

Design and development of a 10 kW permanent magnet synchronous generator prototype for a grid connected low wind speed wind turbine

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ABSTRACT

There is an increasing trend of the use of renewable energy and wind energy is playing an important role. This focus of this research is to propose a design of a generator suitable for a low speed wind turbine where the design wind speed is 8.5 m/s and develop a prototype unit. It consists of 46 poles and its designed electrical output is 3-phase 380volt 50Hz 10kW with a synchronous rotational speed of 130rpm. The 10kW generator is driven by a motor to test its power generation performance. Finally, an analysis of a permanent magnet synchronous generator usage in a HAWT integration is given in the study.

Keywords: Wind energy, Permanent magnet synchronous generator

1. INTRODUCTION

Electricity is usually produced through the combustion processes of traditional fuels such as coal, oil or natural gas whose carbon emission is considered harmful to the Earth's atmosphere. The costs of these fuels have been steadily increasing over the last 30 years. Global warming is also another worrying long-term impact. Therefore, it is essential that renewable energy sources must be developed in order to replace these traditional fuels. Wind energy is one of the renewable energies that have been focused on all over the world in the last few decades (Poul Erik, et al.). In Thailand, there have been interests from both public and private sectors and the authority has also indicated that wind energy will form part of the country's power production in the future (Electricity Generating Authority of Thailand, EGAT). Wind energy is harvested through the use of a wind turbine which converts the kinetic energy of the air mass flowing past the blade into mechanical kinetic energy and eventually to drive the generator to produce electricity. At present, wind turbine generators can be classified into a Permanent Magnet Synchronous Generator (PMSG) type and an induction wound rotor. N. Bianchi and A. Lorenzoni has studied the

performances of both types and concluded that the PMSG type has an advantage over the latter because it does not lose electrical current through circuit excitation so its total power output is higher, hence a higher efficiency. The characteristic comparison is summarized in Table 1.

This work will present design procedures and development processes of a 10kW permanent magnet synchronous generator prototype for a Horizontal Axis Wind Turbine (HAWT). The wind turbine rotor design has been completed in an earlier work and the blade design process will not be covered here. The 8 meter rotor diameter wind turbine has a cut-in speed of 3 m/s which is suitable for the low-speed wind condition in Thailand where the average annual wind speeds range from 2.0-4.5 m/s in most areas [4]. The rated wind speed is 8.5m/s. The generator will undergo a series of tests by driving it using an 11kW AC motor to determine its characteristics. The study will include an analysis of the generator test results and the wind turbine integration.

Table 1 Comparison between 100kVA WR and SPM generators

	Induction wound rotor (WR)	Synchronous Permanent Magnet (SPM)
ω_m (rad/s)	78.5	78.5
Supply for the excitation circuit (winding)	Yes	No
Efficiency (%)	93.6	96.0

2. PMSG DESIGN AND DEVELOPMENT

2.1 Generator Design

Since the wind turbine permanent magnet synchronous generator is designed to be grid connected, its

characteristics can be easily defined, i.e. the output must be 240 V line to neutral and 50 Hz. Equations (1) and (2) define the relationships between the generator diameter (D) and its rotation speed (n_s).

$$Q = LC_o D^2 n_s \quad (1)$$

$$n_s = \frac{120f}{p} \quad (2)$$

Where Q is the kVA rating of machine, C_o is the output coefficient, f is the electrical frequency and p is the number of poles (Tawatchai Attawiboonkun, 1997) and (A. K. SAWHNEY, 1977)

2.2 Wind Energy Conversion

The power produced by the wind turbine rotor is given by

$$P = \frac{1}{2} C_p \rho (A_t - A_n) v^3 \quad (3)$$

Where P is the power produced, C_p is the power coefficient, ρ is the air density, A_t denotes the turbine rotor swept area, A_n denotes the generator cross sectional area, and v is the average wind speed over the rotor swept area (Tony Nurton e al., 2001). Equation (3) is derived from the kinetic energy of the air mass passing through the rotor.

The presence of the generator behind the rotor has an adverse effect on the electricity producing performance because of the blockage effect. This is characterized by the term in the brackets in equation (3) which indicates the rotor effective swept area. Figure 1 illustrates that the PMSG has a larger cross section area when compared with an induction generator.

Table 2 shows the relationship between the PMSG diameter and its required rotation speed in order to produce 10kW of electrical power at different values of diameters. A small diameter would require a high rotation speed and vice versa. The remaining swept area indicates the effective area that is not affected by the blockage from the downstream structure as a percentage of the area of an 8.5 m diameter circular swept area. A cost estimate is computed using the cost of raw materials and it varies linearly with the volume of the generator.

The design generator diameter is 1 meter. This value is selected is due to manufacturing constraint that the available laser cutter facility for cutting silicon steel sheets is only capable of handling up to 2 meter of length. The silicon steel is also available in 1.20 m wide sheets. The generator frame is to be constructed by rolling a 30mm sheet of steel into a tubular shape before making a precise circular inner shape on a lathe. The maximum inner diameter of the frame is limited by the available machinery at 2 meter. Finally, the material and processing costs as shown in Table 1 must be taken into consideration too.

Table 2 The relationship between the PMSG diameter, rotation speed and material cost estimates

Stator Diameter (m)	Generator Speed (rpm)	Remaining Area (m ²)	Cost Estimated (Baht)
0.5	366	99.7	113,960
1.0	130	98.6	415,611
1.5	71	96.9	987,384
2.0	46	94.5	1,742,902
2.5	33	91.3	2,710,013
3.0	25	87.5	3,888,312
3.5	20	83.0	5,277,501

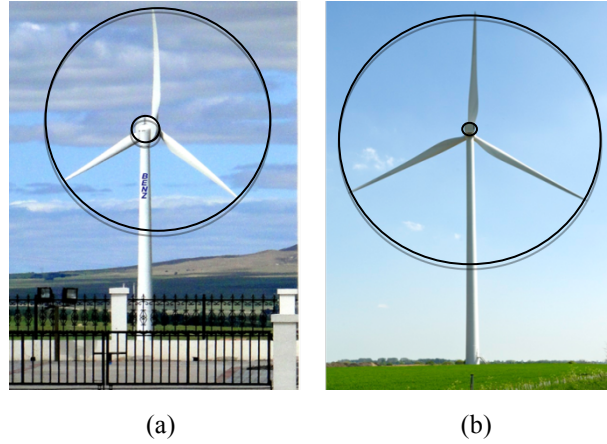


Fig. 1 The cross section area of a permanent magnet synchronous generator (a) is relatively larger than that of an induction generator (b) which produces a smaller rotor effective swept area due to the blockage effect.

2.3 10 kW Generator Prototype for Grid Connected Design

The components of the 10kW PMSG prototype have been calculated using the instruction (A. K. SAWHNEY, 1977)

The generator manufacturing processes were outsourced to local electrical workshops and steelworks in Bangkok. Only assembly processes were completed onsite.

The generator's rated power output is 3-phase 380volt 50Hz 10kW with a synchronous rotational speed of 130rpm. The stator internal diameter is 1.00m. Both stators and rotors are 67mm thick and consist of 134 sheets of 0.5mm thick 50RM400 silicon steel. The stator winding is done with conductor S.W.G.12, while each pole on the rotor contains 15 pieces of 4500 gauss cylindrical shaped NdFeB permanent magnet. The magnet diameter is 10mm and is 15mm in length. They are arranged in a specially prepared polyoxymethylene (POM) block to ensure that their positions and the induced magnetic field are uniform in all the poles.

3. PMSG CONSTRUCTION AND TESTING PROCEDURE

The 10kW PMSG consists of the following main parts (1) stator and rotor (2) generator frame.

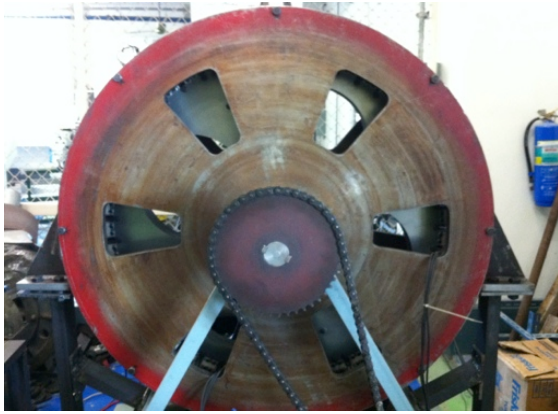


Fig. 2 The complete PMSG is housed inside the 1.20m diameter steel frame and the shaft is driven through a chain and sprocket connection.

3.1 Stator and Rotor

The air gap between the stator and rotor is only 1 mm wide, therefore all components must be manufactured to a very precise dimension. Carbon steel sheets are cut using laser in order to satisfy this high precision requirement.

3.2 Generator Frame

The frame does not only provide cover to the stator and rotor but also helps with the shaft alignment and gives support to the shaft. A 30 mm thick steel sheet is cold-rolled and welded at the ends to form a tubular shape. It is then turned on a lathe to precisely cut the inner section to house the stator. Similarly, the front and rear panels are chamfered on a lathe to achieve the perfect fit with the frame.

3.3 Generator Testing Procedure

The generator test is done by using an 11kW motor to drive it. A step-down chain and sprocket with ratio of 6.55:1 is installed between the motor and the generator shafts. The motor power input is controlled using an inverter whose input ranges between 0-50 Hz with an increment of 5Hz.

The voltage time histories at each rotation speed are recorded using an oscilloscope. These readings are used to determine the electrical output frequency and average voltage.

The grid connection synchronization electronics are installed to control the output at 240V and 50Hz which is the national standard. This is achieved by adjusting the motor controlling inverter frequency which controls the system power input. When the grid connection is satisfied, the generator is automatically restricted to rotate at a fixed speed of 130RPM. An increase in power input will lead to higher torque and higher electrical power output. The power factor, current, and power output are recorded using the measurement tools.

4. RESULTS AND DISCUSSIONS

Prior to synchronize the generator to the electrical grid, the generator must be tested to ensure that it is capable of producing compatible electricity output. This is

performed by testing the generator at various rotation speeds to determine the point where the output voltage is precisely 240V and the frequency is 50Hz. These information are given in figures 3 and 4.

The generator output is controlled by the grid connection electronics to match the Electricity Generation Authority of Thailand (EGAT) electrical grid, i.e. phase voltage of 240V and frequency of 50Hz. The measurements are only taken when this condition is satisfied. It is found that the PMSG can produce a maximum power of 6.8kW instead of the rated power of 10kW as shown in figure 6. This drop in maximum power output is due to the ¹ armature reaction .

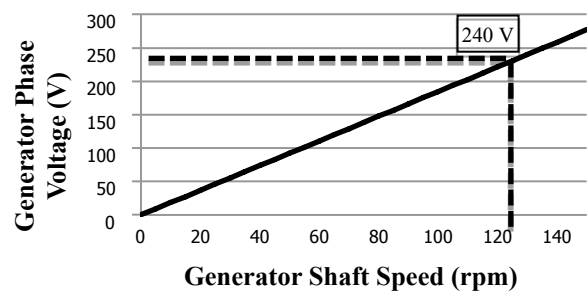


Fig. 3 The generator shows a linear relationship between the shaft rotating speed and the phase voltage.

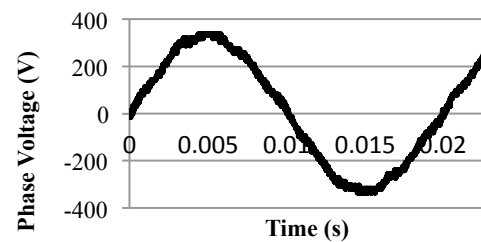


Fig. 4 At a shaft speed of 130RPM, the generator phase voltage output shows a sinusoidal characteristic with a period of 0.02 sec. or 50Hz. The peak phase voltage is 339V and the mean (RMS) voltage is 240V.

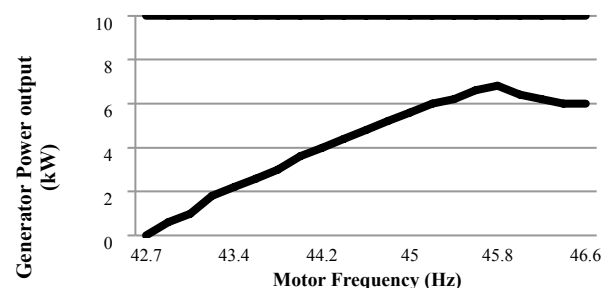


Fig. 5 The grid connected PMSG power output increases linearly with the AC motor controlling inverter frequency. The output power peaks at 6.8kW.

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Armature reaction is the effect of magnetic field set up by armature current on the distribution of flux under main poles of a generator. (B.L. THERAJA & A.K. THERAJA, 2007)

In order to achieve the power rating of 10kW, a higher magnetic field intensity is required. The PMSG has power factors in the region between 0.90-1.00 which is higher than the industry standard of 0.80 as illustrated in figures 6 and 7.

The generator's efficiency has been found to be in the region of 70%-82% depending on the power input and the average value is 77%. (Note that the generator efficiency determination is to be discussed in a separate publication.) A connection with a commercially available grid inverter is required to synchronise the electrical power output with the notional grid and its efficiency is approximately 77%.

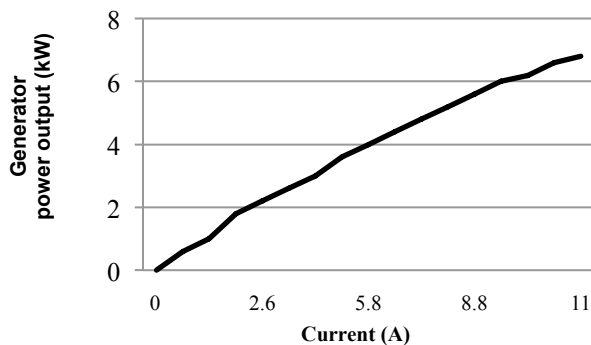


Fig. 6 At an output voltage of 240V, the generator shows a linear relationship between the current and power output up to 6.8 kW.

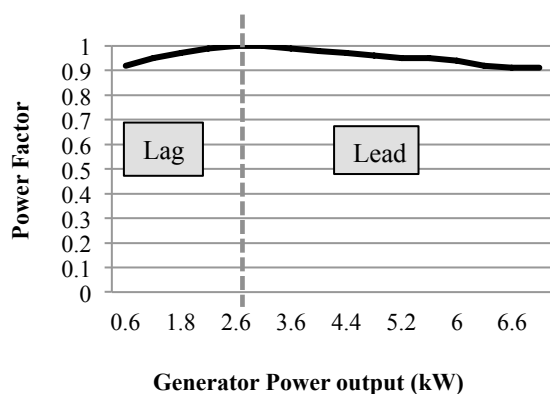


Fig. 7 The generator power factor ranges between 0.90-1.00 which is above an industry average of 0.80.

CONCLUSION

Although the PMSG designed and developed in this work does not match the designed rating, it can be rectified with higher magnetic field intensity. The production is feasible and possible with technology in Thailand. The actual PMSG installation in the wind turbine unit will require further studies in the area of power electronics as the wind turbine rotor rotation speed is always random. The large cross section area of PMSG also causes flow blockage which reduces the rotor effective swept area rendering a gearless configuration unfeasible for a 10kW wind turbine.

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