16th Australasian Fluid Mechanics Conference
Crown Plaza, Gold Coast, Australia
2-7 December 2007

The Concept of a Smart Wind Turbine System

R.N. Sharma[1] and U. Madawala[2]

[1]Department of Mechanical Engineering
[2] Department of Electrical and Computer Engineering
The University of Auckland, Auckland 1142, NEW ZEALAND

Abstract

The concept of a smart wind turbine with telescopic blades was analyzed using a mathematical model based on the blade element – momentum theory. The telescopic blade concept uses the idea of extending the turbine blades when wind speeds fall below rated level, hence increasing the swept area, and thus maintaining a relatively high power output. It is shown for a typical site, that the annual energy output of such a wind turbine that could double its blade length, could be twice that of a corresponding turbine with fixed length blades. From a cost analysis, it is shown that the concept would be feasible if the cost of the rotor could be kept less than 4.3 times the cost of a standard rotor with fixed length blades. Given the telescopic blade turbine system exhibits a more-or-less linear maximum power curve, as opposed to a non-linear curve for the standard turbine, an innovative hybrid mechanical-electrical power conversion system is proposed.

Introduction

The power output of a wind turbine P depends upon its efficiency or power coefficient C_P, the swept area $A = \pi d^2/4$ given by the diameter of the turbine blades d, and the wind speed U,

$$P = C_P \frac{1}{2} \rho A U^3 \tag{1}$$

To maximize the power output, blades with improved efficiency and thus higher C_P can be employed. However this can often be accompanied by increased cost of manufacture and thus negating any benefits. Larger blades can be used to sweep large area A, but appropriate ultimate states strength must be built into both the components and the structure which can again add considerably to the cost; Manwell et al [1]. Some studies in recent times have considered increasing the wind speed through the plane of the rotor using diffusers, but the idea has proven not to be feasible; see for example Phillips et al [2]. Current wind turbine technology utilizes wind turbine blades of fixed length. Various strategies such as variable pitch and speed, flexible blades, and teetered rotors have been used to increase energy capture and reduce system loads.

Recently, the concept of variable length blades has been proposed as a means of increasing the energy yield of the turbine; Pasupulati et al [3]. As shown in Figure 1, this concept involves the idea of telescopic blades, which are extended to increase swept area when wind speeds drop below rated levels. Tests conducted by Energy Unlimited Inc have shown that the energy yield of their variable length bladed turbine increased by 30%. It has also been asserted that the use of variable length blades could improve the economics of wind turbines operating at any site, and particularly at low wind sites. While this concept is at development stage, studies are focusing on a wind turbine system with variable length blades that will allow higher energy capture in low wind conditions while minimizing mechanical loads in high wind conditions.

This paper reports on an analytical investigation of the variable length blade concept in order to understand the extent of its increased energy-yield potential. For this investigation, a mathematical model based on the blade element – momentum theory was created to calculate the performance of the turbine at given conditions. With wind speed data for a specified location, the model also incorporates a Weibull wind speed distribution that allows the annual energy output to be calculated as a criterion of comparison. Different blade configurations (including different chord and pitch angle variation) for telescopic and standard blades were then analysed. A first order cost analysis is presented to determine the feasibility of the concept. The concept of an innovative power conversion system is also outlined.

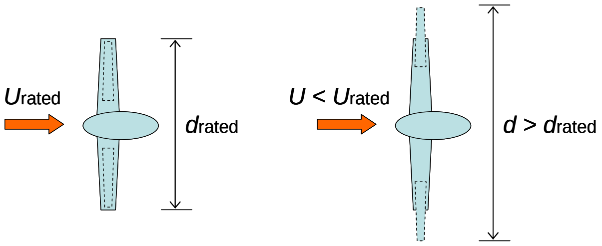


Figure 1. The telescopic wind turbine blade concept

Turbine Performance Analysis

The performance of the wind turbine was computed using blade element - momentum theory, the details for which are well documented; see Manwell et al [1] for example. In this treatment, the blade is divided up into a discrete number of radial elements, as shown in Figure 2, and the forces acting on each element are computed using the aerodynamic characteristics of the blade section. These are then combined with forces obtained from conservation of linear and angular momentum applied to the air that passes around each blade element. The interference of the turbine blades with air are quantified using an axial interference factor a that represents the fraction of longitudinal momentum lost by the air, and a tangential flow interference factor a’ that represents the swirl imparted to air as it flows past the turbine blades.

The analysis followed by inclusion of appropriate loss factors then leads to two equations [1],

$$\frac{a\,f}{1-a} = \frac{\sigma_r}{4\sin^2\phi}\left(C_x - \frac{\sigma_r}{4\sin^2\phi}C_y^2\right) \times \frac{1-a}{1-a\,f} \tag{2}$$

$$\frac{a'\,f}{1+a'} = \frac{\sigma_r\,C_y}{4\sin\phi\cos\phi} \times \frac{1-a}{1-a\,f} \tag{3}$$

Equations (2) and (3) need to be solved iteratively for the axial and tangential flow interference factors *a* and *a*' at each blade element. Alternatively, optimum values for these factors may be assumed, and either the blade chord (*c*) or the pitch (β) distribution obtained. In these equations,

$$\phi = \tan^{-1} \frac{U(1-a)}{\Omega r (1+a')} \tag{4}$$

$$C_x = C_L \cos\phi + C_D \sin\phi \tag{5a}$$

$$C_y = C_L \sin\phi - C_D \cos\phi \tag{5b}$$

$$\sigma_r = N c / 2\pi R \tag{6}$$

$$f = f_T \times f_R \tag{7}$$

$$f_T = \frac{2}{\pi} \cos^{-1}\left(\exp\left(-\frac{N}{2} \times \frac{R-r}{r} \times \frac{1}{\sin\phi} \right) \right) \tag{8}$$

$$f_R = \frac{2}{\pi} \cos^{-1}\left(\exp\left(-\frac{N}{2} \times \frac{r-R_R}{r} \times \frac{1}{\sin\phi} \right) \right) \tag{9}$$

and Ω = rotational speed of the rotor; C_L and C_D are section lift and drag coefficients obtained from the local angle of attack $\alpha = \phi - \beta$; N = number of blades; f_T and f_R are Prandtl's (see Glauert [4]) blade tip and root correction factors; and R_R = blade root radius. For the present study, the blade element – momentum theory was implemented using Matlab$^{\text{TM}}$. The iterative procedure enabled the computation of turbine performance as well as optimisation of the turbine blades.

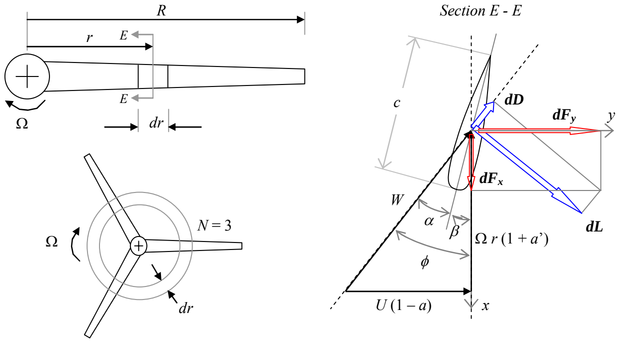


Figure 2. Analysis of the wind turbine using the blade element method

Annual Energy Output Calculations

The annual energy output of the wind turbine was calculated from the turbine performance characteristics obtained at different wind speeds applied against wind speed characteristics. The statistical characteristics of mean wind speed are described adequately by the Weibull distribution (see Cook [5]),

$$Q(>U) = B \exp\left(-\left(U / U_C \right)^k \right) \tag{10}$$

in which $Q\,(>U)$ = annual probability that mean wind speed U is exceeded, B = fraction of the year where there is at least some wind, U_C is a scaling factor and k is a form parameter. The probabilities can be used to estimate the hours in a year that the wind blows in specified wind speed bands for the computation of energy yield. In this study, wind speed data for the city of Auckland New Zealand were analysed and used: $B = 0.876$, $U_C = 5.65$ m/s, and $k = 1.95$; see Figure 3.

The wind speed range of operation of the wind turbine was divided up into a number of bands and the probabilities of the wind speed being in each band was calculated using Equation (10). The number of hours in a year the wind speeds are in each band were simply obtained by a product of the corresponding probability and the total number of hours in a year. For each turbine option, the power generated by the turbine was obtained at the median wind speed within each band. This was then used with the corresponding number of hours per year to compute the energy yield of the turbine per annum.

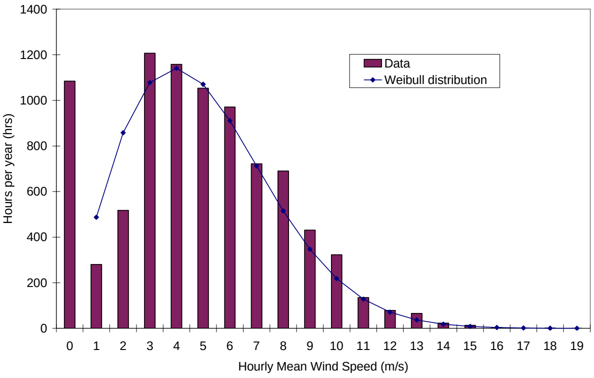


Figure 3. Hourly mean wind speed distribution for Auckland, NZ

The Reference Wind Turbine

The reference wind turbine with fixed length blades considered in the study is the Bergey XL1 rotor with a 2.5m rotor diameter; see Figure 4. It has a power rating of 1000W at a wind speed of 11m/s (Bergey [6]). Its blades are made of pultruded fibreglass and have fixed pitch and constant chord of 100mm. Further details of this turbine are given in Table 1.

Figure 4. The Bergey XL1

Type	3 Blade Upwind	*Maximum Power*	~ 1,300 Watts
Rotor Diameter	2.5 m (8.2 ft.)	*Cut-Out Wind Speed*	None
Start-up Wind Speed	3 m/s (6.7 mph)	*Furling Wind Speed*	13 m/s (29 mph)
Cut-in Wind Speed	2.5 m/s (5.6 mph)	*Blade Pitch Control*	None, Fixed Pitch
Rated Wind Speed	11 m/s (24.6 mph)	*Overspeed Protection*	AutoFurl
Rated Power	1000 Watts	*Gearbox*	None, Direct Drive
Rotational Speed	490 Rpm at Rated Speed	*Generator*	Permanent Magnet Alternator

Table 1. The Bergey XL1 wind turbine details

The optimum fixed blade pitch for this rotor was first determined. In doing so, a tip-speed ratio $\lambda_{rated} = \Omega_{\text{rated}} R = 5.83$ based on the rated conditions given in Table 1 was used. The NACA 0018 airfoil section (Sandia Laboratories [7]) was assumed since Bergey XL1 uses a patented SH3045 airfoil, data for which is not available. An optimum blade pitch and maximum power coefficient were obtained,

$$\beta_{optimum} = 2.8° \quad \text{and} \quad C_{P(MAX)} = 0.40 \tag{11}$$

The generated power, is expressed in terms of efficiency η that accounts for losses in power (mechanical, electrical, etc),

$$P_G = \eta P = \eta C_P \tfrac{1}{2} \rho A U^3 \tag{12}$$

Since P_G = 1000W at U_{rated} = 11m/s, and P_G = 1300W at furling wind speed U_{furl} = 13m/s, then using the already computed $C_{P(MAX)}$ gives,

$$\eta_{rated} = 0.63 \quad \text{and} \quad \eta_{furl} = 0.50 \tag{13}$$

The analysis also assumed optimal generator operation, meaning a constant tip-speed ratio at all wind speeds. Thus the rotational speed of the rotor varies according to $\Omega = \lambda_{rated}\, U / R$. Further assumptions included: (a) zero power output below the start-up wind speed of 3m/s; and (b) constant power output between the furling wind speed of 13m/s to the cut-off wind speed of 25m/s.

The Telescopic Blade Wind Turbine

The telescopic blade idea involves multiple blade sections that extend out when wind speeds drop below rated level. The simplest form would consist of two sections capable of extending to almost twice the original rotor radius when fully extended; see Figure 5. With telescopic blades, the rotor diameter or radius is controlled according to the wind speed level, especially when the speeds fall below rated level. In this study, a simple but nevertheless realistic criterion based on limiting blade root bending moment was used to control the blade length. As a first approximation, the thrust force on the blade was assumed to act at the mid-point of each blade section between its ends. Consequently, the blade root bending moment at rated wind speed is given by

$$M_{rated} = C_T \tfrac{1}{2} \rho U_{rated}^2 \left(c_1 \left(R_{rated} - R_R\right)\right) \times \tfrac{1}{2}\left(R_{rated} + R_R\right) \tag{14}$$

When the second stage is extended at a wind speed $U < U_{rated}$, then the blade root bending moment becomes

$$M = C_T \tfrac{1}{2} \rho U^2 \left[\begin{array}{l} c_1 \left(R_{rated} - R_R\right) \times \tfrac{1}{2}\left(R_{rated} + R_R\right) \\ + c_2 \left(R - R_{rated}\right) \times \tfrac{1}{2}\left(R + R_{rated}\right) \end{array}\right] \tag{15}$$

The maximum second stage blade extension R can be found by equating the right-hand-sides of Equations (14) and (15) i.e. when the blade root bending moment at wind speeds below rated is maintained at the rated level. Hence we have

$$\frac{R}{R_{rated}} = \sqrt{\frac{1 - \left(R_R / R_{rated}\right)^2}{\left(c_2 / c_1\right)\left(U / U_{rated}\right)^2} - \frac{1 - \left(R_R / R_{rated}\right)^2 - \left(c_2 / c_1\right)}{\left(c_2 / c_1\right)}} \tag{16}$$

If we now assume that the chord length of the second stage is close to that of the first i.e. $c_2 / c_1 \approx 1$,and that $R_R / R_{rated} << 1$, then Equation (15) can be simplified to

$$\frac{R}{R_{rated}} = \frac{1}{\left(\dfrac{U}{U_{rated}}\right)^2} \tag{17}$$

Extension ratios R / R_{rated} from Equations (15) and (16) are plotted against velocity ratio U / U_{rated} in Figure 6 for a range of chord ratios c_2 / c_1 and fixed blade root radius ratio R_R / R_{rated} = 0.1. This suggests that if a two-stage blade system that is capable of approximately doubling the blade radius is to be used, then maximum advantage can only be extracted to only about half the rated wind speed. For example, if R_{rated} = 1.25m and U_{rated} = 11m/s, then a telescopic blade system would involve second stage actuation between radii of 1.25m to 2.5m from wind speeds of 11m/s to 5.5m/s. Below 5.5m/s, the total blade radius would remain at 2.5m.

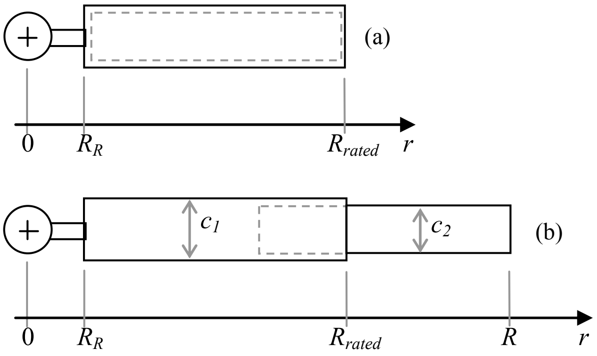


Figure 5. A simple telescopic blade system (a) $U = U_{rated}$, (b) $U < U_{rated}$

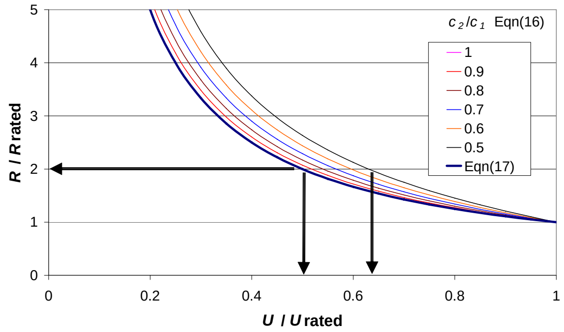


Figure 6. Rotor radius versus wind speed

Results and Discussion

The annual energy output was computed for several configurations of the standard fixed length blade turbine, and for the telescopic blade turbine. The configurations were as follows:

Option 1: rotor blade with radius of 1.25m, optimum chord and pitch angle distribution.
Option 2: rotor blade with radius of 1.25m, optimum chord distribution but constant pitch angle, i.e. no twist.
Option 3: rotor blade with radius of 1.25m, constant chord and constant pitch angle.
Option 4: rotor blade with radius variable between 1.25m and 2.5m from the rated wind speed of 11m/s down to a

wind speed of 5.5m/s (see Figure 10), constant pitch angle (no twist) but optimum chord distribution; pitch control, i.e. the whole blade can rotate.

Option 5: rotor blade with radius variable between 1.25m and 2.5m from the rated wind speed of 11m/s down to a wind speed of 5.5m/s (see Figure 5), constant pitch angle (no twist) but optimum chord distribution; fixed blade, i.e. no pitch control.

Option 6: rotor blade with radius variable between 1.25m at a wind speed of 11m/s and 2.5m at a wind speed of 5.5m/s, constant pitch angle (no twist) and constant chord; fixed blade.

A comparison of the annual energy output from the analysis for various options appears in Figure 7, showing that in each of the variations considered, the annual energy output (*AEO*) is doubled for a turbine with telescopic blades, which is quite a significant increase.

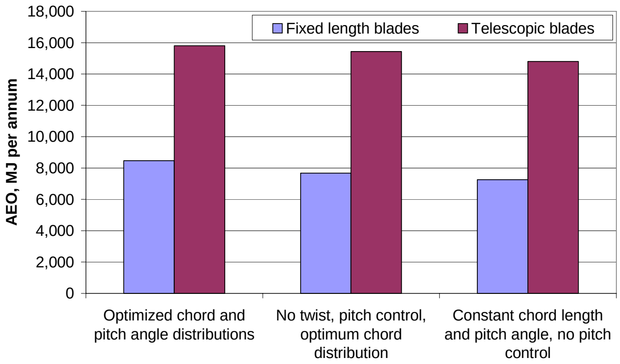


Figure 7. Comparison of annual energy outputs

To understand this fully, we consider the power curves for two different options. Figure 8 shows plots of turbine power versus rotation speed at different wind speeds for fixed length blade Option 2, while similar plots for telescopic blade Option 5 are shown in Figure 9. A comparison of these shows a remarkable increase in power with telescopic blades over fixed length blades, in particular at lower wind speeds. Consequently, the optimum or maximum power curve with telescopic blades not only lies significantly above that with fixed length blades, but it is linear with rotational speed as opposed to its quadratic nature with fixed length blades. This might be an advantage from the point of view of the design of a generator and controller to track the maximum power points of the turbine for maximising the output.

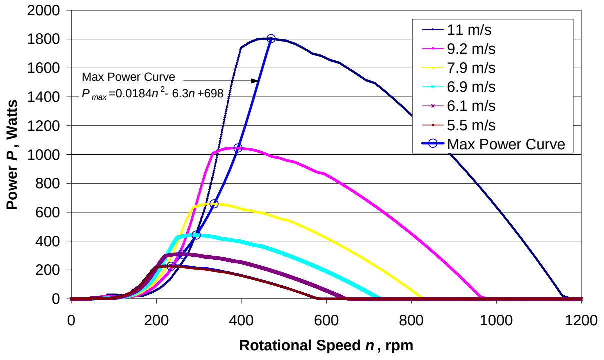


Figure 8. Power curves for turbine with fixed length blades - Option 2

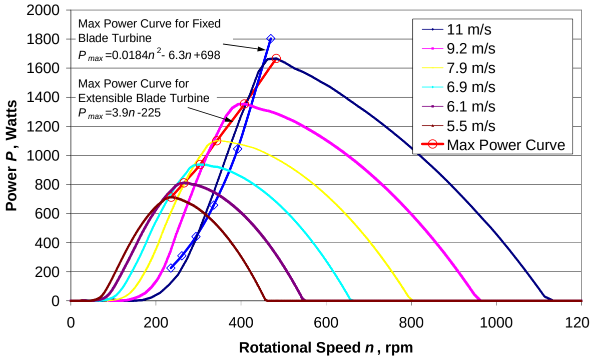


Figure 9. Power curves for turbine with telescopic blades - Option 5

Cost Effectiveness

While it is readily established that a telescopic blade system could result in doubling of the annual energy output (*AEO*) of a turbine with fixed length blades, this has to be weighed against the cost of producing the wind turbine $C(WT) = C(Rotor) + C(OtherParts)$ = sum of costs of rotor and other parts. To this end, a specific cost factor *SCF* for the wind turbine, defined as the ratio of the cost of producing the unit to its annual energy output,

$$SCF = \frac{C(WT)}{AEO} = \frac{C(Rotor) + C(OtherParts)}{AEO} \qquad (18)$$

may be used as a means of comparison. A fact sheet on wind turbine manufacturing by Ancona and McVeigh [8] puts the cost of the rotor at 30% of that of the whole wind turbine. Assuming that the added costs are mostly associated with that for the new telescopic rotor system while the cost of the other parts $C(OtherParts)$ is insignificantly affected, then Equation (18) is used to establish that for the telescopic blade system to be cost effective, it must be able to be produced at less than 4.33 times the cost of producing a standard rotor with fixed length blades.

Mechanical-Electrical Energy Conversion Innovations

Mechanical to electrical power conversion in wind turbine systems is achieved through a variety of techniques [1]. These techniques vary from one type of wind turbine to another and are application specific, with their own advantages and disadvantages. Typical power-speed characteristic of wind turbines indicate that for any given wind speed the amount of power delivered by the turbine is maximum only at one turbine speed. Therefore as the wind speed varies it is imperative to capture the maximum possible power of the wind turbine, and this is usually achieved by tracking the maximum power versus turbine speed trajectory (see Figures 8-9) through a controller. In most cases, as in Figure 8, the maximum power trajectory of the turbine is non-linear and as such the controller design is somewhat complicated. However, the maximum power trajectory of the proposed telescopic blade wind turbine is approximately linear as shown in Figure 9, and thus the controller for maximum power tracking can be implemented with relative ease.

A hybrid electrical energy conversion system shown in Figure 10, is proposed for the telescopic blade wind turbine. The energy conversion system consists of a Permanent Magnet (PM) generator, a super-capacitor bank, a bi-directional converter, a battery storage and an inverter, and is capable of capturing maximum power from the turbine. The multi-pole PM generator, shown in Figure 11 is a unique design as it uses a slot-less winding and a plastic stator core, and operates at a variable speed being directly coupled to the turbine. It has 14 poles and is designed to deliver 1.5kW at 110V DC at 450 rpm. The air-gap flux density distribution of the generator is shown in Figure 12.

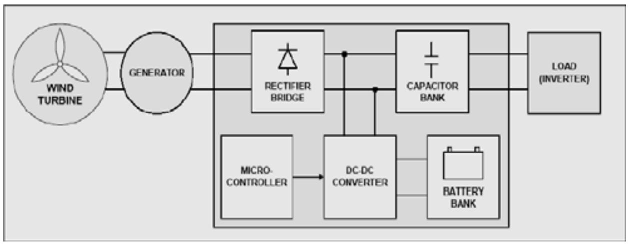


Figure 10. A schematic of the hybrid energy conversion system

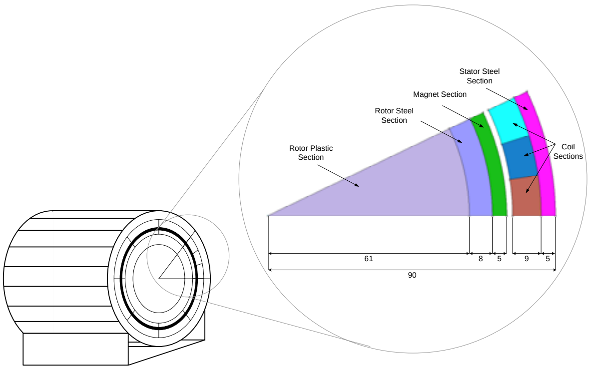


Figure 11. Proposed PM generator

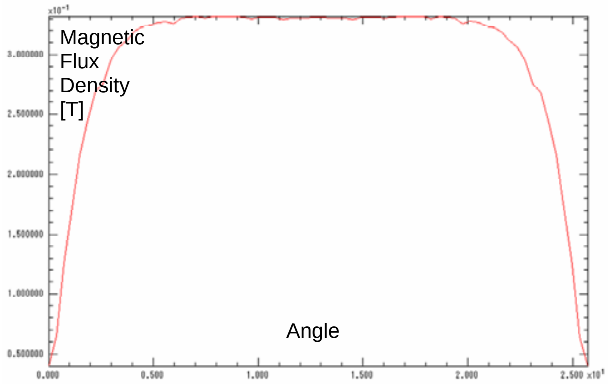


Figure 12. Air-gap flux density distribution over each magnet

A scale-down version of the prototype hybrid system is shown in Figure 13. The super-capacitor bank of the above system acts as an energy buffer for the battery, load and turbine, and significantly improves the quality of the generated electricity by supplementing or absorbing the sudden power fluctuations caused by both load and turbine. Furthermore it enhances the battery life by limiting the energy transfer from battery to situations where either the generation or load exceeds the capacity of energy buffer. An intelligent micro-processor based controller continuously monitors the DC bus (super-capacitor) voltage and operates the bi-directional converter either in Buck or Boost mode in accordance with load requirement and energy captured by the turbine. The speed of the turbine and hence the generator is controlled in accordance with the maximum power trajectory to ensure that the maximum possible energy is captured at all wind speeds.

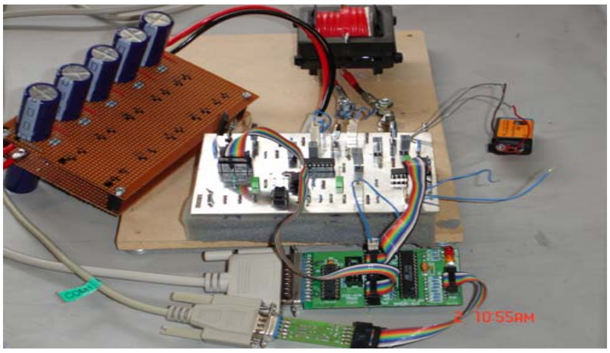
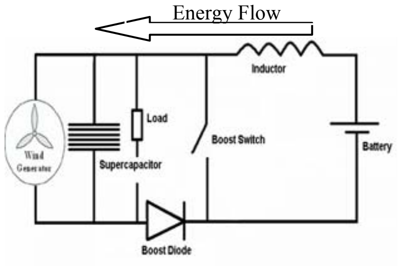
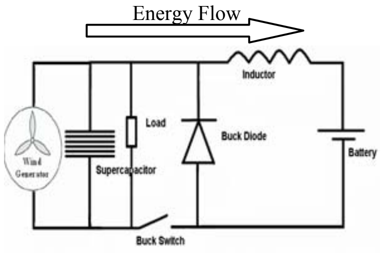


Figure 13. A scale-down version of the prototype hybrid system

In situations where energy captured by the turbine is less than that required by the load, the converter is operated in the Boost mode as shown in Figure 14(a), supplementing the turbine energy with that drawn from the battery. Similarly, whenever the generated energy is more than that required by the load, the converter is operated in the Buck mode as in Figure 14(b) to store excess energy in the battery for later retrieval. A unique current mode controller that has a variable current reference regulates the rate of energy flow between the super-capacitor bank and the battery, in accordance with the maximum power trajectory of the turbine. Simulations for the performance of the converter are currently underway and results will be reported in the near future.



(a)



(b)

Figure 14. Bi-directional converter

Conclusions

The concept of a wind turbine with telescopic blades has been analysed using a mathematical model based on the blade element – momentum theory. It is shown that for a typical site, the annual energy output of such a wind turbine whose diameter could be doubled, is almost twice that of a corresponding turbine with fixed length blades. From a simplified cost analysis, it is concluded that the concept would be feasible if the cost of the rotor could be kept less than 4.3 times the cost of a standard rotor with fixed length blades. Given that the telescopic blade turbine system exhibits a more-or-less linear maximum power curve (as opposed to a non-linear curve for the standard turbine), an innovative hybrid mechanical-electrical power conversion system is proposed.

Acknowledgments

The grant support from the Research Committee of the University of Auckland is gratefully acknowledged.

References

[1] Manwell, J. F., McGowan, J. G., Rogers, A. L., 2002. Wind Energy Explained: Theory, Design and Application. John Wiley & Sons Ltd

[2] Phillips, D.G., Richards, P.J., Flay R.G.J., 2002, CFD modelling and the development of the diffuser augmented wind turbine. Wind & Structures – An International Journal, 5, (2-4), 267-276.

[3] Pasupulati, S.V., Wallace, J., Dawson, M., 2005. Variable Length Blades Wind Turbine. http://www.osti.gov/energycitations/servlets/purl/841190-OF8Frc/841190.PDF, Energy Unlimited Inc.

[4] Glauert, H., 1948. The elements of aerofoil and airscrew theory. Cambridge University press.

[5] Cook, N.J., 1985. The Designer's Guide to Wind Loading of Buildings Structures, Part 1. Butterworth, London.

[6] Bergey, 2006. BWC XL.1 Wind Turbine & BWC XL.1 Specification Sheet. http://www.bergey.com/Products/XL1.html, Bergey.

[7] Sandia Laboratories, 1981. Aerodynamic Characteristics of Seven Symmetrical Airfoil Sections Through 180-Degree Angle of Attack for Use in Aerodynamic Analysis of Vertical Axis Wind Turbines.

[8] Ancona, D., McVeigh, J., 2001. Wind Turbine - Materials and Manufacturing Fact Sheet. Retrieved on 28/04/2006, from: http://www.generalplastics.com/uploads/technology/WindTurbine-MaterialsandManufacturing_FactSheet.pdf