http://dx.doi.org/10.5370/JEET.2012.7.2.273

Power Regulation of Variable Speed Wind Turbines using Pitch Control based on Disturbance Observer

Youngjun Joo* and Juhoon Back†

Abstract – Most variable speed wind turbines have pitch control mechanisms and one of their objectives is to protect turbines when the wind speed is too high. By adjusting pitch angles of wind turbine, the inlet power and the torque developed by the turbine are regulated. In this paper, the difference between the real wind speed and its rated value is regarded as a disturbance, and a component called disturbance observer (DOB) is added to the pre-designed control loop. The additional DOB based controller estimates the disturbance and generates a compensating signal to suppress the effect of disturbance on the system. As a result, the stability and the performance of the closed loop system guaranteed by an outer-loop controller (designed for a nominal system without taking into account of disturbances) are approximately recovered in the steady state. Simulation results are presented to verify the performance of the proposed control scheme.

Keywords: Disturbance observer, Pitch control, Power regulation, Variable speed wind turbine

1. Introduction

Because of concern about environmental pollution, the interest in renewable energy for generating electricity rapidly grows. Especially, the wind energy is the most competitive renewable energy because it is clean and economical. There are several ways to transform the wind energy into the electrical energy. Among them, the horizontal-axis wind turbine is mostly used and for decades, majority of wind turbines were operated at a fixed speed. Recently, researches on variable speed wind turbines have been increased in a considerable amount [1-4].

Compared to fixed speed wind turbines, variable speed wind turbines have advantages as follows:

(1) The efficiency of the generating power can be increased below the rated wind speed when an appropriate control strategy is applied.

(2) The aerodynamic power induced by wind turbulence can be stored in the inertia of the wind turbine. Thus, the drive train mechanical fatigue and the power fluctuation can be reduced.

In order to control the output power of variable speed wind turbines, many papers have been focused on the generator torque control. Recent papers employed gain scheduling [5], high order sliding mode control schemes [6], disturbance observer [7], etc. The control objective of these papers is to maximize the power when the wind speed is low and to limit the power when the wind speed is above the rated value.

However, as wind turbines become larger, the control strategy which solely relies on the generator torque became inefficient because the aerodynamic power produced by the turbine, which is proportional to the square of turbine's size, has been increased dramatically. Moreover, due to the nature of wind, which varies violently, it sometimes exceeds the rated value. Thus, most of the large scale wind turbines recently developed are equipped with variable pitch mechanism to adjust or regulate the inlet power from the wind and several pitch control methods are introduced, for example, PID [1], H_∞ [8]. But these controllers show limited performance against the wind speed fluctuation.

This paper introduces a pitch control scheme for variable speed wind turbines with a disturbance observer (DOB) based inner-loop structure. It is noted that DOB approach has been widely applied in industry, including optical disk drive systems, robot arm control, and etc [9]. It is because of its simple structure as well as the powerful ability for compensating plant uncertainties and rejecting disturbances. Another advantage of DOB is that it is an inner-loop controller, and works in harmony with the pre-designed (outer-loop) controller which is designed without taking into account disturbances and uncertainties.

To achieve the goal, we focus on the situation when the wind speed is greater than its rated value. The difference between the real wind speed and its rated value is regarded as a disturbance, and a DOB based inner-loop controller is designed so that the disturbance is estimated and attenuated. As a result, it recovers the performance of the pre-designed controller, which has been designed assuming that the wind speed is at its rated value.

The proposed idea is applied to a wind turbine system and simulation results show that the power fluctuation has been reduced considerably and the generating power

† Corresponding Author: School of Robotics, Kwangwoon Univerity, Korea. (backhoon@kw.ac.kr)
* ASRI, School of Electrical Engineering, Seoul National University, Korea. (yjjoo@cdsl.kr)
Received: January 6, 2011; Accepted: February 1, 2012

remains almost constant in the steady state.

This paper is organized as follows. Section 2 summarizes the dynamic model of the wind turbine, the maximum power point tracking (MPPT) control strategy, the power controller, and the DOB approach. In Section 3, a DOB based pitch controller is presented. Simulation results are provided to verify the performance of the proposed scheme in Section 4. Finally, Section 5 concludes the paper.

2. System Models and Control Objectives

In this section, we describe mathematical models of the system (see Fig. 1) and control strategies used in the paper. In addition, we briefly review the DOB structure.

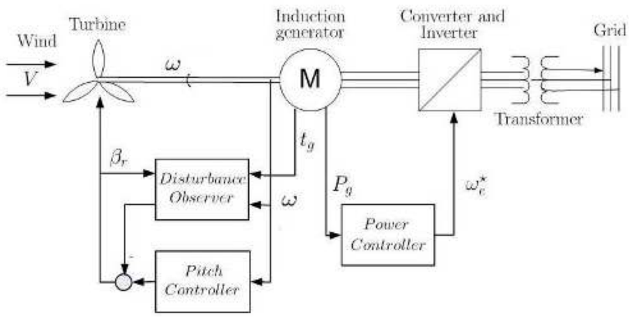

Fig. 1. System configuration.

2.1 Wind turbine model

The aerodynamic power absorbed by the turbine is given by the following relation.

$$P_w = \frac{1}{2}\rho\pi R^2 C_P(\lambda,\beta)V^3 \tag{1}$$

where ρ is the air density, R is the wind turbine rotor radius, $C_p(\lambda,\beta)$ is the power coefficient, V is the wind speed, β is the pitch angle, and λ is the tip speed ratio defined by

$$\lambda = \frac{R\Omega}{V} \tag{2}$$

where Ω denotes the turbine rotor speed.

The power coefficient $C_p(\lambda,\beta)$ used in this paper is given by

$$C_p(\lambda,\beta) = c_1(c_2\frac{1}{\Gamma} - c_3\beta - c_4\beta^{c_x} - c_5)e^{-\frac{c_6}{\Gamma}}$$
$$\frac{1}{\Gamma} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{1+\beta^3} \tag{3}$$

where c_1, c_2, c_3, c_4, c_5, c_6, and c_x are nonnegative constants determined by blade shape [11].

We use one mass drive train model described by

$$J_w\dot{\omega} = T_w - t_g \tag{4}$$

where $\omega = N\Omega$ is the electrical rotor speed, N is the gear ratio, J_w is the moment of inertia, T_w is the aerodynamic torque developed by the turbine, and t_g is the generator reaction torque. The aerodynamic torque T_w is determined by

$$T_w = \frac{P_w}{\Omega} = \frac{1}{2}\rho\pi R^3 C_T(\lambda,\beta)V^2 \tag{5}$$

where $C_T(\lambda,\beta) = C_p/\lambda$ is the torque coefficient. The electrical rotor speed ω will be used throughout this paper instead of the turbine rotor speed Ω.

It is assumed that the pitch actuator has the first order dynamics given by

$$\dot{\beta} = -k\beta + k\beta_r \tag{6}$$

where k is a positive constant, β_r is the pitch angle command.

For the generator, we consider the steady-state model since the dynamics of the generator is much faster than those of other parts. The V/f PWM converter is assumed to have a first order transfer function. For more detailed models, the readers are referred to [1, 2].

2.2 Wind turbine control strategy [1-4]

Fig. 2 shows the power versus rotor speed relationship for wind turbines when the pitch angle β is fixed at 0°. The curves P_{wi} represent the aerodynamic power when the wind speed is V_i, and $P_g^\star$ stands for the reference of the generator output power. ω_R and P_R are rated values of the rotor speed and the generator power, respectively.

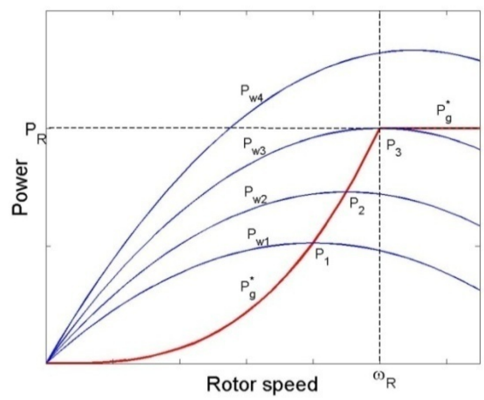

Fig. 2. Aerodynamic power versus rotor speed.

When $\omega \le \omega_R$, the objective of control strategy is to track the maximum power points such as P_1, P_2, and P_3.

Note that the trajectory $P_1 \sim P_3$ is a function, which is proportional to the cube of ω, i.e., $P_g^\star = C_{pg}\omega^3$ where C_{pg} is a positive constant. On the other hand, when $\omega > \omega_R$, we choose to track the curve $P_g^\star$ so that the power is limited to P_R. This means that the generator output power is limited to its rated value. Note that this strategy is just one of many strategies introduced in the literature [3].

Note that in the above rated wind speed region, any operating point along $P_g^\star$ is locally unstable, while it is stable below the rated wind speed. It means that the variation of the wind speed may lead to instability of the system because of the characteristic of the aerodynamic power. See [3] for detailed arguments on stability. This can be avoided by using pitch control. If the pitch angle is adjusted properly so that P_w is limited to the rated generator power P_R, then the torque and the rotor speed fluctuation can be reduced.

One way to achieve this is to control the pitch angle so that ω is fixed at ω_R, because if this has been achieved, and if the generator power is maintained at $P_g = C_{pg}\omega_R^3 = P_R$, then the equilibrium we obtain is the point with $P_w = P_R$ due to the relations (4) and (5). In summary, in the region $\omega > \omega_R$, we will design a pitch controller to make $\omega = \omega_R$.

2.3 Power control method [1]

The objective of the power control is to make the electric output power P_g tracks the reference $P_g^\star$ by controlling the slip frequency of the induction generator. This is done by a PI controller given by

$$\begin{aligned} \omega_s^\star &= K_{wp}(1 + \frac{1}{K_{wi}s})(P_g - P_g^\star), \\ \omega_e^\star &= \omega + \omega_s^\star \end{aligned} \tag{7}$$

where $\omega_s^\star$ is the reference for slip frequency and $\omega_e^\star$ is the reference to the V/f PWM converter. Note that the reference $P_g^\star$ is determined by the rotor speed ω and only the power controller is active in the region $\omega \leq \omega_R$, while it works together with the pitch controller to regulate P_g to P_R in the region $\omega > \omega_R$.

2.4 Review of disturbance observer

In this section, we briefly review the DOB scheme shown in Fig. 3. To simplify the problem, consider a first order system whose transfer function is given by

$$P(s) = \frac{g}{s+a}$$

where $g \neq 0$ and a are unknown but bounded constants.

$P_n(s)$ denotes the nominal transfer function of $P(s)$. Assume that a controller $C(s)$ has been designed for the nominal plant $P_n(s)$ and it is guaranteed that the closed-loop system ($P_n(s)$ and $C(s)$) is stable and can track a reference input y_r with a good performance, provided that there is no disturbance d.

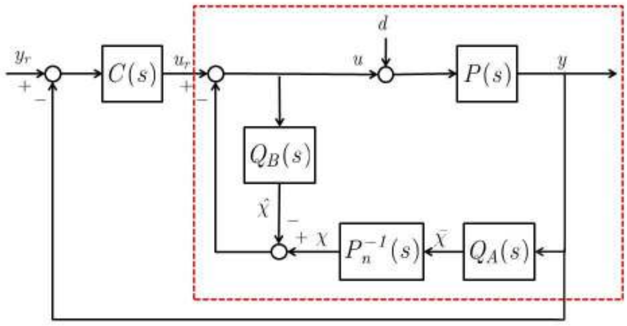

Fig. 3. Basic structure of disturbance observer.

If $P(s) = P_n(s)$ and it were completely known, then we can see from Fig. 3 that the input $u + d$ is given by $u + d = P_n^{-1}y$. Of course, this is not realistic because, in general, P_n^{-1} is not proper. One solution to this problem is to introduce a low pass filter given by

$$Q_A(s) = \frac{a_0}{\tau_q s + a_0}$$

so that the signal $\chi = P_n^{-1}Q_A(s)y$ is approximately the same as $u + d$, especially in the low frequency range. Now, we also introduce a low pass filter $Q_B(s)$ to obtain $\hat{\chi} = Q_B(s)u$. Note that if $Q_A(s) = Q_B(s)$, then it follows that $\chi - \hat{\chi} \approx d$ in the low frequency range and hence we use this signal to approximately cancel the disturbance d.

The idea can be explained in the state space. Let the system $P(s)$ be realized as

$$\dot{x} = -ax + g(u + d), \; y = x, \; x \in \mathbb{R}, \tag{8}$$

and the low-pass filter $Q_A(s)$ is realized as

$$\dot{q} = -\frac{a_0}{\tau_q}q + \frac{a_0}{\tau_q}y, \; \bar{\chi} = q, \; q \in \mathbb{R}. \tag{9}$$

The parameter τ_q is a sufficiently small positive constant, which is closely related to the bandwidth of the filter. $Q_B(s)$ has the same structure as $Q_A(s)$ and is realized by

$$\dot{p} = -\frac{a_0}{\tau_q}p + \frac{a_0}{\tau_q}(u_r + \hat{\chi} - \chi), \; \hat{\chi} = p, \; p \in \mathbb{R}. \tag{10}$$

The inverse dynamics [12] of nominal plant ($P_n^{-1}(s)$ in Fig. 3) is derived as follows.

$$\chi = \frac{\bar{a}}{\bar{g}}q + \dot{q} \tag{11}$$

where $\bar{a}$ and $\bar{g}$ are the nominal values of a and g, respectively.

Using singular perturbation theory, one can conclude that the states p and q converge to some values (or trajectories) in a very short time so that the quasi-steady-state system [13] becomes

$$\dot{x} = -\bar{a}x + \bar{g}u_r,\ y = x. \tag{12}$$

Note that the disturbance d is completely eliminated in the Eq. (12). Moreover, in the quasi-steady-state, the uncertain values (a and g) of $P(s)$ present no longer and are replaced by corresponding nominal values. For more details on the robust stability and performance recovery, the readers are referred to [9, 14].

3. Design of DOB based Pitch Controller

In this section, we propose the DOB based pitch controller to limit the aerodynamic power in the region $\omega > \omega_R$. As discussed in Section 2.2, the purpose of pitch controller is to regulate ω so that $\omega = \omega_R$.

3.1 Pitch angle as control input

Although the dynamics of the rotor speed (5) is linear, the aerodynamic torque described in (4) is highly nonlinear with respect to the tip speed ratio λ and the blade pitch angle β. Since our objective is to regulate the input power when the wind energy is greater than the rated value, the main control action is to reduce the inlet wind energy by controlling the pitch angle β. In order to design the DOB based pitch controller, we first rewrite the Eq. (5) so that the system becomes input affine [13]. Furthermore, to simplify the problem, the input gain is linearized around the operating point where $V = V_R$ (rated wind speed), $\omega = \omega_R$ (rated electrical rotor speed), and $\beta = \beta_0 = 0°$.

From the Eqs. (4)-(5) and the fact that the tip speed ratio λ is a function of the rotor speed ω and the wind speed V, the drive train model is rewritten as a linear system with perturbation. (Here, we used Taylor series expansion.) Namely,

$$\begin{aligned}\dot{\omega} &= \frac{1}{2J_w}\rho\pi R^3 C_T(\lambda,\beta)V^2 - \frac{1}{J_w}t_g \\ &= f(\omega,\beta,V) - \frac{1}{J_w}t_g \\ &= F_1\omega + F_2\beta + F_3 V - \frac{1}{J_w}t_g + f_u(\omega,\beta,V) \\ &= F_1\omega + F_2\beta + F_3 V_R - \frac{1}{J_w}t_g + f_u(\omega,\beta,V) + F_3 V_D\end{aligned} \tag{13}$$

where $F_1 := \partial f/\partial\omega\big|_{(\omega_R,\beta_0,V_R)}$, $F_2 := \partial f/\partial\beta\big|_{(\omega_R,\beta_0,V_R)}$, $F_3 := \partial f/\partial V\big|_{(\omega_R,\beta_0,V_R)}$ and $f_u(\omega,\beta,V)$ consists of $f(\omega_R,\beta_0,V_R) - F_1\omega_R - F_2\beta_0 - F_3 V_R$ and high-order nonlinear terms. The rotor speed ω and the blade pitch angle β are the state and the control input, respectively. In order to effectively deal with the situation, the wind speed is greater than the rated value, the uncertain wind speed V is decomposed as $V = V_R + V_D$ where V_R is the known rated wind speed while V_D is unknown.

The dynamics of the wind turbine model, which contains the drive train model derived above and the pitch actuator is given by

$$\begin{aligned}\dot{\omega} &= F_1\omega + F_2\beta + F_3 V_R - \frac{1}{J_w}t_g + \bar{f}_u(\omega,\beta,V), \\ \dot{\beta} &= -k\beta + k\beta_r, \\ y &= \omega\end{aligned} \tag{14}$$

where $\bar{f}_u(\omega,\beta,V) = f_u(\omega,\beta,V) + F_3 V_D$. Here, we define the output of this dynamics y as the rotor speed since the purpose of pitch control is to make ω converge to ω_R. It is also intended to emphasize the feedback signal we will use when we apply the DOB structure introduced in Section 2.4. We emphasize that the control signal which will be developed in the sequel is β_r.

3.2 Design of DOB based pitch controller $(\omega > \omega_R)$

Fig. 4 shows the structure of the proposed controller. It is seen that the pitch controller is composed of the outer-loop PID controller and inner-loop DOB. Note that the PID controller corresponds to the controller $C(s)$ in Fig. 3. It is designed to regulate ω to ω_R and has the following form.

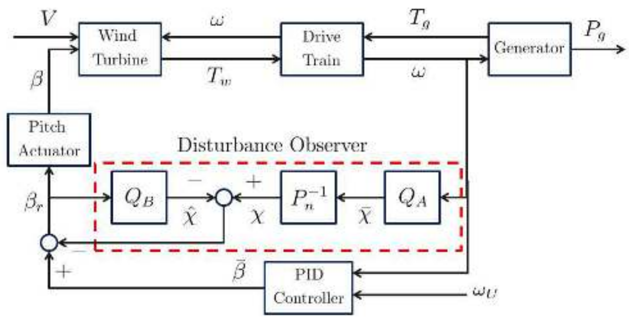

Fig. 4. DOB based pitch controller.

$$\bar{\beta} = K_{pp}(1 + \frac{1}{K_{pi}s} + \frac{K_{pd}s}{1+\gamma K_{pd}s})(\omega - \omega_U) \tag{15}$$

where $\bar{\beta}$ is the controller output, ω_U is a value slightly greater than ω_R, and K_{pp}, K_{pi}, K_{pd}, and γ are design parameters. It is noted that in (15), ω_U is used rather than ω_R in order to avoid the chattering effect when the wind speed varies around its rated value. In addition, as explained in Section 2.4, the parameters for PID controllers are chosen for disturbance free nominal model (16) for the system (14), which will be derived shortly.

In order to design the inner-loop controller based on

DOB, the nominal model of the wind turbine based on (14) is derived as

$$\begin{aligned}\dot{\omega}_N &= F_1\omega_N + F_2\beta_N + F_3V_R - \frac{1}{J_w}t_g,\\ \dot{\beta}_N &= -k\beta_N + k\bar{\beta},\\ y_N &= \omega_N.\end{aligned} \tag{16}$$

Here, it is noted that the Eq. (14) does not satisfy the matching condition. In other words, the disturbance $\bar{f}_u$ and the input β_r are not on the same line. But, in practice, the pitch actuator dynamics is much faster than the drive train dynamics, that is to say, compared with F_i, the magnitude of the parameter k is relatively large. In addition, the pitch actuator dynamics is stable for the positive parameter k, which means that the pitch angle β converges to the input of the pitch actuator β_r sufficiently fast. Thus, we temporarily ignore the pitch actuator dynamics so that the inverse dynamics of the nominal plant is derived as follows.

$$\tilde{\beta} = \frac{1}{F_2}(\dot{\omega} - F_1\omega - F_3V_R + \frac{1}{J_w}t_g). \tag{17}$$

With this result, we design the inner-loop controller as

$$\begin{aligned}\dot{q} &= -\frac{a_0}{\tau_q}q + \frac{a_0}{\tau_q}y, \quad \bar{\chi} = q,\\ \dot{p} &= -\frac{a_0}{\tau_q}p + \frac{a_0}{\tau_q}\beta_r, \quad \hat{\chi} = p,\\ \chi &= \frac{1}{F_2}(\dot{\bar{\chi}} - F_1\bar{\chi} - F_3V_R + \frac{1}{J_w}t_g)\\ &= \frac{1}{F_2}(\dot{q} - F_1q - F_3V_R + \frac{1}{J_w}t_g)\\ \beta_r &= \bar{\beta} + \hat{\chi} - \chi.\end{aligned} \tag{18}$$

As seen in Fig. 4, DOB generates $\hat{\chi} - \chi$ and this signal is added to the output of PID controller resulting the input for pitch actuator β_r is generated. Note that β_r corresponds to u and $\bar{\beta}$ corresponds to u_r in Fig. 3.

In order to analyze the stability and the performance of the closed loop system, we define $\tau_\beta = k^{-1}$ and the states q and p are transformed into ξ and η as follows.

$$\xi := q - \omega, \quad \eta := p - \frac{1}{F_2}\dot{q}. \tag{19}$$

With these variables, the overall system (14) and (18) becomes

$$\begin{aligned}\dot{\omega} &= F_1\omega + F_2\beta + F_3V_R - \frac{1}{J_w}t_g + \bar{f}_u,\\ \begin{bmatrix}\tau_\beta\dot{\beta}\\ \tau_q\dot{\xi}\\ \tau_q\dot{\eta}\end{bmatrix} &= \begin{bmatrix}-1 & \frac{F_1}{F_2} & 1\\ -\tau_qF_2 & -a_0 & 0\\ -a_0 & a_0\frac{F_1}{F_2} & 0\end{bmatrix}\begin{bmatrix}\beta\\ \xi\\ \eta\end{bmatrix} + \begin{bmatrix}f_\beta\\ -\tau_qf_\xi\\ f_\eta\end{bmatrix}\\ &:= A_f\begin{bmatrix}\beta\\ \xi\\ \eta\end{bmatrix} + \begin{bmatrix}f_\beta\\ -\tau_qf_\xi\\ f_\eta\end{bmatrix}\end{aligned} \tag{20}$$

where

$$\begin{aligned}f_\beta &:= \frac{1}{F_2}(F_1\omega + F_2\bar{\beta} + F_3V_R - \frac{1}{J_w}t_g),\\ f_\xi &:= F_1\omega + F_3V_R - \frac{1}{J_w}t_g + \bar{f}_u,\\ f_\eta &:= a_0\bar{\beta} - a_0\frac{1}{F_2}\bar{f}_u.\end{aligned}$$

Since the small parameters τ_β and τ_q are different, we use the multi-parameter singular perturbation theory. Let

$$D = \begin{bmatrix}\frac{\tau}{\tau_\beta} & 0 & 0\\ 0 & \frac{\tau}{\tau_q} & 0\\ 0 & 0 & \frac{\tau}{\tau_q}\end{bmatrix}, \quad \tau = (\tau_\beta\tau_q)^{\frac{1}{2}}.$$

Then the Eq. (20) is rewritten as follows.

$$\begin{aligned}\dot{\omega} &= F_1\omega + F_2\beta + F_3V_R - \frac{1}{J_w}t_g + \bar{f}_u,\\ \tau\begin{bmatrix}\dot{\beta}\\ \dot{\xi}\\ \dot{\eta}\end{bmatrix} &= DA_f\begin{bmatrix}\beta\\ \xi\\ \eta\end{bmatrix} + D\begin{bmatrix}f_\beta\\ -\tau_qf_\xi\\ f_\eta\end{bmatrix}.\end{aligned} \tag{21}$$

With the result of (21), it can be seen that the system shows two time scale behavior since τ is sufficiently small. Indeed, the dynamics of rotor speed ω is relatively slow and that of β, ξ and η is relatively fast. Moreover, if the fast dynamics part is D-stable, i.e., the matrix DA_f is Hurwitz, then the states β, q and p converge to $\beta^\star$, $\xi^\star$, and $\eta^\star$ where

$$\begin{aligned}\beta^\star &= \bar{\beta} - \frac{1}{F_2}\bar{f}_u, \quad \xi^\star = 0,\\ \eta^\star &= \bar{\beta} - \frac{1}{F_2}(F_1\omega + F_2\bar{\beta} + F_3V_R - \frac{1}{J_w}t_g + \bar{f}_u)\end{aligned}$$

when the positive constants τ_β and τ_q are sufficiently small. (Note that $\beta^\star$, $\xi^\star$, and $\eta^\star$ are obtained from (21) with $\tau = 0$.) Finally, The quasi-steady state subsystem (with $\beta = \beta^\star$) becomes

$$\begin{aligned}\dot{\omega} &= F_1\omega + F_2\bar{\beta} + F_3V_R - \frac{1}{J_w}t_g,\\ y &= \omega.\end{aligned} \tag{22}$$

So, the overall system behaves like the disturbance-free nominal system which is not affected by V_D. The following result summaries the stability result.

Theorem 1: Suppose that
(1) the quasi-steady-state system (22) with pre-designed pitch controller (15) is asymptotically stable,
(2) the overall system (21) is D-stable, i.e., the matrix DA_f is Hurwitz,

(3) V and f_u are bounded and continuously differentiable with bounded derivatives.

Then, the overall system (14) and (18) is stable and behaves like the quasi-steady-state system (22) after the transient of fast dynamics of β, ξ, and η, if τ_β and τ_q are sufficiently small.

Proof: The proof easily follows from the multi-parameter singular perturbation theory [15] and the state space analysis of the DOB theory [9, 14].

Remark 2: The assumption (3) in Theorem 1 always holds because the function f_u depends on the torque coefficient C_T and it is continuously differentiable with bounded derivatives.

4. Simulations

Simulations are performed to evaluate the proposed scheme. The results are shown in p.u. (per unit) expression. The parameters for the wind turbine, DOB and PID controller are given in Appendix and the other system parameters are taken from [1].

Fig. 5 shows the wind speed considered in the simulation. It is determined by Kaimal spectra, where the mean is 1.5 (p.u.) and the turbulence intensity is 15%. We concentrate on the situation in which the wind speed is greater than its rated value because the pitch controller operates in the region $\omega > \omega_R$. (Note that the power controller is also active in this region.)

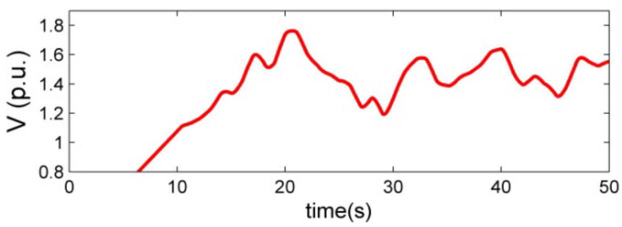

Fig. 5. Wind speed.

The simulation result of the power regulation can be seen in Figs. 6 and 7. (In Figs. 6 and 7, the blue and red lines represent the results with the conventional PID controller and those with proposed controller and each figure includes five parts: the generator output power, the input torque, the pitch angle, the rotor speed, and the torque coefficient.) One can see the difference clearly in Fig. 7 where all the responses are shown in detail. The generator output power P_g of both controllers does not exceed 0.87 (p.u.) after the transient response. Compared to its rated value 0.86 (p.u.), the power regulation is well achieved. However, the output power of the PID controller fluctuates.

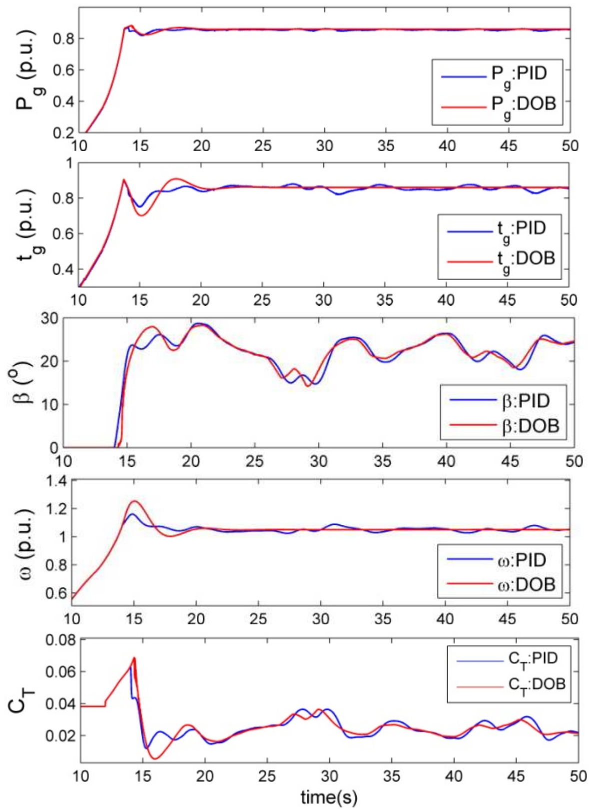

Fig. 6. Simulation for power regulation. (From the top to the bottom, P_g, t_g, β, ω, and C_T)

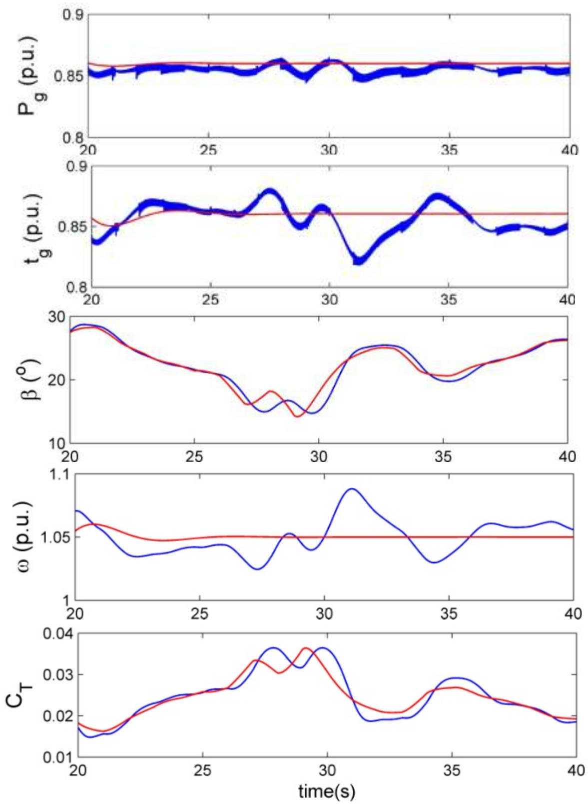

Fig. 7. Zoom of Fig. 6. (From the top to the bottom, P_g, t_g, β, ω, and C_T)

One can also see that the generator torque t_g of the proposed controller shows a better performance over the PID controller. (Using PID controller, the torque fluctuation is almost 0.05 (p.u.).) This means that the proposed controller reduces the effect of wind speed variation substantially. It is believed that this is because the DOB regulates the rotor speed tightly (see the graph of angular speed).

Regarding the performance recovery, one can see from Fig. 8 that the proposed controller recovers the performance of the outer-loop PID controller that is designed for the nominal plant (the blue line represents the response when the wind speed is fixed at 1 (p.u.).).

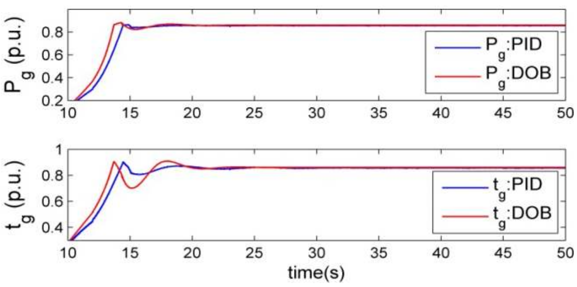

Fig. 8. Nominal performance ($V = V_R$) of PID controller and performance recovery by DOB.

5. Conclusion

In order to regulate the generator power above the rated wind speed region, this paper proposes a DOB based pitch control scheme for variable speed wind turbines. The difference between the real wind speed and rated wind speed is considered as a disturbance and the nonlinearities of wind turbine dynamics have been treated as model uncertainties. The simulation results show that the proposed DOB based pitch controller shows a better performance over the conventional PID.

Appendix

(1) System Parameters

Rotor radius: R=14 (m)
Rated wind speed: V_R=13 (m/s)
Moment of inertia: J_w=4 (s)[1]
Gear ratio: N=26.8
Constant of pitch actuator dynamics: k=0.12 (s)
Parameters of torque coefficient:
c_1=0.5, c_2=116, c_3= 0.4, c_4=0, c_5=5, c_6=21, x=0

(2) Control Parameters

Rated turbine rotor speed: Ω_R=1 (p.u.)
Rated electrical rotor speed: ω_R=1 (p.u.)
Reference of electrical rotor speed: ω_U=1.05 (p.u.)
Rated generator power: P_R= 0.86 (p.u.)
Generator output power reference constant: C_{pg}=0.86
Parameters of power controller: K_{wp}=0.5, K_{wi}=1
Parameters of pitch controller:
K_{pp}=100, K_{pi}=0.7, K_{pd}=0.8, γ=5
Parameters of DOB: a_0=1, τ_q=10^{-3}

Acknowledgements

This work was supported by the New & Renewable Energy of the Korea Institute of Energy Technology Evaluation and Planning(KETEP) grant funded by the Korea government Ministry of Knowledge Economy. (No. 20093021020030) The present research has been conducted by the Research Grant of Kwangwoon University in 2011.

References

[1] N. Horiuchi and T. Kawahito, "Torque and power limitations of variable speed wind turbines using pitch control and generator power control," *in Proceedings of IEEE PES SM 2001 Conference*, Vancouver, Canada, Jul. 2001, pp. 638-643.
[2] P. Novak, T. Ekelund, I. Jovik, and B. Schmidtbauer, "Modeling and control of variable-speed wind-turbine drive-system dynamics," *IEEE Contr. Syst. Mag.*, vol. 15, no. 4, pp. 28-38, Aug. 1995.
[3] W. E. Leithead and B. Connor, "Control of variable speed wind turbines: design task," *Int. J. of Control*, vol. 73, no. 13, pp. 1189-1212, Nov. 2000.
[4] E. Muljadi and C. P. Butterfield, "Pitch-controlled variable-speed wind turbine generation," *IEEE Trans. on Ind. Applicat.*, vol. 37, no. 1, pp. 240-246, Feb. 2001.
[5] F. D. Bianchi, R. J. Mantz, and C. F. Christiansen, "Control of variable-speed wind turbines by LPV gain scheduling," *Wind Energy*, vol. 7, no. 1, pp. 1-8, Mar. 2004.
[6] F. Velenciaga and P. F. Puleston, "High-order sliding control for a wind energy conversion system based on a permanent synchronous generator," *IEEE Trans. on Energy Convers.*, vol. 23, no. 3, pp. 860-867, Sep. 2008.
[7] Z. Hu, J. Wang, Y. Ma, and X. Yan, "Research on speed control system for fixed-pitch wind turbine based on disturbance observer," *in Proceedings of WNWEC 2009*, Nanjing, China, Sep. 2009, pp. 1-5.
[8] M. Geyler and P. Caselitz, "Robust multivariable pitch control design for load reduction on large wind

[1] The inertia constant is expressed in seconds, defined as $J_w = \frac{0.5 J \omega_b^2}{P_{nom}}$ where J, ω_b, and P_{nom} are the turbine's moment of inertia ($kg \cdot m^2$), the base speed of the rotor, and machine nominal power (VA), respectively.

turbin-es," *J. of Solar Energy Eng.*, vol. 130, no. 3, pp. 1-12, Aug. 2008.

[9] H. Shim and Y. Joo, "State space analysis of disturbance observer and a robust stability condition," *in Proceedings of 46th IEEE CDC*, New Orleans, LA, USA, Dec. 2007, pp. 2193-2198.

[10] Y. Joo, J. Back, and S. H. Song, "Power and torque limitations of variable speed wind turbines using pitch control based on disturbance observer," *in Proceedings of 16th Int. Conf. on Electrical Engineering*, Busan, Korea, Jul., 2010.

[11] S. Heier, *Grid Integration of Wind Energy Conversion Systems*, John Wiley & Sons, New York, 1998.

[12] A. Isidori, *Nonlinear Control Systems*, Third Ed., Spr-inger, 1995.

[13] H. K. Khalil, *Nonlinear Systems*, Third Ed., Prentice Hall, 2002.

[14] J. Back and H. Shim, "Adding robustness to nominal output-feedback controllers for uncertain nonlinear systems: A nonlinear version of disturbance observer," *Automatica*, vol. 44, no. 10, pp. 2528-2537, Oct. 2008.

[15] H. K. Khalil and P. V. Kokotovic, "Control of linear systems with multiparameter singular perturbations," *Automatica*, vol. 15, pp. 197-207, 1979.

Youngjun Joo received the B.S and the M.S. degrees in the School of Electrical Engineering and Computer Sciences from Seoul National University in 2005 and 2007, respectively. He is currently working toward the Ph.D. degree in the School of Electrical Engineering and Computer Sciences, Seoul National University, Seoul, Korea. His research interests include disturbance observer, robust control, and wind power systems.

Juhoon Back received the B.S. and the M.S. degrees in Mechanical Design and Production Engineering from Seoul National University, in 1997 and 1999, respectively. He received the Ph.D. degree from the School of Electrical Engineering and Computer Science, Seoul National University, Seoul, Korea, in 2004. From 2005 to 2006, he worked as a research associate at the Control and Power Group, Electrical and Electronic Engineering, Imperial College London, UK. From 2007 to 2008, he was a BK21 contract professor at Korea University, Korea. Since 2008 he has been at Kwangwoon University, Seoul, Korea, where he is currently an assistant professor in the School of Robotics. His research interests include control system theory and design, wind power systems, and multi agent systems.