	Volume of copper (winding)
ρ_{cu}	:	Electrical resistivity (Ωm)
f	:	Frequency of rotor (Hz)
B_g	:	Flux density of the air gap (T)
R_s	:	Stator-winding resistance (Ω)
I_{load}	:	Full load current of machine (A)
P_{out}	:	Output power (kW)
P_{Loss}	:	Power loss (kW)
P_{mech}	:	Mechanical (rotational) power loss (kW)
P_{cu}	:	Copper loss (W)
P_{eddy_cu}	:	Eddy current power loss in the wire (W)
η	:	Efficiency

APPENDIX



Appendix: HAFG design according to design algorithm

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