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Gain-Scheduled Control of Blade Loads in a Wind Turbine-Generator System by Individual Blade Pitch Manipulation

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SUMMARY

A gain-scheduled control of the blade loads using individual blade pitch manipulation for onshore wind turbine-generator systems was developed to further reduce unbalance in the blade loads during rotation. The development was conducted through a numerical analysis of the NREL 5MW-onshore wind turbine-generator system using the aeroelastic simulation code (FAST) and the measured high wind speed data. In this control, the proportional gains for the blade load control are varied depending on the collective blade pitch instead of the inflow wind speed. The calculated signal for the individual blade pitch manipulation is superposed on the collective blade pitch signal to control the generator speed. First, the sensitivity of the proportional gains to variations in the blade thrust loads is analyzed to reveal the unique gain-scheduled rule. Then, the system performances, including the variations in the blade thrust loads as well as the generator speed and generator power, under the developed gain-scheduled blade load control are analyzed to demonstrate its effectiveness. The results revealed that the gain-scheduled rule considering the control stability has fine performances of the blade thrust load variations, as compared with conventional fixed-gain control and gain-scheduled control based on the stability limit as well as the collective blade pitch manipulation with no blade load control.

1. INTRODUCTION

Wind power generation is one of solutions to overcome energy-security and global-warming problems. Recently, there has been much attention paid to offshore wind power generation systems because the area available to install onshore systems is limited and offshore wind conditions are better and more stable than onshore ones. In areas with very deep waters, including Japan, floating offshore wind turbine-generator systems are more attractive than bottom-mounted offshore systems. Floating offshore systems require the design of the platform structure to withstand severe operating conditions. This is because fatigue loads acting on the main parts of floating offshore systems increase due to platform motions induced by waves as well as winds. Moreover, unbalanced distribution of the blade thrust load during rotation, which is caused by spatial distribution of the inflow wind speed to a large rotor, increases the platform motions. Thus, the reduction in the unbalanced distribution of the blade thrust load is required.

Employing individual blade pitch manipulation, in which each blade pitch is manipulated individually depending on the blade loads, is effective to reduce the unbalanced distribution of the blade thrust load during rotation. Previous studies on individual blade pitch manipulation have been reported for an onshore system [1] and floating offshore systems [2,3]. In these previous studies, the proportional gains of the feedback control for the blade loads were fixed at any inflow wind speed. However, the blade load characteristics vary depending on the inflow wind speeds because the blade pitch nonlinearly increases with the inflow wind speed in order to maintain the rated generator speed/power. Thus, individual blade pitch manipulation using a fixed proportional gain may not have sufficient reduction performance of the unbalanced distribution of the blade thrust load. Moreover, no setting guideline for fixed proportional gain was provided in these previous works [1-3].

With such a background and review of the previous works, the present study develops a gain-scheduled control of the blade loads using individual blade pitch manipulation to further reduce unbalance in the blade thrust load during rotation. The development is conducted through a numerical analysis of the NREL 5MW-onshore wind turbine-generator system using the aeroelastic simulation code (FAST) and the measured high wind speed data. In this control, the proportional gains for the blade load control are varied depending on the collective blade pitch instead of the inflow wind speed. The calculated signal for the individual blade pitch manipulation is superposed on the collective blade pitch signal to control the generator speed. First, the sensitivity of the proportional gains to the variations in the blade thrust load is analyzed to reveal the unique gain-scheduled rule. Then, the system performances, including the variations in the blade thrust load as well as the generator speed and generator power, under the developed gain-scheduled blade load control are analyzed to demonstrate its effectiveness.

2. ONSHORE WIND TURBINE-GENERATOR SYSTEM

2.1 System Configuration

A general view of the target onshore wind turbine-generator system is shown in Fig. 1. A wind turbine-generator is installed on the top of a tower. The wind turbine-generator consists of a propeller-type wind turbine, gearbox, double-fed induction generator, PWM converter, PWM inverter, and controller. The AC power output of the induction generator with variable voltages and frequencies is connected to a grid through the PWM converter and inverter.

2.2 System Control Method

The target system has two control modes based on generator torque and blade pitch manipulations: variable-speed mode at low wind speeds [4] and constant-speed mode at high wind speeds. The present study focuses on the constant-speed mode. As shown in Fig. 2, the target system installs multi-loop controllers consisting of generator speed control and blade load control. The manipulated variables in the generator speed control are the generator torque and collective blade pitch. The individual blade pitch signal, which is the manipulated variable in the blade load control, is superposed on the collective blade pitch signal.

2.2.1 Generator speed control

At high wind speeds, the blade pitch is collectively manipulated depending on the generator speed and the mean blade pitch signal, in order to maintain the generator speed at a rated value. The mean value of the three blade pitch is employed for the gain-scheduling. In addition, the generator torque is manipulated to maintain the generator power at a rated value. According to a

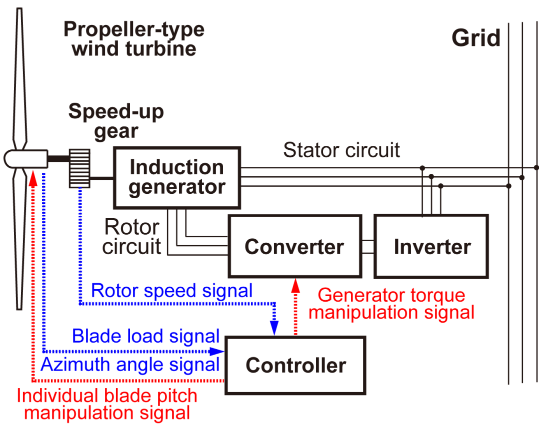

Fig. 1 Configuration of wind turbine-generator

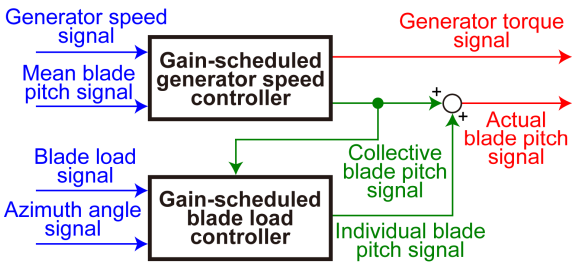

Fig. 2 Configuration of generator speed and blade load controllers

gain-scheduled proportional-plus-integral action, the collective blade pitch signal for the generator speed control, $\theta_{\mathrm{BC}}^{\mathrm{S}}$, is calculated by the following equation:

$$\left.\begin{aligned} \theta_{\mathrm{BC}}^{\mathrm{S}}(t) &= G_{\mathrm{K}}^{\mathrm{N}}(t) K_{\mathrm{P}}^{\mathrm{N}} \left[\Delta n_{\mathrm{G}}(t) + \frac{1}{T_{\mathrm{I}}^{\mathrm{N}}} \int \Delta n_{\mathrm{G}}(t) dt \right] \\ \Delta n_{\mathrm{G}}(t) &= n_{\mathrm{G}}^{\mathrm{F}}(t) - n_{\mathrm{G}}^{\mathrm{R}} \end{aligned}\right\} \tag{1}$$

where $G_{\mathrm{K}}^{\mathrm{N}}$ is a gain scheduled factor as a function of the mean blade pitch; $K_{\mathrm{P}}^{\mathrm{N}}$ is a proportional gain [deg/rpm]; $T_{\mathrm{I}}^{\mathrm{N}}$ is an integral time [s]; Δn_{G} is a generator speed deviation from a rated generator speed [rpm]; $n_{\mathrm{G}}^{\mathrm{F}}$ is a generator speed filtered by a first-order lag element [rpm]; and $n_{\mathrm{G}}^{\mathrm{R}}$ is a rated generator speed [rpm]. To compensate for changes in the system operating point, G_{K} is expressed as a function of the mean blade pitch $\bar{\theta}_{\mathrm{B}}$ [deg] by the following equation:

$$G_{\mathrm{K}}^{\mathrm{N}}(t) = \frac{1}{1 + \frac{\bar{\theta}_{\mathrm{B}}(t)}{K_{\mathrm{K}}^{\mathrm{N}}}} \tag{2}$$

where $K_{\mathrm{K}}^{\mathrm{N}}$ is a gain-scheduled coefficient [deg]. Furthermore, the generator torque is inversely manipulated in response to the filtered generator speed, so as to maintain the generator output at the rated value $P_{\mathrm{G}}^{\mathrm{R}}$ [kW] as follows:

$$\tau_{\mathrm{G}}(t) = \frac{P_{\mathrm{G}}^{\mathrm{R}}}{\frac{2\pi}{60} n_{\mathrm{G}}^{\mathrm{F}}(t) \eta_{\mathrm{G}}} \tag{3}$$

where η_{G} is the generator efficiency.

2.2.2 Blade load control

The block diagram of the gain-scheduled blade load controller is shown in Fig. 3. The objective of this blade load control is to reduce unbalance of the blade loads during rotation. First, the loads of three blades, which is a function of the azimuth angle, are converted to the two non-rotating orthogonal components, i.e., d and q axes, which represent the vertical and horizontal components of the blade loads in the rotation field. The d and q axis components of the blade loads, L_{d} and L_{q}, are calculated by the following Coleman transformation [1]:

$$\begin{pmatrix} L_{\mathrm{d}}(t) \\ L_{\mathrm{q}}(t) \end{pmatrix} = \frac{2}{3} \begin{bmatrix} \cos\varphi(t) & \cos\left(\varphi(t) + \frac{2}{3}\pi\right) & \cos\left(\varphi(t) + \frac{4}{3}\pi\right) \\ \sin\varphi(t) & \sin\left(\varphi(t) + \frac{2}{3}\pi\right) & \sin\left(\varphi(t) + \frac{4}{3}\pi\right) \end{bmatrix} \begin{pmatrix} L_1(t) \\ L_2(t) \\ L_3(t) \end{pmatrix} \tag{3}$$

where L_1, L_2, and L_3 are each blade load [Nm]; and φ is an azimuth angle [deg]. From L_{d} and L_{q}, the d and q axes components of the blade pitch field, $\theta_{\mathrm{Bd}}^{\mathrm{S}}$ and $\theta_{\mathrm{Bq}}^{\mathrm{S}}$, are uniquely calculated using the gain-scheduled proportional action:

$$\left.\begin{aligned} \theta_{\mathrm{Bd}}^{\mathrm{S}}(t) &= G_{\mathrm{K}}^{\mathrm{L}}\left(\theta_{\mathrm{BC}}^{\mathrm{S}}(t)\right) K_{\mathrm{d}}^{\mathrm{L}} L_{\mathrm{d}}(t) \\ \theta_{\mathrm{Bq}}^{\mathrm{S}}(t) &= G_{\mathrm{K}}^{\mathrm{L}}\left(\theta_{\mathrm{BC}}^{\mathrm{S}}(t)\right) K_{\mathrm{q}}^{\mathrm{L}} L_{\mathrm{q}}(t) \end{aligned}\right\} \tag{4}$$

where $K_{\mathrm{d}}^{\mathrm{L}}$ and $K_{\mathrm{q}}^{\mathrm{L}}$ are proportional gains [deg/Nm]; and $G_{\mathrm{K}}^{\mathrm{L}}$ is a gain scheduled factor as a function of the collective blade pitch signal. Moreover, $\theta_{\mathrm{Bd}}^{\mathrm{S}}$ and $\theta_{\mathrm{Bq}}^{\mathrm{S}}$ are converted to the azimuth coordinate to calculate the individual blade pitch signal by the following reverse

Coleman transformation [1]:

$$\begin{pmatrix}\theta_{\mathrm{B1}}^{\mathrm{S}}(t)\\ \theta_{\mathrm{B2}}^{\mathrm{S}}(t)\\ \theta_{\mathrm{B3}}^{\mathrm{S}}(t)\end{pmatrix}=\begin{bmatrix}\cos\varphi(t) & \sin\varphi(t)\\ \cos\left(\varphi(t)+\frac{2}{3}\pi\right) & \sin\left(\varphi(t)+\frac{2}{3}\pi\right)\\ \cos\left(\varphi(t)+\frac{4}{3}\pi\right) & \sin\left(\varphi(t)+\frac{4}{3}\pi\right)\end{bmatrix}\begin{pmatrix}\theta_{\mathrm{Bd}}^{\mathrm{S}}(t)\\ \theta_{\mathrm{Bq}}^{\mathrm{S}}(t)\end{pmatrix} \tag{5}$$

To obtain the actual individual blade pitch signal, $\theta_{\mathrm{B1}}^{\mathrm{S}}$, $\theta_{\mathrm{B2}}^{\mathrm{S}}$, and $\theta_{\mathrm{B3}}^{\mathrm{S}}$ are superposed on the collective blade pitch signal $\theta_{\mathrm{BC}}^{\mathrm{S}}$.

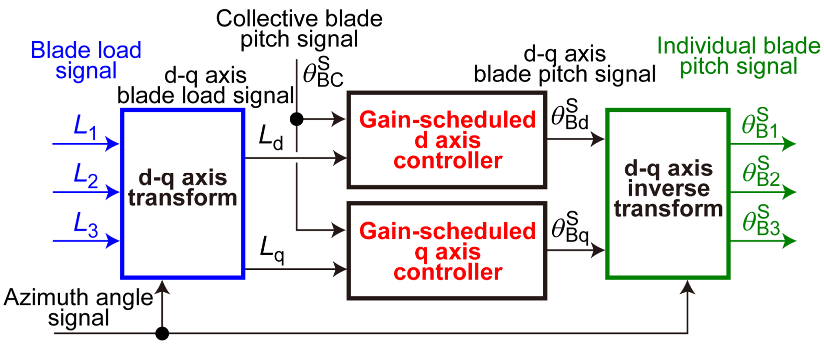

Fig. 3 Block diagram of blade load controller using individual blade pitch manipulation

3. SIMULATION MODEL

The aeroelastic analysis tool FAST Ver. 7 [5], developed in the National Renewable Energy Laboratory (NREL), is used for dynamic simulation studies. In FAST, the aerodynamic characteristics of a propeller-type wind turbine, elastic responses of the drivetrain, the turbine blades. and the tower, and control responses of the generator speed and blade thrust loads are coupled. The wind turbine-generator has 11 degrees of freedom: the rotation and shaft torsion for the drivetrain, and the first and second flapwise modes and the first edgewise mode for each blade. The tower has four degrees of freedom: the first and second fore-aft modes and the first and second side-to-side modes. Thus, the total number of degrees of freedom is 15. The aerodynamic characteristics of a propeller-type wind turbine, considering the dynamic stall and skewed inflow effects, are calculated by AeroDyn [6], which is embedded in FAST as a subroutine.

4. DYNAMIC CHARACTERISTIC ANALYSIS

4.1 Calculation Condition

4.1.1 System specifications

The target wind turbine-generator is the NREL 5-MW machine [6]. The wind turbine is an upwind and three-blade type, and its rotor diameter is 126 m. The rated power output of 5 MW is generated at the rated wind speed of 11.4 m/s and the rated rotor speed of 12.1 rpm. The maximum speed of collective blade pitch manipulation is 8 deg/s.

4.1.2 Control condition

For the generator speed control, the set point of the generator speed is the rated value, i.e., 1173.7 rpm, which is calculated from the rated rotor speed and the speed-up ratio of the drivetrain. The proportional gain $K_{\mathrm{P}}^{\mathrm{N}}$ and integral time $T_{\mathrm{I}}^{\mathrm{N}}$ in the generator speed control are set at 0.113 deg/rpm and 2.33 s, respectively. The gain scheduled coefficient $K_{\mathrm{K}}^{\mathrm{N}}$ is set to 6.3 deg. The time constant of the first-order lag filter for the generator speed is 0.637 s to avoid control action induced by the first edgewise mode of the blades. These control parameters were developed by NREL [6] for onshore systems.

For the blade load control, the thrust bending moment at the blade root part is the controlled variable. This is because the final objective of this control is to reduce unbalance of the blade thrust load during rotation for floating offshore applications. K_d^L and K_q^L are set to be the same value, on the basis of [7]. The gain-scheduled factor for the blade load control is determined through the following sensitivity analysis of the proportional gain.

4.1.3 Input condition

The wind data for the analysis were measured on an isolated island in Japan [8]. The wind speed distribution to the vertical direction, i.e., wind shear, is considered by using a power law, in which the exponent is 0.14. The following analysis focuses on the three levels of the mean wind speeds at the hub height of around 15, 18, and 21 m/s. For each mean wind speed, the six different wind data for 750 s are employed; the simulation result for first 150 s is discarded due to initial unstable behaviors. The inflow direction of the wind is fixed and conformed to the rotor shaft at the start of the analysis; thus, yaw control is not conducted.

The time steps to solve the differential equations and to calculate the aerodynamic characteristics of the wind turbine are 0.0125 and 0.0250 s, respectively.

4.2 Sensitivity Analysis of Proportional Gain of Blade Load Control

To obtain an appropriate gain-scheduled rule in the blade load control, the sensitivity of the proportional gain to the variations in the blade thrust loads , L_d and L_q, at constant inflow wind speeds is first analyzed. Figure 4 shows the total amplitude of L_d and L_q as a function of the constant inflow wind speed under various proportional gain settings of the blade load control. The constant inflow wind speed ranges from 12 to 24 m/s, at which the target system is operated in the constant-speed mode. At any constant inflow wind speed, the total amplitudes of L_d and L_q decrease with the increase in the proportional gain. However, the total amplitudes of L_d and L_q significantly increase in the case of excessively large proportional gain because the high frequency-fluctuations in L_d and L_q are induced by the decrease in the control stability. This characteristic of the total amplitudes of L_d and L_q is remarkable at higher inflow wind speeds. Thus, the proportional gain, in which the total amplitudes of L_d and L_q are minimized, decreases with the increase in the constant inflow wind speed.

Based on this sensitivity analysis, the stability limit gain is defined as the proportional gain,

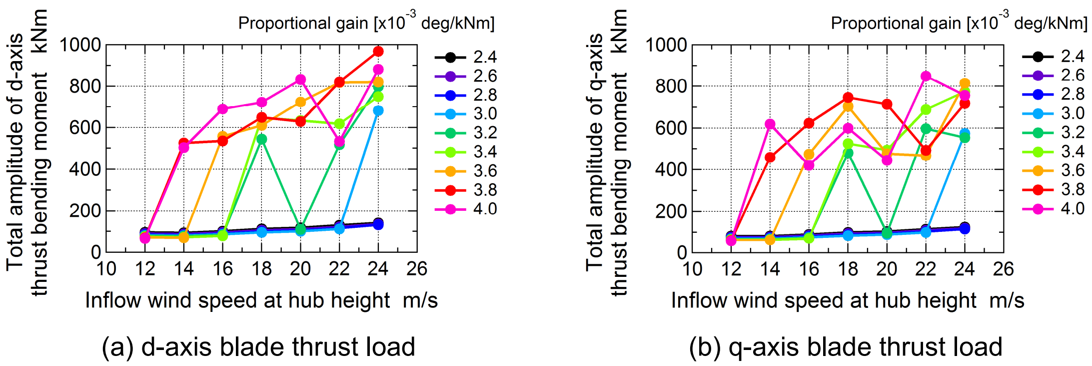

Fig. 4 Sensitivity of proportional gain of blade load control to total amplitude of blade thrust loads

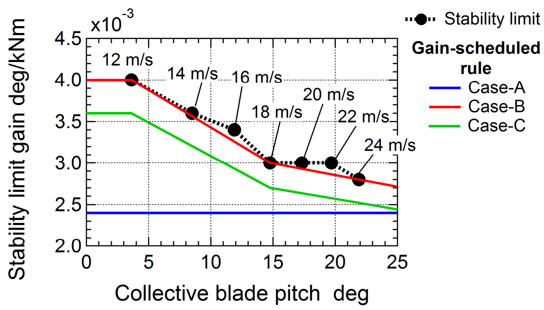

Fig. 5 Relationship between stability limit gain and collective blade pitch

in which the total amplitudes of L_d and L_q are minimized. The relationship between the stability limit gain and the collective blade pitch and constant inflow wind speed is presented by the marks in Fig. 5. The stability limit gain nonlinearly decreases with the increase in the collective blade pitch and constant inflow wind speed. From the analysis of the stability limit gain, three cases of the gain-scheduled rules, Case-A, Case-B, and Case-C, are developed. The proportional gain settings in the three gain-scheduled rules are also shown in Fig. 5. In these gain-scheduled rules, the proportional gain of the blade load control is varied depending on the collective blade pitch instead of the inflow wind speed for the consideration of the dynamic behavior of the blade thrust loads to the inflow wind speed. In Case-A, the proportional gain is fixed at any collective blade pitch to prevent the high frequency-fluctuations in L_d and L_q; this is a conventional gain setting for the blade load control. In Case-B, the proportional gain is varied so as to trace the stability limit gain. In Case-C, the proportional gain is set at 90% of that in Case-B to improve stability of the blade load control.

4.3 System Operating Behavior Analysis

The introduction effect of the developed gain-scheduled control for the blade thrust loads in the system operating behavior under filed wind condition is analyzed. Figure 6 shows typical system operating behavior during 15 s in the case of employing the three cases of the blade load control by the individual blade pitch manipulation (IBP) as well as only the generator speed control by the collective blade pitch manipulation (CBP). The inflow wind speed at the hub height, the pitch angle of the one blade (Blade-1), the rotor speed, the generator power, and the blade thrust loads (L_d and L_q) are focused on.

First, the behaviors other than the blade thrust loads are analyzed. The collective blade pitch follows the variation trend in the inflow wind speed at the hub height; however, the manipulation of the collective blade pitch in response to the inflow wind speed is smoothed due to the lag response of the rotor. The individual blade pitch is manipulated with the period of around 5 s in any case of the gain-scheduled rule. This period corresponds to the rotation period of the blade. The manipulation trend of the individual blade pitch is similar to that of the collective

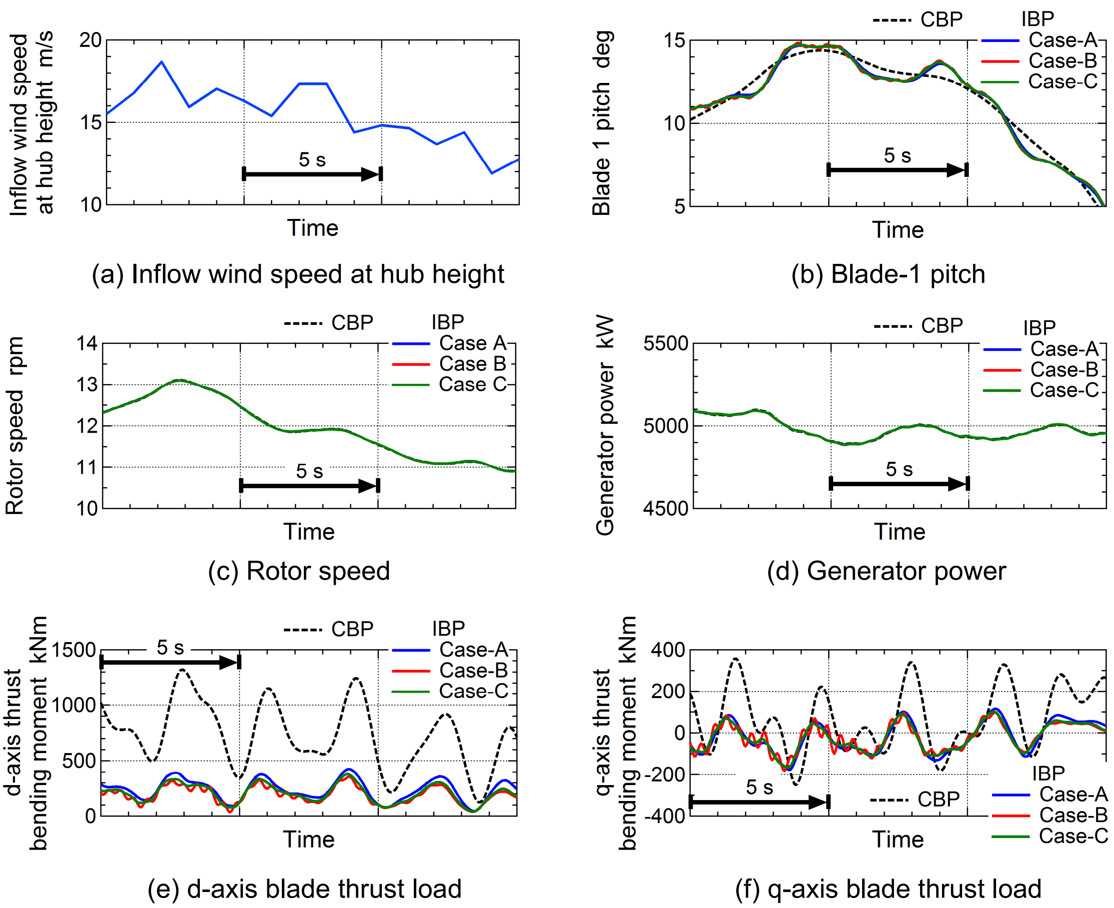

Fig. 6 System operating behavior under high wind speeds

blade pitch because the individual blade pitch signal is superposed on the collective blade pitch signal. The rotor speed, of which the lag response is caused by the large moment of inertia of the rotor, is hardly influenced by the individual blade pitch manipulation with a short period. The generator power is not also influenced by the individual blade pitch manipulation and well maintained at the rated value in any blade pitch manipulation. This is due to the generator torque manipulation depending on the filtered generator speed.

The blade thrust load behavior is greatly different between the two blade pitch manipulations. L_{d} in the collective blade pitch manipulation shows the positive value and widely fluctuates with the rotation period. The positive value of L_{d} indicates that the blade thrust load in the upper half-plain of the rotor is larger than that in the lower half-plain of the rotor owing to the wind shear. In the individual blade pitch manipulation, the variation and positive value of L_{d} are significantly reduced. This is because the each blade pitch is individually manipulated so as to reduce the blade thrust load in the upper half-plain and to increase the blade thrust load in the lower half-plain. L_{q} in the collective blade pitch manipulation also fluctuates widely and the mean value of L_{q} during rotation shows the positive value. These results are caused by the tilt angle of the wind turbine of -5.0 deg [6]; the tilt angle changes the attack of angle of the blade in the left half-plain and the right half-plain of the rotor. The unbalance of L_{q} during rotation is reduced by employing the individual blade pitch manipulation.

Finally, the impact of the gain-scheduled rules for the blade load control is analyzed. The blade thrust load behavior of Case-B, in which the gain-scheduled rule is set to trace the stability limit gain under the constant inflow wind speeds, exhibits high-frequency fluctuations. This means that the control stability in Case-B is insufficient under the wind speed fluctuations. In Case-C where the proportional gain is smaller than that in Case-B, the high-frequency fluctuations of the blade thrust loads are well reduced and the variations in the blade thrust loads are smaller than those in Case-A with the fixed proportional gains.

4.4 System Performances Analysis

The effectiveness of the gain-scheduled blade load control using the individual blade pitch manipulation is analyzed by the system performances under the field wind conditions. As the system performances, the root mean square (RMS) values of the generator power, the pitch angle of the one blade (Blade-1), and the blade thrust loads L_{d} and L_{q} are compared for the three cases of the blade load control. The results for the three levels of the mean wind speeds at the hub height are shown in Fig. 7. Each result were averaged from the results obtained in six different field wind data. The sampling time interval to calculate the RMS values of the generator power and the blade pitch is 1 s. That for the blade thrust loads is 0.2 and 1 s. The former is to evaluate high-frequency variations in the blade thrust loads. All the results are normalized using the averaged results derived in the collective blade pitch manipulation.

At any mean wind speed of the filed wind data, there is no difference in the RMS value of the generator power among three individual blade pitch manipulations. However, this RMS values are slightly increased by employing the individual blade pitch manipulation as compared with the collective blade manipulation. The RMS value of the blade pitch increases with the mean wind speed of the filed wind data in any individual blade pitch manipulation. This is because the difference in the inflow wind speed between the top and bottom of the rotor increases. The RMS values of the blade pitch in the gain-scheduled blade load controls (Case-B and Case-C) are larger than that in the fixed-gain blade load control (Case-A). The RMS values of the blade pitch in Case-B is the largest at any mean wind speed owing to the largest proportional gain, as shown in Fig. 5.

The RMS of L_{d} and L_{q} with both the sampling time intervals of 0.2 and 1 s are significantly reduced by employing the individual blade pitch manipulation at any mean wind speed. That is, the unbalance of the blade thrust load during rotation is improved. The RMS values of L_{d} and L_{q} with the sampling time interval of 1 s are reduced in the following order: Case-A, Case-C, and Case-B. This order coincides with the descending order of the proportional gain of the blade load control, as shown in Fig. 5. However, the RMS values of L_{d} and L_{q} with the sampling time interval of 0.2 s are the largest in Case-B with the high-frequency variation, as shown in Fig. 6. The difference in these RMS values between Case-B and Case-C is remarkable. It should also be noted that the RMS value of L_{q} with the sampling time interval of 0.2 s in Case-B is almost equal to that in the collective blade pitch manipulation. The increase in the RMS value of L_{d} with the sampling time interval of 0.2 s in Case-C relative to Case-A is slight. From this analysis, it is revealed that Case-C has fine performances of the blade thrust load variations with both the

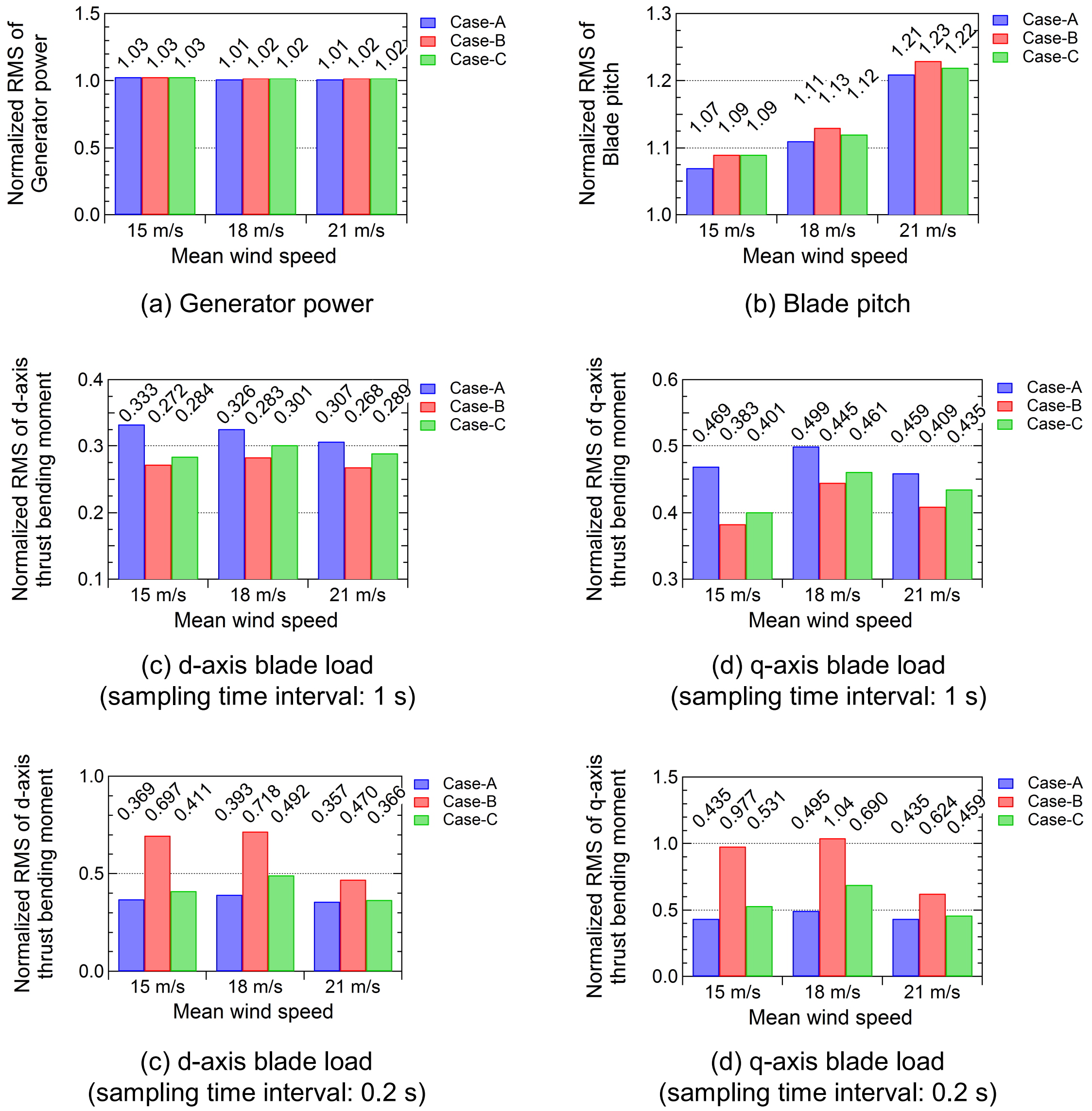

Fig. 7 Normalized RMS values of system behavior under field wind conditions with three levels of mean wind speeds

sampling time intervals of 0.2 and 1 s, as compared with Case-A and Case-B as well as the collective blade pitch manipulation with no blade load control.

5. Conclusions

A gain-scheduled blade load control using individual blade pitch manipulation for onshore wind turbine-generator systems was developed to further reduce unbalance in the blade thrust load during rotation. The development was conducted through a numerical analysis of the NREL 5MW-onshore wind turbine-generator system using the aeroelastic simulation code (FAST) and the measured high wind speed data. In this control, the proportional gains to control the d and q axis components of the blade thrust load, L_{d} and L_{q}, are varied depending on the collective blade pitch instead of the inflow wind speed. The calculated signal for the individual blade pitch manipulation is superposed on the collective blade pitch signal to control the generator speed. The derived results are summarized as follows:

1) The sensitivity analysis of the proportional gain of the blade load control under the constant inflow wind speed revealed that the stability limit gain decreases with the increase in the inflow wind speed. From this analysis, the gain-scheduled rule, in which the proportional gain of the blade load control is varied depending on the collective blade pitch signal for the

generator speed control, was developed.

2) The system operating behavior analysis showed that the blade load control by the individual blade pitch manipulation significantly reduces the unbalance in the blade thrust load during rotation. Employing the gain-scheduled control further reduces the blade thrust load variations as compared with the conventional fixed-gain control; however, the gain-scheduled rule based on the stability limit induced high-frequency variations in the blade thrust loads.
3) Employing the blade load control did not increase the generator power variation as compared with the collective blade pitch manipulation. However, the blade pitch variation increased especially in the gain-scheduled rule based on the stability limit.
4) The reduction effect of the blade thrust loads by the individual blade pitch manipulation depended on the sampling time interval. The gain-scheduled rule based on the stability limit well reduced the variation with the sampling time interval of 1 s; however, it increased the variation with the sampling time interval of 0.2 s. The gain-scheduled rule considering the control stability provided the smaller variation with the sampling time interval of 1 s than the fixed-gain control, and the variation with the sampling time interval of 0.2 s almost equal to the fixed-gain control.

From this analysis, it is revealed that Case-C has fine performances of the blade thrust load variations with both the sampling time intervals of 0.2 and 1 s, as compared with Case-A and Case-B as well as the collective blade pitch manipulation with no blade load control.

Although the proportional gains to control L_{d} and L_{q} were set to be equal in the present study, the separate gain-scheduled control may further improve the reduction effect of the blade thrust load variations. The application of the developed gain-scheduled control for the blade thrust loads to floating offshore systems is a future issue.

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