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**Original** Article

# Low cost fabrication of permanent magnet for low speed wind turbine generators using waste motors

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# Abstract

This study is devoted to the reuse of waste motors modified to serve as wind turbine generators. The generator is designed to be a high performance permanent magnet synchronous wind generator (PSWGs). The 10kW waste motor was modified to a 6kW generator by changing the rotor to a neodymium magnet with 12 poles and reforming the SWG#18 copper coils at the stator. The results indicated high induced voltage and low harmonic distortion, as well as high generator efficiency. The output power of this generator is 4kW at a wind speed of 12 m/s. S809 aerofoil blades were used for this system and the design incorporated an electrical post used for the tower. Therefore, as a waste motor and electrical post are used, the device can be fabricated at a low cost to produce a wind turbines for low speed winds suitable for southern Thailand.

Keywords: PSWGs, wind turbine, waste motor

### 1. Introduction

During the past two decades, it has become wellknown that construction and demolition (C&D) waste has extreme negative effects on the environment and has attracted worldwide attention from both researchers and industry practitioners. Thailand is the one of many countries generating C&D waste in increasing amounts (Gui, Hongping, & Hongxia, 2010). The solid waste from agriculture and municipalities has been characterized as one of the fastest growing waste categories. A typical household could expect to discard approximately 68 items over twenty years including: 20 cell phones, 10 computers, 7 televisions, 7 VCRs or DVD players, and several answering machines (Gui, Hongping, & Hongxia, 2010). One of the greatest solid waste types is machinery, which can be reused or modified to create new units with high efficiency. Households play a crucial role in the management of waste electrical and electronic equipment (WEEE) and the success of WEEE recycling programs depends on their participation. Getting WEEE to designated drop-off locations is a household's statutory duty in countries such as Germany, Japan, Switzerland, and South Korea (Manomaivibool & Vassanadumrongdee, 2012). The proposed policy in Thailand calls for local government to buy back and consolidate WEEE for environmentally sound recycling. This policy has the potential to get household WEEE consolidated into the formal recycling sector. Additional research is needed on the collection of WEEE in developing countries to learn how to lessen pollution and other environmental impacts caused by recycling (Manomaivibool & Vassanadumrongdee, 2012).

Nowadays, the energy issue has become important for all countries in the world, so reduction of the consumption of traditional energy and support for the development of

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renewable energy are the keys to sustainable development (Ying & Hongyan, 2012). In recent decades there has been extreme growth in the world population while the consumption of energy resources has also been increasing. However, the traditional energy forms such as oil, coal, hydrocarbons, etc. generate an enormous amount of greenhouse gases and cause environmental pollution and ecological deterioration of the environment. Therefore, many researchers have tried to develop wind power, and the benefits of wind power are interesting (Ying & Hongyan, 2012). In Thailand the best wind energy potential is around the coast of the Gulf of Thailand in land areas with higher elevations. The average annual wind speed is 6.4 m/s measured at an elevation of 50 m. The electricity generated from wind power in Thailand has been increasing in quantity continuously in both government and private sectors (Chingulpitak & Wongwises, 2014).

Based on wind energy research in Thailand, the provincial electricity authority (PEA) is demonstrating electricity generation with one 1.5 MW turbine at Sating Phra District in Songkhla province of southern Thailand. The wind turbine used is made in China, namely model YFKF01-500/4, and has the highest productivity in Thailand. This turbine has a horizontal axis driven with an asynchronous generator gear box, with a pole height of 80 m and blade diameter of 77 m. The turbine starts up generating electricity at a wind speed of 3 m/s and maximum productivity is at a wind speed of 11.5 m/s. The turbine can be cut-off at a maximum wind speed of 21 m/s (Chingulpitak & Wongwises, 2014). However, this turbine is really operated only with winds exceeding 3 m/s and the maintenance is not easy needing a team of technicians. Therefore, Thailand needs to develop low speed wind turbine generators for local application.

The permanent magnet synchronous generator (PMSG) based on the wind turbine can be easily connected to the grid via back-to-back converters. The PMSG has shown high efficiency in power enhancement and excellent performance to extract maximum power from the wind (Nasiri, Milimonfared, & Fathi, 2014). Low speed wind generators have a problem with cogging torque that could be improved via pole and slot. The small scale wind power applications need a cost effective and mechanically simple generator for serving as a reliable energy source (Gyeong & Tae, 2013).

Generally, the generator and accessories for wind turbines purchased from the market tend to be costly. In this study, a waste motor is modified to serve as a generator by installing a permanent magnet in part of the rotor and reinstalling the coil in the stator. The new low cost generator is connected with the blades form a wind turbine set that generates maximally 6 kW electric power. A concrete electricity pole is used for the tower supporting the wind turbine assembly.

# 2. Permanent Magnet Synchronous Generator

A permanent magnet synchronous generator is appropriate for wind turbines. Recently, permanent magnets have been widely used in wind turbines because these generators match perfectly with the requirements for building a low speed wind turbine (Kallaste, Vaimann, & Pabut, 2012), with the attributes including simple construction, light weight, slow speed, high power, variable speed, low torque, and low price. The main problem of this generator is that the cogging torque must be eliminated by skewing the slot of the stator (Abbaszadeh, RezaeeAlam, & Teshnehlab, 2012). Figure 1 exhibits the general structure of the rotor arranged with the magnetic surface. The N-pole and S-pole have a complete flux circuit; the magnetic flux passes from the rotor through to the air-gap, laminate steel, coil in the stator, air-gap, and then passes back to the rotor again to complete a closed loop (Hsiao, Yeh, & Hwang, 2014).

$$\oint = \frac{F}{\Re} \tag{1}$$

$$\mathbf{F} = \boldsymbol{\phi} \boldsymbol{\mathfrak{R}} \tag{2}$$

$$\phi = \frac{\Phi \Re}{\Re} \tag{3}$$

Based on the magnetic equivalent circuit, the flux density ( $\phi$ ) of the magnet passes through air and stator in the generator. The drive force in the magnetic circuit of the electromagnet is the magnetomotive force F= Ni, that produces a flux  $\phi$  against magnetic reluctance  $\Re$ . Therefore, the flux density  $\phi$  is related to the ratio of F and  $\Re$  as shown in equation (1). This implies equation (2) for the magnetomotive force F, in terms of flux density  $\phi$  and reluctance  $\Re$ . Equation (2) is substituted into equation (1) forming the formula of flux density as equation (3) showing the ratio between  $\phi \Re$  and  $\Re$ . Therefore, equation (3) can explain that flux density depends on the initial flux density  $\phi \Re$  through each material which results in a different value for  $\Re$  (Sen, 1989).

$$\phi = \frac{\Phi_r 2\Re_m}{2\Re_m + 2\Re_g + \Re_s + \Re_r} = \frac{\Phi_r 2\Re_m}{2\Re_m + 2K_r \Re_m} = \frac{\Phi_r}{1 + K_r \frac{\Re_g}{\Re_m}}$$
(4)



Figure 1. Schematic diagram of the permanent magnet synchronous generator (PMSG) shows the magnetic flux between rotor and stator (Hsiao, Yeh, & Hwang, 2014).

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Where  $\Phi_r$  is rotor flux,  $\Re_m$  is magnet reluctance,  $\Re_g$  is air reluctance,  $\Re_s$  is stator reluctance,  $\Re_r$  is rotor reluctance and  $K_r$  is the rotor leakage factor. The magnetic flux can be derived as shown (Hsiao, Yeh, & Hwang, 2014) in equation (4). Based on Figure 1, the steel reluctance ( $\Re_r + \Re_s$ ) is small relative to air-gap reluctance  $\Re_g$ ; the steel reluctance can be eliminated by introducing a correction coefficient  $K_r$  slightly greater than unity to multiply  $\Re_g$  to account for the neglected ( $\Re_r + \Re_s$ ). For a machine with surface magnets under consideration, the leakage and reluctance factors are typically in the ranges 0.9-1.0 and 1.0-1.2, respectively, while the flux concentration factor is ideally 1.0 (Hsiao, Yeh, & Hwang, 2014).

$$E_{f} = 4.44f \phi_{f} NK_{w}$$
(5)

Here  $E_f$  is excitation voltage, f is frequency,  $\phi_f$  is the flux per pole to the excitation current I<sub>f</sub>. N is the number of turns in each phase and  $K_w$  is the winding factor. Figure 2 (a) shows the field current if it flows to the rotor field winding that induces a sinusoidal distributed flux  $\phi_f$  in the gap. If the rotor is rotated by the prime mover that generated the excitation voltage  $E_f$  it obeys equation (5), while the rotor permanent magnet can directly give the flux density  $\phi_r$  that generated the excitation voltage  $E_f$ . This is shown in equation (6), and the excitation voltage  $E_f$  is related through equations (4) and (5). The excitation voltage  $E_f$  is proportional to the generator speed n and rotor flux  $\phi_r$ . The  $\phi_r$  and the number of poles p are constant for a permanent magnet. Therefore,  $E_f$  is only proportional to the generator speed n shown in equation (7).

$$E_{f} = 4.44f \left( \frac{\phi_{r}}{1 + K_{r} \frac{\Re_{g}}{\Re_{m}}} \right) NK_{w} = 4.44 \left( \frac{np}{120} \right) \left( \frac{\phi_{r}}{1 + K_{r} \frac{\Re_{g}}{\Re_{m}}} \right) NK_{w}$$
(6)

 $E_{f}\alpha n$ 



Figure 2. (a) The field current  $I_f$  flows through the rotor field winding to induce the flux density  $\emptyset_f$ , (b) The rotor flux density  $\emptyset_r$  generated directly from the magnet.

# 3. Methodology

# 3.1 Electrical generator

The 10kW waste motors are very commonly available in antique electrical stores and consume three-phase

380V<sub>ac</sub> electric power. The motor is a bi-directional machine. Therefore, it can transform wind energy into mechanical energy after adapting certain parts. In order to obtain electrical energy, it would be necessary to fabricate changes in the motor to obtain a generator. The design of this motor is very simple. A modified stator is needed to reduce the cogging torque that affects the starting torque. Therefore, the slot on the stator requires a design of proper thickness for the stator tooth tips. If these stator tooth tips are too thin, then they are likely to be subject to magnetic saturation, increasing the cogging torque. The thickness of the tooth tips should be the same as the width of the slot opening. Moreover, the width of the slot opening affects the cogging torque. Reducing the width of the slot opening to reduce permeance variation between the teeth of the stator could decrease the cogging torque (Srisiriwanna & Konghirun, 2012).

(7)

Epoxy/mica should be inserted into the slot in the stator to support the copper coil as insulation if the generator stator deteriorates under thermal, electrical, vibrational, and thermal-mechanical stresses when operating (Chen, Cheng, Yue, & Xie, 2006). The motor has 36 slots in the stator for inserting copper coil for phase A, phase B, and phase C, as shown in Figure 3. The coils used SWG#18 with 40 turns per

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Figure 3. The rotor and stator of the transformed 36-slot motor.

slot and were coated with varnish (Bell & Sung, 1997) to prevent short circuiting.

Figure 3 shows the structure of the rotor and the stator. An air gap of 2.5 mm was formed between rotor and stator for constant reluctance to flux flowing from the rotor to the stator. Further, the magnetic fields embedded in the rotor slots were uniformly spaced over a rotor magnet pole; the magnet had a curved shape included in the circular surface of the rotor which could smoothly move magnetic flux to the stator. The smoothness of the air gap helps the electromotive force waveform with low harmonic distortion. Water insulation was improved at the turbine to weather proof the device. The ball bearings were replaced with water pump bearings, and rubber strips were placed to seal possible water entrances while the coating was reinforced with paint.

The original rotor from the waste motor contained the copper coil and laminate, the shaft was inserted in the center of the rotor, and the end of shaft could be connected to an assembly of blades. The commercial type neodymium magnets (52.10 [outer] x40x10mm) and (46.90 [inner] x40x10mm) with arc shape were fixed on the surface of the rotor. There were 48 small surface-fixed magnets in the rotor for 12 poles attached by Loctite glue 331, which gave the magnetic flux 0.46 T/ magnet path equivalent to the one created by the coil when working as a motor. Table 1 shows the parameters of the permanent magnet synchronous generator after it was modified from the 10 kW waste motor.

### 3.2 Blade structure design

The blade used in this research was a 3 meter blade adapted from a design study (Barnes, Morozov, & Shankar, 2015). The blade was produced from fiberglass and epoxy resin laminates, with sharply decreasing fatigue resistance with fiber content. Excellent fatigue resistance is shown with aligned strand reinforcement at 46-68% fiber by volume and several resins (Mandell, Samborsky, & Miller, 2013). The geometry of the blade is designed to follow (Barnes, Morozov, & Shankar, 2015), which blends a circular cross section at the blade root to a thick S809 aerofoil at the 25% span. The chord tapers and thickens from a maximum 25% of the blade span to a minimum at the tip. The aerodynamic

Table 1. Parameters of the wind generator designed.

No.	Parameter	Value
1.	Electrical generator	Permanent Magnet
		Synchronous Generator
2.	Number of Copper coil	18#SWG
3.	Phase number	3 phase
4.	Pole number	12 poles
5.	Turn number per coil	480 turns/phase
6.	Synchronous Speed	500 rpm
7.	Efficiency	72.61%
8.	Resistance per phase (A)	2.00 Ω/phase
9.	Resistance per phase (B)	2.05 Ω /phase
10.	Resistance per phase (C)	2.00 Ω /phase
11.	Inductance per phase (A)	14.5 mH/phase
12.	Inductance per phase (B)	14.5 mH/phase
13.	Inductance per phase (C)	14.5 mH/phase
14.	Insulators per phase A-Neutral	$>35 \text{ G} \Omega/\text{phase}$
15.	Insulators per phase B-Neutral	$>35 \text{ G }\Omega/\text{phase}$
16.	Insulators per phase C-Neutral	$>35 \text{ G} \Omega$ /phase

specifications are designed so that the twist of the blade varies, decreasing from root to tip. Structural spar contained in the blade by webs located at the 10% and 60% chords at the blade root and the 15% and 45% chords from the 25% span outwards. The details of thickness, twist, and chords are shown in Table 2. The location and shape of the six aerofoils, each with different chords and twist, are shown in Figure 4. The blade was formed by resin fiber using vacuum assisted resin infusion moulding (VARIM). VARIM is a composite manufacturing processing to fabricate high quality and large scale components. In this process, dry pre-form fabrics are placed in an open mould and a plastic vacuum bag is placed on the top of the mould. One side of the mould is connected with a resin source and a vacuum pump. The liquid resin infuses into the reinforcing fibers thanks to the vacuum drawn through the mould. Curing and de-moulding steps follow the impregnation process to complete the product (Goren & Atas, 2008). The main steps of the process are:

1. A dry fabric or pre-form and accompanying materials such as release films, peel plies are laid on the tool surface.

2. The pre-form is sealed with a vacuum bag and the air is evacuated by the vacuum pump.

3. Liquid resin with hardener from external reservoir is drawn into the component by vacuum.

4. The liquid resin with hardener is infused into the pre-form until there is complete impregnation.

5. Curing and de-moulding steps finish the product.

The components of the infusion process utilized in the work are shown in Figure 5. Three blades are formed for a wind turbine in this study.

# 3.3 Performance test of generator

The proposed permanent magnet synchronous generator (PMSG) was experimentally tested, with the operation shown in Figure 6(a) and the linear graph exhibits the electrical power versus rotational speed of the generator in Figure 6(b). 6kW of lamps were used as the load while continuously increasing the rotational speed to the maximum

Table 2. Baseline blade geometry design for the blade of the NACA S809 aerofoil

Span	Chord (mm)	Thickness (%)	Twist (Deg)	Aerofoil	Spar location
0	173	100	12.0°	Circle	10-60%
25	264	55	11.9°	S809	10-45%
35	255	43	9.9°	S809	10-45%
55	174	27	4.3°	S809	10-45%
75	104	21	1.3°	S809	10-45%
100	47	18	$0.1^{\circ}$	S809	10-45%



Figure 4. The baseline geometry.



Figure 5. (a) The vacuum assisted resin infusion molding (VARIM) process and (b) the final product from the VARIM process.



Figure 6. (a) The proposed permanent magnet synchronous generator (PMSG) is experimentally tested for the operating speed range. (b) The electric power from the generator was tested using lamps at the load of up to 6 kW.

of range. The PMSG was operated at 50-500 rpm with the sinusoidal waveform of three phases having peak to peak voltage around 220  $V_{ac}$  at 50Hz, as shown in Figure 7(b-d), while the sinusoidal waveforms compared with the entire 3 phase system as shown in Figure 7(a) as expected of a permanent magnet synchronous generator.

The corresponding harmonic spectra for rotor and stator voltages are shown in Figure 8(a-c). The PMSG is a three-phase generator that had total harmonic distortion (THD) of 1.4%, 1.6% and 1.9%, respectively. According to IEEE 519-1992, the harmonic voltage distortion on power systems of 69kW and below is limited to 5.0% and THD has individual harmonic limits of 3% (Blooming & Carnovale, 2006). The resultant and the component fluxes rotate in the air-gap at the same speed, governed by equations (6) and (7). The phase vector diagram of these fluxes is shown in Figure 8(d). The rotor flux  $\phi_r$  induced the voltage  $E_f$  and produced the vector sum of the fluxes from the magnets, which have almost the same magnitudes but are phase-shifted by 120 degrees.



Figure 7. The PMSG is operated at the speed 500 rpm with sinusoidal waveform of three-phase current having peak to peak voltage around  $220 V_{ac}$  at 50 Hz.



Figure 8. The harmonic spectra for rotor and stator voltages are shown in (a-c) while the electrical phase vector is shown in (d).3.4 Application

This wind turbine was a novel design in that by using an electric post (reinforced concrete) for the tower it was low cost and made of readily available materials. The wind turbine was fabricated by casting with box holes, so the electrical post can be inserted in the hole of the turbine as shown in Figure 9 (a-c). Wind energy is one alternative energy source in Thailand that is located near the equator and has low to moderate wind speeds that average 3-5 m/s (Glassbrook et al., 2014). Surat Thani is located in southern Thailand and has high potential for wind energy. The properties of this PMSG generator facilitate practical implementation of such wind power. Figure 10 shows the measured power curve for the PMSG generator operated with wind speed at 1.2 m/s, designed for wind speed of 12 m/s, and with cut-off wind speed at 14 m/s. The wind power output is limited to 4kW, which is the average from the data logger. However, electricity can still be generated at a wind speed of 2 m/s.

The electric power was measured daily by the data logger and showed power peaks of 1.3 kW around 2-4 pm, depending on the wind speed each day, as shown in Figure 11(a). The electric power was collected monthly in 2013-2014 (average each day); the power was highest around 33kW in February, and 10kW in November. Additionally, the average power over the year was approximately 24 kW. The PMSG should be co-operated with blades because the wind speed is low. The turbine can start at wind speed of 1.2 m/s, is optimal for 12 m/s, and has cut-off wind speed of 14m/s. The details of the wind turbine properties are exhibited in Table 3.



Figure 9. (a) schematic sketch of the wind turbine assembly on an electric post of reinforced concrete. (b) The installation of the wind turbine system onto the electric post at 16 meter height. (c) The low cost wind turbine.



Figure 10. Measured power curve for the wind turbine using PMSG generator.3.4 Economic analysis



Figure 11. (a) Measured daily electric power from the PMSG generator, and (b) measured monthly electric power.

Table 3. Parameters of the wind turbine generator using waste motor.

No.	Parameter	Value
1.	Rotor Diameter (blade)	6 m.
2.	Blade Material	Fiberglass Reinforced Plastic
3.	Number of Blades	3
4.	Cut- in Wind Speed	1.2 m/s
5.	Rate Wind Speed	12 m/s
6.	Cut-off Wind Speed	14 m/s
7.	Survival Wind Speed	25 m/s
8.	Rated Output Power	4 kW
9.	Maximum Output	6 kW
	Power	
10.	Rated Output Voltage	380 VAC
11.	Generator Type	3 Phase Permanent Magnet
		Generator
12.	Height of tower (m)	16 m (concrete electrical post)
	2	· · · · · · · · · · · · · · · · · · ·

These wind turbine systems were designed to operate for 20 years with financial estimates consisting of the fixed costs and the variable costs totaling 160,400 baht. The indicators of financial analysis were based on electricity production of 9,091.68 kW/year with 3% maintenance/year, 7% salvage value and the value of 4.50 baht/unit. Economic analysis was considered in terms of net present value (NPV), benefit cost ratio (BCR), internal rate of return (IIR), and payback period (PBP). The results are shown in Table 4.

 Table 4.
 Estimates of economic feasibility for this wind turbine system.

	Indicator	Value
1.	Net Present Value	224,295.18
2.	Benefit Cost Ratio	2.254
3.	Return on investment	20.26%
4.	Payback time	13.18 years

Table 4 reveals a payback time of 13.8 years because of the area of installation in which the median wind speed must be taken into account, but it did show positive NPV at electricity for 17.64 baht/kW as shown in Figure 12.



Figure 12. Estimates of payback for this wind turbine system on an annual basis.

# 4. Conclusions

Thailand is located in a tropical area where the wind speed is low speed but generators for wind turbine systems are commonly designed for high speed and with a high capital cost. In response, this study revealed successful fabrication of a generator for wind turbines at a low cost, for low speed, and using readily available materials. The generator can be modified from waste motors and the tower set-up from electric posts. The generator can be operated from wind speeds of 1.2 m/s, is designed for wind speed of 12 m/s, and has cut-off wind speed of 14 m/s. The wind power output is limited to 4kW. In the future, this novel generator will help recycle waste motors to wind turbine generators that can serve in small wind farms in Thailand.

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