Control of a 10 kW wind turbine variable pitch system under operating conditions

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Abstract:
This article presents the design of two variable pitch system controllers for a 10 kW wind turbine. The first is a proportional-integral (PI) controller and experimental data of its operation is shown. A disturbance accommodating control (DAC) strategy is used to design the second controller in order to overcome PI's limitations. Performances of both control strategies are compared with a non-linear model based on the FAST code. The relative production improvement caused by the variable pitch operation is presented.

Keywords: Small Wind Turbine; Proportional-Integral Control; Disturbance Accommodating Control

1 Introduction

On the NSERC Wind Energy Strategic Network's (WESNet) initiative, a downwind, 10 kW, 8 m diameter wind turbine developed by a team of Canadian researchers has recently been installed at the Wind Energy Institute of Canada. Its distinctive features are a permanent magnet synchronous generator (PMSG) and an inverter enabling a variable speed operation, and a variable blade pitch system. The latter is particularly innovative as the majority of the comparable size wind turbines operate at fixed pitch. This control device aims to regulate the angular rotor speed for strong winds in order to increase the electricity production [2]. The 1 MW Elkraft wind turbine project has shown that variable pitch operation could bring a 4.68% production increase when compared to fixed pitch operation [8].

In this article, a proportional-integral (PI) controller is designed to drive the WESNet wind turbine’s variable pitch system in order to achieve good power production. The linear model used to design it is presented in section 2. In the third section, experimental data of the wind turbine operation shows some limitations of the PI controller. A disturbance accommodating control (DAC) strategy is used to achieve better performance. In section 4, a non-linear model is built and experimental data is used to ensure that the actuator, the sensor and the generator/inverter simulated behaviours are accurate (it is important to note that control systems of the PMSG and of the variable pitch system are completely independent). This model is then used to compare the two control strategies. The last section confirms that, according to simulations, the variable pitch energy consumption doesn’t outweigh the enhanced power production that it brings along.
2 Linear dynamic model

The WESNet turbine theoretical produced power $P$ with respect to wind speed is shown in figure 1a. For winds under the nominal speed $v_0 = 9.5$ m/s, the turbine operates at variable rotor speed where maximizing power production is achieved through the inverter’s maximum power point tracking (MPPT) strategy. For a wind speed equal to or above $v_0$, the production remains constant at the nominal power $P_0$ in order to maintain maximum generator efficiency and to limit mechanical loads on the turbine. Equation (1) demonstrates that if the generator torque $T_{gen}$ and the generator efficiency $\eta_{gen}$ are constant, keeping a stable $P_0$ requires a constant angular rotor speed $\Omega_0$.

$$P = \Omega \cdot T_{gen} \cdot \eta_{gen} \quad (1)$$

The variable pitch system allows to regulate the rotor speed. Indeed, a modification of the pitch angle $\beta$, that is to say a rotation of the blade around its own axis, modifies the aerodynamic torque $T_{aero}$ and thus the rotor acceleration, as demonstrated by:

$$J_{rot} \cdot \dot{\Omega} = T_{aero} - T_{gen} \quad (2)$$

where $J_{rot}$ represents the rotor inertia and $\dot{\Omega}$ the angular rotor acceleration. The relationship between $T_{aero}$ and $\beta$ is non-linear. Figure 1b shows the required pitch angle in order for $P_0$ to remain constant despite a wind speed change. However, only angular rotor speed is available to control the blades’ pitch, since wind speed is not a measured signal.

For the WESNet turbine, $T_{aero}$ as a function of $\beta$ is computed in a FAST simulation [7]. However, a non-linear simulation with this design code is not suitable to design a control strategy [2, 9]. To overcome this problem, a tool is available in FAST to linearize the model around an operating point and to extract a simplified model as presented in eq. 3.

$$\Delta \dot{\Omega} = A\Delta \Omega + B\Delta \beta + B_d \Delta v \quad (3)$$

$$A = \frac{\partial T_{aero}/\partial \Omega}{J_{tot}} \quad ; \quad B = \frac{\partial T_{aero}/\partial \beta}{J_{tot}} \quad ; \quad B_d = \frac{\partial T_{aero}/\partial v}{J_{tot}}$$

Relation (3) stems from (2) [9]. $A$, $B$ and $B_d$ respectively translate the rotational speed, the pitch angle and the wind speed influence on the aerodynamic torque. The $\Delta$ signs means that only a variation around the operating point is considered. For the WESNet turbine, this point corresponds to $\Omega = 220$ RPM, $\beta = -5^\circ$ and $v = 9.5$ m/s. The FAST linearization resulted in $A = -0.1567$, $B = -4.8808$, $B_d = 0.8742$ and $C = 9.5490$ ($C$ is used in section 5).

3 Design of the PI controller

To design a controller according to the classical control theory, eq.(3) must be separated in two transfer functions, one expressing the angular speed according to pitch angle, the other according to wind speed (see figure 2). To form the closed loop, a proportional-integral (PI) controller identified $H(s)$ is added
in order to control the pitch angle according to rotational speed (see [9] for a justification of the use of a PI). Eq. (4) is the closed loop transfer function of the bloc diagram in figure 2. Its characteristic equation shows that if a small settling time and no overshoot are required, it is better to choose a high \( K_I \) and a \( K_P \) to obtain real poles. Such characteristics demand an excessive effort from the actuator and increase the energy consumption, which impact on the global wind turbine energy production. Parameters \( \omega_n \) and \( \zeta \) are thus chosen to allow approximately a \( \pm 15 \) RPM error on angular speed and to reduce the amplitude of the actuator movements.

\[
\frac{\Omega(s)}{v(s)} = \frac{\Omega_d(s)}{1 - H(s) \cdot G(s)} = \frac{CB_d s}{s^2 - (A + CBKP)s - CBKI}
\]

Starting values of 0.6 rad/s for \( \omega_n \) and of 0.6 to 0.7 for \( \zeta \) are recommended in [3]. In the end, values of \( \omega_n = 0.6 \) rad/s et \( \zeta = 1 \) are chosen by simulating the angular speed response to a few suggested wind cases of the IEC 61400-2 standard [5] with the bloc diagram of figure 2 in Simulink®. These values corresponds to \( K_P = 0.0224 \) rad/RPM and \( K_I = 0.0077 \) rad/(RPM-s). A 4 Hz sampling frequency is used in the simulation.

Measurements from the WESNet turbine operation for two distinct wind spectrum are shown in figure 3 in black lines. An adjustment of the gains to \( K_P = 0.0158 \) and \( K_I = 0.0017 \) is required in order to optimize the wind turbine performances according to the generator/inverter experimental behaviour. Although it was first considered inactive above the nominal speed \( v_0 \), the inverter control system stays in action no matter what the wind speed is, causing generator torque variations. The new \( K_P \) and \( K_I \) values lead to an increased settling time that diminishes the interactions between the two control systems. Compared to the previous one, the new gain set also helps lower the system’s sensitivity to measurement noise. Even if good performance is achieved with the PI controller, another control strategy is needed in order to meet two objectives: reduce the number of overspeed hit (the safety limit is set to 275 RPM) and minimize solicitation (and thus energy consumption) of the variable pitch system.

All measurements, except wind speed, were realized in accordance with the IEC 61400-12-1 standard [5]. The anemometer measuring \( v \) is not situated within the prescribed distance from the turbine and is not at hub height. Winds used for the simulations are therefore adjusted to the correct height using a power law and a landscape roughness of \( z_0 = 0.08 \) m (see [4] for details about this method).

4 Modifications to the non-linear model

Figure 3 shows in grey lines the results of a simulation carried out with the non-linear model realized with FAST in Simulink®. This model is used to compare the two control strategies. A few key components behaviours in Simulink® are refined based on experimental data. Firstly, a noise proportional to angular speed of a 10 RPM standard deviation at 220 RPM is added to measured wind speed. Secondly, a low-pass filter’s time constant is fixed to 0.075 s and a 0.007 s delay is imposed after the controller in order to fit the actuator experimental response. An example of the simulated response is given on figure 4. Thirdly, MPPT’s influence is reproduced by defining \( P(\Omega) \) and \( T_{gen}(\Omega) \) relationships with look-up tables and by putting a 1 s delay before applying \( T_{gen} \) on the rotor. This method presents the best trade-off between realism and execution time. \( P(\Omega) \) relation is approximated from experimental data of a one-day period. \( T_{gen}(\Omega) \) curve is calculated from \( P(\Omega) \) with eq. (1). Both relationships are presented on figure 4.

Globally, figure 3 shows that the non-linear model is able to reproduce adequately the turbine experimental behaviour. This statement is based only on curves mean values and fluctuations, as the simulated wind and the one to which the turbine is exposed are not synchronized.
Design of the DAC controller

This section presents the DAC-based controller designed to overcome limitations of the PI control strategy described in section 3. Its main advantage is the ability to estimate the amplitude of a known waveform disturbance and to cancel (or to limit) its effect on the system. The linear state-space model used by the DAC is composed of the plant and of the disturbance waveform generator, where $u_d$ is the disturbance input vector and $z_d$ the disturbance states. In this particular case, the wind can be represented as a step function with $F = 0$ and $\Theta = 1$.

\[
\dot{x} = Ax + Bu + B_d u_d \\
\dot{z}_d = F z_d
\]

The control law is based on observed states $\hat{x}$, observed disturbances $\hat{u}_d$ and gains $G$ and $G_d$ to obtain $u = G\hat{x} + G_d \hat{u}_d$. Gain $G$ can be calculated by minimizing a quadratic cost function (LQ method). This enables a balance between state deviation and control effort via $Q$ and $R$ constants. Gain $G_d$ must satisfy equation $BG_d + B_d \Theta = 0$ for the disturbance to be cancelled out and the error to converge to zero. Gains $K$ and $K_d$ of the state observers are found by placing the system’s closed loop poles in order for the observed states to quickly yield the real values and to minimize influence of noise on measurements. Block diagram of figure 5 is a discrete equivalent of the equations found in [1] and is based on the linearized model of eq. (3). Signals $y_k$ and $u_k$ are respectively the speed measurement received and the pitch command sent by the DAC-based controller and $\hat{u}_d$ is the observed disturbance.

Results of the non-linear simulations are presented on figure 6 for the PI (black lines) and for the DAC controller (gray lines). For both wind cases, the DAC reduces $\beta$ fluctuations. To achieve that, a high weighting is given to control effort with values of $Q = 0.0035$ and of $R = 1$, and observers poles are placed at 0.98 and at 0.65 on a discrete map for $K$ and $K_d$ respectively to slow down the system response. Moreover, the DAC strategy gives a mean wind speed estimate, as shown on the $v$...
Figure 4: Adjustments to the non-linear model: (a) comparison of the actuator experimental and simulated response to an input (b) generator experimental power curve for December 18, 2012 (operation data in grey), (c) corresponding generator torque curve.

Figure 5: Bloc diagram of the DAC controller with current observers (the variables identified with the exponent $A^{di}$ were converted in the discrete domain).

\[
\hat{v}_{d,k} = 6.5 \hat{u}_{d,k} \cdot \frac{\hat{v}_{d,k-1}}{21} + v_0
\]  

6 Variable pitch system performance

To achieve $\Omega$ regulation, the variable pitch system average simulated consumed power is lower for the DAC than for the PI. Indeed, a 34 W power was demanded by the PI against 20 W for the DAC for wind case (a). This improvement is seen as well for case (b), with 37 W for the PI and 23 W for the DAC. For both wind cases, an experimental produced power of around 8.8 kW was maintained. This translates to a variable pitch relative simulated energy consumption of only around 0.4% for the PI and of less than 0.3% for the DAC. Those values are well under the 4.68% production increase of the Elkraft wind turbine when operating at variable pitch rather than at fixed pitch. Therefore, based on the simulations, the variable pitch operation brings a gain of production of over 4% for the 10 kW WESNet wind turbine. However, the DAC control strategy reached the overspeed limit as many times as the PI control strategy.

7 Conclusion

In this article, a PI and a DAC-based controller are developed to equip the 10 kW WESNet wind turbine. Experimental data of its operation with the PI was used to improve the quality of a non-linear model built with FAST and Simulink®. Simulations were carried out with this model to
Figure 6: Results for the PI controller (black lines) and DAC controller (grey lines) for wind cases of figure 3.

compare the performance of both controllers. This parallel shows a reduced variable pitch system power consumption with the DAC. Based on simulations and on results of the Elkraft project, variable pitch operation caused a global wind turbine production increase of over 4%. Two other advantages of this strategy are its ability to give an estimate of the wind speed and the possibility to add other states (e.g. the tower acceleration) to the control algorithm. The DAC controller will be installed in the WESNet wind turbine in the near future, and its experimental performance will be compared with the PI.

References