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Determining the Air Gap Length of an Axial Flux Wound Rotor Synchronous Generator

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Abstract

The air gap length of the designed axial flux wound rotor (AFWR) synchronous generator is determined properly according to the design parameters. One of the distinct advantages of an axial flux (AF) machine is its adjustable air gap. An AF generator's performance might be controlled by adjusting its air gap. The designed generator has a small-scale capacity that has 1 kW, 380 V, and 50 Hz. The windings are laid into slots made from laminated core. The slots are carved in the face of the stator and rotors. The generator has a single-double-sided slotted wound stator sandwiched between twin rotors. The effect of air gap changes on its performance can be seen from the calculation results using the given equations. The results reveal electric quantities suited to the machine's effective performance. The smaller the air gap, the greater the efficiency and power factor and the smaller the armature current and voltage. The efficiency and armature current for 0.1 cm air gap are 85.30 % and 1.815 A, respectively.

Abstrak

Penentuan Lebar Celah Udara Generator Sinkron Fluks Aksial Rotor Belitan. Lebar celah udara generator sinkron fluks aksial rotor belitan (AFWR) perlu ditentukan dengan tepat sesuai dengan parameter desain. Salah satu kelebihan dari mesin fluks aksial (AF) adalah celah udaranya yang dapat diatur. Kinerja generator AF dapat diatur dengan mengatur celah udaranya. Generator yang dirancang merupakan mesin berkapasitas skala kecil yang memiliki 1 kW, 380 V, dan 50 Hz. Belitan-belitannya diletakkan didalam alur yang terbuat dari inti besi laminasi. Alur-alurnya terletak pada permukaan stator dan rotor. Generator tersebut memiliki satu stator belitan beralur dua sisi yang terletak diantara dua rotor. Pengaruh perubahan celah udara terhadap kinerjanya dapat dilihat dari hasil perhitungan dengan menggunakan persamaan-persamaan tertentu. Hasilnya menunjukkan besaran listrik yang sesuai dengan kinerja efektif mesin. Semakin kecil celah udara, semakin besar efisiensi dan faktor daya sedangkan arus armatur dan tegangannya semakin kecil. Efisiensi dan arus armatur pada celah udara 0,1 cm masing-masing adalah 85,30% dan 1,815 A

Keywords: Synchronous generator, axial flux, wound rotor, air gap, efficiency

1. Introduction

Axial flux permanent magnet (AFPM) machines have a number of distinct advantages over radial flux machines (RFMs). They can be designed to have a higher power-to-weight ratio resulting in less core material. Moreover, they have planar and easily adjustable air gaps. The noise and vibration levels are lower than the conventional machines. Also, the direction of the main air gap flux can be varied and many discrete topologies can be derived. These benefits present the AFPM machines with certain advantages over conventional RFMs in various applications [1].

Besides these benefits, the flux density of AFPM machine is reduced due to the large air gap. However, one important advantage of this machine is that the structure transfers the heat from the stator frame very easily. Therefore, machine electrical loading can be relatively high. This is an important feature of axial flux machines because it is crucial to have a suitable shape and size that matches the space limitations of certain applications such as electric vehicles. From a construction point of view, brushless AFPM machines can be designed as single-sided or double-sided, with or without armature slots, with or without an armature core, with either internal or external permanent magnet rotors,

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with either surface mounted or interior permanent magnet, and as single-stage or multi-stage machines. Stator and rotor positions can be interchanged, the number of stators and rotors can be multiplied, and the air gap length can easily be varied. Some configurations of AFPM machines are shown in Figure 1 [2].

This research determines the proper air gap length and analyzes the effect of air gap changes on the performance of a three-phase axial flux synchronous generator, including how the gap affects the generator's efficiency, current, power factor and voltage. The ideal air gap length can obtain the highest efficiency with limited power output is explored.

When the rotor's rotation is not constant as a result of the lack of constant prime mover rotation, the output voltage generated by the generator varies. To make a constant voltage, the flux should be controlled by varying the field current flowing through the rotor winding. Therefore, the expected advantage of this study is to obtain a precise measurement of the length of the air gap on a high efficiency axial flux wound rotor (AFWR)

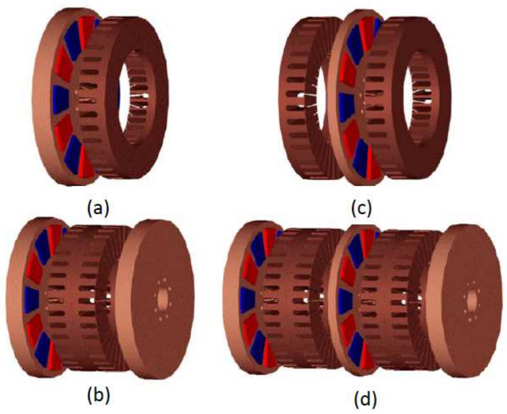

Figure 1. Axial Flux Machine Configurations. (A) Single Rotor-Single Stator Structure, (B) Two Rotor-Single Stator Structure, (C) Single Rotor-Two Stator Structure, (D) Three Rotor - Two Stator Structure

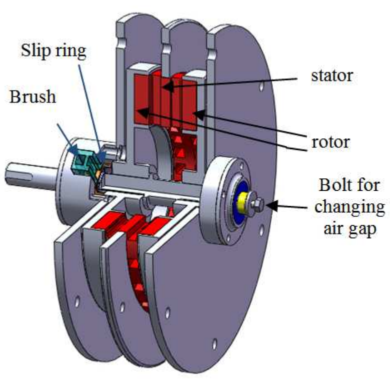

Figure 2. The Designed AFWR Synchronous Generator Includes the Adjustable Air Gap

synchronous machine having 1 kW capacity. Since this machine has eight poles, the mechanical speed becomes 750 rpm.

The AFPM machine is an electrical machine with high power and high efficiency as well as small dimensions and lower price. There have been many studies concerning various matters of AFPM machines. However, no study has been performed on a three-phase AFWR synchronous generator in which the air gap can be varied. Air gap changes can affect machine parameters such as efficiency, armature current, power factor and terminal voltage. Thus, the proper air gap length can determined according to the optimal machine parameters.

In the case of engine/generator sets most interest has focused on axial flux generator topologies that have two rotor discs and one stator disc. Such an axial flux generator can be usefully integrated with an engine as it is axially very short and thus can be mounted directly on the engine output shaft, eliminating the need for separate bearings or couplings. The generator has, or can be designed to have, a moment of inertia that makes the flywheel redundant [3].

An axial flux machine with a wound rotor is referred to as an axial flux wound rotor (AFWR). A cross sectional schematic of the designed AFWR machine is shown in Figure 2. The AFWR generator consists of two wound rotors that two windings are connected to in parallel. The stator of the AFWR generator is located between two opposing wound rotors. The double-sided rotors is simply called twin rotors with slots are located on the sides of the stator and at the rotor lamination core.

2. Methods

The design of the axial flux synchronous generator is done using calculations based on the equations of the axial flux and radial flux machines. Equations applied are related to electric circuits, magnetic circuits and mechanics on the stator and the rotor. The MATLAB program is used for accuracy and precision calculations, while SolidWorks software is used to draw the machine and its parts.

The design of the synchronous generator is started by determining the specifications of the machine, then selecting materials and assigning design parameters. Before processing the design of the electrical circuit, the magnetic circuit and the mechanics, the optimal parameters associated with the specification of the machine are first assumed. At the end of the design process, the machine's performance is expected to meet the need, such as the output power, terminal voltage and power factor. If the performance has not met yet, the design process should be repeated by changing the

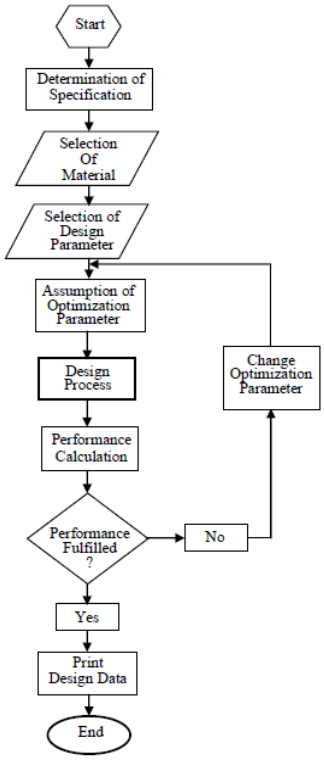

Figure 3. Flow Chart of the Design Process

optimization parameters. If the performance has been met, the design data sheet can be printed. Stages of the design are shown in the flow chart in Figure 3. The calculation process in designing the machine aims to obtain the proper air gap length with the previously fixed power output.

This designed machine is a three-phase axial flux wound rotor (AFWR) synchronous generator where magnetic flux lines cross the air gap in an axial direction with the machine axis. The stator and rotors are disc shaped and located in parallel next to each other. The stators having two side slots are located between twin slotted rotors. Windings are then laid into slots carved in the rotors and stators faces shown in Figure 4.

In principle, the electromagnetic design of AFPM machines is similar to their radial flux PM (RFPM) counterparts with cylindrical rotors. However, the mechanical design, thermal analysis and assembly process are more complex [4]. The specifications of the three-phase AFWR synchronous generator designed are nominal (rated). Quantities include the output power, terminal voltage (phase to phase), frequency, rotor rotation, and power factor. The input power and the load torque are on the shaft of the prime mover, which rotates the generator rotor windings. The rotor winding is connected to a source of direct current so that the field current flows through the field winding. The field current produces a steady-state magnetic field in the rotor.

One of the advantages of an axial flux machine is its adjustable air gap. A drawback of radial flux synchronous and induction machines is their fixed air gap that can not be adjusted. The smaller the air gap length, the larger air gap magnetic flux density needed and the larger the field current that should be supplied to the generator. If the nonmagnetic air gap is large, a high energy magnet is required. The air gap magnetic flux density decreases as the air gap increases [5]. The relationship between magnetic flux density and the air gap is shown in Figure 5.

Axial flux generators can be designed as single or multiple air gap machines. In this paper, the designed generator has two air gaps between the stator and rotors. The effect of air gap length changes on the permeance, the reluctance, and eventually on the electric quantity of the generator such as current are expressed in the equations below [4,6]. The mean magnetic flux density in the air gap decreases under each slot opening due to an increase in the reluctance. The change in the mean magnetic flux density caused by slot openings corresponds to a fictitious increase in the air gap [4]. It assumes that the flux density in air gap B_g is regular in the axis-direction [7].

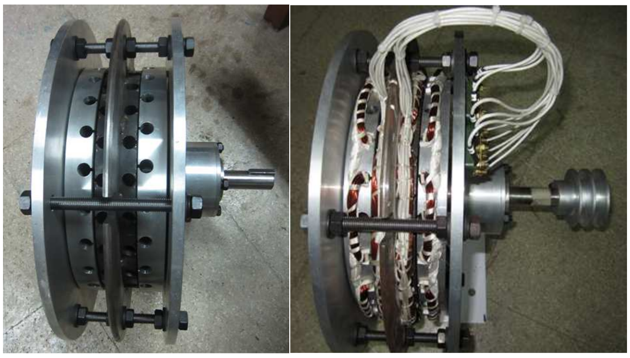

Figure 4. The Slotted Stator and Rotors, Before and After Winding

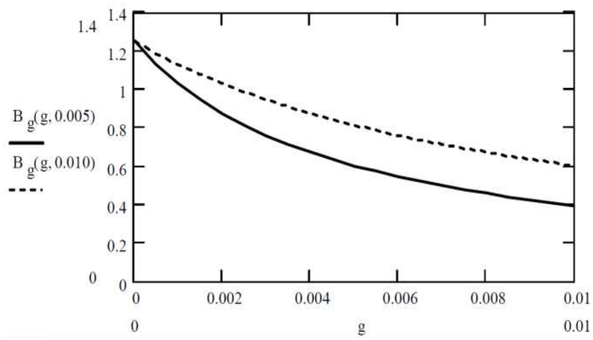

Figure 5. Magnetic Flux Density in the Air Gap (T) as a Function of the Air Gap (M) in the AFPM Machine

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The relation between fictitious g' and physical air gap g is expressed with the aid of Carter coefficient $k_C > 1$, i.e.,

$$g' = gk_C \qquad (1)$$

The nonferromagnetic air gap in the calculation of Carter's coefficient is

$$g' \approx 2g + {}^{2h_M}/_{\mu_{rrec}} \qquad (2)$$

h_M is the rotor winding axial thickness, and 2 h_M is the axial thickness of the rotor. Assuming that the relative recoil magnetic permeability ≈ 1 ($\mu_{rrec} \approx 1$)the nonmagnetic air gap is large, i.e., the total air gap is equal to two mechanical clearances plus the thickness of a winding with its relative magnetic permeability close to unity.

The coefficient of the slot leakage permeance is

$$\lambda_{1s} = \frac{h_{11}}{3b_{11}} + \frac{h_{12}}{b_{11}} + \frac{2h_{13}}{b_{11}+b_{14}} + \frac{h_{14}}{b_{14}} \qquad (3)$$

The coefficient of inner end connection leakage permeance is

$$\lambda_{1e} = 0{,}34q_1\left(1 - \frac{2}{\pi}\frac{\omega_c}{l_{1e}}\right) \qquad (4)$$

in which the average coil pitch $\omega_c = \tau$.
The coefficient of differential leakage permeance is

$$\tau_{d1} = \frac{\pi^2(10q_1^2+2)}{27}\sin\left(\frac{30^o}{q_1}\right) - 1 \qquad (5)$$

The specific permeance of the differential leakage flux is

$$\lambda_{1d} = \frac{m_1 q_1 \tau k_{\omega 1}^2}{\pi^2 g' k_{sat}}\tau_{d1} \qquad (6)$$

The nonferromagnetic air gap in the calculation of Carter's coefficient is based on the equation (2)

$$g' \approx 2g + 2h_M$$

Assuming that h_M = rotor winding thickness and $h_M = l_{1e}$, the air gap of the slotted armature AF machine is relatively small ($g \leq 1$ mm) and the air gap magnetic flux density can increase to 0.85 T. $k_{sat} = 1$ (saturation factor).

The equivalent air gap g' is only equal to the nonmagnetic gap (mechanical clearance) g for a slotless and unsaturated armature. To take into account slots (if they exist) and magnetic saturation, the air gap g is increased to $g' = gk_ck_{sat}$, where $k_c > 1$ is Carter's coefficient taking into account slots, and $k_{sat} > 1$ is the saturation factor of the magnetic circuit defined as the ratio of the MMF per pole pair to the air gap magnetic voltage drop (MVD) taken twice.

The specific permeance between the heads of teeth is

$$\lambda_{1t} = \frac{5\frac{g'}{b_{14}}}{5+4\frac{g'}{b_{14}}} \qquad (7)$$

should be added to the differential specific permeance $\lambda_{1d}$of slotted stator windings.

The stator (one unit) leakage reactance has been calculated according to equation (7) in which

$$\frac{l_{1in}}{L_i}\lambda_{1ein} + \frac{l_{1out}}{L_i}\lambda_{1eout} \approx \frac{l_{1e}}{L_i}\lambda_{1e} \qquad (8)$$

The armature leakage reactance X_1 is the sum of the slot leakage reactance X_{1s}, the end connection leakage reactance X_{1e}, and the differential leakage reactance X_{1d} (for higher space harmonics), i .e.,

$$X_1 = X_{1s} + X_{1e} + X_{1d} \qquad (9)$$

$$X_1 = 4\pi f \mu_o \frac{L_i(N_1)^2}{pq_1}\left(\lambda_{1s}k_{1x} + \frac{l_{1in}}{L_i}\lambda_{1ein} + \frac{l_{1out}}{L_i}\lambda_{1eout} + \lambda_{1d}\right) \qquad (10)$$

$$X_1 = 4\pi f \mu_o \frac{L_i(N_1)^2}{pq_1}\left(\lambda_{1s}k_{1x} + \frac{l_{1e}}{L_i}\lambda_{1e} + \lambda_{1t} + \lambda_{1d}\right) \qquad (11)$$

k_{1x}= 1 is the skin-effect coefficient for leakage reactance.

The armature reaction reactances can be calculated by

$$X_{ad} = X_{aq} = 2m_1\mu_o f\left(\frac{N_1 k_{w1}}{p}\right)^2 \frac{(R_{out}^2 - R_{in}^2)}{g'}k_{fd} \qquad (12)$$

k_{fd} and k_{fq} are form factors of armature reaction in the d and q-axis, respectively. For the configuration of an axial flux machine, $k_{fd} = k_{fq}$ and $X_{ad} = X_{aq}$. The machine has two axes of symmetry, the direct axis which is the centerline of the poles, and the quadrature axis, which is the centerline between the poles [6].

The synchronous reactance of a synchronous machine (sine-wave machine) is defined as the sum of the armature reaction (mutual) reactance X_{ad}, X_{aq} and stator (armature) leakage reactance X_1, i.e.,

$$X_{sd} = X_{sq} = X_{ad} + X_1 \qquad (13)$$

The armature currents is calculated on the basis of equations (13), (14) and (15). The currents of an overexcited machine are

$$I_{ad} = \frac{V_1(X_{sq}\cos\phi - R_1\sin\phi) - E_f X_{sq}}{X_{sd}X_{sq} + R_1^2} \qquad (14)$$

$$I_{aq} = \frac{V_1(R_1\cos\phi + X_{sd}\sin\phi) - E_f R_1}{X_{sd}X_{sq} + R_1^2} \qquad (15)$$

$$I_a = \sqrt{I_{ad}^2 + I_{aq}^2} \qquad (16)$$

The load angle can be approximately calculated using equation (17) [6].

$$\delta = tan^{-1}\frac{I\,X_q\,cos\phi}{E + I\,X_q\,cos\phi} \quad (17)$$

where δ is the load angle between the voltage V_1 and EMF E_f (q-axis).

$$\delta = \Psi - \varphi \quad (18)$$

The angle Ψ is between the q-axis and armature current I_a.

The phasor diagram can also be used to find the output electric power calculated by equation (19).

$$P_{out} = m_1 V_1 I_a cos\phi = m_1 V_1 \left(I_{aq} cos\phi - I_{ad} sin\phi\right) \quad (19)$$

The output apparent power in the stator is

$$S_{out} = m_1 V_1 I_a \quad (20)$$

Power factor is

$$cos\varphi = \frac{P_{out}}{S_{out}} \quad (21)$$

The losses in the stator winding can be calculated by

$$\Delta P_{1w} = m_1 I_a^2 R_1 \approx m_1 I_a^2 k_{1R} R_{1dc} \quad (22)$$

For the designed AFWR synchronous generator, the proper air gap must still be determined. For small PM synchronous motors, the air gap (mechanical clearance) between the stator core and rotor poles or pole shoes should be 0.3 to 1.0 mm [6,8], and can even reach 1.5 mm [9]. The smaller the air gap, the lower the starting current drawn by the motor. On the other hand, the effect of armature reaction and detent (cogging) torque increases as the air gap decreases. In the case of the slotted stator, the air gap is small (g ≤0.5 mm) and the air gap magnetic flux density can increase to 0.85 T [6].

3. Results and Discussion

MATLAB was used to calculate the AFWR machine's parameter values to analyze the machine based on output power. Core losses and friction and windage losses are assumed to be 5% and 7% of the output power, respectively [10, 11]. The research issue is directed to determine the proper air gap length on the generator power output rated and the highest effeciency. The output power is set to a fixed quantity initially as a parameter design, while the highest efficiency is sought. Changing the air gap length, the performance of the machine also changes.

The optimal efficiency of the generator is obtained by determining the proper air gap length. The machine operation specifications required for design are shown in Table 1. The calculation results showing the performance of the machine at an output power of 1 kW and efficiency of 85.30% are shown in Table 2. By varying the air gap, the other machine parameters also vary, such as armature current, terminal voltage and power factor. In the efficiency calculations, the air gap length is stretched from narrow to wide while the efficiency and output power is checked and selected to match the rated value.

Based on the above calculations, an air gap length of 0.1 cm resulted in optimal efficiency. With this air gap length, the rated terminal voltage of the generator obtained is also as high as 380 V. The relationships between air gap and terminal voltage are shown in Table 3. The effect of air gap changes on efficiency, armature current and power factor are shown in Figures 6, 7, and 8, respectively.

In this designed AFWR synchronous generator, air gap changes are also desired to understand the effect of the inductive load attached to the terminal. Loading the

Table 1. Required Specifications of Machine Operation

Quantity (unit)	Value
Output power (W)	1.000
Terminal voltage (V)	380
Number of poles	8
Frequency (Hz)	50
Power factor	0.83

Table 2. Optimization Parameters for an Efficiency of 85.30% and Output Power of 1 kW

Quantity (unit)	Value
Air gap (cm)	0.1
Excitation voltage (V)	11
Number of stator turns per phase	440
Diameter of stator conductor (mm)	0.5

Table 3. The Current, Efficiency, and Voltage with Respect to the Inductive Load

Load		Current (A)	Efficiency (%)	Terminal Voltage (V)	Voltage Regulation (VR)
(%)	(W)				
25	250	0.447	58.44	374.76	1.398
50	500	0.894	73.48	369.34	2.887
75	750	1.340	80.37	363.74	4.472
100	1.000	1.788	84.30	357.95	6.161

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generator with different magnitudes of inductive loads will affect the current, terminal voltage, efficiency and voltage regulation. The generator is loaded with inductive load from small to full loads at 25% intervals. The higher the inductive load, the higher the current and the efficiency. However, as the load continues to increase, the voltage drop becomes higher, creating a lower terminal voltage and a higher voltage regulation. The effect of inductive load changes on current, efficiency, terminal voltage and voltage regulation are shown in Table 3.

In the present study, the efficiency of the three-phase AFWR synchronous generator is 85.30%. While the efficiency of an induction motor (copper rotor) is 82.8% [12], that of an asynchronous motor (*single layer*) is 71.5%, and that of an asynchronous motor (three-phase sinusoidal) is 76.6% [11] and a TORUS generator is 81.18% [13], with nearly the same power output of the AFWR synchronous generator. The AFWR synchronous generator's efficiency is obtained by utilizing the optimization parameters that have been previously calculated.

The slot fill factor for rectangular conductors and low voltage machines can be assumed to be 0.6, since the average slot fill factor for low voltage machines with a round stator conductor is about 0.4 [4]. The stator and rotor dimensions, including their slots are kept constant in the optimization calculation. Therefore, the change in number of windings and conductor diameter should be verified to determine whether they meet the requirement for the slot dimension . Verification of the requirement is based on the slot fill factor. For 220 conductors per slot and a conductor diameter of 0.5 mm obtained from the above calculations, the slot fill factor is 0.3629. The stator and rotor slots that have been wound are shown in Figure 4. In standard motors, copper occupies only half of the slot winding space, because the slot fill factor is about 0.5 [5].

Air gap changes affect the efficiency, the current and the power factor of the machine. The larger the air gap, the higher the current is that passes through the load, but the lower the efficiency and power factor. Figures 6, 7, and 8 show the efficiency, armature current, and power factor with respect to the air gap for the AFWR synchronous generator.

Air gap changes also affect the load torque, total losses, and the temperature rise. If the air gap increases, the efficiency and the power factor will decrease. Meanwhile, the larger the air gap, the higher the terminal voltage. Similarly, the losses and the temperature rise in the machine will be higher. Figure 9 shows the terminal voltage with respect to the air gap.

From the AFWR generator design calculation results that have been obtained using MATLAB software, complete images can be made by SolidWorks. If the calculation results of the stator, rotor, slots and teeth dimensions are not right, they will lead to inaccuracies in the images or errors when drawn by SolidWorks.

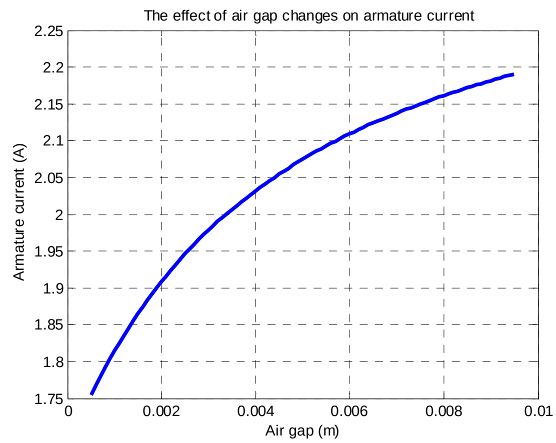

Figure 7. Armature Current with Respect to the Air Gap

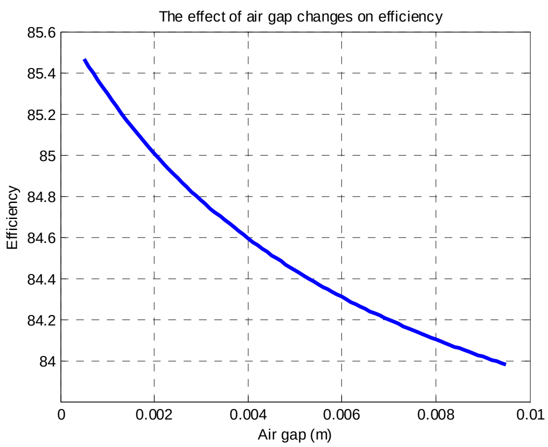

Figure 6. Efficiency with Respect to the Air Gap

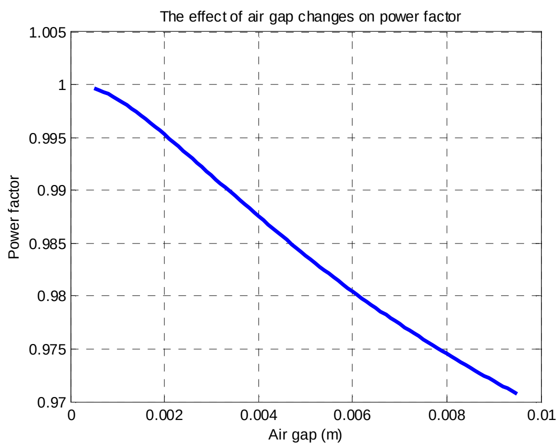

Figure 8. Power Factor with Respect to the Air Gap

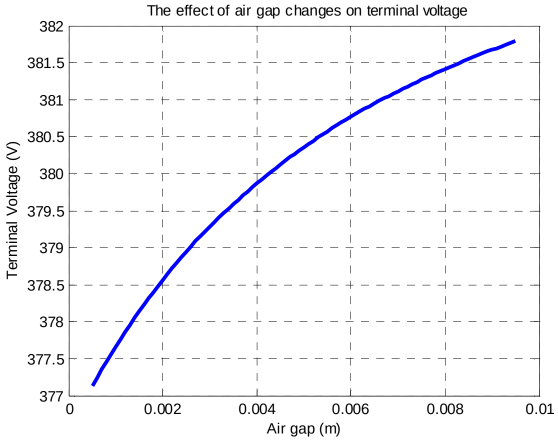

Figure 9. Terminal Voltage with Respect to the Air Gap

The efficiency of 85.30% obtained at the air gap of 0.1 cm, the excitation voltage of 11 V, the stator conductor diameter of 0.5 mm, and the number of stator windings per phase of 440 turns are constrained to the output power of 1 kW. If in the process of calculating machine parameters, the efficiency is increased more than 85.30%, the machine parameters will change including the output power, whereas the output power has been previously fixed. From the calculation of three-phase AFWR synchronous generator, the efficiency is higher than the efficiency of another AC machines because it has lower total losses such as core and rotational losses.

The total loss in the AFWR machine is 175.79 W, while in the TORUS AF machine it is 231.9 W [13]. Similarly, the total loss in the induction machine (copper rotor), those of the asynchronous machines of single layer and three-phase winding are higher than the AFWR machine (229.2 W [12], 337 W, and 402 W [11], respectively. The dominant loss in the machines is the copper loss that is proportional to the square of the machine current [14].

For 440 turns per phase of stator winding, 220 conductors per slot, and a stator winding conductor diameter of 0.5, a slot fill factor of 0.3629 is obtained. The slot fill factor still meets the requirement because it is under the value of 0.4 for low voltage machines with round conductors. The conductor sizes obtained from the calculation results have not been adjusted to the size of the conductors found in the market.

4. Conclusions

For the AFWR synchronous generator having design parameters of 1 kW, 380 V and 50 Hz and two air gaps, the length of each air gap between the stator and rotor is 0.1 cm. This is the proper design of the air gap length because it meets the design parameter requirements. Air gap length changes might affect the reactance of the machine and eventually affect other electric parameters such as armature current and terminal voltage. The smaller the air gap, the greater the efficiency and the power factor, and the smaller the armature current and terminal voltage. The efficiency and the armature current of this air gap length are 85.30% and 1.815 A, respectively.

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