Individual Blade Pitch and Camber Control for Vertical Axis Wind Turbines

Pradeep Bhatta, Michael A. Paluszek and Joseph B. Mueller
Princeton Satellite Systems, Inc., 33 Witherspoon Street, Princeton, NJ 08542, USA
{pradeep,map,jmueller}@psatellite.com

Abstract: In this paper we present a dynamical systems model and control algorithms for a small, vertical axis wind turbine (VAWT). The wind turbine is designed for the domestic market, including regions without very favorable wind conditions. Good performance at low wind speeds is an important requirement for developing an economically viable, suburban VAWT. The performance of a VAWT can be greatly enhanced by incorporating estimation and control capabilities. Individual blade pitch and camber controls are considered in our VAWT design. Pitch control is achieved by rotating each individual blade about its vertical axis, while camber control is realized using a trailing edge flap on each blade. Using camber and pitch controls help in creating a greater force differential across the turbine than using pitch control alone. In this paper we present a simple strategy for implementing pitch control and demonstrate the resulting efficiency improvement through a simulation.

1. Introduction

Vertical axis wind turbines (VAWTs) are attractive for suburban applications because of their relative ease of installation and maintenance. The more common horizontal axis wind turbines (HAWTs) have been known to have higher efficiencies, but using simple control strategies help in dramatically improving VAWT efficiencies. In this paper we present some technologies pursued at Princeton Satellite Systems for creating an advanced VAWT prototype. Efficiency improvements can be realized in several ways, including (i) individual blade actuation, (ii) power electronics control for maximum power point tracking, (iii) model-based control algorithms (iv) state and parameters estimation, and (v) high efficiency power converters.

2. Individual Blade Actuation

We consider a vertical axis wind turbine (VAWT) incorporating mechanisms that enable independent pitching of individual blades. The blades are provided with flaps that can be independently regulated for adjusting camber. Using camber and pitch controls help in creating a greater force differential across the turbine than using pitch control alone. This will allow VAWT operation over a wide range of wind speeds, improve tolerance to wind variations and permit the turbine to self-start.

Figure 1 shows a schematic (top view) of the VAWT blade configuration. Two or more blades (three, in the case of the shown diagram) are mounted on a vertical support structure. They each have a pivot that allows individual pitching (i.e., rotation about their pivot axis), and a trailing edge flap for camber control. The pitch and trailing edge flap of each blade are independently controlled using local actuators.

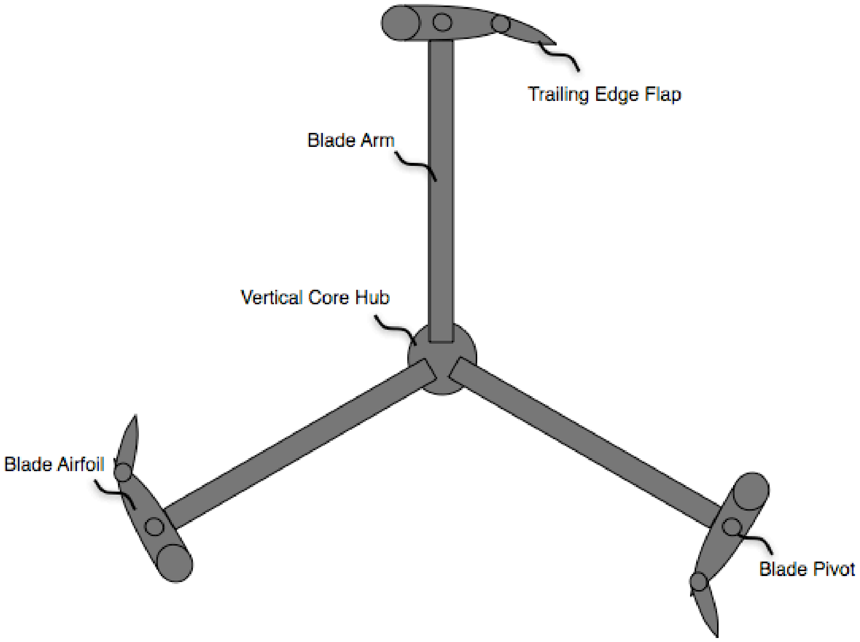

Figure 1: Schematic of Individual Blade Controlled Vertical Axis Wind Turbine

Figure 2 shows a schematic (front view) of the base of the VAWT rotor-generator assembly. An axial flux Halbach generator magnet assembly is attached to the blade assembly through a vertical shaft. Alternative generator configurations may also be used.

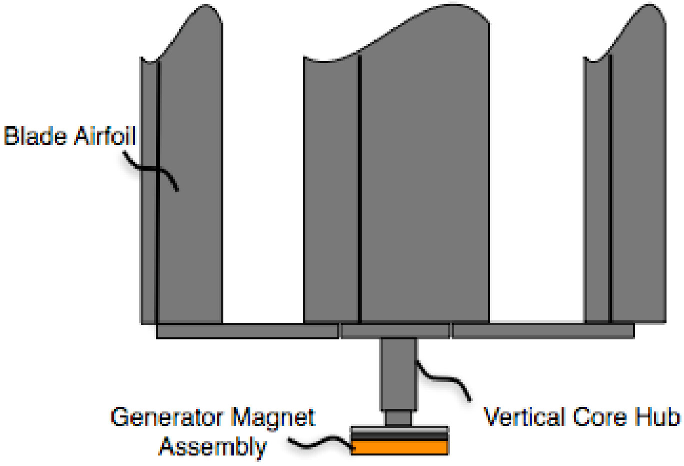

Figure 2: Schematic of VAWT-generator assembly

3. VAWT Aerodynamics

VAWT aerodynamic modeling is complex. The blade elements, in general, may operate both unstalled and stalled. There is a hysteresis effect associated with getting in and out of stall. The blade elements also experience wakes due to themselves and other blade elements. The combination of these effects renders accurate aerodynamic modeling very challenging. There have been several efforts in that direction that have yielded a suite of models with varying complexity. All these models make several approximations, and need to be validated by experiments.

Complex aerodynamic models often must be simplified for the purpose of control synthesis. We consider a simple aerodynamic model, and outline a procedure for estimating the parameters of the model in Section 7. The estimation can be done apriori, and refined during the operation of the VAWT.

Figure 3 shows a schematic of the angular notation for an individual blade (flaps are not shown for simplicity). In the figure V_b is the velocity of the blade relative to the center of rotation, and V_w is the effective wind velocity. We note that one can use momentum-based models to obtain an estimate of V_w. This estimate can be further refined using state estimation, as described in Section 7. Vector -W represents the velocity of the blade relative to the effective wind. The angle ϕ represents the blade rotation angle, α_0 is the angle from V_b to W, α is the angle of attack (the angle from W to the chord line of the blade), and γ is the blade pitch angle.

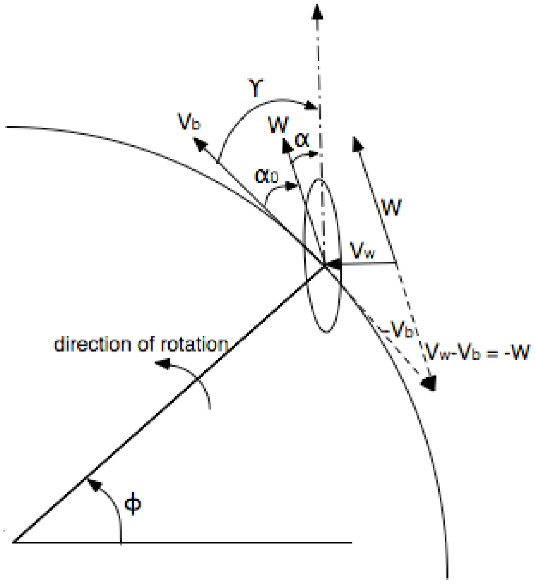

Figure 3: Blade Angles

The aerodynamic drag force D acts in the direction of - W, whereas the aerodynamic lift force acts perpendicular to W. We consider a lift and drag profile for the respective coefficients, C_D and C_L, as shown in Figure 4, that matches well with data for the NACA 0012 symmetric airfoil.

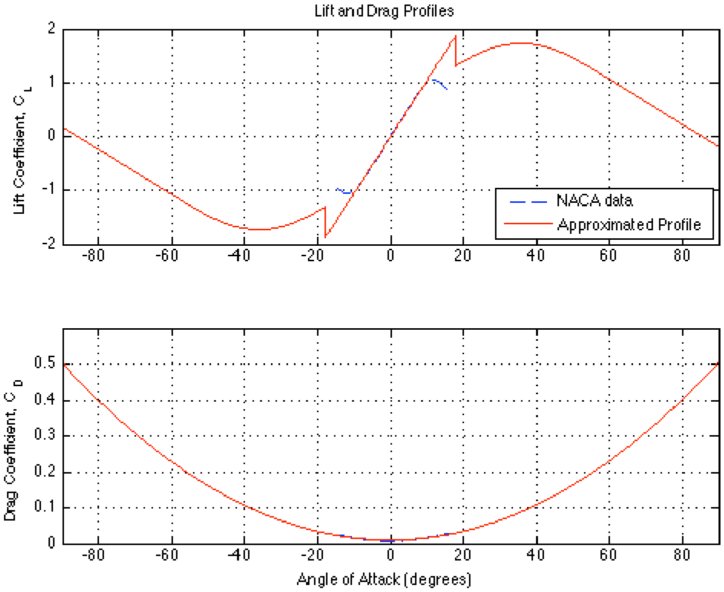

Figure 4: Lift and Drag Profiles

The dynamics of the rotation of a multi-bladed VAWT can be described by the following equations:

$$\begin{aligned} J_r \frac{d\phi}{dt^2} &= \tau - \tau_g \\ J_b \frac{d\gamma}{dt^2} &= u_p, \end{aligned}$$

where J_r is the total moment of inertia of the VAWT rotor, $J_{b,i}$ is the moment of inertia of the i^{th} blade, and $u_{p,i}$ is the corresponding pitch control torque. τ_g is the feedback electromagnetic toque discussed in Section 4. The total aerodynamic torque is

$$\tau = \sum_{i=1}^{n} \tau_i \quad ,$$

where τ_i is the aerodynamic torque on each individual blade and n is the number of blades. τ_i is given by

$$\tau_i = C_{T,i} \frac{1}{2} \rho A W^2 R \quad ,$$

where ρ is the density of air, A is the reference area, R is the radius of the rotor, and $C_{T,i}$ is the tangential force coefficient, made up of contributions from the lift and drag coefficients:

$$C_{T,i} = -\left(C_{L,i} \sin \alpha_i + C_{D,i} \cos \alpha_i\right)$$

The total power captured by the rotor is given by

$$P_r = \sum_{i=1}^{n} \tau_i \dot{\phi}$$

3. Permanent Magnet Synchronous Generators

Permanent magnet generators (PMGs) offer an attractive option for wind power extraction. They eliminate the need for a gearbox, increase energy extraction efficiency and are less noisy. PMGs can be controlled electronically making it possible to regulate the reactive flow into the grid as part of the generator control and maintain the power factor close to 1. They are highly efficient with numbers as high as 97% quoted [Lovatt et al, 1998]. A variant being developed for electric cars is the Halbach array motor [Greaves et al, 2003] that uses a ring of magnets in a Halbach configuration that concentrates the flux on one side. This eliminates the need for back iron thus lowering the mass of the rotor and increasing the magnetic flux. It also eliminates cogging torques due to the inherently sinusoidal air gap field distribution. A similar generator design for the wind turbine leads to lower nacelle mass and consequently less expensive and more aesthetically pleasing tower designs.

We consider the dynamical model presented by [Chinchilla et al, 2006] in the magnetic flux reference system for a surface mounted permanent magnet generator.

$$\begin{aligned} u_d &= -Ri_d - L\frac{di_d}{dt} + L\Omega i_q \\ u_q &= -Ri_s - L\frac{di_q}{dt} - L\Omega i_d + \Omega\psi \end{aligned}$$

where L and R are the inductance and resistance of the generator respectively, Ω is the generator speed, (i_d, i_q) are current components, (u_d, u_q) are applied terminal voltage components, and ψ is the flux due to the permanent magnets. The electromagnetic torque is given by

$$\tau_g = \frac{3}{2}p\psi i_q,$$

where p is the number of pole-pairs. The current components, and as a result the electromagnetic torque, can be controlled by means of the applied voltage. The applied voltage can be regulated through a power converter interface. In the next section we describe matrix converters, which have been proposed for use with wind energy conversion systems.

4. Matrix Converters

A matrix converter can be used for efficiently processing the three-phase electrical output from the VAWT. Matrix converters use an array of controlled, bidirectional semiconductor switches to convert AC power from one frequency to another. They generate a variable output voltage with unrestricted frequency. Matrix converters do not have a dc-link circuit and do not use large energy storage elements.

MOSFETs (for low power) and IGBTs (for high power) enable implementation of bidirectional switches make the matrix converter technology very attractive for AC power handling. Figure 5 shows a schematic of the matrix converter set up [Wheeler et al, 2002], showing the power stage containing nine bidirectional switches, the input filter block and the clamp circuit. The input filter minimizes the high frequency components in the input currents and reduces the impact of perturbations of input power. The input filter can be realized using inductor - capacitor combinations, with parallel damping resistors. The clamp circuit provides overcurrent/overvoltage protection, and is implemented using fast recovery diodes.

We adopt the switching control strategy of reference [Nikkhajoei and Iravani, 2005] for the matrix converter. Figure 6 shows results of a steady state simulation. The generator input at 300 Hz is converted to a 60 Hz output for interfacing with the grid. A switching frequency of 7200 Hz is employed. There is a duty cycle factor that can be adjusted to regulate the ratio of output to input voltage, up to a maximum value. The output is passed through a low-pass filter to filter out the high frequency switching harmonics.

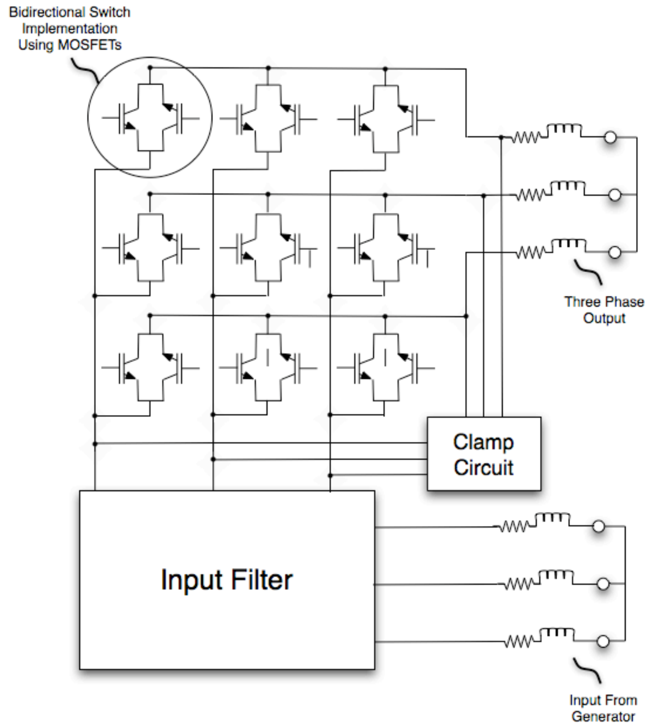

Figure 5: Schematic of a Matrix Converter

6. Control Law and Simulations

We note that the time-scales of the matrix converter-generator subsystem and the aerodynamics are different. For the purpose of pitch control we do not have to consider the transients of the generator and matrix converter dynamics. Generator torque can be considered as a control input for the VAWT drive train system.

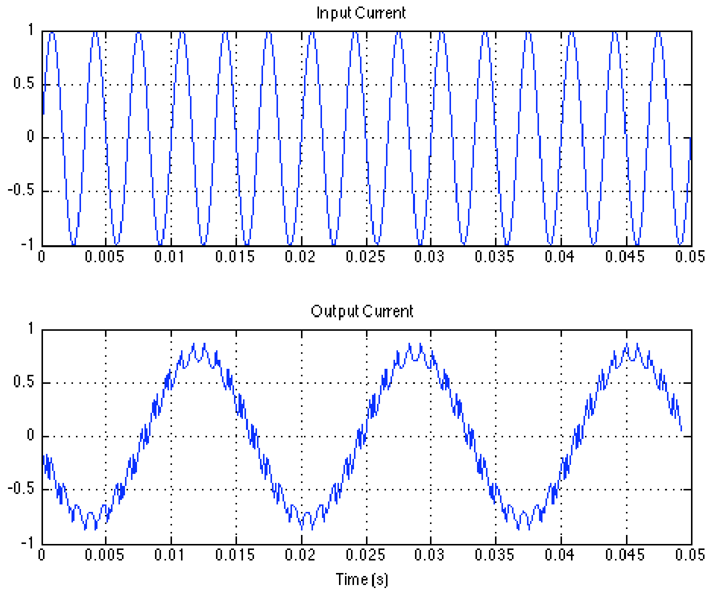

Figure 6: Matrix converter steady state simulations

In the blade aerodynamics model we have control inputs in the form of blade pitch torque and generator feedback torque. We do not explicitly consider camber control in our treatment here for simplicity – c amber control essentially provides another degree of freedom for regulating the lift and drag forces acting on a blade element. We choose individual blade pitch in order to maximize the lift to drag ratio over the entire cycle of rotation in such a way that the force on each blade contributes positively to power extracted for most of the rotation cycle. The following control strategy is employed:

$$u_p = -K_p(\alpha - \alpha_{ref}) - K_d\dot{\gamma},$$

$$\alpha_{ref} = \begin{cases} -\alpha_m \text{ if } \alpha_0 > 0 \\ \alpha_m \text{ if } \alpha_0 < 0 \end{cases},$$

where $K_p,\ K_d > 0$ are control gains, and α_m is the reference angle of attack magnitude. The value of α_m is chosen as high as possible, but sufficiently smaller than the magnitude of the stall angle of attack. The pitch angle control law ensures that the blade does not get into stall, and that the tangential force component on the blade contributing to positive power extraction is high throughout the entire rotation cycle. The electromagnetic torque control is chosen to stabilize the rotation speed of the blade to a desired value, Ω_{des}:

$$\tau_g = K_{\tau_g,1}(\Omega - \Omega_{des}) + K_{\tau_g,2}\int(\Omega - \Omega_{des})\,.\mathrm{d}t,$$

where $K_{\tau_g,1},\ K_{\tau_g,2} > 0$ are control gains. For an ambient effective wind speed V_w there is an associated optimal rotation speed that can be determined by experiments. Generator torque control is used so that the VAWT tracks this optimal rotor speed.

Figures 7 and 8 illustrate the benefit of using individual blade control. Here we consider a VAWT with the following parameters: ρ = 1 $\mathrm{kg/m^3}$, R = 0.75 m, A = 2 m^2, J_r = 3 kg.

m^2, J_b = 9.17exp(-4) kg. m^2, V_w = 1.5 m/s, and Ω_{des} = 8 rad/s. We use the approximated lift and drag profiles shown in Figure 4. For the pitch-controlled VAWT simulation, we pick the control gains as follows: $K_p = 20$, $K_d = 1$, $K_{\tau_g,1} = 20$, $K_{\tau_g,2} = 10$. The control parameter α_m is set to 14 degrees. For the constant pitch simulation, the first two control gains are set to 0. The initial angular speed is set to 11 rad/s.

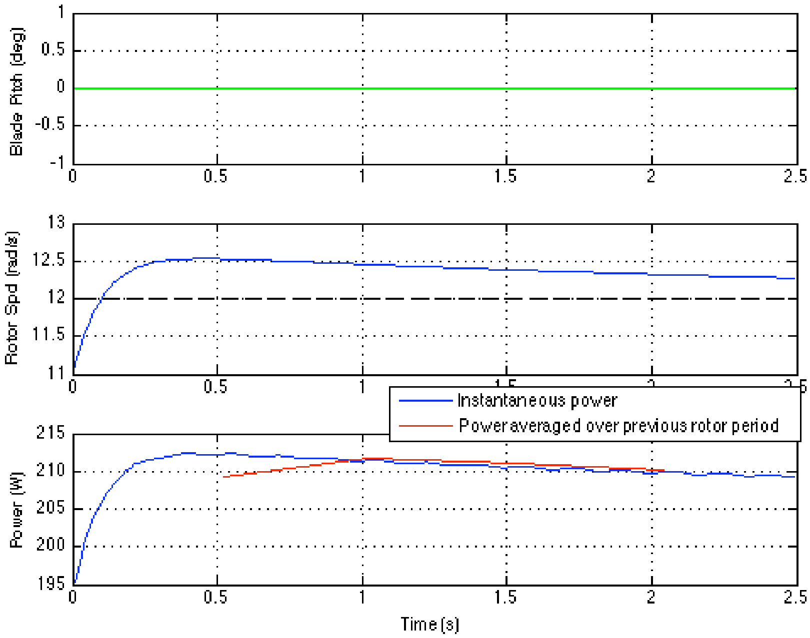

Figure 7: Simulation of fixed-pitch VAWT

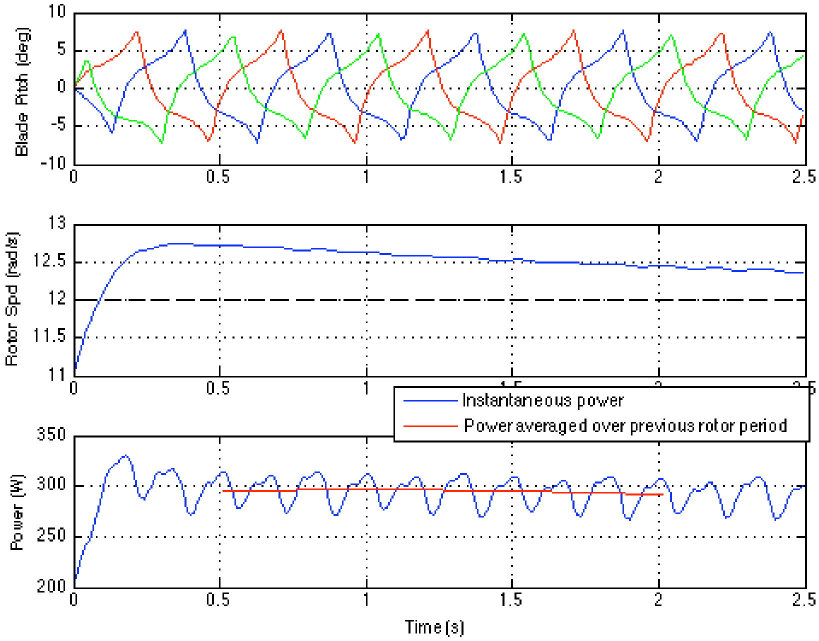

Figure 8: Simulation of variable-pitch VAWT

The average rotor power for the constant pitch VAWT is 209 W, whereas for the pitch-controlled VAWT, the average rotor power is 293 W. This huge gain in power extracted will be offset by the power required to implement pitch control. Also, fatigue considerations may require smaller K_p, K_d, and uncertainty in stall may require use of a smaller α_m. Both these measures will lead to lower power extraction improvements over the constant pitch case. However, the overall gain in power extraction efficiency appears to be high enough to justify the costs of incorporating pitch control.

7. State and Parameter Estimation

State estimators minimize sensing requirements of the system, and parameter estimators will allow model-based control algorithms to work effectively in mass produced VAWTs. State and parameter estimation are standard techniques used in actively controlled mechanical, aerospace and electronic systems. We propose the application of unscented Kalman filters (UKF) for implementing state and parameter estimators for the VAWT system.

The UKF uses the unscented transformation (UT), and does not require the computation of any derivatives or Jacobians of the state equations or measurement equations. Instead of just propagating the state, the filter propagates a set of sample, or sigma, points that are determined from the a priori means and covariance of the state. The sigma points undergo UT during each update. The posterior mean and covariance are computed from the transformed sigma points. A summary of UKF equations and the systematic procedure for implementing UKF are described in [Wan and van der Merwe, 2000; VanDyke et al, 2005]. An example of applying UKF for parameter estimation of a wind energy conversion system drive train dynamics parameter is given in [Bhatta and Paluszek, 2007].

Figure 9 shows a block diagram of an overall VAWT system set up. In this set up, rotor speed and wind velocity measurements are used to compute estimates of V_w and α.

8. Conclusions

In this paper we have presented advanced technology concepts that can enhance the efficiency of a vertical axis wind turbine (VAWT). We have demonstrated power extraction improvements as a result of employing pitch control. Applying simple pitch control laws lead to large improvements in the amount of power extracted. The use of Halbach-array permanent magnet generators, matrix converters and on-board state/parameter estimators all contribute towards a highly efficient VAWT.

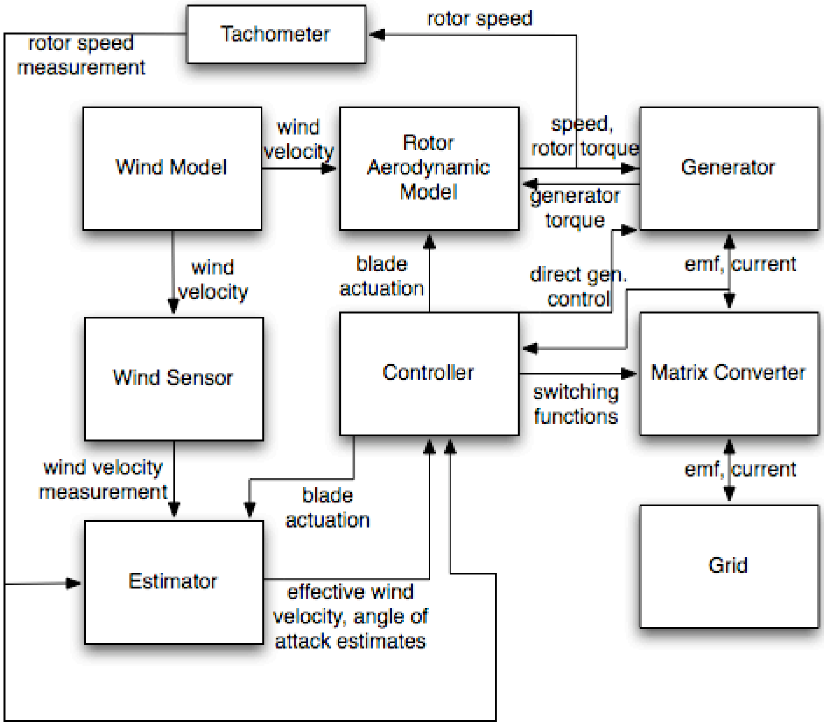

Figure 9: Block diagram of overall VAWT system, incorporating the estimator.

References

[Lovatt et al, 1998] Lovatt, H. C., Ramsden, V. S., and Mecrow, B. C., Design of an in-wheel motor for a solar-powered electric vehicle. IEE Proceedings – Electric Power Applications, Vol 145, No. 5, pp 402-408, (1998)
[Greaves et al, 2003] Greaves, M. C., Simpson, A. G., Guymer, B. D., Walker, G. R. and Finn, D. A., Ironless wheel motor for a direct drive vehicle application. Proc. Australian Universities Power Engineering Conference, (2003).
[Chinchilla et al, 2006] Chinchilla, M., Arnaltes, S., and Burgos, J. C., Control of permanent magnet generators applied to variable-speed wind energy systems connected to the grid. IEEE Transactions on Energy Conversion, Vol 21, No. 1, pp 130-135, (2006).
[Wheeler et al, 2002] Wheeler, P. W., Rodriguez, J., Clare, J. C., Empringham, L., and Weinstein, A., Matrix converters: A technology review. IEEE Transactions on Industrial Electronics, Vol 29, No. 2, pp 276-288, (2002).
[Nikkhajoei and Iravani, 2005] Nikkhajoei, H. and Iravani, M. R., A matrix converter based micro-turbine distributed generation system. IEEE Transactions on Power Delivery, Vol 20, No. 3, pp 2182-2192, (2005)
[Wan and van der Merwe, 2000] Wan, E. A. and van der Merwe, R., The unscented Kalman filter for nonlinear estimation. Proc. IEEE Adaptive Systems for Signal Processing, Communications, and Control Symposium, pp 153-158 (2000).
[VanDyke et al, 2005] VanDyke, M. C., Schwartz, J. L. and Hall, C. D., Unscented Kalman filtering for spacecraft attitude state and parameter estimation. Advances in Astronautical Sciences (2005).
[Bhatta and Paluszek, 2007] Bhatta, P. and Paluszek, M. A., Nonlinear estimation and control for small-scale wind turbines. Proc. World Wind Energy Conference (2007).