Design and Testing of a Low Cost Peak-Power Tracking Controller for a Fixed Blade 1.2 kVA Wind Turbine

Horizon Gitano, Soib Taib, and Mohammad Khdeir

Abstract – **Wind turbines are a common source of electrical power generation in rural sites around the world. The power generated by a wind turbine at a given wind speed is a non-linear function of rotor speed. This results in a specific rotor speed for maximum power production at each wind speed. A control system incorporating a Pulse Width Modulated DC-DC converter has been designed to vary the load on the wind turbine thereby forcing it to operate at its maximum power point. Another important feature of the controller is the application of electrical stall-breaking of the turbine. The circuit was then tested on a turbine test bed simulating various wind speeds, and the "peak-power tracking" capability and electrical breaking capability were verified. The system gave an overall efficiency of 70 to 80% over a wide range of wind speeds and PWM duty cycles.**

Index Terms − **Wind Turbine, DC-DC converter, Peak Power Tracking, Power Controller.**

I. INTRODUCTION

Wind turbines are widely used for supplying electrical power in isolated areas of high wind. They are considered an excellent alternative to diesel generators being environment friendly. In addition, they are economically competitive in more remote regions requiring no transportation of fuel. Wind electrical generators are composed of a wind turbine, electrical generation unit, controller and the load which may be bank of batteries, electrical pumps, or any other direct current loads [1][2]. The block diagram of a wind turbine system is shown in Fig. 1.

The wind turbine coverts the wind power to shaft power directly spinning a permanent magnet rotor following the design of Hugh Piggott [3]. The stator is a three-phase, Y-configuration rectified to DC inside the electrical generator unit. The controller takes the DC output of the generator and couples it to the load.
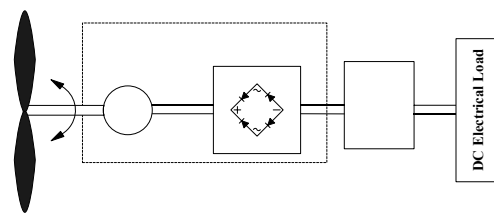
Fig. 1. Schematic diagram of a wind turbine system

The rotor speed changes with time, due to changes in the wind speed. This continuous change of wind speed affects the output power of the system, and thus efficiency [3].

This paper is dedicated to the design of the wind turbine controller. The controller must be able to perform the following tasks:

- Output Power limiting
- Track the peak output power of the turbine at nominal wind velocities by controlling the rotational speed of the rotor
- Provide overspeed protection via an electrical breaking system

The breaking system consists of a dump load which can be directly connected across the generator output via a relay. Several such dump loads may be employed allowing varying levels of speed control, or they can be used for turbine breaking only.

The design of the power tracker is the most critical part of the controller. It must be capable of measuring the output power of the system and adjusting the load on the wind turbine. The output power is measured via a voltage divider in parallel with the load, and a current sensing resistor in series with the load. The load on the generator is varied by adjusting the duty cycle of a DC-DC converter. It updates the measured values periodically, thereby continually adjusting the duty cycle for maximum power extraction.

II. WIND TURBINE CHARACTERISTICS

The output power of the wind turbine is function of wind velocity cubed. It can be described mathematically by (1).

$$P_{Turbine} = 0.5 C_P \rho A V_{wind}^3 \qquad (1)$$

where $P_{Turbine}$, C_P, ρ, A, and V_{wind} are turbine power (Watts), power coefficient (dimensionless), air density (kg/m^3), blade swept area (m^2), and wind speed (m/s), respectively [1][2] and [5].

Both swept area and air density are constants while the controlling of the wind speed is beyond the scope of this paper. Therefore, to maximize the output power of the wind turbine we have to optimize the value of the power coefficient. The power coefficient is a strong, non- linear function of the "Tip Speed Ratio"; as shown in Fig. 2 [5] and [6]. The *Tip Speed Ratio* is the speed of the tip of the turbine divided by the wind speed. For a turbine of radius R, and rotor speed ω_{rotor} the tip-speed-ratio, λ, is thus:

$$\lambda = \frac{\omega_{rotor}R}{V_{wind}} \qquad (2)$$

Where V_{wind} is the speed of the wind at turbine hub height. In order to maximize C_p we vary the load on the turbine to achieve a rotor speed ω_{opt} of:

$$\omega_{opt} = \frac{\lambda_{opt}V_{wind}}{R} \qquad (3)$$

The optimum tip-speed ratio λ_{opt} is a constant dependent on turbine blade design for fixed blade turbines. Thus for every wind speed there will be a different rotor speed for maximum power production. Fig. 3 shows the ideal power produced as a function of rotor speed for several different wind speeds. The goal of our controller is to adjust the rotor speed to operate at its maximum power point for each wind speed [6].

III. THE DESIGN OF THE BUCK CIRCUIT

The basic elements of the buck circuit are shown in Fig. 4. It is composed of single switching element. This makes it simple and more efficient compared to other DC-step-down choppers. The buck circuit provides an average output voltage (V_o) that is less than the average
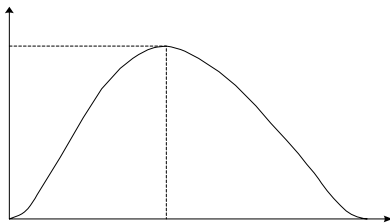

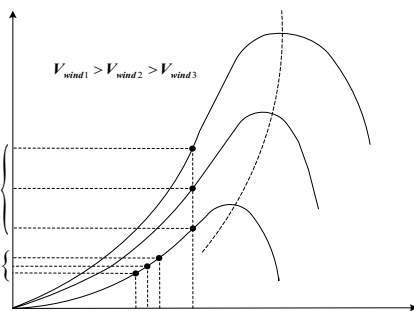Fig. 2. The variation of the power factor with tip-speed-ratio

Fig. 3. Wind turbine characteristics

input voltage (V_i) by a specific factor. This factor is the duty cycle of the circuit (D), which is the ratio of the switching element conduction time to the full period time. The function of the inductor and the capacitor in the circuit is to smooth the output current and voltage, respectively[7].

$$V_o = DV_i \qquad (3)$$

As switching time plays a significant role in the efficiency (η) of buck circuit, it must be considered in the design. According to (4), the higher frequency of the PWM (f) results in a higher efficiency at constant load resistance R_L, and constant duty cycle.

$$\eta = \frac{(t_{ON}f)^2V_i}{R_LI_i} \times 100\% \qquad (4)$$

An *Insulated Gate Bipolar Transistor (IGBT)* is used as the switching element of the circuit. It was chosen because of its ability to handle a higher current as well as its fast switching speed[8]. The IGBT gate is controlled by an IGBT driver. The duty cycle of the driver is determined by the microcontroller, according to the values of the sensing elements in the circuit. To enhance the switching time of the circuit, the freewheeling diode was replaced by a schottky diode[9]. All power components were sized appropriately for 1.2 kVA operation.

The sensing resistors of the buck circuit are used to measure the output power of the system. A very small resistor in series with the load is used to measure the output current of the circuit. In addition, a voltage divider is used to normalize the value of the output voltage into a value between 0 & 5 V for reading by the controller. The final buck circuit is shown in Fig. 5.

Varying the duty cycle of the switching element changes the wind turbine loading level. Zero duty cycle means that the switching element is always OFF and no load is connected to the wind turbine. Thus the maximum rotational speed will be achieved when the duty cycle is zero. Increasing the duty cycle decreases the output impedance of the system, which adds more load to
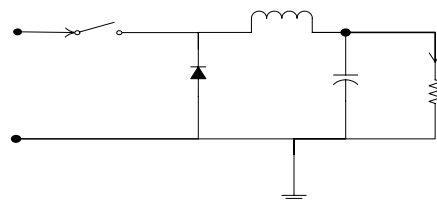
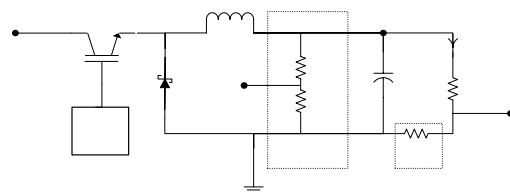

Fig. 4. The basic elements of a buck circuit

Fig. 5. The final schematic of the buck circuit

the wind turbine; thereby slowing the rotor. The rotor reaches the minimum speed when duty cycle is one.

A simple model suffices to determine the relationship between the duty cycle of the dc-dc converter and the expected shaft speed. Assuming a constant power input and efficiency the output electrical power I^2R should also be constant. The resistance is essentially an average between the connected load resistance R (weighed by the switch 'on' time) and an infinite resistance (weighed by the switch 'off' time), thus the effective average resistance is R/D where D is the duty cycle. For a Permanent Magnet (PM) DC motor or generator such as ours, the relationship between the generator current and rotor speed is linear decreasing from the stall current I_{stall} at rotor speed $\omega = 0$, to zero at the unloaded speed ω_{NL}. Mathematically we would write:

$$I = I_{stall} - I_{stall}\left(\frac{\omega}{\omega_{NL}}\right) \qquad (5)$$

Knowing that I^2 times the effective resistance R/D is constant allows us to write:

$$I_{stall}^2\left(1 - \frac{\omega}{\omega_{NL}}\right)^2 \frac{R}{D} = C \qquad (6)$$

Where C is a constant. Rearranging to solve for the rotor speed ω we have:

$$\omega = \omega_{NL} - \omega_{NL}\left(\frac{CD}{I_{stall}^2 R}\right)^{0.5} \qquad (7)$$

This shows that the rotor speed will decrease as the square root of the duty cycle. The factor $\omega_{NL}(C / I_{stall}^2 R)^{0.5}$ represents the speed decrease from ω_{NL} at a duty cycle of unity. If we assume that the load can completely stall the rotor, i.e. $\omega = 0$ at D = 1, then we can rewrite the relationship as:

$$\omega = \omega_{NL}\left(1 - D^{0.5}\right) \qquad (8)$$

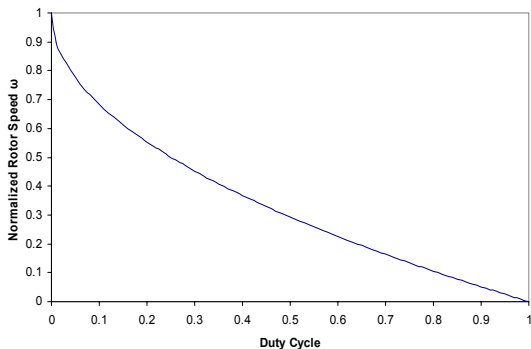This relationship is shown graphically in Fig. 6.

Fig. 6. Rotor speed versus duty cycle for an ideal DC-DC converter and load

IV. BRAKING SYSTEM

Some environmental conditions, for instance hurricanes, include very high wind speeds. This may result in runaway and destruction of the wind turbine. Additionally, it may be a necessary to stop the wind turbine spinning, if there is a mechanical or electrical fault or even during preventive maintenance. Thus some kind of braking system for the wind turbine is required.

Many turbines include a mechanical braking design (i.e. furling or tilting the axis of the turbine away from incoming wind). Alternatively, frictional beaks may be incorporated into the wind turbine. The disadvantage of such system is the short life expectancy and additional system cost and complexity [4] and [10]. Another option is to provide electrical braking. Under high wind conditions heavy dump loads may be connected directly to the generator to slow the turbine enough causing the blades to "stall" aerodynamically. Once stalled, the torque produced by the turbine is greatly reduced, and it spins at a very slow speed [4].

The braking system design is shown in Fig. 7. It consists of a relay that will connect the voltage of the generator to a dump load upon the triggering of its coil. In sufficiently strong winds the generator output will exceed a pre-set trigger level (i.e. breaking threshold). Even while charging the nominal load, the controller measures the generator voltage via a voltage divider into analogue input channel. When the generators voltage exceeds the breaking threshold, the breaking relay is activated, connecting a high power, low resistance dump load directly to the generator output.

The purpose of adding anti-shock inductor in series with the dump load and the generator voltage is to avoid arcing at the contacts.

Stalling the wind turbine to avoid run away is the primary purpose of the breaking system. It can also be used to avoid the over charging the load (i.e. batteries) when the output voltage of the buck circuit is too high. The presence of different dump loads is helpful in the partial reducing the turbine power to the load by converting it to heat in the dump loads. Alternatively some useful loads (such as pumps) can be used as dump loads, only being actuated at high wind speeds. The response of the braking circuit is shown in Fig. 8. Breaking is initially overridden manually, and the generator is allowed to run over the breaking threshold limit, which for this test was set at 11.8V. At approximately 7 seconds breaking is re-enabled, and the controller immediately goes into breaking mode, reducing the rotor speed to less than 30 rpm. At intervals of approximately 10 seconds the controller releases the breaks allowing the turbine to spin up until the threshold is again exceeded, and breaks are reapplied. This continues until the wind speed is reduced below the breaking threshold, and normal operation ensues.
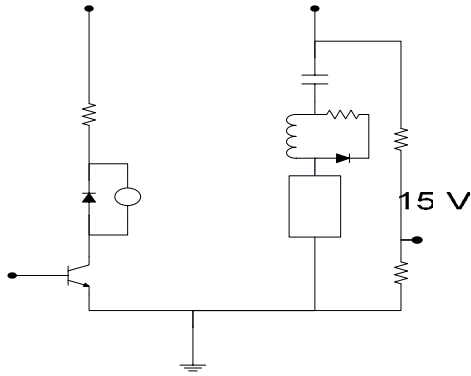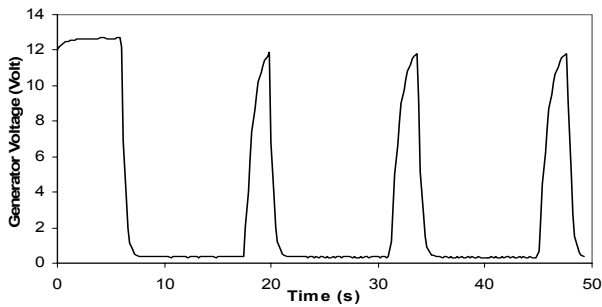
Fig. 7. The schematic of the braking circuit

Fig. 8 Braking system response at a threshold of 11.8 V

V. THE MICRO-CONTROLLER

The micro-controller is responsible for measuring the input voltage and the output power of the wind turbine, and then making decisions based on the readings. The controller used for this project is PIC16F818.

The important features of this controller are the built-in PWM generator and five analog-to-digital converter channels. The frequency of PWM is held constant, but the duty cycle is controllable either automatically or manually depending on the running mode of the program.

The sequence of the program operations is shown in Fig. 9. The controller was programmed to operate in two different modes: Test Mode and Auto-Run Mode. The user can select between them via a switch. Under the test mode, the duty cycle is varied manually through two push buttons. One button is used to decrease the duty cycle and another is used to increase it. The purpose of this mode is to allow flexibility for taking data.

The auto-run mode is used in normal operation. In this mode the duty cycle is continuously incremented by an amount *Step*, which may be either positive or negative. Initially the duty cycle is set low with a positive *Step*. At each cycle of the program execution the output power is measured and compared to the previous cycle's power. If the current power value is less than the power at the previous cycle, then the sign of *Step* is reversed. In all cases, the duty cycle is then incremented by the value of *Step*, which may actually be negative, thereby decreasing the value of the duty cycle.

This "gradient" method will result in operation around the peak of the power curve, and will also allow quick adaptation to varying wind speeds without measuring either wind speed or turbine RPM directly.
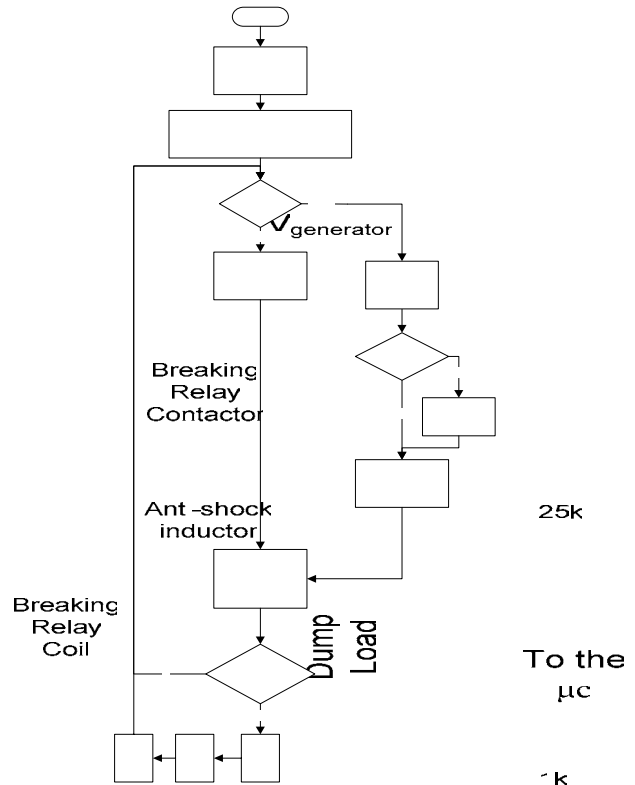

Fig. 9. Program flowchart

Some of the variables are initialized in the beginning of the program as following:
- Duty Cycle: 7%
- Step size: +7, positive sign means increase
- Read initial value of the power on the first run of the controller
- Set the breaking threshold voltage.

VI. TEST BED

Our controller is being designed for implementation on a fixed-blade horizontal-axis wind turbine in Mozda, India [3]. Lacking direct access to the target wind turbine we built a test bed which has a similar characteristic to that of the wind turbine, though at lower power levels.

The test bed is composed of DC motor that drives two phase AC generator. The output AC voltage is rectified and filtered using a diode bridge and a capacitor. The output DC voltage of the test bed is simulating the output DC voltage of the wind turbine. DC power supply which feeds the DC motor simulates the wind speed. The differences between our test bed and the wind turbine are shown in schematically in Fig. 10.
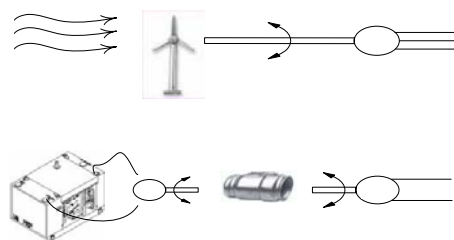

Fig. 10. Differences between the test bed and the turbine

Several tests were performed on the test bed. First, it was necessary to ensure that the test bed has a single maximum in the power curve at a constant supply voltage. Secondly, we wanted to verify that the peak in the power curve changed as a function of input power. Fig. 11 and Fig. 12 show the difference in behavior at different power supply conditions and they prove the presence of distinct peaks at different simulated wind speeds.

The initial testing of the DC-DC controller was aimed at establishing the relationship between duty cycle and rotor speeds at a constant load resistance and supplied current to the DC motor, i.e. simulated wind speed. As can be seen in figure 13, varying the duty cycle has a strong influence on the rotor speed of the test bed. At the tested load and supply configuration the rotor speed was reduced from 2250 rpm at 5% duty to 515 RPM at a duty cycle of 85%.

VII   POWER TRACKING TESTING

The controller was tested on the test bed to prove its ability to track the maximum power. Two tests were done initially using the auto-run mode to prove the ability of the controller to track the power starting from different values of the duty cycle. The duty cycle in the first test, shown in Fig. 14, starts from the highest duty cycle. At 100% duty cycle with the given load and simulated wind speed the rotor is turning at less than 500 RPM. The circuit decreases the duty cycle, allowing rotor to speed up and increasing the output voltage, and thus power. This
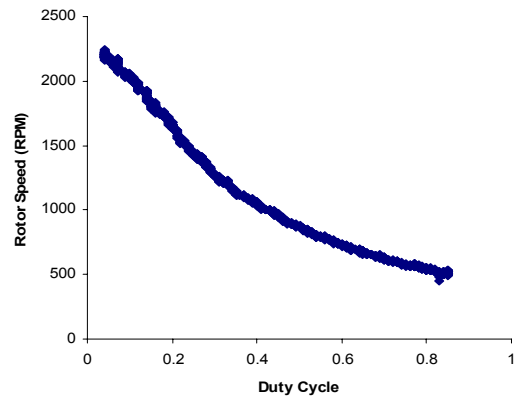
Fig. 13. The effect of the Duty cycle on the rotor speed in the test bed

direction is continued for several program cycles until the peak power is passed at around 1000 RPM. The controller then wanders back and fourth about this peak power output.

Fig. 15 shows another run beginning at very low duty cycle. As the test bed is lightly loaded it operators at high speed (2300 RPM), because the duty cycle is low the output voltage is also low (around 7V). As the duty cycle is increased the test bed is loaded, slowing down, and the output voltage increases. Again this continues until the system is operating near the peak power output at approximately 1250 RPM, 13.5V. Some scatter in the output data can be seen. This is due to the mechanism system dynamics. Once-the duty cycle is changed the electrical output increases nearly instantly. The increased load does not immediately change the rotor speed, however, due to rotor inertia. Thus each step up in duty cycle results in an 'arc' up (as voltage output increasing) and to the left (as the system gradually slows to a new steady state operating point). Similarly decreases in duty cycle will result in arcs down and to the right. As data was taken continuously during operation, these 'arcs' then deviate from the actual steady-state operating curve.

Fig. 16 shows the system response to varying simulated wind speeds. Initially the system is started at low duty cycle (the nominal start condition) and it quickly stabilizes at the optimum power point near 1200 RPM and 13.5V output. The DC motor is then given less power simulating a second wind speed and the system again stabilizes as the new peak power, now 900 RPM and 12V. Finally, a lower wind speed is tested and the system finds a peak power at 500 RPM and 10.2 V.
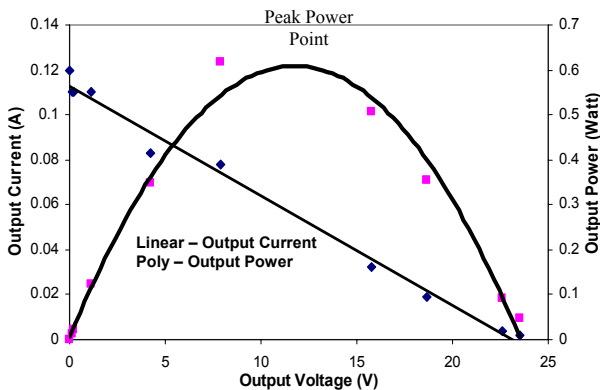
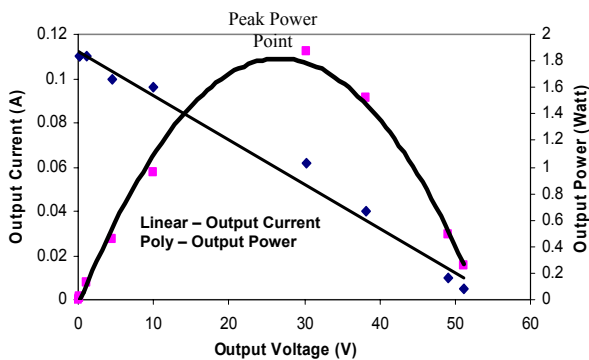Fig. 11. Test Bed response for variable resistive load at low simulated wind speed

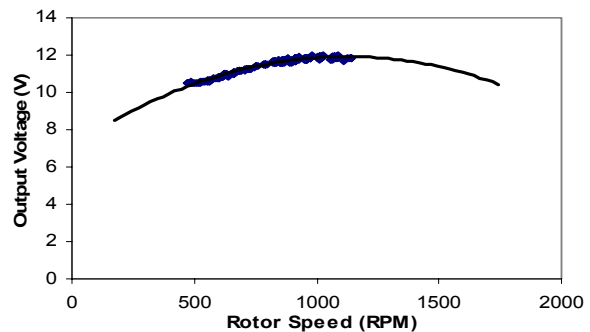Fig. 12. Test Bed response for variable resistive load at higher simulated wind speed.

Fig. 14. Auto Power tracking starting from high duty cycle at constant load
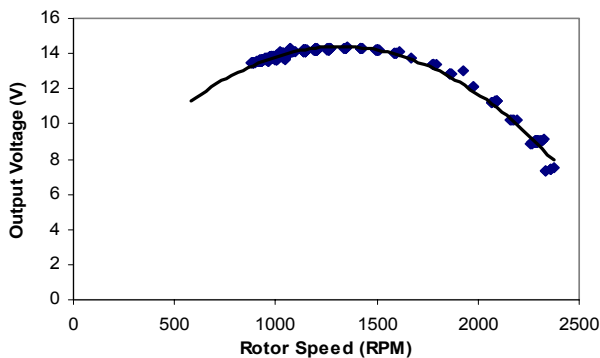
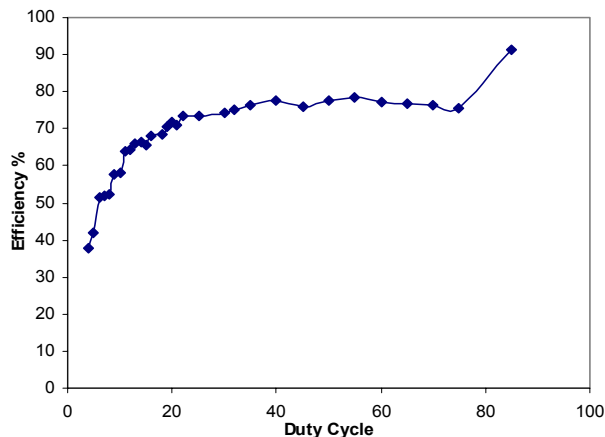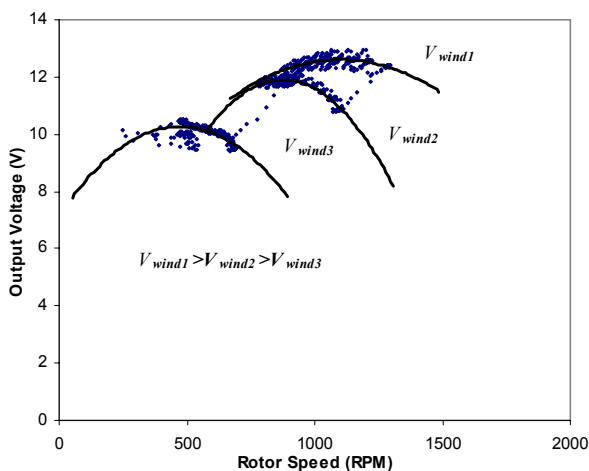Fig. 15. Auto Power tracking starting from low duty cycle at constant load

Fig. 16. Auto power tracking at different simulated wind speeds and constant load

Fig. 17 shows the efficiency as a function of duty cycle. The efficiency varies non-linearly with duty cycle at constant load, and constant PWM frequency. The inductor has a significant effect on the efficiency, because of its influence on the output current [9], and it will suffer I^2R losses as well. The change in the efficiency can be divided into three stages. At very low duty cycles, less than 20%, the discharge time of the inductor is less than the OFF time of the pulse width modulation signal. This results in a discontinuity of the output current and lost efficiency.

The discontinuity time decreases with the increase of the duty cycle, because the OFF time of the pulse width modulation gets smaller. Above 20% duty cycle the inductor current never reaches zero because the discharge time of the inductor becomes greater than the IGBT OFF time. From about 20% to 80% the buck circuit is fully performing as step-down-converter with an average efficiency of approximately 76%. Above 80% duty cycle the efficiency jumps to 90% because the OFF time of PWM is insufficient to drive the IGBT fully OFF. In this case the DC-DC converter begins to act as low impedance resistive link between the generator and the load.

VIII CONCLUSION

A simple, low cost wind turbine controller has been developed. Its peak power tracking capability and electrical braking function have been verified on a test bed simulating various wind speeds. The resulting controller

Fig. 17 The change in the efficiency versus duty cycle at constant load and constant frequency

should have parts cost of less than $30 an output efficiency of 70-80% and be capable of power up to 1.2 kW.

IX FURTHER WORK

The circuit will continue to be tested and characterized on a high-power test bed. A final weatherized version will be instrumented for performance verification and implemented on the target turbine in Mozad, India.

APPENDIX A COST OF THE COMPONENTS

Table 1 Approximate prices of electrical components

Item	Function	Price (USD)
IRG4PC50U	High current N-type IGBT. The switching element of the buck circuit.	7.9
BU810	NPN transistor to transfer the braking pulse from the micro-controller to the relay.	2.09
IR2117	IGBT gate driver	2.06
PIC16F818	PIC microcontroller	1.72
BC108	PNP transistor. To transfer PWM signal to the IGBT driver	0.82
470uF, 200V capacitor	To filter the output voltage of the Buck circuit	2.35
Inductor	To filter the output current of the buck circuit	5.5
MBR1535CT	Schottky diode for the buck circuit	2.5
L7800	Voltage regulator	0.47
Miscellaneous Components	Resistors, switches, etc…	3.5

APPENDIX B THE PARAMETERS OF MOZDA HAWT

- 48 V, 1.2 kVA, Y connected three phase AC generator
- The rotor has 12 poles
- Stator has 9 coils, each coil made from 1.1 mm diameter enameled copper.

ACKNOLEDEMENTS

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