

Determining The Excitation Voltage of Axial Flux Wound Rotor Synchronous Generator

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Abstrak

Generator fluks aksial rotor belitan mempunyai belitan medan yang dihubungkan dengan sumber tegangan dc. Dengan mengatur tegangan eksitasi, maka unjuk kerjanya dapat diatur untuk memenuhi kebutuhan tegangan beban yang terpasang pada terminalnya. Generator yang dirancang berkapasitas skala kecil yang mempunyai 1 kW, 380 V and 750 rpm. Generator mempunyai satu stator belitan dua sisi beralur yang diapit oleh rotor kembar. Pengaruh perubahan tegangan eksitasi terhadap unjuk kerja dapat dilihat dari hasil perhitungan yang menggunakan persamaan-persamaan. Hasil-hasil perhitungan menunjukkan besaran listrik telah memenuhi unjuk kerja mesin. Semakin tinggi tegangan eksitasi, semakin rendah rugi-ruginya sedangkan efisiensi dan tegangan terminal semakin tinggi. Telah diperoleh bahwa untuk tegangan eksitasi 11 V, maka efisiensi dan tegangan terminalnya masing-masing 85,12 % and 380 V.

Kata kunci: generator sinkron, fluks aksial, tegangan eksitasi, efisiensi, torsi

Abstract

The axial flux wound rotor generator has field winding that must be connected to a dc voltage source. By varying the excitation voltage, its electric performance might be controlled to meet the need of a load voltage attached to its terminal. The designed generator is small-scale capacity which has 1 kW, 380 V and 750 rpm. The generator has a single double-sided slotted wound stator sandwiched between twin rotor. The effect of excitation voltage changes on its performance can be seen from the result of calculations using the given equations. The calculation results reveal electric quantities suited with respect to performance of the machine. If the voltages increase, the losses will decrease; but higher the excitation voltage, higher the efficiency and the terminal voltage. It has been found out that for the excitation voltage 11 V, the efficiency and the terminal voltage are 85.12 % and 380V respectively.

Keywords: synchronous generator, axial flux, excitation voltage, efficiency, terminal voltage

1. Introduction

As for the axial flux permanent magnet (PM) machines, they have a number of distinct advantages over radial flux machines (RFM). 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 less 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 AFMs with certain advantages over conventional RFMs in various applications [1].

Besides these benefits, the flux density 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 suitable shape and size to match the space limitation is crucial for some applications such as electric vehicle. 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 armature core, with internal or external PM rotors, with surface mounted or interior PMs and as single stage or multi-stage machines. Stator and rotor positions can be interchanged, the number of stator and rotor can be multiplied and the air gap distance can easily be varied. Some configurations of axial flux permanent magnet machines as shown in Figure 1 [2].

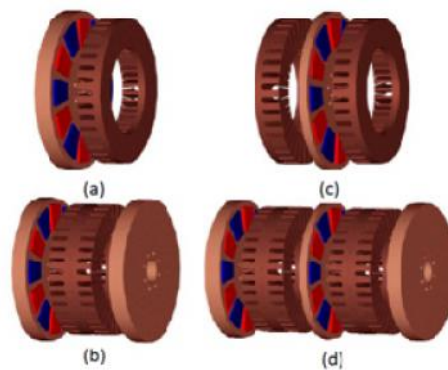


Figure 1. Axial flux machine configurations. (a) Single rotor - single stator structure, (b) Two rotor - single stator structure, (c) Single rotor -two stator structure, (d) Three rotor - two stator structure

Electrical machine which has high power and high efficiency and also small dimensions while lower price is the axial flux permanent magnet machine. However, the study has not been performed yet in three phase axial flux wound rotor synchronous generator which the excitation voltage can be varied. The excitation voltage changes can affect machine parameters such as efficiency, losses and terminal voltage.

This research will analyze the effect of the excitation voltage changes on the performance of three phase axial flux synchronous generator. How it affects the efficiency, the current and the terminal voltage. With the limited generator output power, it will be sought at what excitation voltage is varied to obtain the highest efficiency. When the rotation of generator rotor is not constant caused by the prime mover rotation that is not constant, the output voltage generated by the generator varies. To make constant output voltage, the flux should be controlled by varying the field current flowing through the rotor winding. Therefore the expected advantage of the result of this study is to obtain a precise excitation voltage on the axial flux wound rotor (AFWR) synchronous machine having the capacity 1 kW with high efficiency. Since a large number of poles can be accommodated, these machines are ideal for low speed applications.

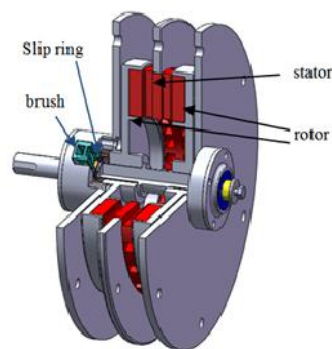


Figure 2. AFWR synchronous generator

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 so 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 wound rotor is referred to as an axial flux wound rotor (AFWR). A cross sectional schematic of the AFWR machine is shown in Figure 2. The AFWR generator consists of two wound rotor that two windings are connected in parallel. The stator of

AFWR generator is located between two opposing wound rotors. The double-sided rotor simply called twin rotor with slots are located at sides of stator and rotor lamination core.

2. Research Method

The design of axial flux synchronous generator is performed by calculations based on the equations of the axial flux and the radial flux machines. The applied equations 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 for drawing the machine and its parts.

The design of synchronous generator is started with determining 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, it is first assumed the parameter optimizations associated with the specification of the machine. It is expected at the end of the design process, the performance of the machine is met the need. If the performance has not met yet, then the design process should be repeated by changing 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 process of optimization in the design of the machine aims to obtain higher efficiency with power output fixed previously.

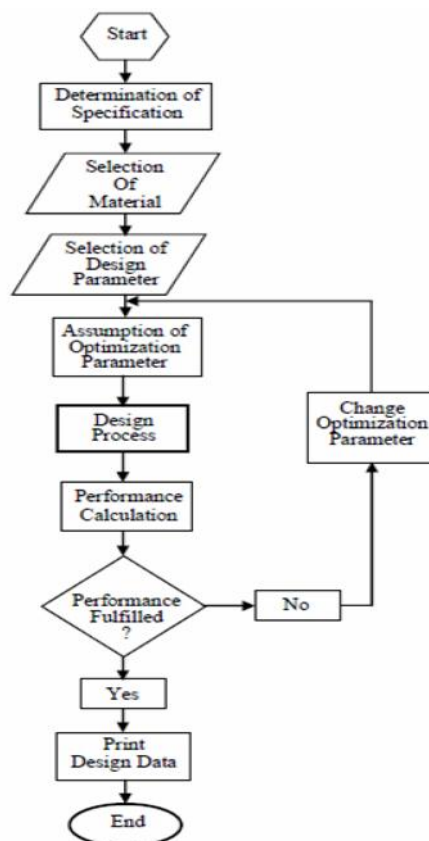


Figure 3. The flow chart of design process

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

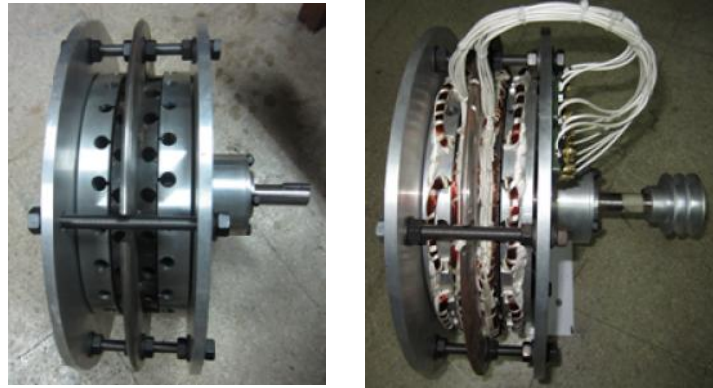


Figure 4. The slotted stators and rotor, before and after winding

In principle, the electromagnetic design of AFPM machines is similar to its radial flux PM (RFPM) counterparts with cylindrical rotors. However, the mechanical design, thermal analysis and assembly process are more complex [4]. Specifications of three phase AFWR synchronous generator designed is the nominal quantity (rated). Quantities include 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 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.

If the field winding is connected to the excitation voltage source, the field current flows in the winding. One way to increase the efficiency of synchronous generator is by increasing the excitation voltage [5]. The field current flowing in the rotor winding can be adjusted to control the output voltage. Adjusting the field current means controlling the flux produced in the rotor winding. The internal generated voltage in the stator winding is proportional to the flux. Relation between the field current and the internal generated voltage is shown in Figure 5. With this characteristic, it is possible to find the internal generated voltage of the generator for any given field current [6].

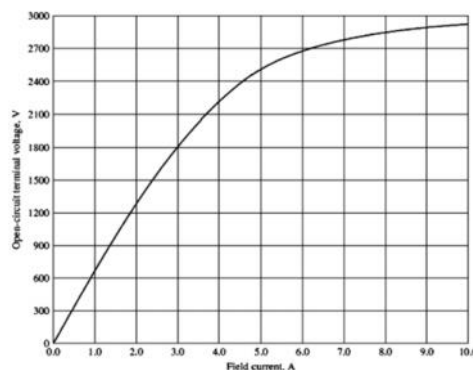


Figure 5. Open-circuit Characteristics of a synchronous generator

The quantities of the machine affected by the excitation voltage such as power output, armature current, losses and temperature are expressed the equations below [4, 7]. The real electrical output power of the synchronous generator can be expressed in phase quantities as

$$P_{out} = m_1 V_1 I_a \cos \varphi \quad (1)$$

Stator cooling coefficient (C_c)

$$C_c = \frac{0.031}{1+0.1V_a} \quad (2)$$

Where V_a is peripheral speed

Stator dissipation coefficient (C_{ds})

$$C_{ds} = \frac{S_{stc}}{C_c} \quad (3)$$

Total losses in the stator (P_{ST})

$$P_{ST} = \Delta P_{1w} + P_{core} \quad (4)$$

stator temperature rise (θ_{st})

$$\theta_{st} = \frac{P_{ST}}{C_{ds}} \quad (5)$$

The field winding should be design for a voltage from 15 to 20 percent less than the exciter voltage to allow for the drop in voltage between field and the exciter and to allow for variations in the reluctance of magnetic field. Assuming an exciter voltage V_r and keeping 20% of exciter voltage in reserve the voltage across the field coil, the field winding voltage

$$V_f = (1 - 0.2)V_r \quad (6)$$

Voltage across each field coil

$$E_{fe} = \frac{V_f}{2p} \quad (7)$$

Resistance of each field winding

$$R_f = \rho \frac{N_{ft} l_{fav}}{S_f} \quad (8)$$

Current in field winding

$$I_f = \frac{E_{fe}}{R_f} \quad (9)$$

Dissipation coefficient (C_{dr})

$$C_{dr} = \frac{S_{rc}}{C_f} \quad (10)$$

Total loss in rotor (P_{fT})

$$P_{fT} = P_{fcl} + P_{bcl} \quad (11)$$

Rotor temperature rise (θ_{ft})

$$\theta_{ft} = \frac{P_{fT}}{C_{dr}} \quad (12)$$

Losses produced by the machine in thermal consist of electrical and mechanical losses:

1. Copper losses (ΔP_{1w}) are the resistive heating losses in thearmature winding and the field winding.

2. The core losses (P_{core}) are the hysteresis losses and eddy current losses occurring in the metal of the machine. The core losses are taken as 5% of output power.
3. Friction and windage losses ($P_{f\&w}$). Friction losses are losses caused by the friction of the bearings in the machine, while windage losses are caused by the friction between the moving parts of the machine and the air inside the motor's casing. The friction and windage losses are taken as 1% of output power [7].
4. Excitation losses (P_{exci}) contain field winding DC losses and brush and slip-ring losses. In the design of drop voltage in each brush is less than 1 volt [5].
5. Stray load losses or miscellaneous losses (ΔP_{stray}) are taken as 20% of the total copper losses.

Efficiency at full load

$$\eta_{ff} = \frac{P_{out}}{P_{in}} \times 100\% \quad (13)$$

Load torque

$$\tau_{load} = \frac{P_{out}}{\omega_m} \quad (14)$$

In the synchronous machine, the rotor turns at the same speed as the stator magnetic field

$$\dot{S}_{sync} = \dot{S}_m$$

3. Results and Analysis

The values of machine parameter obtained by the calculation with the help of MATLAB are used for analysis of the machine based on the output power. Core losses and friction and windage losses are assumed 5% and 7% of the output power respectively [1, 8]. The research issue is directed to excitation voltage changes that affect losses, efficiency and load torque of the machine. The output power is set to a fixed quantity initially, while the efficiency is sought to the highest quantity. Changing the excitation voltage, losses and efficiency also change. The efficiency is sought in the optimal value but with a fixed output power. The optimum efficiency is obtained by changing the excitation voltage. The machine operation specifications required are shown in Table 1.

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

The calculation results related to the performance of the machine at the output power 1 kW and the efficiency 85.12% are shown in Table 2. In the calculation of the efficiency, the excitation voltage is ranged from low to high values while the efficiency and output power is checked and selected.

3.1. Excitation Voltage Parameter

The excitation voltage 11 V obtained from the calculation reveals the best solution (optimal efficiency). The effect of excitation voltage changes on losses, efficiency, output power and torque are shown in Figure 6, 7, 8 and 9 respectively. The calculation results showing the performance of the machine at the output power 1 kW and the efficiency 85.12% are shown in Table 2.

Table 2. Optimization parameter on the efficiency 85.12% and the output power 1kW.

Quantity (Unit)	Value
Excitation voltage (V)	11
Line current (A)	1.94
Losses (W)	183.7
Load torque (Nm)	13.4

If the excitation voltage increases, then the efficiency, output power, load torque, terminal voltage and stator temperature will increase too as shown in Figure 7, 8, 9, 10 and 11. Meanwhile, losses will decrease as shown in Figure 6.

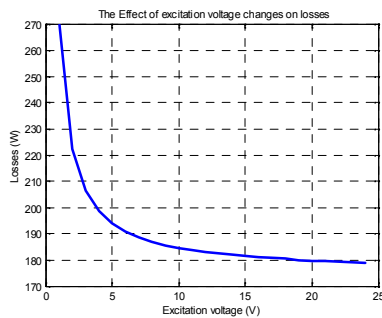


Figure 6. Relationships between excitation voltage and losses

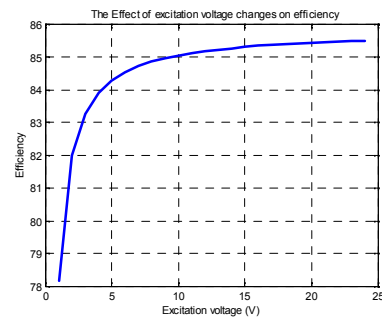


Figure 7. Relationships between excitation voltage and efficiency.

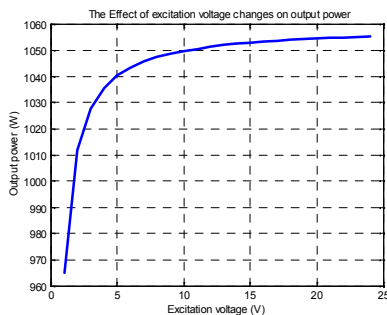


Figure 8. Relationships between excitation voltage and output power.

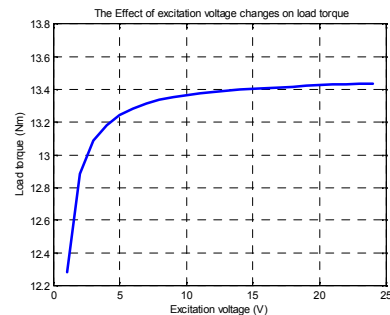


Figure 9. Relationships between excitation voltage and load torque

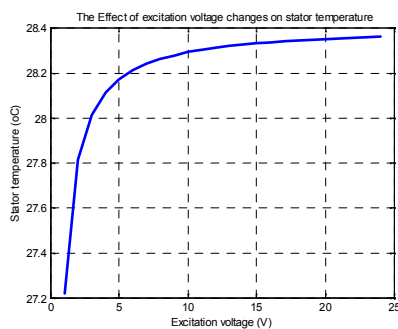


Figure 10. Relationships between excitation voltage and stator temperature.

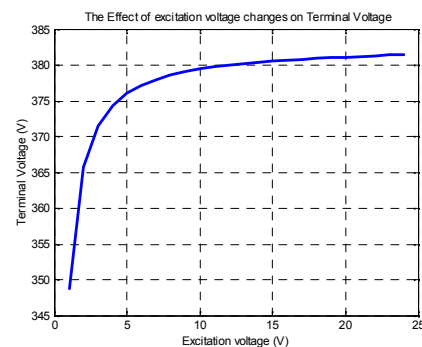


Figure 11. Relationships between excitation voltage and terminal voltage.

3.2. Design Analysis

Calculation of the effect of excitation voltage changes on AFWR generator has been performed by Matlab software. The changes of excitation voltage affect the performance of the machine. The higher the excitation voltage, the higher output power, terminal voltage, efficiency, load torque and stator temperature, but the lower the losses.

The magnitude of the losses is inversely related to the output power. The smaller a machine's losses, the larger the output power it is capable of achieving, so that the efficiency and load torque will be larger.

According to Ohm's law that the electrical current flowing in a circuit is directly proportional to the voltage. Therefore, if the voltage is increased, the current will increase too. While temperature in the stator is affected by its losses and the losses are directly proportional to current squared. Therefore, if the excitation voltage increases, the stator temperature increases too.

The efficiency of 85.12% obtained on the excitation voltage 11 V and total losses 183.7 W are constrained to the output power of 1 kW. If the efficiency in the calculation is changed, then machine parameters are changed too including power input and power output.

4. Conclusion

The excitation voltage required for supplying field winding in the rotor must be determined properly, so that the performance of AFWR synchronous generator can be obtained according to design parameter. If the excitation voltage increases, the output power, efficiency, terminal voltage and load torque of the machine increase too. But the losses of the machine decrease. The increased excitation voltage is constrained by the capacity of the designed machine. It is found out that for the excitation voltage of 11 V, the efficiency and the terminal voltage are 85.12% and 380 V respectively.

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