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Wind Turbine Generation System Implemented with a Claw Pole Alternator

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Abstract: One of small wind turbine expensive constituents is its generator. The automotive alternator is considered as a cheaper alternative for generators in small wind turbines. In this paper, an off-the-shelf recycled automotive claw pole alternator is modeled with an assumed small wind turbine. The wind turbine’s characteristics have been designed to match the power requirements of the alternator. The dynamic response of the alternator to wind speed variations is modeled in Matlab/ simulink and the effect of turbine blades’ inertia on the generator speed and by extension on the wind turbine’s performance coefficient indicates the need for a speed control mechanism to attain turbine optimal power operation. Other requirements for adaptation of the claw pole alternator are investigated and discussed in this paper.

Keywords: Claw Pole Alternator, Wind Turbine Matlab/ Simulink Model, Small Wind Turbine, Wind Power.

I. INTRODUCTION

For developing countries, availability of affordable clean energy is required as a driving force for development. The cost of transporting energy to some regions is quite expensive and it may be cheaper to locally produce the energy to be consumed in the region. The use of small scale energy ranges from domestic purposes such as home entertainment, cooking, computing, lighting to commercial applications such as telecommunication equipment in Base stations. The availability of this energy can give better quality of life to residents of remote locations. More remote villages can be integrated to the telecommunication network because of reduced capital cost of installing equipment. Specifically considering the telecommunication service providers, the periodic cost of fuelling internal combustion engines at remote base stations can be saved while zero pollution is also achieved with small scale wind turbines. Many small wind turbines have been developed but market penetration has been slow or even non-existent in developing countries because of lack of local maintenance and high cost of the product.

One of the goals of this thesis is to explore more affordable small wind turbines with easily accessible spare parts and maintenance. The possibility of using automotive alternators (also known as claw-pole alternators or Lundell alternators) for wind turbines has been indicated. Typical passenger vehicle and light truck alternators use Lundell or claw-pole field construction, where the field north and south poles are all energized by a single winding, with the poles looking like fingers of two hands interlocked with each other. The claw pole alternators have been in existence for more than 50 years and are currently being manufactured at cost effective price. They are easily available in auto spare part shops and are quite affordable. The application of claw pole alternators in small wind turbines could make the construction and availability of such turbines feasible in developing societies where stable grid power is still unavailable [1].

II. SMALL WIND TURBINE SYSTEM

Small wind turbines are an attractive alternative for off-grid electrification and water pumping, both as stand-alone applications and in combination with other energy technologies such as photovoltaic, small hydro or Diesel engines. While all wind turbines, both MW-class utility turbines and small wind generators, are subject to the fluctuating nature of the wind, there are several reasons why it is more difficult to guarantee the performance of a small wind turbine. First, the smaller inertia of rotor/generator leads to significant transient effects in response to changing wind speeds. Moreover, often small wind turbines rely on passive mechanisms for aligning the rotor with the wind direction, such as lifting forces acting on a tail vane in the case of an upwind rotor or axial (drag and lift) forces acting on the rotor in the case of a downwind turbine. Therefore, under conditions of varying wind directions, an incomplete alignment of wind turbine and wind direction may occur, and the alignment error can be expected to be a function of the turbulent time scales present at the site [2].

Small scale turbines for residential use are available; they are usually approximately 2.1–7.6 m in rotor blade diameter and produce power at a rate of 300 to 10,000 watts at their rated wind speed. Some units have been designed to be very lightweight in their construction, e.g. 16 kilograms allowing sensitivity to minor wind movements and a rapid response to wind gusts typically found in urban settings and easy mounting much like a television antenna. Small wind turbines can be used to generate electricity to charge batteries, to power DC or AC loads and for grid connection. The electricity generated by small wind turbines can be used for either autonomous (off-grid) applications or grid connected applications as shown in Fig.1. Off-grid systems are not connected to any larger generating system while grid-connected systems (distributed generation) are connected to a larger distribution (utility) network. The greatest potential for small wind turbines lies in off-grid systems, particularly in developing countries with many remote households far from the nearest grid and where the expected revenue derivable from grid extension is often too small to justify the huge capital investment. The major drawback of such system is that a storage system is required since wind is not present at all times. As a result batteries are included so that excess generated electricity can be stored during periods of high winds and to provide electricity during periods of low and no wind.

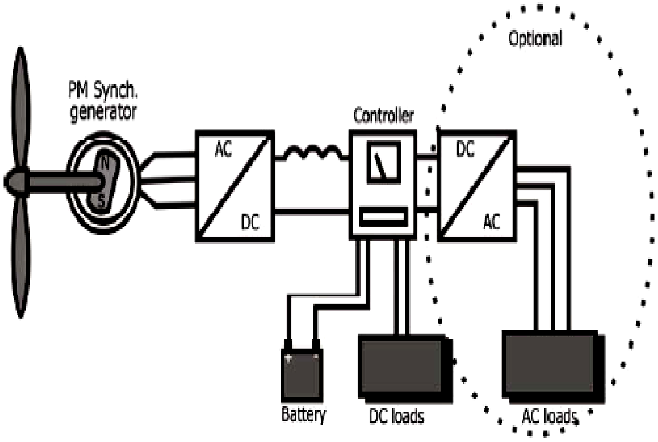

Fig.1.Off-grid wind electricity generation [3].

Table I summarizes the various applications of small wind turbines which can be broadly grouped into off-grid applications. The most traditional use of small wind turbines is in isolated (off-grid) applications such as rural electrification, water pumping, telecommunication sites and farms. Small systems of less than 1kW are commonly used as DC systems in which generated energy is stored in a battery and used to supply DC loads. Just like large wind turbines most modern small wind turbines use a three-bladed rotor with aerodynamic sections (airfoils), although designs with two or four blades are occasionally encountered.

An important distinguishing feature of a wind turbine is the tip speed ratio. The tip speed ratio is a measure of the relation between the rotor blade tip speed and the wind speed. This ratio plays a crucial role in determining the efficiency of the wind turbine. To utilize power in the wind efficiently the rotor has to have suitable rotational speed relative to its size (rotor diameter) and wind speed. Tip speed ratio of a wind turbine depends on the number of blades: fewer blades implies high tip speed ratio. This implies, for instance, that for turbines with the same rotor diameter, 2-bladed turbine needs a higher rotational speed than a 3-bladed turbine.

Optimal tip speed ratio can be calculated for different rotor types. Wind turbines with low tip speed ratios are suitable for low speed applications such as water pumping and other mechanical uses. High tip speed ratio wind turbines are suitable for electricity generation [2].

TABLE I: Applications of Small Wind Turbines [4]

Power rating	Off-grid applications							
P < 1kW	+		+	+	+	+		
1kW < P < 5kW	+	+	+	+	+	+	+	
5kW < P < 50kW		+				+	+	+
50kW < P < 100kW							+	+
Small wind turbine applications	Battery charging	Water pumping	Street lighting	Water purification	Remote houses	Farms	Village electrification	Mini grid

An expression generally used to describe the power harnessed by a 3-bladed horizontal axis wind turbine from the wind is:

$$P_w = \frac{1}{2} C_p(\lambda, \theta) \pi r^2 v^3 \rho \tag{1}$$

Where,

P_w = Wind mechanical power
$C_p(\lambda,\theta)$ = coefficient of performance: function of λ and θ
λ = tip speed ratio
θ = pitch angle of rotor blades
πr^2 = rotor blade swept area where r is rotor radius
v = wind velocity
ρ = air density

$$\lambda = \frac{r\omega_G}{vG} \tag{2}$$

Where,

G = Gearbox ratio,
ω_G=Generator rotor speed

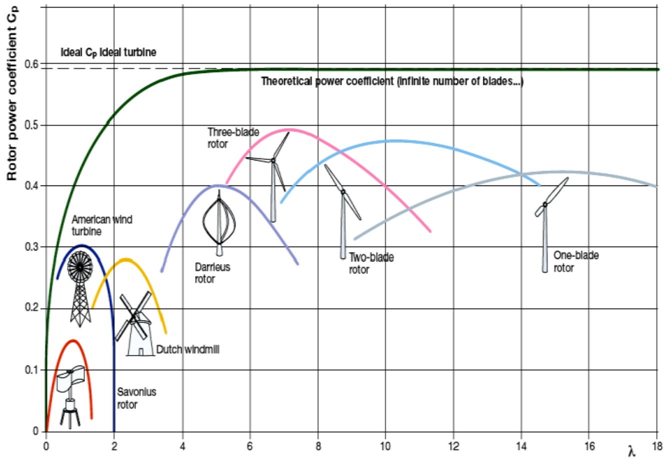

Fig.2.C_p–λ Characteristics of different wind turbine blade designs [1].

Wind turbine coefficient of performance (C_p) is dependent on the ratio of the turbine's blade tip speed to the wind velocity (λ or TSR). It is also dependent on the turbine's blade pitch angle (θ). An illustration of the relationship between C_p and TSR for different wind turbines types is shown in Fig 2. The 3-bladed turbine is seen to have the highest coefficient of performance at an optimal tip speed ratio [1].

III. CLAW POLE ALTERNATOR

The alternator is used in automobiles for supplying electrical power. It consists of a rotor mounted on the two end bearings of the machine frame, a stator, six diodes, and a regulator. The type of generator used in the automotive alternator is a wound-field three-phase synchronous generator. Its rotor is made of iron pole pieces and many turns of fine wire, which are mounted over the shaft of the machine. The rotor coil leads are traced out through slip rings and brushes to the external circuit. When the rotor coils are energized, an electromagnetic field is produced. This magnetizes one set of six teeth claw poles at magnetic north and the other set at magnetic south. The stator of the alternator consists of a three-phase winding usually connected in star. The output of the stator is fed to the three-phase rectifier made of six semiconductor diodes to give a DC voltage and then regulated to battery voltage. The regulator begins to function when the alternator reaches cut-in speed, which is approximately 1000 rpm at its shaft. The output voltage of the alternator increases linearly with speed if field current is maintained constant.

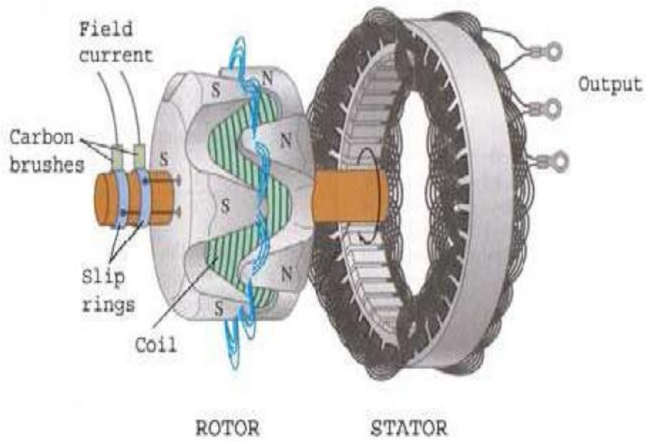

Fig.3. Exploded view of an automotive alternator [1].

Automotive alternators are designed to yield nominal voltage for charging the vehicle's battery at the vehicle's idle speed; at higher speeds, if the voltage is not regulated, it would result in a very high over-voltage for the battery. Fig.3 shows a conventional alternator rotor and stator. In the automobile, the voltage is controlled by an internal regulator that continuously samples the battery voltage and adjusts the field current accordingly. The field current is controlled by varying the duty-cycle of the pulse-width modulated (PWM) voltage applied to the field winding. This is illustrated in Fig.4. As the electrical load increases (more current is drawn from the alternator), the output voltage falls. This drop in output voltage is detected by the voltage sampler which increases the duty-cycle to increase the field current and hence raise the output voltage. Similarly if there is a decrease in electrical load (the output voltage climbs), the duty cycle decreases to reduce the output voltage.

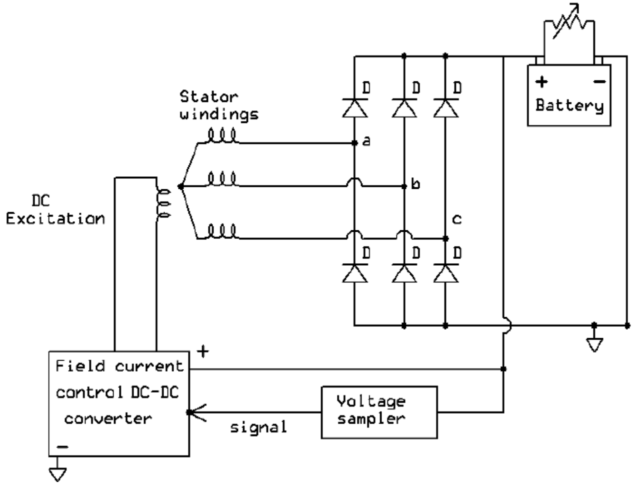

Fig.4. Circuit equivalent of the automotive alternator system.

Automotive alternators are classified according to the output voltage/current characteristics and the field winding adjustment whereby the optimal point of operation will be dependent on the most frequent speed of the prime mover. Currently, the voltage output of automotive alternators is 14V for small cars and 28V for trucks and bigger cars. The maximum alternator output is limited by heating of the rotor and stator windings and by magnetic saturation of the machine. Conventional alternators used in automobiles are limited to about 1.5kW maximum output power at 9000 rpm. The peak efficiency for an alternator tends to occur at 30-40% of its maximum output which corresponds to shaft speed between 2000-2500 rpm. [1]

IV. MODELING OF PROPOSED SMALL WIND TURBINE SYSTEM

The horizontal axis wind turbine is preferred for this application because of its higher performance coefficient. The gear system to be used is the chain drive system because of its preferred characteristics. The field current control will consist of constant current supply from a battery at start up while the alternator will supply its own field current during running.

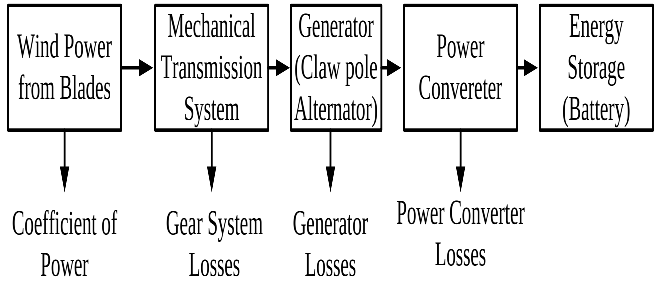

Fig.5.Model block diagram.

A centrifugal switch would also be used to automate the field winding at suitable wind speeds. The DC chopper is proposed as method of maintaining maximum point operation of the turbine. The system parts can be blocked together to yield an overall proposed system as described in Fig.5. For the purpose of this design, a cut-in wind speed of 2.5m/s is used with a gear ratio of 1:10. This corresponds to a cut in shaft speed of $\frac{2.5m/s}{(4/2)m} \times \frac{1}{1/60} \times 10 = 750\,rpm$ at the alternator. The cut out wind speed is set at 25 m/s (6000 rpm). The alternator has the inherent quality of running at very high speeds (as high as 8000 rpm) without disintegrating.

TABLE II: Assumed Three Blades Rotor Wind Turbine Parameters

Rotor blade diameter (2r)	4 m
Rated wind speed (v_r)	5 m/s
Rated alternator speed ($\omega_{G,r}$)	157 rad/s (~1500rpm)
Rated shaft input power to alternator(mechanical power)	1.5 kW (from chosen Generator)
Rated alternator output power	0.6 kW(from chosen Generator)
Optimum tip speed ratio or blade tip speed divided by wind speed (λ_{opt})	6.5(from Fig2 can be selected between 5.5 and 11.5)
Maximum aerodynamic coefficient ($C_{p,max}$)	47% (from Figure 2 can be selected between 0.33 and 0.49)
Air density (ρ)	1.225 kg/m^3

TABLE III: Claw Pole Alternator Parameters

Parameters	Values
N_S (stator copper turns)	36
k_w winding factor	0.8
τ_p pole pitch (m)	0.025
l_S stator stack length (m)	0.04
α_p π/2 (degrees)	59.4
N_f (field copper turns)	400
l_g air-gap length (m)	0.00035
$k_S k_C$ Saturation factor & Carter factor	1.3
μ_0 air permeability (H/m)	1.26E-06

Other assumed parameters of the wind turbine are indicated in Table II. For the optimal tip speed ratio and power coefficient, a suitable turbine diameter that harnesses rated wind power (shaft input power) for the generator is computed. The wind turbine converts wind velocity to mechanical power obtainable from the wind. This conversion is based on Equation (1).The constituents of the wind turbine block are shown in Fig.6. The alternator is a 12-pole synchronous generator with salient poles. In a salient pole synchronous machine, if the excitation is varied over the normal operating range, the effect of the saliency on the power or torque developed is not significant. Only at low excitation does the power or torque due to saliency become important. Cylindrical-rotor theory can also be used for salient pole machines except at low excitation or when high accuracy is required. The main parameters that describe the characteristics of the claw pole alternator are described in Table III. The voltage regulator and claw pole alternator model are described in Fig.7 and the complete model is showed in Fig.8.

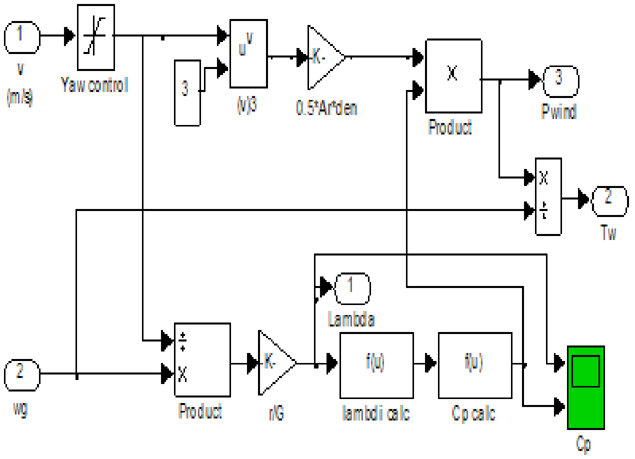

Fig.6. Wind turbine model.

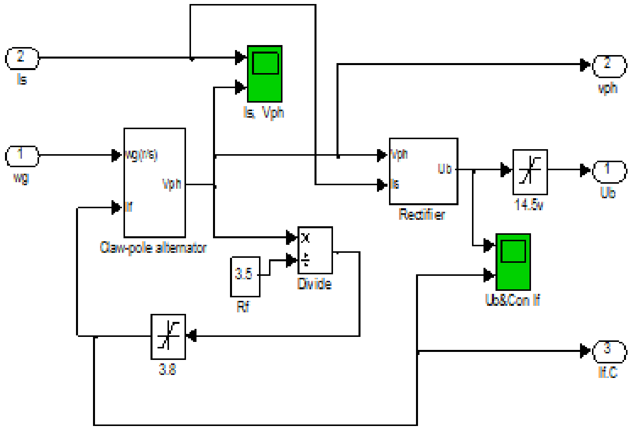

Fig.7.Regulator and alternator model.

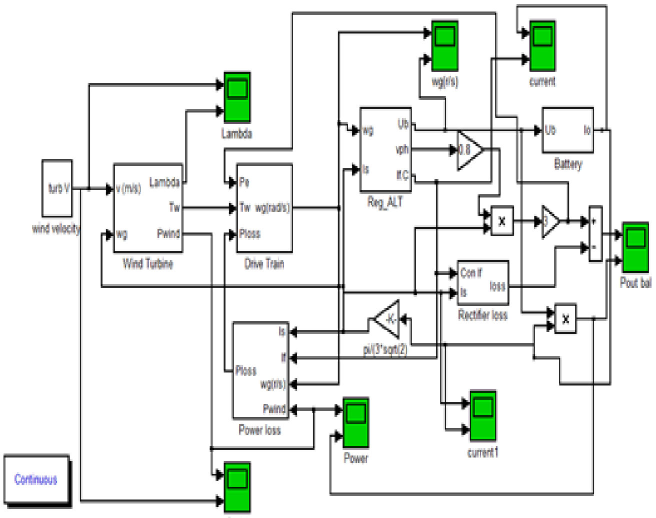

Fig.8. The complete small wind turbine model.

V. SIMULATION OF PROPOSED SMALL WIND SYSTEM

The simulation was run with the oscillating wind speed for a 30-seconds-duration. The wind profile and tip speed ratio is shown in Fig.9.

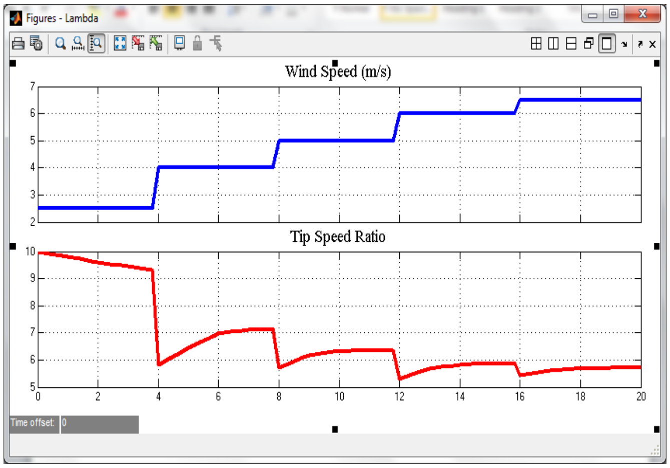

Fig.9. Wind speed profile and lambda.

It can be observed the tip-speed ratio oscillates abruptly as wind speed changes. This is because the generator shaft acceleration is slower than wind acceleration. This is due to the effect of inertia on the shaft speed which alters the tip speed ratio of the turbine and concurrently shifts the wind turbine from operating at the optimal power coefficient. Fig.10 shows the wind power output from turbine and wind speed. The output voltage from the alternator rises almost instantaneously to battery charging voltage at a cut-in shaft speed of 2.5 m/s. The alternator's inbuilt regulator controls the field winding in order to keep the voltage output suitable for battery charging. The generator torque provides some damping for the alternator speed and keeps it from overshoot during wind speed changes. Fig.11 shows the rectifier output voltage and field current regulating during 25 second wind speed changing. In Fig.12, the comparison of wind power output and the battery input power is shown.

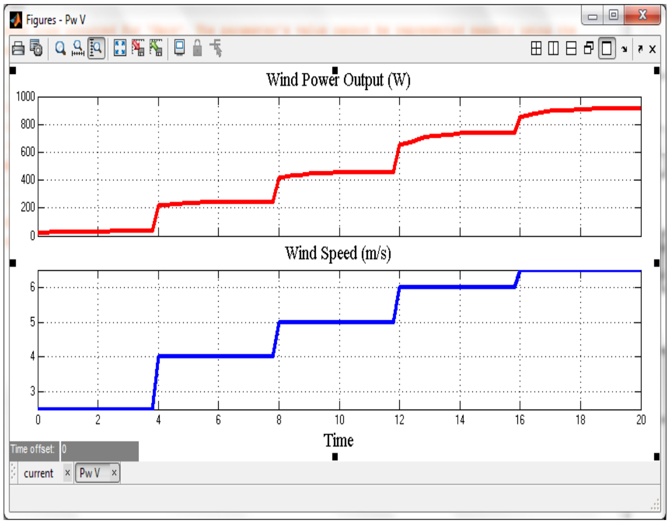

Fig.10. Wind power output and wind speed.

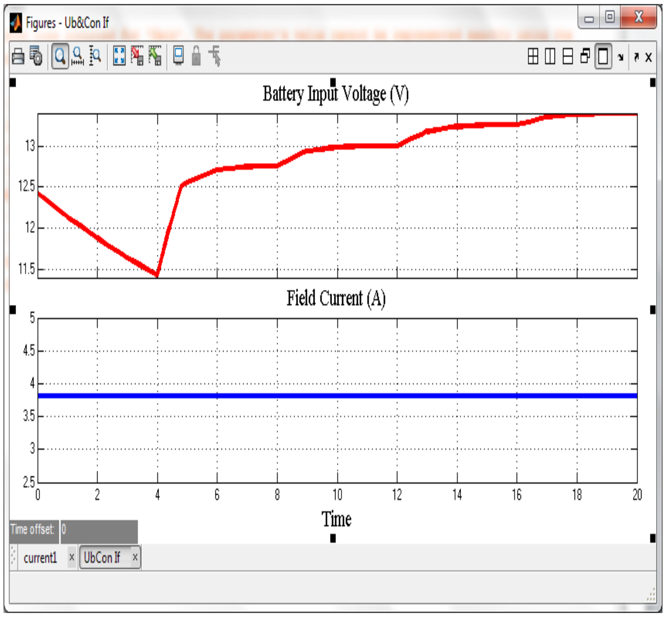

Fig.11.Rectifier output voltage and field current of alternator.

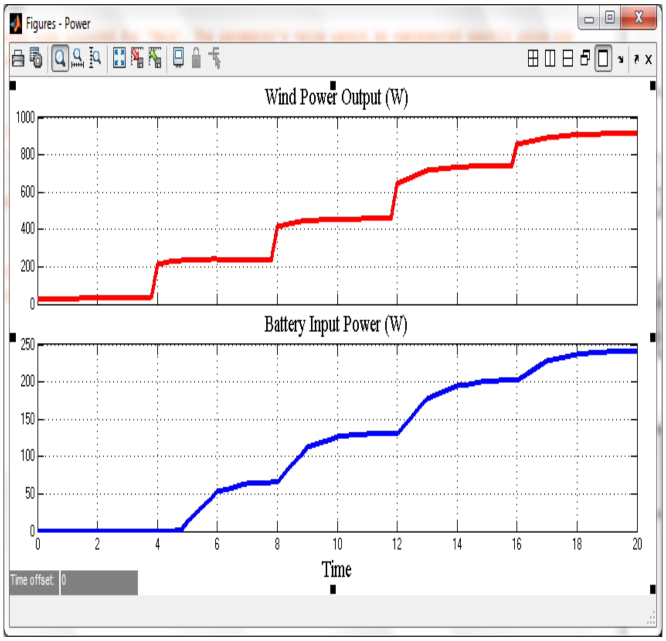

Fig.12.Wind Power Output and Battery Input Power.

VI. CONCLUSIONS

This paper presents the feasibility of using a recycled automotive claw pole alternator in a small wind turbine has been evaluated. The field winding is supplied from the battery at start up and self supplied from the alternator during running. In order to automate this system, a centrifugal switch or speed switch installed on the shaft would be necessary for switching 'on' the field winding when sufficient wind speed is attained and 'off' when there is insufficient or excessive wind speed. Claw pole alternator speed lag and shifts the tip-speed ratio from optimal point there by reducing the power coefficient of the turbine. This leads to lower power harnessed from the wind. The model also indicated that the machine's inherent power losses provided sufficient load torque to keep the generator speed from overshoot that may occur due to the effect of inertia of the turbine's blades. Adapting the gear ratio to a lower value showed that optimal operation could be attained possibly because generator speed is more in phase with wind speed for optimal tip-speed ratio. However, if a different battery with a different charge capacity is to be connected at output, the wind turbine will cease to operate at optimum because the torque balance for which the gear ratio fits will be lost.

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