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개선된 가변속 풍력발전기의 주파수 평활화

Improved Frequency Mitigation of a Variable-Speed Wind Turbine

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(Mingguang Li · Dejian Yang · Yong Cheol Kang · Junhee Hong)

Abstract - For a power grid that has a high wind penetration level, when wind speeds are continuously fluctuating, the maximum power point tracking (MPPT) operation of a variable-speed wind turbine (VSWT) causes the significant output power fluctuation of a VSWT, thereby significantly fluctuating the system frequency. In this paper, an improved power-smoothing scheme of a VSWT is presented that significantly mitigates the frequency fluctuation caused by varying wind speeds. The proposed scheme employs an additional control loop based on the frequency deviation that operates in combination with the MPPT control loop. To improve the power-smoothing capability of a VSWT in the over-frequency section (OFS), the control gain of the additional loop, which is set to be inversely proportional to the rotor speed, is proposed. In contrast, the control gain in the under-frequency section is set to be proportional to the rotor speed to improve the power-smoothing capability while avoiding over-deceleration of the rotor speed of a VSWT. The proposed scheme significantly improves the performance of the power-smoothing capability in the OFS, thereby smoothing the frequency fluctuation. The results clearly demonstrate that the proposed scheme significantly mitigates the frequency fluctuation by employing the different control gain for the OFS under various wind penetration scenarios.

Key Words : Variable-speed wind turbine, Power smoothing, Frequency mitigation, Over-frequency section, Control gain

1. Introduction

For an electric power system with a high penetration level of wind power, the significant variation of wind speed results in difficulties in keeping the system frequency within a narrow range[1]. This is because variable-speed wind turbines (VSWTs) such as doubly-fed induction generators (DFIGs) and fully-rated converter-based VSWTs perform maximum power point tracking (MPPT) operation[2]. To mitigate these problems, some countries including Korea have specified the requirements on the ramp rates of the output power of a wind power plant (WPP)[3, 4].

To mitigate the frequency fluctuation, if the system frequency exceeds the nominal frequency (over-frequency section, OFS), the output power generated from a VSWT should be reduced; conversely, in the under-frequency section (UFS) the output power from a VSWT should be increased. A number of methods have been proposed that can mitigate the frequency fluctuation by smoothing the output power of a VSWT[5-11]; these solutions can be roughly divided into two types[11]: those with or without energy storage systems (ESSs). In[5-7], ESSs such as supercapacitors, flywheels, or batteries were suggested to mitigate the output power fluctuation of a VSWT. These additional devices effectively mitigate the power fluctuation, however, an extra cost for installation and maintenance is required, particularly for a large-scale VSWT.

To avoid this, the power-smoothing schemes were suggested that utilizes the rotating masses of a VSWT as an ESS. These schemes employ an additional control loop operating in conjunction with the MPPT control loop[8-10]. They can mitigate the output power fluctuation by releasing the stored energy in the rotating masses of a VSWT to the grid in the UFS or storing energy into the rotating masses in the OFS. This means that the heavy rotating masses of a VSWT, which has the comparable inertia constant to the conventional synchronous generators, can be effectively utilized as an ESS. Additional control loops were suggested based on the measured frequency: the rate of change of frequency loop and/or frequency deviation (Δf) loop[8-10]. In[8, 9], a fixed gain is used for the additional control loops. The use of a large gain can improve the power- smoothing capability of a VSWT, but it might result in over-deceleration

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of the rotor speed in the low-rotor-speed region. In this case, the output power of a VSWT should be abruptly reduced to recover the rotor speed; consequently, this causes a significant frequency fluctuation in the power system. To avoid this, the use of a small gain is inevitable, thereby it provides a limited contribution to mitigating the frequency fluctuation. To improve the power-smoothing capability while avoiding over-deceleration of the rotor speed, a power-smoothing scheme was proposed that employs a variable gain of the rotor speed[10]. In this scheme, the control gain is set to be proportional to the rotor speed; thus, it can effectively release the stored energy in a VSWT to smooth power in the UFS. However, this scheme uses the same control gain for both the OFS and UFS. Thus, even though in the low-rotor-speed region a VSWT has a large potential for storing energy into the rotating masses, this scheme provides a limited contribution to storing energy in the OFS because of a small gain.

This paper proposes a power-smoothing scheme of a VSWT that improves the frequency-mitigating capability in the OFS. The proposed scheme employs an additional control loop based on the frequency deviation operating in conjunction with the MPPT control loop. To improve the frequency-smoothing capability, the control gain of the additional control loop for the OFS is proposed that is set to be inversely proportional to the rotor speed. In contrast, the control gain in the UFS is set to be proportional to the rotor speed. The performance of the proposed scheme is investigated under various wind penetration levels using an EMTP-RV simulator.

2. Power-Smoothing Schemes of a DFIG

This section describes the overall features of the two conventional power-smoothing schemes suggested in[9] and[10], and the proposed scheme, which use the Δf loop for power smoothing. In this paper, the scheme in[9] is denoted as Scheme #1 and the scheme in[10] as Scheme #2.

The power reference (P_{ref}) in Scheme #1, Scheme #2, and the proposed scheme consists of the output for the MPPT control loop (P_{MPPT}) and the output of the Δf loop (ΔP) as in:

$$P_{ref} = P_{MPPT} + \triangle P = k_g \omega_r^3 + \triangle P \tag{1}$$

where ω_r is the rotor speed; and k_g is constant and is set to 0.512.

This paper aims to improve the power-smoothing capability of a DFIG, particularly in the OFS. Fig. 1 shows the operational features of the proposed scheme. While Scheme #2 uses the same control gain for both the UFS and OFS, the proposed scheme employs the different control gains separately defined in the UFS and OFS, as in:

$$K_{UFS}(\omega_r) = \frac{300}{\omega_{\max} - \omega_{\min}}(\omega_r - \omega_{\min}), \quad \text{for } \triangle f \le 0 \tag{2}$$

$$K_{OFS}(\omega_r) = \frac{-300}{\omega_{\max} - \omega_{\min}}(\omega_r - \omega_{\min}) + 600, \ \text{for } \triangle f > 0 \tag{3}$$

where $K_{UFS}(\omega_r)$ and $K_{OFS}(\omega_r)$ are the control gains in the UFS and OFS, respectively; $\omega_{\min}$ and $\omega_{\max}$ are set to 0.7 p.u. and 1.25 p.u., respectively.

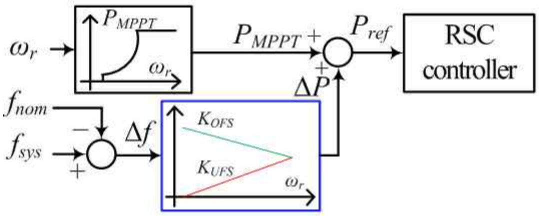
Thus, ΔP in the UFS and OFS can be obtained as:

$$\triangle P = \begin{cases} -K_{UFS}(\omega_r)\triangle f, & \text{for } \triangle f \le 0 \\ -K_{OFS}(\omega_r)\triangle f, & \text{for } \triangle f > 0 \end{cases} \tag{4}$$

$K_{UFS}(\omega_r)$, which represents the lower straight line between ($\omega_{\min}$, 0) and ($\omega_{\max}$, 300) in Fig. 1(b), is deliberately set to be proportional to ω_r while setting $K_{UFS}(\omega_{\min})$ to be zero so that the power-smoothing capability of the proposed scheme is similar to Scheme #2. The reason for this is as follows. If $K_{UFS}(\omega_{\max})$ is set to be larger than 300, the proposed scheme can provide better power - smoothing capability even in the UFS than Scheme #2 by releasing a larger amount of energy. However, this paper aims to improve the power-smoothing capability by employing the different control gain in the OFS while keeping the power-smoothing capability in the UFS similar to that of Scheme #2. As shown in Fig. 1(b), $K_{UFS}(\omega_r)$ is slightly larger than that in Scheme #2.

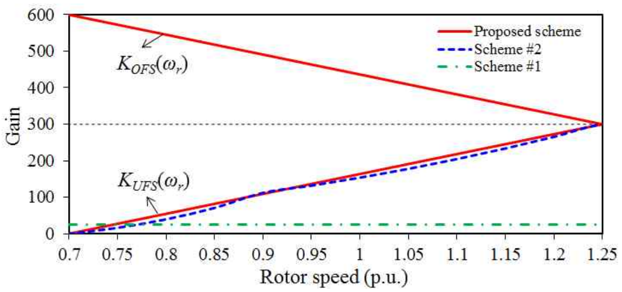
Conversely, in the OFS a DFIG should store energy into the rotating masses to mitigate the output power fluctuation of a DFIG, thereby reducing the frequency deviation. In the low-rotor-speed region, a DFIG has a larger potential for storing energy into the rotating masses than in the high-rotor-speed region and thus the control gain in the low-rotor-speed region should be set to be larger. This means that the control gain for the OFS should be monotonously decreasing with ω_r; in addition, the control gain in the OFS should be larger than that in Scheme #2. Thus, $K_{OFS}(\omega_r)$, which represents the upper straight line between ($\omega_{\min}$, 600) and ($\omega_{\max}$, 300) in Fig. 1(b), is set to be inversely proportional to ω_r. The reason for this is as follows. Larger gains than 600 at $\omega_{\min}$ and 300 at $\omega_{\max}$ can be set to improve the power-smoothing capability, but attention should be paid on more activations of the pitch-angle controller, thereby causing energy losses. In contrast, smaller gains than 600 at $\omega_{\min}$ and 300 at $\omega_{\max}$ might cause less power-smoothing capability. In this paper, these values are obtained based on a large number of simulation results considering the activations of the pitch-angle controller and power-smoothing capability; however, $K_{OFS}(\omega_{\min})$ and $K_{OFS}(\omega_{\max})$ can be set to other values depending on the design purposes.

As shown in Fig. 1(b), the control gain for Scheme #1 is irrespective of ω_r while the control gain in Scheme #2 is monotonously increasing with ω_r. In addition, for Scheme #1 and Scheme #2 the same control gains are used in both the UFS and OFS. In contrast, the different control gains for the UFS and OFS are defined. $K_{UFS}(\omega_r)$ is set to be proportional to ω_r, which is similar to that of Scheme #2. Thus, ΔP in the proposed scheme in the UFS is similar to that in Scheme #2. Conversely, $K_{OFS}(\omega_r)$ is set to be much larger than that of Scheme #2. Thus, ΔP in the proposed scheme in the OFS is much larger than that in Scheme #2. Therefore, the power-smoothing capability of the proposed scheme can be improved in the OFS while keeping the power-smoothing capability in the UFS similar to that of Scheme #2.



RSC: Rotor-side controller, f_{nom}: nominal frequency, f_{sys}: system frequency

(a) Control scheme of the proposed power-smoothing scheme



(b) Control gains of the Δf loop for Scheme #1, Scheme #2, and the proposed scheme

Fig. 1 Operational features of the proposed power-smoothing scheme

3. Model System Layout

Simulations were carried out to validate the efficacy of the proposed power-smoothing scheme based on an EMTP-RV simulator. As shown in Fig. 2, the model system consists of six synchronous generators, a static load of 220 MW and 79 MVAr, a 330-MW asynchronous motor, and an aggregated DFIG-based WPP. To model the power system that has a low ramping capability, all synchronous generators are modeled as steam turbine generators; the steam turbine governor model is the IEEEG1 steam governor model[12]. The droop settings for synchronous generators are set to 5%, which is the typical setting of synchronous generators used in Korea's power system.

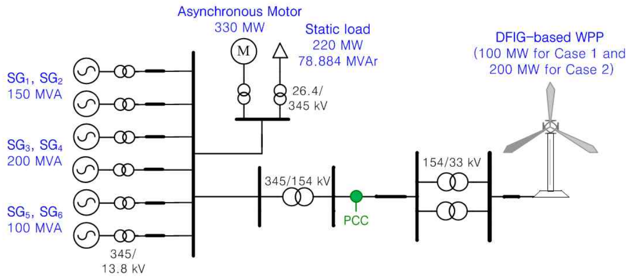


Fig. 2 Model system.

4. Simulation Results

This section compares the performance of the power-smoothing schemes under the scenarios by varying wind speeds with the wind penetration levels of 18% and 36%, in which the installed capacity for the WPP are 100 MW for Case 1 and 200 MW for Case 2, respectively. In this paper, the wind penetration level is defined as the installed capacity of a WPP divided by the total load[13].

Fig. 3 shows the wind profile of the WPP with the average wind speed of 7.5 m/s ranging from 4.7 m/s to 11.3 m/s. The performance of the proposed scheme is investigated compared to those of Scheme #2, Scheme #1 with the fixed gain of 25, and MPPT operation.

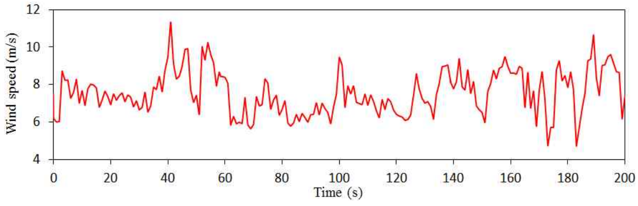
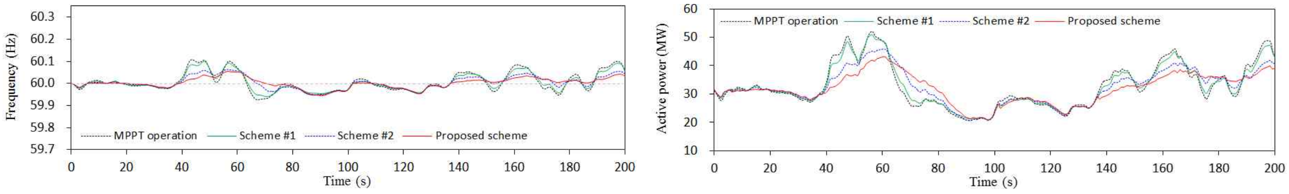


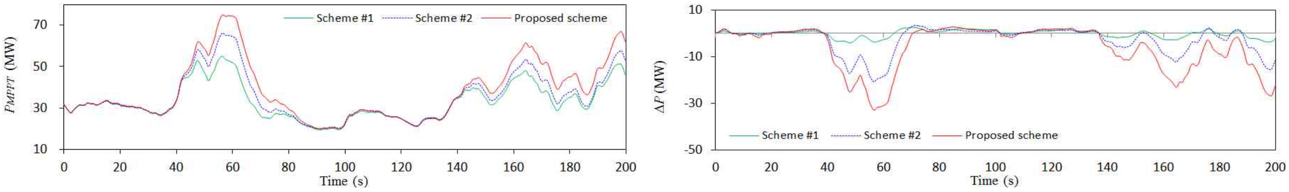
Fig. 3 Wind profile of the WPP

4.1 Case 1: Wind Penetration Level = 18%

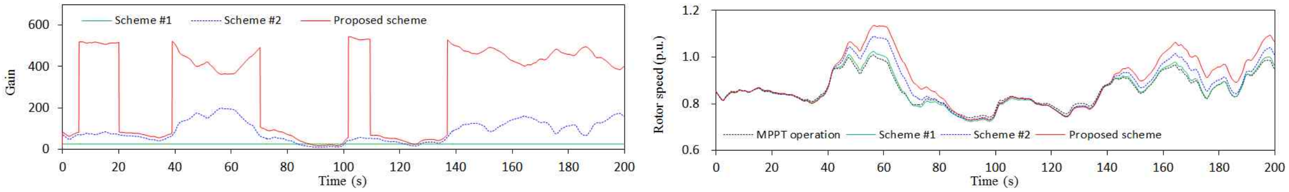
As shown in Fig. 4(a), the frequency fluctuation of the proposed scheme is significantly mitigated more than those



(a) Frequency (b) Output power of the WPP



(c) P_{MPPT} of the WPP (d) ΔP of the WPP



(e) Control gain of the WPP (f) Rotor speed of the WPP

Fig. 4 Simulation results for Case 1

Table 1 Results for Case 1

	MPPT operation	Scheme #1	Scheme #2	Proposed scheme
RMS $\{\Delta f\}$ (Hz)	0.044	0.039	0.029	0.024
$\Delta f_{\max}$ (Hz)	0.107	0.100	0.063	0.055
Operating Range of ω_r for WPP (p.u.)	0.269	0.300	0.359	0.406

of Scheme #1 and Scheme #2 because the proposed scheme significantly smooths the output power fluctuation of the WPP by adjusting $K_{UFS}(\omega_r)$ and $K_{OFS}(\omega_r)$ in the UFS and OFS, respectively (see Fig. 4(b)).

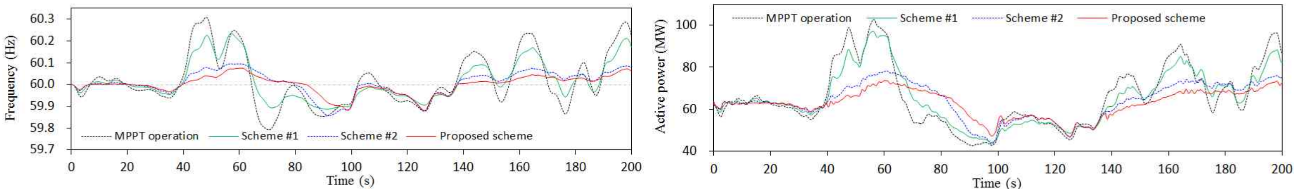
As shown in Table 1, the root mean square (RMS) values of Δf in Scheme #1, Scheme #2, and the proposed scheme are 0.039 Hz, 0.029 Hz, and 0.024 Hz, respectively. The maximum frequency deviation ($\Delta f_{\max}$) in the proposed scheme is 0.055 Hz, which is less than that of Scheme #1 by 0.045 Hz and less than that of Scheme #2 by 0.008 Hz. In addition, the operating range of ω_r in the proposed scheme is wider than those in the conventional schemes because the proposed control gain in the OFS is larger than those of the conventional schemes. As a result, the proposed scheme effectively utilizes the rotating masses of a DFIG while performing power smoothing.

4.2 Case 2: Wind Penetration Level = 36%

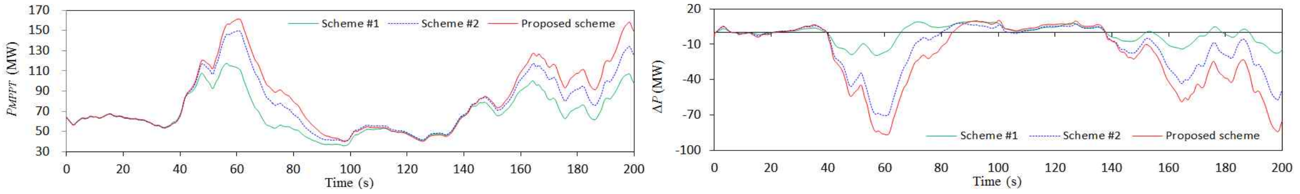
As the wind penetration level increases, the system frequency fluctuation becomes more significant; therefore, this subsection investigates the performance of the proposed scheme for a higher wind penetration level.

Fig. 5 shows the results for Case 2, which is identical to Case 1 except for a higher wind penetration level. As in Case 1, the frequency fluctuation is lessened compared to those of the conventional schemes, as shown in Fig. 5(a).

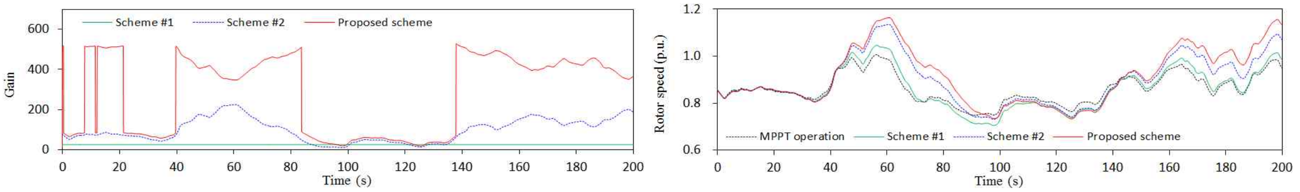
As shown in Table 2, the RMS value of Δf in the proposed scheme is 0.042 Hz, which is less than that in Scheme #1 by 0.050 Hz and less than that in Scheme #2 by 0.015 Hz. $\Delta f_{\max}$ in the proposed scheme is 0.075 Hz, which is less than that in Scheme #1 by 0.160 Hz and less than that in Scheme #2 by 0.020 Hz. Note that the RMS value of Δf, in an MPPT operation in Case 2 are approximately three times those in Case 1. However, the RMS value of Δf and $\Delta f_{\max}$ in the proposed scheme in Case 2 are less than twice those in Case 1. Thus, the proposed scheme can improve the frequency-mitigating capability compared to Scheme #2, Scheme #1, and an MPPT operation for a higher wind penetration level. Further, as in Case 1, the operating range



(a) Frequency (b) Output power of the WPP



(c) P_{MPPT} of the WPP (d) ΔP of the WPP



(e) Control gain of the WPP (f) Rotor speed of the WPP

Fig. 5 Simulation results for Case 2.

Table 2 Results for Case 2

	MPPT operation	Scheme #1	Scheme #2	Proposed scheme
RMS $\{\Delta f\}$ (Hz)	0.122	0.092	0.057	0.042
Δf_{max} (Hz)	0.309	0.235	0.095	0.075
Operating Range of ω_r for WPP (p.u.)	0.259	0.342	0.404	0.431

of ω_r in the proposed scheme is 0.431 p.u., which is the largest among the schemes. As a result, the proposed scheme effectively utilizes the rotating masses while performing power smoothing.

5. Conclusions

This paper proposes a power-smoothing scheme of a DFIG that significantly improves the frequency-mitigating capability in the OFS. The proposed scheme employs an additional control loop based on the frequency deviation operating in conjunction with the MPPT control loop. To improve the frequency-mitigating capability in the OFS, the different control gain is proposed that is set to be inversely proportional to the rotor speed.

The results clearly indicate that the proposed scheme effectively smooths the output power fluctuation of a WPP by employing the different control gain for the OFS, thereby mitigating the frequency fluctuation under various wind penetration levels. In addition, the proposed scheme effectively utilizes the rotating masses of a VSWT while performing power smoothing. Hence, it will help reduce the size of ESSs required to mitigate the system frequency fluctuation caused by varying wind speeds.

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