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Output Control of Three-Axis PMSG Wind Turbine Considering Torsional Vibration Using H Infinity Control

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Abstract: Due to changes in wind, the torque obtained from the wind turbine always fluctuates. Here, the wind turbine and the rotor of the generator are connected by a shaft that is one elastic body, and each rotating body has different inertia. The difference in inertia between the wind turbine and the generator causes a torsion between the wind generator and the generator; metal fatigue and torsion can damage the shaft. Therefore, it is necessary to consider the axial torsional vibration suppression of a geared wind power generator using a permanent magnet synchronous generator (PMSG). In addition, errors in axis system parameters occur due to long-term operation of the generator, and it is important to estimate for accurate control. In this paper, we propose torque estimation using H_∞ observer and axial torsional vibration suppression control in a three inertia system. The H_∞ controller is introduced into the armature current control system (q-axis current control system) of the wind power generator. Even if parameter errors and high-frequency disturbances are included, the shaft torsional torque is estimated by the H_∞ observer that can perform robust estimation. Moreover, by eliminating the resonance point of the shaft system, vibration suppression of the shaft torsional torque is achieved. The results by the proposed method can suppress axial torsional vibration and show the effect better than the results using Proportional-Integral (PI) control.

Keywords: wind turbine; PMSG; H infinity output control

1. Introduction

Environmentally friendly renewable energy is attracting attention, and its introduction rate is increasing. In particular, wind power generation has a low cost of power generation and can generate a large amount of power in a small space compared to solar power generation [1]. The variable speed wind power generation system using permanent magnet synchronous generator (PMSG) is simple in structure and high in efficiency. It is also used in large wind power generation systems [2–4]. The capacity factor is reduced due to the failure of the wind power generator system [5]. The cause of failure of a wind power generator includes breakage of anemometer, blade and shaft. If the anemometer is broken, the proper rotational speed can not be maintained. In particular, failure due to shaft breakage has a long stop time due to repair. The shaft system of the wind power generator consists of rotating bodies of different mass. Due to changes in wind, the torque obtained from the wind turbine blade surface always fluctuates. When this mechanical power changes, the difference in mass causes an angular deviation in the shaft system, and a torsional stress is applied. It is an axial torsion phenomenon and occurs when an excessively large torsional stress is applied. Excessive axial torsion causes metal fatigue and causes the shaft system to break. Moreover, in the shaft system, the gearbox is a mechanical element that is easily damaged. Therefore, shaft torsional vibration suppression of a synchronous generator considering a gearbox is required. Up until now, gear elements have not been sufficiently considered with regard to axial torsional vibration suppression [6–8]. In addition, research has been conducted to measure the axial torsional torque. However, it is difficult to measure shaft torsional torque in an actual rotating machine. There is a need for a method to estimate the torsional torque to perform the control [9]. H_∞ control is one of the control methods for wind turbines [10]. This control method has high performance and stability for systems with parameter and modeling errors [10,11].

In this research, we propose an axial torsional vibration suppression control for a geared wind turbine generator system using the H_∞ observer to estimate the axial torsional torque. The H_∞ observer can perform robust estimation for axis systems in which parameter errors, etc., are likely to occur. Moreover, the H_∞ controller is introduced to the armature current control system of the variable speed wind power generator to achieve the suppression of the shaft torsional torque vibration. The simulation results compare the proposed method with the conventional Proportional-Integral (PI) control that does not take into account suppression. Simulations have been conducted with the software MATLAB/Simulink to validate the model and the control schemes. Parameter gains of PI controller are chosen by empirical knowledge.

2. Wind Turbine System

Wind energy received at the blade surface is transmitted through the shaft to PMSG and converted to electrical power. This electric power is supplied to the system via the converter and the inverter. This section describes the configuration of the PMSG wind power generation system. A Diagram of the wind turbine generator system is shown in Figure 1.

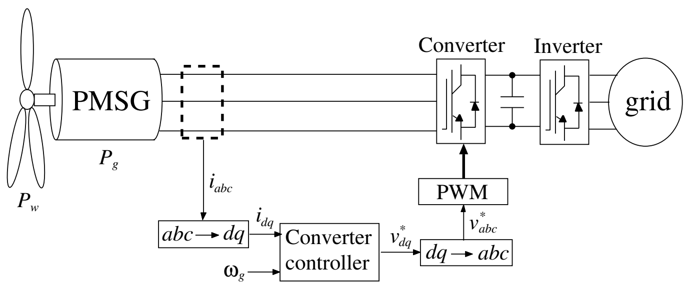


Figure 1. Configuration of power conversion control system of permanent magnet synchronous generator (PMSG) wind turbine.

2.1. Wind Turbine Model

Wind turbine output P_w and torque T_w that can be taken by the wind turbine are approximated by the following equation [12].

$$P = 0.5C_p(\lambda, \beta)\rho\pi R^2 V_w^3, \tag{1}$$

$$T_w = 0.5C_p(\lambda, \beta)\rho\pi R^3 V_w^2/\lambda. \tag{2}$$

where, V_w is wind speed, ρ is air density, R is wind turbine blade surface radius, C_p is wind turbine output coefficient, $\lambda = \omega_w R V_w$ is peripheral speed ratio, ω_w is wind turbine rotation speed, β is pitch angle. C_p is an output coefficient approximated by the ratio of the pitch angle and the tip speed of the blade. Power coefficient C_p is given by [12–14].

$$C_p = 0.22(116\lambda_i - 0.4\beta - 5)\exp(12.5\lambda_i), \tag{3}$$

$$\lambda_i = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1},$$

$$\lambda = \frac{\omega_w R}{V_w}. \tag{4}$$

2.2. Three Inertial System Axis Model

In this paper, we model the shaft system with gears by Three inertia system as shown in Figure 2 [6,15]. The equation of motion at each mass point is as follows [1,16].

$$J_1 \frac{d\omega_1}{dt} = T_w - T_{12} - (D_1 + d_{12})\omega_1 + d_{12}\omega_2, \tag{5}$$

$$J_2 \frac{d\omega_2}{dt} = T_{12} - T_{23} - (D_2 + d_{12} + d_{23})\omega_2 + d_{12}\omega_1 + d_{23}\omega_3, \tag{6}$$

$$J_3 \frac{d\omega_3}{dt} = T_{23} - T_g + d_{23}(\omega_2 - \omega_3) - D_3\omega_3, \tag{7}$$

$$T_{12} = K_{12}(\theta_1 - \theta_2), \tag{8}$$

$$T_{23} = K_{23}(\theta_2 - \theta_3), \tag{9}$$

where each variable is as shown in Table 1 [7,17]. In addition, the damper components (D_1, D_2, D_3, d_{12}, d_{23}) were neglected in order to assume a more unstable case of the shaft system this time. The frequency response of the axis system is as shown in Figure 3, and there are two resonance points. The resonance point is removed for axial torsional vibration suppression control.

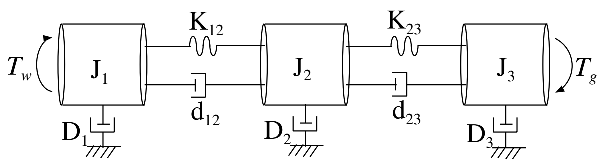


Figure 2. Three mass model.

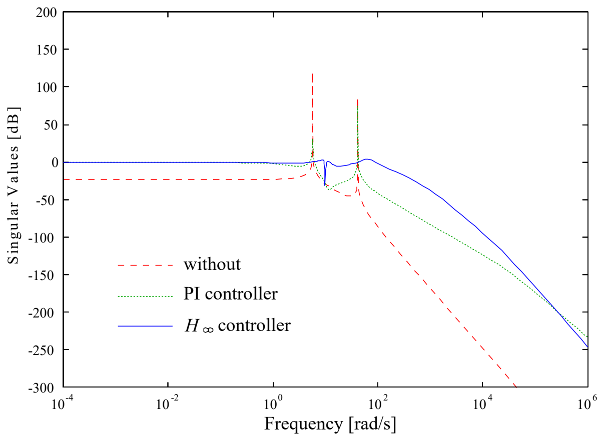


Figure 3. Frequency response of the shaft system.

2.3. PMSG

The voltage equation and the torque equation on the rotational coordinate axis (d − q axis) of PMSG are given as follows.

$$v_d = R_a i_d + L_d \frac{di_d}{dt} - \omega_1 L_q i_q, \tag{10}$$

$$v_q = \omega_e L_e i_d + R_a i_q + L_q \frac{di_q}{dt} + \omega_e K, \tag{11}$$

$$T_g = p\{K i_q + (L_d - L_q) i_q i_d\}, \tag{12}$$

v_d and v_q is d_q axis voltage, i_d and i_q is dq axis current, L_q is d_q axis armature inductance, K is electromotive force coefficient, p is pole pairs and each variable is as shown in Table 1 [7,17].

Table 1. PMSG parameters.

rated output P_g	2 MW
resistance R	50 μΩ
d axis inductance L_d	5.0 mH
q axis inductance L_q	3.75 mH
number of pole pairs p	11
field flux K	136.25 V · s/rad
Generator inertia J_3	0.168×10^6 kg · m^2

2.4. Converter of Generator Side

Currently, the AC-DC-AC link method is commonly used for power conversion method in wind power generation equipment. Figure 4 shows a conventional generator-side converter control configuration [7]. Here, the electric torque of the wind power generator is controlled by the current control on the rotational coordinate axis (dq axis). In this paper, salient pole type PMSG is used, and the d axis current command value i_d is obtained from the following equation to achieve high efficiency operation [18].

$$i_{dref} = \frac{K}{2(L_d - L_q)} - \sqrt{\frac{K^2}{4(L_q - L_d)} + (i_q)^2}. \tag{13}$$

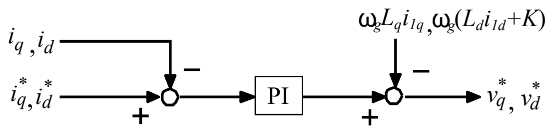


Figure 4. Generator side converter control system.

3. Shaft Torsional Control System Using H_∞ Observer

3.1. H_∞ Observer

In this research, the gain design of the observer and the torsional vibration controller are designed using H_∞ control. In an actual rotating machine, it is difficult to measure the torque, and a method of estimation is needed. In this chapter, we adopt H_∞ observer which can estimate robustly against disturbance, etc. The H_∞ system model is shown in Figure 5. w is the disturbance due to the parameter error, and n is the observation noise. The H_∞ controller reduces the transfer function H_∞ norm from the disturbance to the controlled variable output. The H_∞ observer is a state observer that estimates torque that can not be measured directly. It has robust characteristics against disturbances and parameter errors. From Equations (5)–(9) and Figure 5, the state equation of the plant system is given as follows [7,19].

$$\dot{x}(t) = \mathrm{A} \cdot x(t) + \mathrm{B} \cdot u(t), \tag{14}$$

$$y(t) = C \cdot x(t), \tag{15}$$

$$A = \begin{bmatrix} 0 & 0 & 0 & -\frac{1}{J_1} & 0 \\ 0 & 0 & 0 & \frac{1}{J_2} & -\frac{1}{J_2} \\ 0 & 0 & 0 & 0 & \frac{1}{J_3} \\ K_{12} & -K_{12} & 0 & 0 & 0 \\ 0 & K_{23} & -K_{23} & 0 & 0 \end{bmatrix},$$

$$B = \begin{bmatrix} \frac{1}{J_1} & 0 \\ 0 & 0 \\ 0 & -\frac{1}{J_3} \\ 0 & 0 \\ 0 & 0 \end{bmatrix},$$

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 & 0 \end{bmatrix}.$$

where, $x(t) = [\omega_1 \omega_2 \omega_3 T_{12} T_{23}]$ is T state variable, $u(t) = [T_w T_g]$ is Input to the axis torsional system, $y(t) = \omega_3$ is the observed output. Therefore, H_∞ observer design problem represents following equation.

$$\min_\gamma \left\| \begin{matrix} W, T_{w \to \hat{y}} \\ W_2 T_{n \to \hat{y}} \end{matrix} \right\|_\infty \leq \gamma$$

Here, w is disturbance due to the parameter error, Estimated noise is $\tilde{n}$. $T_{w \to \hat{y}}$ is the transfer function from the parameter error to the observer estimate, $T_{n \to \hat{y}}$ is the transfer function from the observed noise to the observer estimate. The weight function W_1 was set as a low-pass filter characteristic in order to take parameter errors, which is a disturbance in the low frequency region, into consideration (Figure 6a). The weighting function W_2 was designed as a high-pass filter characteristic (Figure 6b) in order to take into account observation noise of high frequency. The H_∞ observer was designed using these weight functions, and the H_∞ controller, which is the observer gain, was designed by the LMI approach [20]. The frequency characteristics of the H_∞ observer are shown in Figure 7. Figure 7a is a singular value plot of the transfer function from the plant output value to the observer estimated value. It can be confirmed that the gain in the high frequency region can be reduced, and the H_∞ observer reduces the response to noise. Figure 7b is a singular value plot of the sensitivity function of the observer system. It can be confirmed that the sensitivity to errors in the low frequency region can be reduced. Next, the estimation accuracy of the designed observer is verified. Figures 8–13 show simulation results in the axis system including high frequency noise and parameter error. Here, the parameter error gives an error of -20% for the inertia coefficient J_1, J_2, J_3 and the stiffness coefficient K_{12}, K_{23}. The high frequency noise was a white noise with a maximum amplitude of 100. From these figures, it can be seen that the estimation accuracy is good even when the designed H_∞ observer includes a disturbance.

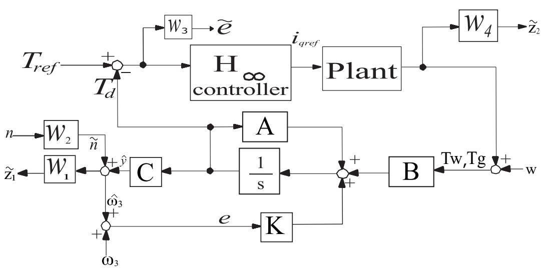
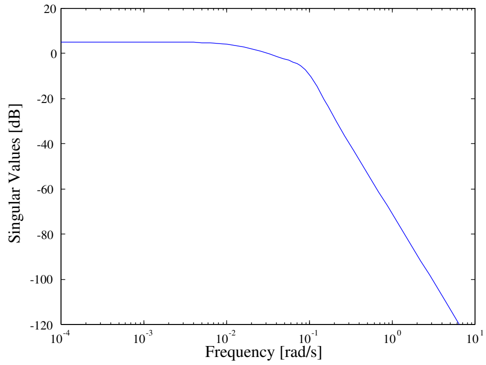
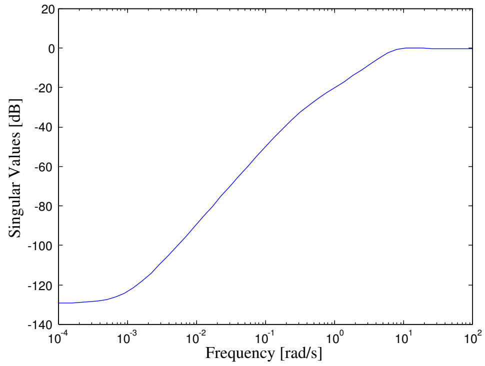


Figure 5. H_∞ System model.

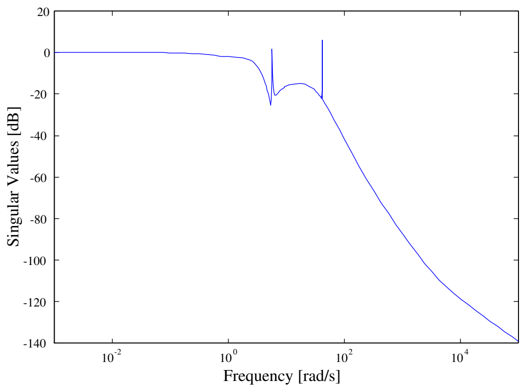


(**a**) Weighting function of low-pass filter characteristics for parameter error (W_1).

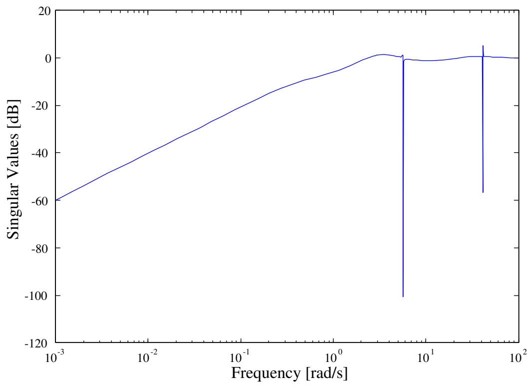


(**b**) Weighting function of high-pass filter characteristics for noise (W_2).

Figure 6. Weighting function of observer.



(**a**) Singular value of H_∞ observer ($y \to \hat{y}$).



(**b**) Singular value of H_∞ observer ($y \to e$).

Figure 7. Singular value of H_∞ observer.

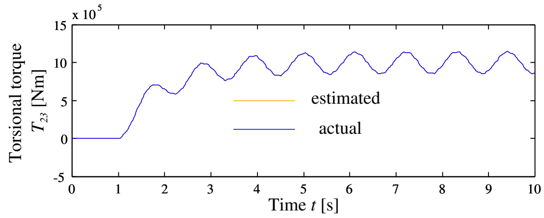


Figure 8. Torsional torque at without parameter error.

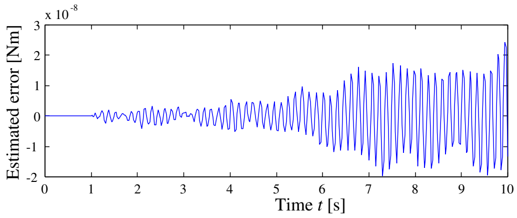


Figure 9. Estimated error at without parameter error.

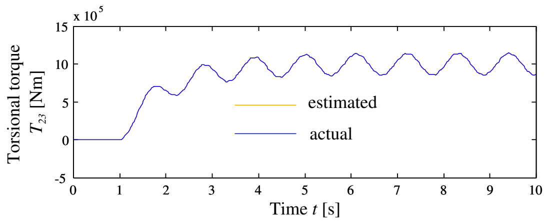


Figure 10. Torsional torque at parameter error −20%.

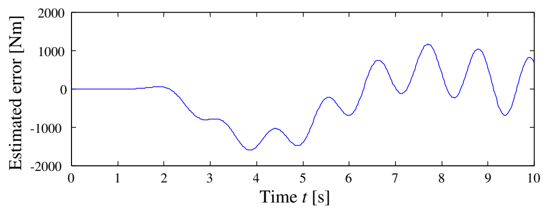


Figure 11. Estimated error of H_∞ observer at parameter error −20%.

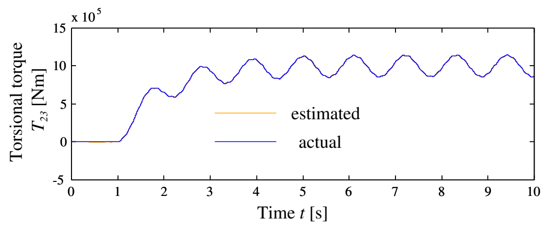


Figure 12. Torsional torque at with white noise.

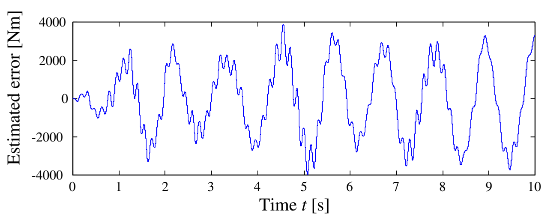
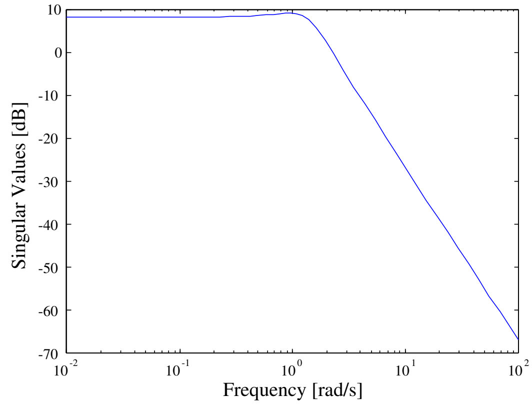


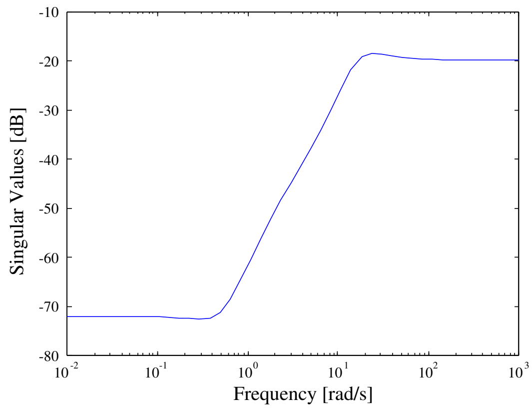
Figure 13. Estimated error of H_∞ observer at with white noise.

3.2. Torsional Vibration Suppression Control

Figure 3 shows the frequency response of the axial system [21]. It can be seen that there are two resonance frequencies in the shaft system. Torsional vibration is suppressed by removing this resonance point. We introduce the H_∞ controller into the armature current control system and control the generator side torque to satisfy the torsional vibration suppression. A shaft torsion torque control system including a weighting function is shown in Figure 5 [7]. ΔT_d as input, and PMSG for suppressing shaft torsional vibration. The q-axis current command value i_q is generated by the H_∞ controller. Here, $\Delta T_d = T_{ref} - T_d$, and T_d is the torsion torque estimated by the H_∞ observer. The weighting functions W_3 and W_4 of the controller for suppressing steady-state deviation and suppressing resonance for following the command value are selected as shown in Figure 14a,b, respectively. The H_∞ controller is designed by the LMI approach of the MATLAB toolbox, and as shown in Figure 3, it can be seen that the elimination of the resonance point is achieved by applying the H_∞ controller.



(**a**) Weight function for steady-state deviation removal for command value tracking (W_3).



(**b**) Weighting function for suppress resonance (W_4).

Figure 14. Weight function of controller.

4. Simulation Results

Table 2 shows each parameter used in the simulation. Figure 15 shows the assumed wind speed. In this paper, control by PI controller is also performed for comparison. The simulation results when the observer's state space model contains parameter errors are shown in Figure 16. The parameter error here is −20% for the inertia coefficients J_1, J_2, J_3 and the stiffness coefficients K_{12}, K_{23}. The axial torsion torque T_{12} between the blade and the gear of the wind power generator and the axial torsion torque T_{23} between the gear and the generator are used. The torsion torques for each shaft are shown in Figure 16b,c. The vibration is very large when the axis torsional vibration suppression control is not performed. The estimation results by H_∞ observer are shown in Figure 16d. From Figure 16c, the shaft torsional torque is estimated by the H_∞ observer even in anomalous wind conditions. Figure 16d,e show that the estimated error is small. As verified in Section 3, the estimation result by the designed H_∞ observer is good and robust even in the case of including parameter error. The control results of PI controller and H_∞ controller are compared. From this, it can be seen that the torsional vibration can be suppressed when the H_∞ controller is used for both sides. Further, these are achieved by controlling the electrical torque of the PMSG from Figure 16h,i. That is, in the simulation result by the H_∞ control, the axial torsional vibration suppression is achieved by frequently controlling the electric torque. For this reason, the generator output in Figure 16j greatly varies compared with the PI control.

Table 2. Wind turbine parameters.

blade radius R	39 m
air density ρ	1.205 kg/m^3
rated wind speed V_ω	12 m/s
Gear ratio N_{gear}	1
Wind turbine inertia J_1	2.173×10^6 kg · m^2
Gear inertia J_2	0.080×10^6 kg · m^2
Shaft stiffness K_{12}	7.554×10^6 N · m/rad
Shaft stiffness K_{23}	90.65×10^6 N · m/rad

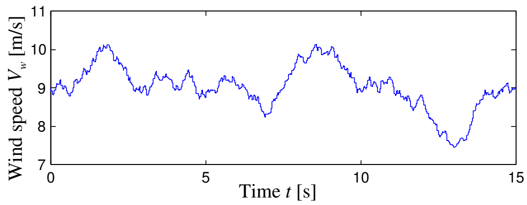
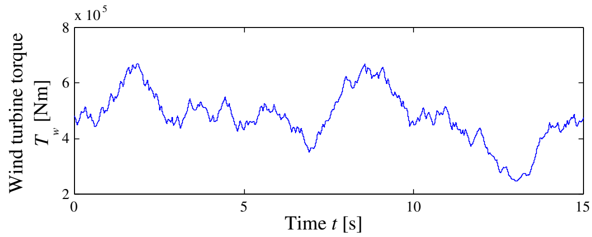
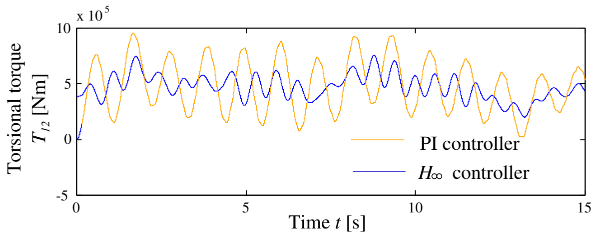


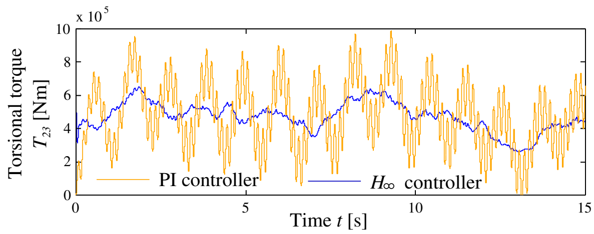
Figure 15. Wind speed.



(**a**) Wind turbine torque T_w.

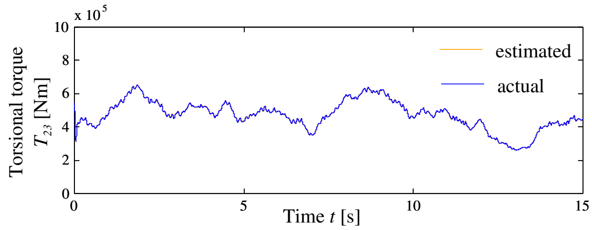


(**b**) Torsional torque T_{12}.

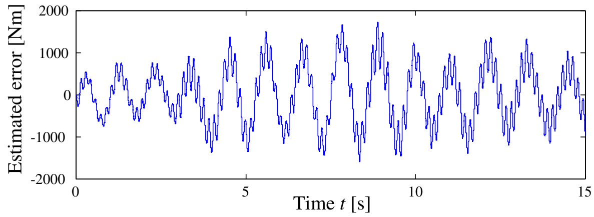


(**c**) Torsional torque T_{23}.

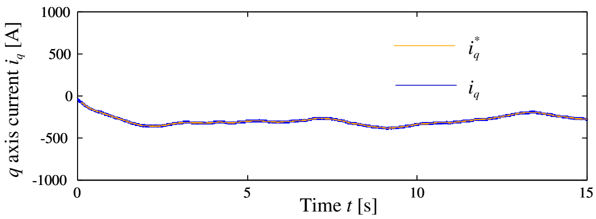
Figure 16. *Cont.*



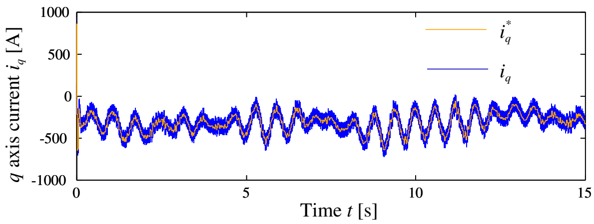
(**d**) Estimated result of torsional torque with H_∞ observer.



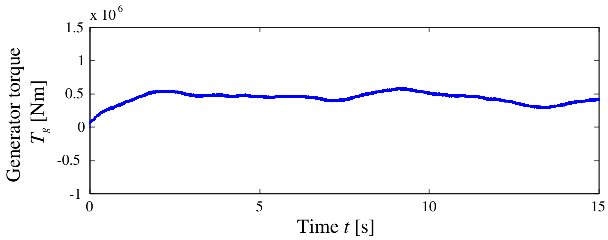
(**e**) Estimated error of torsional torque T_{23}.



(**f**) q axis current (PI controller).

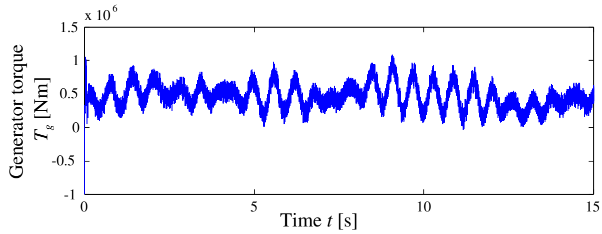


(**g**) q axis current (H_∞ controller).

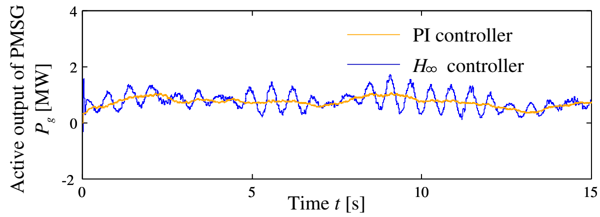


(**h**) Generator torque T_g (PI controller)).

Figure 16. *Cont.*



(i) Generator torque T_g (H_∞ controller).



(j) Active output of PMSG P_g.

Figure 16. Simulation results in Proportional-Integral (PI) control and H_∞ control.

5. Conclusions

For in the PMSG wind turbine generator, we estimated the torsional torque generated by the three inertial system of the wind turbine, the gear box, and the generator with the H_∞ observer and used the H_∞ controller as the armature current control system of the variable speed wind power generator to suppress shaft torsional vibration. While the generator output varied by controlling the electrical torque, the axial torsional vibration in the gear could be suppressed as compared with the case using the PI control. The proposed control method is able to suppress axial torsional vibration. This indicates that the stress suffered by the axial system was relieved. The present result suggest that greater suppression occurred even compared with two-axis H_∞ control and three-axis bandpass filter control methods for axial torsional vibration [22,23]. However, the simulation results show that the output power of the wind turbine is variable. The future challenge is to smooth output power fluctuation while suppressing the axial torsional vibration.

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