

Modeling and analysis of 1kW Wind Turbine Generator Using Matlab Simulink

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ABSTRACT

This paper describes the development scheme of a permanent magnet generator system with small scale wind turbines, where the permanent magnet synchronous generators represent the most common solution. The generator is designed to have no cogging torque so that it can be used with all horizontal turbine designs with high generator efficiency. The work deals with a new wind power plant representation that is used to model the electrical parts of wind power. Simulation results obtained from the model are used to observe the impact of wind fluctuations, wind shear and tower shadow on the power and voltage at the point of common coupling.

Keywords: permanent magnet generator, small scale wind turbine, synchronous condenser, asynchronous generator.

1. List of symbols

A_x Cross-sectional area of copper wire, m²

B flux density, T

\hat{B} Peak flux density, T

B_a coil flux density, T

B_{rem} magnet remanence, T

C capacitance, F

d_m magnet diameter, m

E_{ph} phase EMF, V

E_{line} Line EMF, V

E_{coil} coil EMF, V

E_1 phase voltage, V

g axial distance between **rotor** discs, m

\hat{J} equivalent current density, A/m²

k_1, k_l flux leakage factors

K machine constant

L_{ph}	phase inductance, H
I_d	DC current, A
I_c	capacitance current of windy boy equivalent circuit, A
I_w	windy boy inverter current, A
n_{pall}	number of armature coil in parallel per phase
N	number turns/coil
P	power, W
P_{batt}	battery power, W
P_w	windy boy inverter power, W
r_i	inner radius of armature coil, m
r_0	outer radius of armature coil, m
R_{dc}	equivalent DC resistance, Ω
R_{ph}	phase resistance, Ω
R_{ol}	overlap resistance, Ω
R_L	load resistance, Ω
t_m	magnet thickness, m
V_d	DC voltage, V
V_{d0}	open circuit DC voltage, V
X_{ph}	phase reactance, Ω
λ	flux linkage, Wb
$\hat{\lambda}$	total flux linkage, Wb
μ_0	vacuum permeability
μ_{rec}	recoil permeability
ϕ_a, ϕ_b, ϕ_c	flux in coil segments, Wb
n_{series}	number of armature coil in series per phase
τ	pole pitch, m
u_n	constant = $n\pi / \tau$

ω electrical frequency, rad/s

Suffixes:

WTs wind turbines

WTGs wind turbine generators

PCC point of common coupling

SMA

x co-ordinate axis

2. I. INTRODUCTION

Wind energy has been applied on land since the first windmill was developed by the ancient Persians [1]. There has been a considerable rise in interest in the use of wind energy in recent years due to environmental concerns and growing energy demands. In order to make the use of wind energy more widespread, potential problems and limitations must be studied and then resolved. One of these problems is the connection of wind turbine generators (WTGs) to the grid which can be constrained by power-quality considerations such as the possible deterioration of the voltage and power quality of the network. The torque and power generated by a wind turbine fluctuate as they are much more variable than that produced by other conventional generators. These fluctuations are due to periodic and stochastic terms. Wind velocity is a stochastic phenomenon continuously changing in direction and speed. The term wind shear is used to describe the variation of wind speed with height while the term tower shadow describes the redirection of wind due to the tower structure. It is necessary that they be modeled to study the power quality at the Point of Common Coupling (PCC) of wind power plants. In recent years, the size of wind power plants has increased significantly. The modeling and simulation of a wind farm with a large number of WTs (i.e. 100 WT for example) considering detailed aerodynamic, mechanical, and electrical aspects of each WT is very difficult and impractical therefore; the aggregated wind turbine representation of wind farms is a useful method that can be applied to simulate power systems. The (WTGs) supply real power variation into the upstream grid, and at the same time, in some types of (WTGs), the reactive power consumption is related to the real power production [2].

3. II. Wind Turbine

The wind turbine under study is shown in Fig.1, its generator data is illustrated in table 1.



Fig1. 1kW wind turbine

Table 1. Generator data and parameters of the wind turbine under study

Blades rotor diameter	2.8m (9.18 ft.)
Blade material and quantity	3Pcs / FRP made by hand
Rated power	1000W
Max power	1500W

Rated rotation speed	400(r/min)
Start torque	0.4(N.M)
Generator type	PMG AC Direct Driver
Optional output voltage (DC)	24-48 V
Startup wind speed	3 m/s (6.72 mph)
Rated wind speed	8 m/s (17.92 mph)
Working wind speed	3-25m/s (6.72-56 mph)
Max. design wind speed	40 m/s (89.6 mph)
Tower high	6m(19.68ft)higher available
Top weight	55kg
Coil inductance(mH)	Measured= 5.06, predicted= 5.2
Coil resistance(ohms)	Measured= 0.82, predicted= 0.91

III. THEORY

A. Generator topology

The generator consists of two rotor discs mounted either side of a non-magnetic, non-conducting stator, Fig.2. The magnets are mounted in a N-S-N-S arrangement circumferentially round each rotor plate with the N magnet on one plate facing a S magnet on the other. The flux travels directly across the “air” space between the rotor discs before turning circumferentially in the rotor disc and travelling one pole pitch before turning back across the air-gap. A non-magnetic, non-conducting stator holds a number of circular bobbin wound armature coils positioned circumferentially round the stator. Although generators can readily be designed for any number of phases the generators described in this paper are three phase machines with 16 magnets per disc and 12 armature coils. This combination gives a 240° phase shift between adjacent armature coils and provides for 4 coils per phase. By using simple bobbin wound armature coils it is straightforward to connect the four armature coils per phase in an appropriate series/parallel arrangement so that the generator is suitable for either main-connection or battery charging. Alternatively, armature coils with a different number of turns can be used, the manufacturers simply selecting appropriate coils for the application [3]

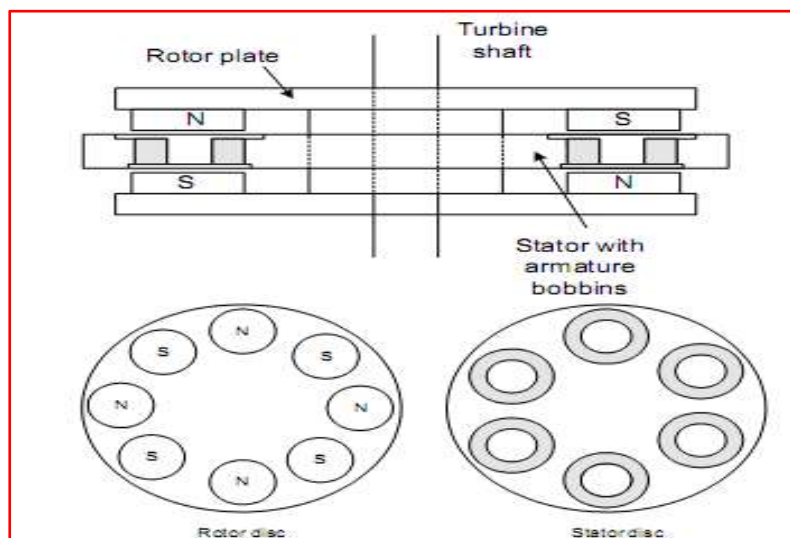


Fig.2. Generator topology [3]

B. Electrical design equations

The flux density distribution is approximately sinusoidal in both radial and circumferential directions so that the flux density profile over a magnet pitch can be thought of as a “sinusoidal hill” described by the following equations [3-5]

$$B_{yn}(x) = \left[\frac{\hat{J}_n \mu_0 \sinh u_n t_m}{u_n \sinh u_n \frac{g}{2}} \right] \cos_n x = \hat{B} \cos u_n x \dots \dots \dots (1)$$

Where, \hat{J}_n is given by

$$\hat{J}_n = \frac{4}{\tau} \frac{B_{rem}}{\mu_0 \mu_{rec}} \sin \frac{u_n}{2} d_m \text{ A / m}^2 \dots \dots \dots (2)$$

A preferred approach is to assume the armature coil to be consternated at its mean axial position, but that the coil is divided into a number of segments in the coil radial with the turns in each of these segments. This concept is shown in Fig.3 with the coil divided into three segments.

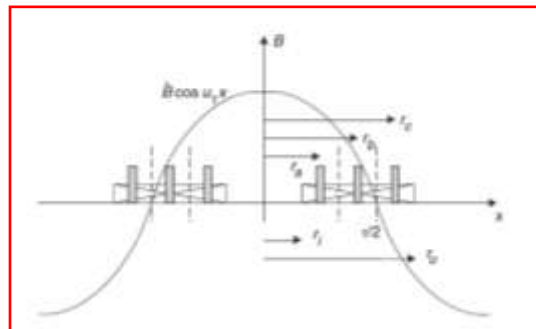


Fig.3 Flux density distribution

Consider the consternated coil at radius r_a ; then the flux throw a small circular element dx , as shown in Fig.4, is

$$d\phi = \hat{B}_1 \cos u_1 x. (2\pi x dx) \dots \dots \dots (3)$$

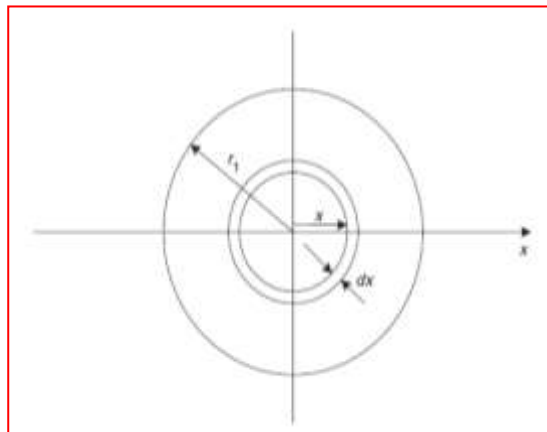


Fig.4 Flux linkage

The assumption of the magnetic flux density forming a “sinusoidal hill” implies an axi-symmetric flux density distribution around each magnet with x being the radial distance from the centre of the magnet. This flux density profile can now be used to derive the flux between the centre of the armature coil and the radius r_a as [3].

$$\phi_a = 2\pi \hat{B} \left[\left(\frac{1}{u_1} \right)^2 (\cos u_1 r_a - 1) + \frac{1}{u_1} (r_a \sin u_1 r_a) \right] \dots \dots \dots (3)$$

If it is assumed that the armature coil is concentrated at its mean axial position, and the coil is divided into three segments a, b and c in the radial direction, with the turns in each of these segments is concentrated at the mean radius of that segment, then the total flux linkage is given by

$$\hat{\lambda} = \frac{N}{3} (\phi_a + \phi_b + k_1 \phi_c) \dots \dots \dots (4)$$

and the coil e.m.f is given by

$$E_{coil} = \frac{2\pi}{\sqrt{2}} f \hat{\lambda} = 4.44 f \hat{\lambda} \dots \dots \dots (5)$$

In equation (4) a flux enhancement factor k_1 is introduced ($k_1 \geq 1$) to compensate for the fact that the flux calculated in the outer coil segment will be slightly less than actual. This is because the analysis assumes that the flux density to be sinusoid ally distributed in all directions round the magnet. However, this is only strictly true in the generator circumferential direction and not in the radial as in this direction the flux density simply reduces to zero. Thus the flux calculated for the outer coil segment will be a slight underestimate. Typically $k_1=1.05$ is used to compensate for this.

A similar approach can be taken in calculating the coil inductance but now the flux profile is assumed to be conical with a trapezoidal cross section. The inductance of an armature coil is then given by [4]

$$L_{coil} = k_L \lambda \dots \dots \dots (6)$$

k_L : is typically about 1.2

The coil resistance depend on the length of size of copper wire used . It is also depend on operating temperature and the length of the mean turn and is given by

$$R_{coil} = \rho \frac{N 2 \pi r_m}{A_x} \dots \dots \dots (7)$$

With the coil flux linkage given by

$$\lambda = B_a N \pi r_i^2 + 2 \frac{B_a N \pi}{(r_0 - r_i)} \left(\frac{1}{12} r_0^4 - \frac{1}{2} r_0^2 r_i^2 + \frac{2}{3} r_i^3 r_0 - \frac{1}{4} r_i^4 \right) \dots \dots \dots (8)$$

The magnetic field produced by an armature coil along its centre-line, Fig.5 is calculated by Ampere's law for 1A excitation as

$$B_a = \mu_0 \frac{N}{g} \dots \dots \dots (9)$$

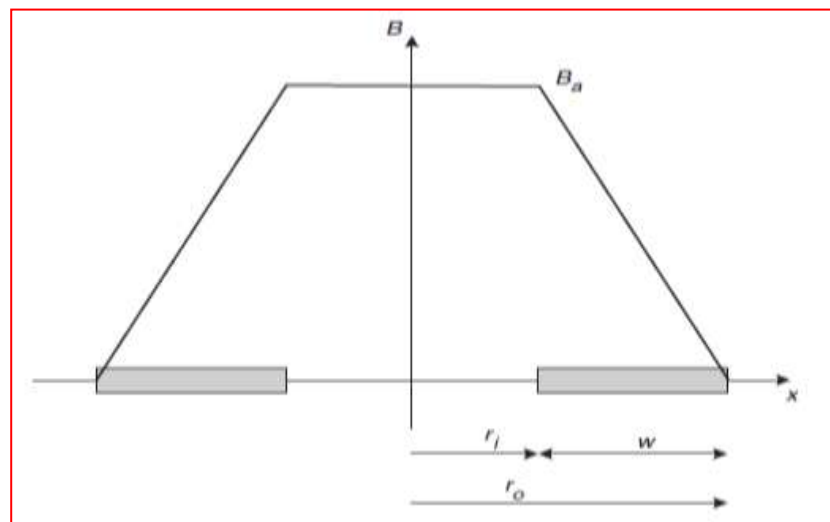


Fig.5 Armature flux density distribution

If the armature coil is assumed to be concentrated at its mean axial position with its turns uniformly across its width, as in Fig.6.

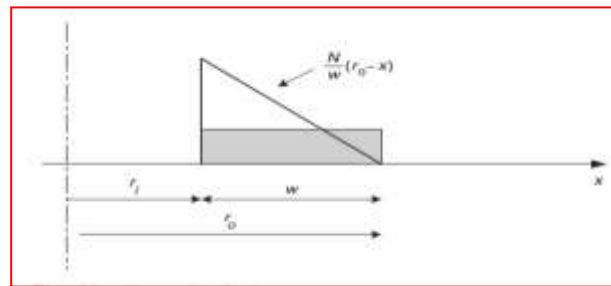
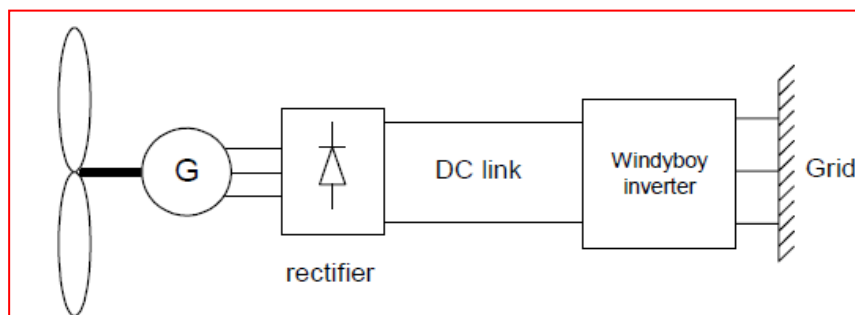


Fig.6 Turns distribution

○ C. Performance equations

The three phase generator output can be dissipated in a three phase resistor bank or, more usually, the output is rectified and used either to charge batteries or used directly as the dc link voltage to supply a grid tie inverter such as the SMA Windy Boy [7] shown in Fig. 7.



The characteristics of SMA windy boy with mains are shown in table2.

Table 2 Windy boy and mains characteristics

Rectifier side	6-pulses diode bridge
Inverter side	6-pulses IGBTs bridge
Filter capacitor	

In either case the generator and rectifier are conveniently represented by an equivalent circuit viewed from the dc side of the rectifier. The equivalent circuit for battery charge applications is shown in Fig. 8. The battery is simply represented by its internal resistance and open circuit e.m.f whilst the generator is modeled by its open circuit e.m.f, its equivalent resistance and the equivalent (R_{ol}) []. If required an additional voltage can easily be included to represent the diode voltage drop in the rectifier.

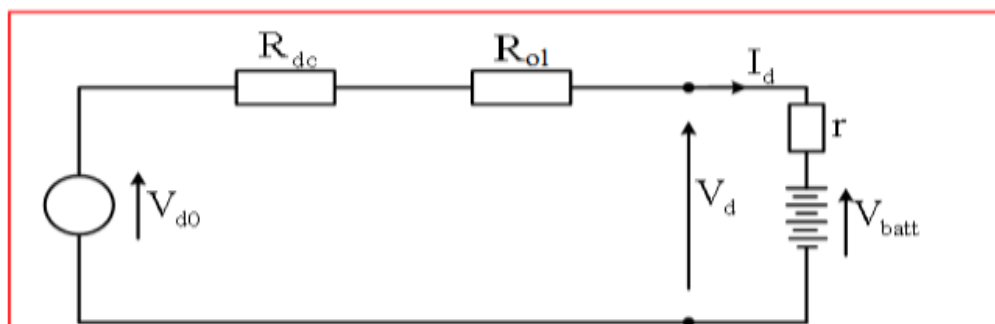


Fig.8. Equivalent dc circuit for battery charging system

For a three-phase, 6-pulse, rectifier the effective armature resistance of the generator is approximately twice the phase resistance i.e.

$$R_{dc} \approx 2R_{ph} \dots \dots \dots (10)$$

The overlap resistance is given by

$$R_{ol} = \frac{3}{\pi} \omega L_{ph} \dots \dots \dots (11)$$

And the open circuit emf is related to the phase voltage by

$$V_{d0} = \frac{3\sqrt{2}}{\pi} E_{line} = 2.34 E_{ph} \dots \dots \dots (12)$$

Simple circuit analysis gives the current as

$$I_d = \frac{V_{d0} - V_{batt}}{R_{dc} + R_{ol} + r} \dots \dots \dots (13)$$

and the battery terminal voltage as

$$V_d = V_{d0} - I_d R_{dc} - I_d R_{ol} \dots \dots \dots (14)$$

The power supplied to the battery is now readily calculated as

$$P_{batt} = V_d I_d \dots \dots \dots (15)$$

For mains, connect the applications through the grid-tie inverter, the battery is simply replaced by the dc link capacitance and the mains connected inverter is modeled by its power transfer characteristics. Fig. 9. represents the case of the SMA Windy Boy, the power transfer characteristic is a linear function that depends on the dc link voltage [7]. As the generator used is a PM generator, for the first approximation, the power transfer is a direct function of turbine speed (neglecting voltage drops in the armature resistance and overlap resistance).

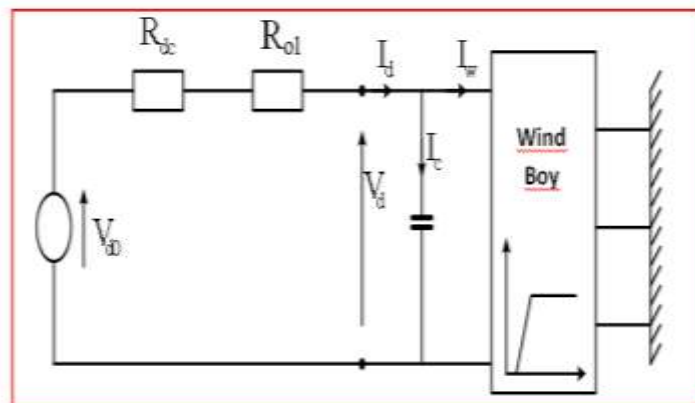


Fig.9. Wind Boy equivalent circuit

For the Windy Boy to operate there must be a dc voltage of at least 260V. The dc link voltage that will correspond to maximum power transfer can be set at any voltage up to 600 V. If it is set at, say, 450V then the inverter would transfer power as a linear function of voltage between 260 and 450V, if it is to voltage above 450V, it would keep the power constant until the over-voltage cut-off condition is reached. This must be below 600V. The analysis of this case determines the current I_w as

$$I_w = \frac{P_w}{V_d} \dots \dots \dots (16)$$

With the remaining equations as following

$$I_d = \frac{V_{d0} - V_d}{R_{dc} + R_{ol}} \dots \dots \dots (17)$$

$$I_c = I_d - I_w \dots \dots \dots (18)$$

$$V_c = \frac{1}{C} \int I_c dt \dots \dots \dots (19)$$

If a resistive load is fed, the generator is simply represented by its per phase equivalent circuit shown in Fig. 10. The analysis of this circuit is straight-forward and gives the terminal power per phase as.

$$P = \frac{E_1^2}{(R_{ph} + R_L)^2 + X_{ph}^2} R_L = \frac{K^2 \omega^2}{(R_{ph} + R_L)^2 + X_{ph}^2} R_L \approx \frac{K^2 \omega^2}{R_L} \dots \dots \dots (20)$$

Where, reactance per phase is

$$X_{ph}^2 = \omega \frac{n_{series}}{n_{pall}} L_{coil} \dots \dots \dots (21)$$

and

$$R_{ph} = \frac{n_{series}}{n_{pall}} R_{coil} \dots \dots \dots (22)$$

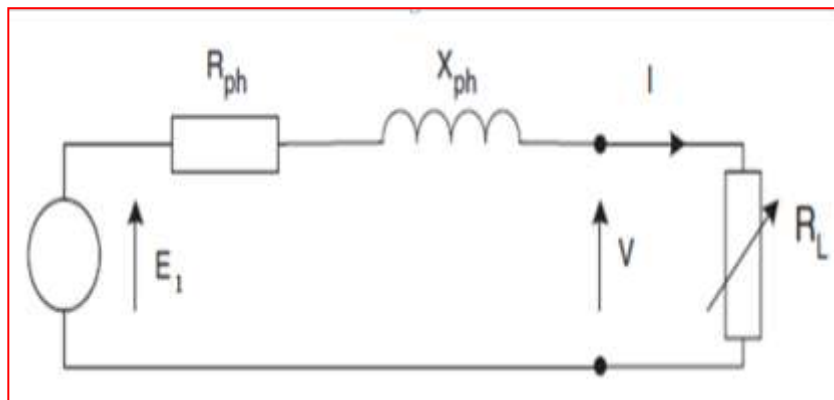


Fig.10. A.C .equivalent circuit for a resistive load

IV. SYSTEM COMPONENT

System component that in modeling are wind turbine (1kW), synchronous consider (380V, 1.25kVA), PF correction capacitor (125VAr), asynchronous generator (380V, 1kVA), secondary load (0-25W) and main load (25W) connected in parallel with load (200W) by 3-phase breaker.

V. SYSTEM MODEL USING MATLAB/ SIMULINK

Wind turbine simulation is important in determining the performances of wind generators and the features offered by a simulator for predicting the energy output and analysis of the energy conversion and system dynamics. The system is modeled using Mat lab Simulink as shown in Fig.11.

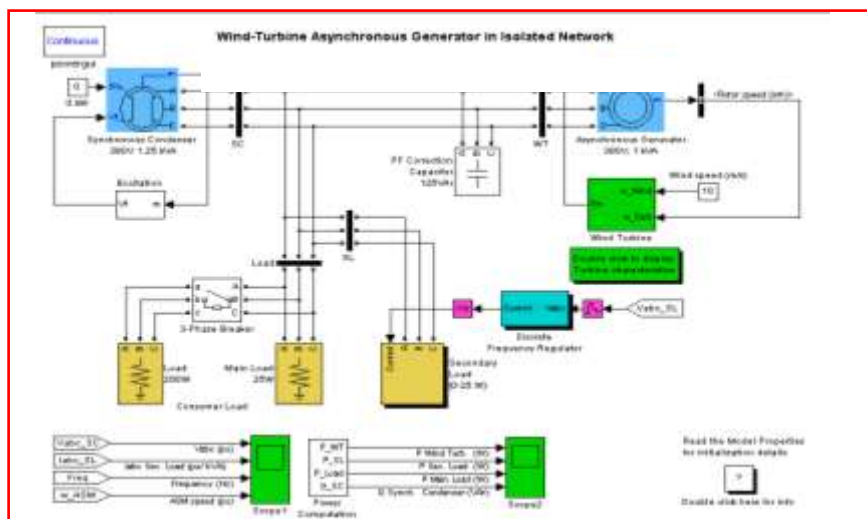


Fig.11. system model using MATLAB/ Simulink

VI. SIMULATION RESULTS

The relationship between the per unit AC three phase source voltage and time is shown in Fig.(12). The relationship between the per unit secondary load

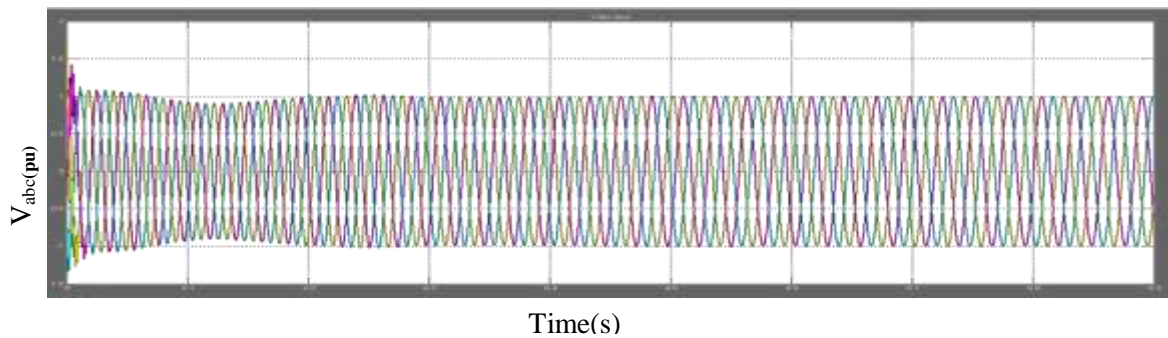


Fig.(12) V_{abc} Vs Time

The relationship between the current with time is shown in Fig.(13).

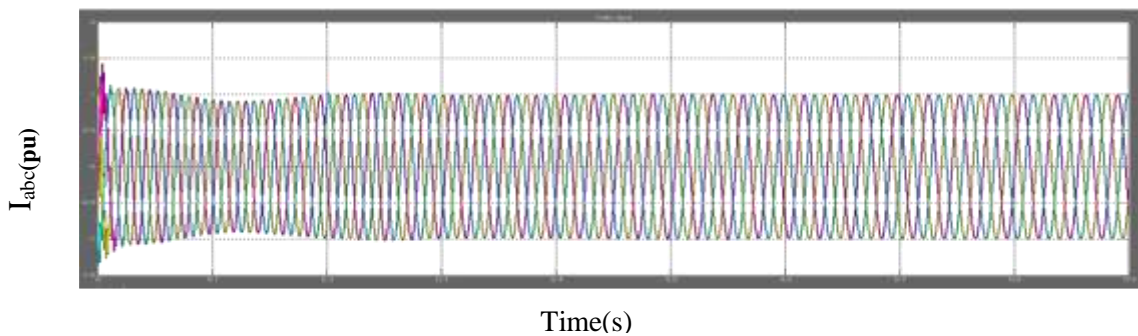


Fig.13 I_{abc} Vs Time.

The relation between the frequency with time is shown in Fig.14.

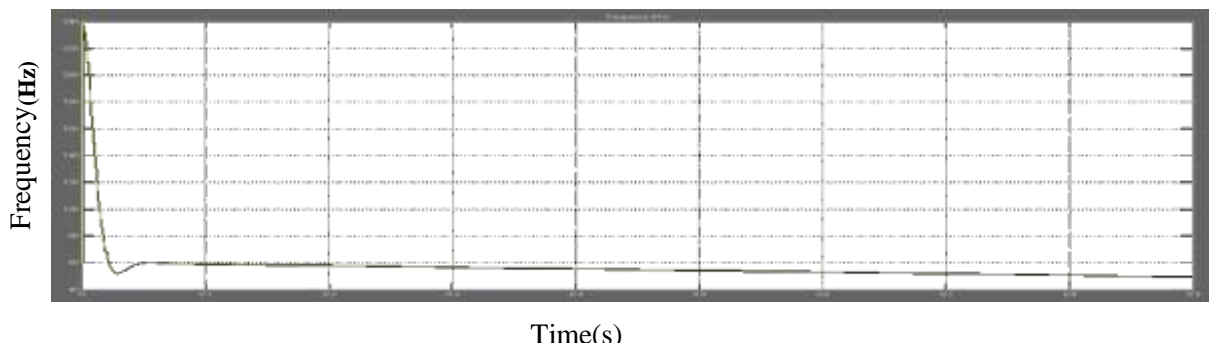


Fig.14.The variation of frequency with time

The relationship between the per unit wind-turbine speed with time is shown in Fig.15.

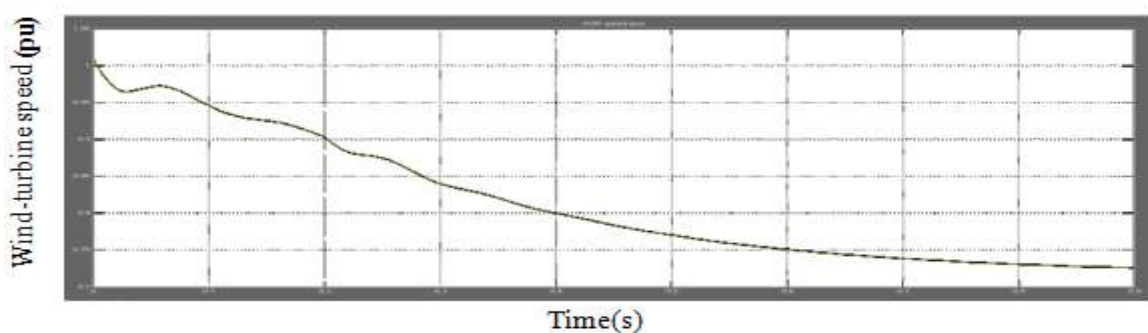


Fig.15.Wind-turbine speed Vs time

The relationship between the power of wind-turbine and time is shown in Fig.16.

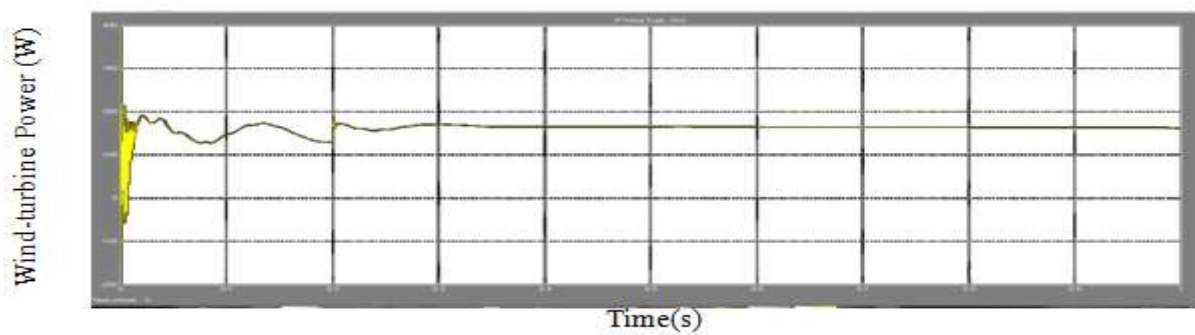


Fig.16. the variation of Wind-turbine power with time

The relationship between the secondary load power and time is shown in Fig.17.

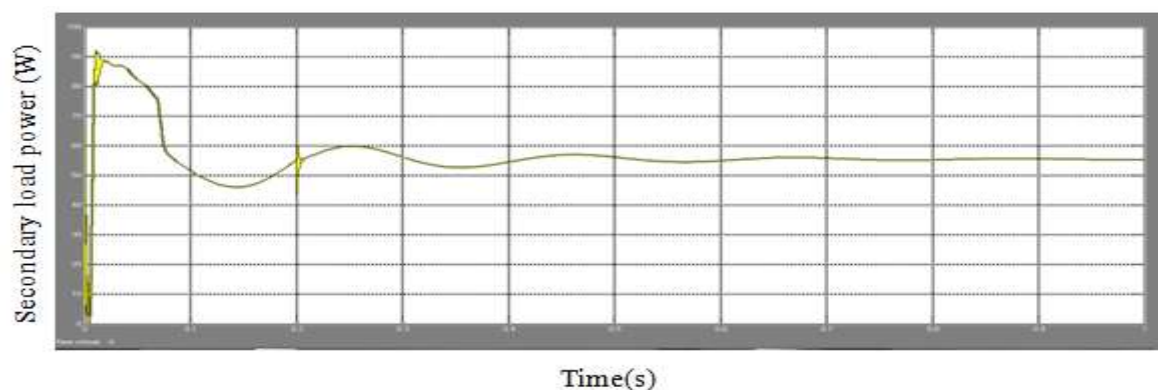


Fig.17. The variation of secondary load power with time

The relationship of main load power with time is shown in Fig.18.

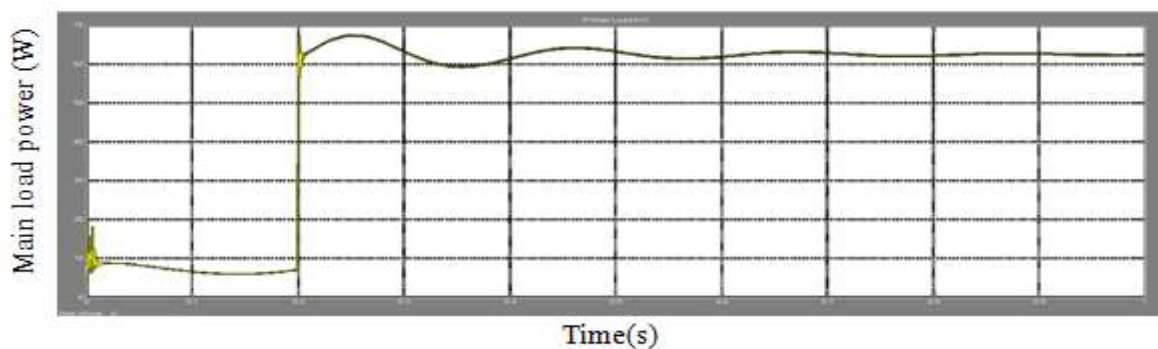


Fig.18. The variation of main load power with time

The relationship of reactive power for synchronous condenser with time is shown in Fig.19.

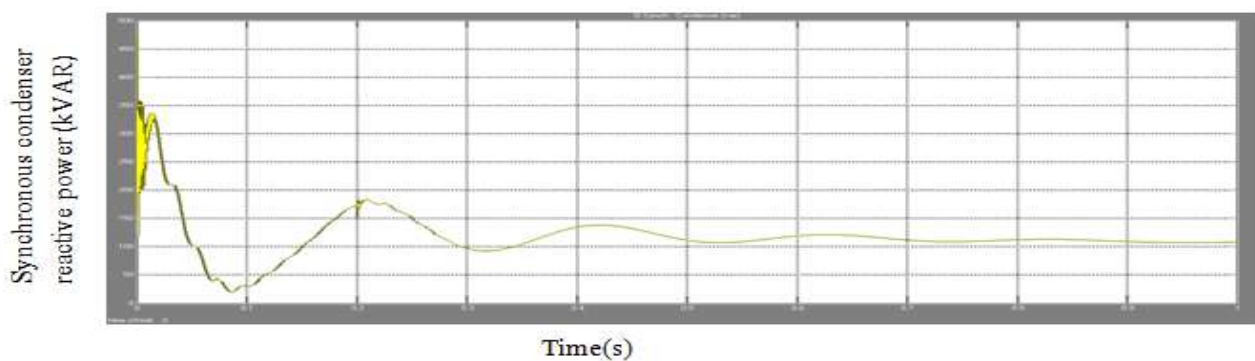


Fig.19. The variation of reactive power for synchronous condenser with time

CONCLUSION

This paper discusses the modeling and performance of a permanent magnet generator to be used with small scale (1kW) wind turbine. The application of power electronics in small scale wind turbine shows that the wind turbine behavior is improved by using power electronic bridges as they are able to act as a contributor to the frequency and voltage control by means of active and reactive power control. Also it can be concluded that the power scaling of wind turbine is an important factor that can affect the reduction of energy cost.

REFERENCE

- [1]. Windmill, "in Microsoft Online Encyclopedia" <http://encarta.msn.com>, 2004.
- [2]. Sudria, A., Chinders, M., Sumber, A., Gross, G. and Ferrer, F. "Wind Turbine operation in power system and grid connection requirements", Center for technological innovation in static converters and drives CITCEA, universitat politecnica de catalunya.
- [3]. Bumby, G.R., Stannard, N. and Martin, R. "A permanent magnet generator for small scale wind turbine"
- [4]. Chalmers, B.J., Wu, W. and Spooner, E., "An axial flux permanent magnet" generator for a gearless wind energy system", IEEE Trans. On Energy Conversion Vol. 14, No. 3, June 1999, pp 749-753.
- [5]. Bumby, J.R., Martin, R., Spooner, E., Brown, N.L. and Chalmers, B.J. "Electromagnetic design of axial flux permanent magnet machines", Proc. IEE – Electrical Power Applications, Vol. 151, No. 2, March 2004, pp 151-160.
- [6]. Bumby, J. R. and Martin, R. "Axial-flux permanent-magnet air-cored generator for small-scale wind turbines", Proc. IEE – Electrical Power Applications, Vol. 152, No. 5, September 2005, pp 1065-1075.
- [7]. Windy Boy Grid Connect Inverter", <http://www.smaamerica.com/windyboy.html#2500>, November 30th 2004.
- [8]. Mohan, N., Underland, T.M. and Robbins W.P. "Power Electronics Converters, Applications and Design", John Wiley and Sons, Third Edition, 2003, ISBN 0-471-429078-2.