A non-linear wind velocity observer for a small wind energy system

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Abstract

In this paper a non-linear strategy is presented to estimate the wind velocity in a variable speed small wind energy system. The approach is based on a non-linear state observer considering the rotational speed and electrical variables as the measured ones. The observer is based on a general non-linear model of the wind turbine characteristic and an assumed wind variation model. This approach is simple and does not require a complex searching algorithm to find the estimates. In addition, the convergence of the estimates can also be analyzed using standard tools. Results of wind velocity estimation using realistic wind profile, representing some wind conditions in the World most southern city of Punta Arenas, show the performance of the proposed approach.

1. Introduction

In a wind energy system , in order to keep a good tracking of the maximum aerodynamic efficiency of the wind turbine under fast variations in the wind profile is important to measure the wind velocity. However, speed velocity measurements do not only require a mechanical sensor located near the wind turbine, but the measurements can also be seriously perturbed by the wind turbine own turbulence. In order to overcome these difficulties a wind velocity estimator can be designed.

Previous schemes, based on static models, rely on iterative methods for solving nonlinear equations [2], the main drawbacks of this proposal is the lack of convergence analysis and the complexity of the algorithms, which must be programmed to satisfy stringent real time constraints.

In this paper, however, an estimator based on a non-linear model of the wind turbine system as well as on a model for the wind characteristics is developed.

2. Wind turbine model

The torque produced in the blades of a fixed-pitch wind turbine is a function of the blade profile, rotational speed, pitch angle and radius of the blades. This can be mathematically written as [1]:

$$T_m(\lambda,V) = \frac{1}{2}\pi\rho\, C_t(\lambda) R^3 V^2, \qquad (1)$$

where V is the effective wind velocity through the blades, $C_t(\lambda)$ is called the torque coefficient, R is the radius of the wind turbine blades and ρ is the air density. The term λ makes the coefficient $C_t(\lambda)$ dependent on both the wind velocity and the rotational speed and is defined as:

$$\lambda = \frac{\omega R}{V}, \qquad (2)$$

the variable ω is the wind turbine rotational speed. The dynamic of the wind turbine is described by:

$$J\frac{d\omega}{dt} = T_m(\omega,V) - B\omega - T_e, \qquad (3)$$

where J is the system inertia, T_e is the generator torque and B is the friction coefficient.

3. Modelling the wind variations

The wind variations are not completely known, and statistical representation of its behaviour does not offer a good model for estimating instant values of the wind velocity. In this case a waveform model, which is generated by a linear combination of some basis functions is used. Thus, the wind profile can be represented as:

$$V(t) = \sum_{i=1}^{N} c_i g(t), \qquad (4)$$

where the linear weighting coefficients c_i on those components are completely unknown and may even jump from time to time in an unknown random-like manner. This technique allows the modelling of wind variations as a linear combination of constants, ramps, polynomials, exponentials, sinusoids, etc. In order to use this model, it must be transformed to a form useful for observer design. Representation (4) can also be expressed as a differential equation, which $V(t)$ is known to satisfy [6]:

$$\frac{d^pV(t)}{dt^p} + \beta_{p-1}\frac{d^{p-1}V(t)}{dt^{p-1}} + \cdots + \beta_1\frac{dV(t)}{dt} + \beta_0 V(t) = 0, \qquad (5)$$

where the coefficients β_i are determined by the basis functions. Using standard transformations (5) can be written in a state space equation as:

$$\begin{aligned}\dot{\mathbf{z}} &= \mathbf{Hz} + \boldsymbol{\delta}(t)\\ V &= \mathbf{Gz}\end{aligned} \qquad (6)$$

where **H** and **G** are known matrices and the elements of $\boldsymbol{\delta}(t)$ are completly unknown sequences of random-intensity random-occurring isolated delta functions. The state **z** represents the state associated with the variable V. A wide range of wind variations can be simulated with the model given by equation (6) and the proper choice of matrices **H** and **G**. For instance, the variations given in Figure 1 can be modeled by the given state space representations.

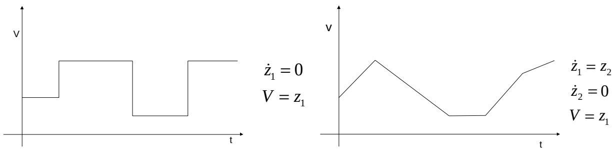

Figure 1. Step and ramp like changes

3. Non-linear Observers

Combining the equations (1)-(3), which represents a highly non-linear system, and the model of the wind variations, an estimator for the unknown variable can be designed. Let us consider the new state, **x**, and the output variable, *y*, defined as:

$$\mathbf{x} = \begin{bmatrix} \omega \\ \mathbf{z} \end{bmatrix}, \qquad y = V \ .$$

Equations (3) and (6) can be written as:

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \begin{bmatrix} T_m(\mathbf{x}) \\ 0 \end{bmatrix} + \begin{bmatrix} T_e \\ \delta(t) \end{bmatrix}$$

$$y = \mathbf{C}\mathbf{x}$$

where the matrices **A** and **C** are defined as:

$$\mathbf{A} = \begin{bmatrix} -\mathbf{B} & \mathbf{0} \\ \mathbf{0} & \mathbf{H} \end{bmatrix}, \qquad \mathbf{C} = [0 \quad \mathbf{G}].$$

Thus, observer will be:

$$\dot{\hat{\mathbf{x}}} = \mathbf{A}\hat{\mathbf{x}} + \begin{bmatrix} T_m(\hat{\mathbf{x}}) \\ 0 \end{bmatrix} + \begin{bmatrix} T_e \\ 0 \end{bmatrix} + \mathbf{K}(y - \mathbf{C}\hat{\mathbf{x}})$$

If $T_m(\mathbf{x})$ satisfies the Lipschitz condition

$$\| T_m(\mathbf{x}_1) - T_m(\mathbf{x}_2) \| \le k_T \| \mathbf{x}_1 - \mathbf{x}_2 \|,$$

then the design of **K** can be carried out by the methods described in [3][4][5].

4. Analysis and comparison for optimal speed tracking

In the work a 7.5kW wind turbine driving a four-pole squirrel cage induction machine is considered. Because the dynamic of the machine is much faster than the dynamic of the mechanical plant, it is assumed that the electrical torque is imposed instantaneously in the machine. The following are the wind turbine parameters: R=2.87m; J=3.5kgm^2, G(Gear Box)=5.07, ρ=1.25kgm^{-3}, B= 0.02Nms^{-1}, $T_{e,max}$ =60Nm. The wind profile shown in Figure 3 was measured in Punta Arenas. Although higher wind velocities can be found in the vast area of Punta Arenas, the wind velocity data used here serve as a proof-to-the concept for the wind velocity observers proposed in this paper. The observer has been tested using longer wind data records, shown in figure 3. From these results the second order model provides clearly more accurate results. However, in the region of fast varying wind speed the estimation error increases.

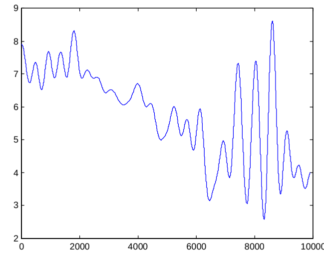

Figure 2. A typical wind profile in Pta. Arenas.

In order to cope with this fast dynamics the model could be improved by adding some extra terms representing faster dynamics.

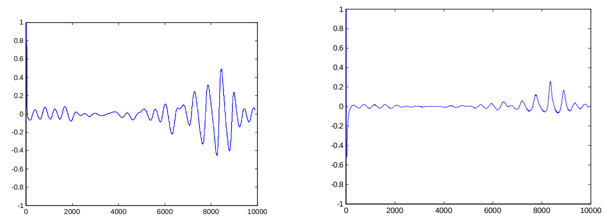

Figure 3. Long term Estimation Error first order and second order model

5. Final remarks.

The use of non-linear observers represents a good alternative compared to the conventional ways to estimate the wind velocity. The structure of the observer is simple and it does not require complex mathematical operations, being in this way easily implemented to satisfy the demanding real time constraints.

6. Acknowledgements.

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