Output Power Coordination Control for Wind Farm in Small Power System

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***Abstract*— Nowadays, wind turbine generator (WTG) is increasingly required to provide control capabilities regarding output power. Under this scenario, this paper proposes an output power control of wind farm (WF) using pitch angle control connected to small power systems. In this control approach, WF output power control is achieved by two control levels: central and local. In central control, WF output power command is determined by fuzzy reasoning which has three inputs for average wind speed, variance of wind speed, and absolute average of frequency deviation. Then, local output power commands of each WTG are given by WF output power command and coordination control, and each WTG ensures WF output power command. The simulation results by using an actual detailed model for wind power system show the effectiveness of the proposed method.**

***Index Terms*— coordination control, frequency deviation, pitch angle control, power system, wind farm**

I. Introduction

There are a lot of isolated islands in the world and power is provided mainly by diesel generation. Heavy oil for diesel generated power needs fuel cost, transport cost and storage cost, which is expensive compared with main islands, and the environment is influenced harmfully by emissions of sulfur oxide and carbon dioxide. On the other hand, since many suitable regions of wind power generation exist in isolated island, wind power generation systems are installed to decrease usage of heavy oil, and it is possible to decrease generation costs. In addition, wind power generation systems are environment-friendly because there is no emission of sulfur oxide and carbon dioxide [1]. However, wind energy is not constant and windmill output is proportional to the cube of wind speed, which causes the generated power of wind turbine generator (WTG) to fluctuate. The generated output power fluctuation increases relative to the increase in installation capacity of the WTGs. Therefore, a provision for frequency deviation is needed in small power system for isolated island. Recently, a provision using power storage system has been proposed [2], however, it is costly. Provisions for stand-alone WTG have also been proposed, such as variable-speed WTG and using pitch angle control [3]-[6]. In these reports, it is intended that output power leveling of WTG or wind farm (WF) is achieved. In addition, in order to consider the effect of WTG output power for power system condition, various control functions which control output power of WTG are proposed in [7], and output power command for each WTG in WF is decided by solving the optimal flow problem in [8]. The purpose of output power leveling is reduction of power system frequency deviation in [3]-[8], however, these reports do not especially consider power system frequency deviation.

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Therefore, this paper presents output power control methodology of WF for frequency deviation in small power system. In this control approach, WF output power control is achieved by two control levels: central and local. In central control, WF output power command is determined by considering power system frequency deviation and wind condition, and it is possible to level and adjust WF output power corresponding to power system frequency deviation. Since wind conditions are different for each WTG, WF output power fluctuates with rapid change of wind speed for a WTG in WF. Then each WTG is controlled to ensure WF output power command by the proposed coordination control.

WF output power command is determined by fuzzy reasoning which has three inputs of average wind speed, variance of wind speed, and absolute average of frequency deviation. Since fuzzy reasoning is used, output power command can change flexibly corresponding to wind speed condition and power system condition. Moreover, high performance pitch angle control based on output power command is achieved by generalized predictive control (GPC) as reported in [5][6]. The simulation results with wind turbulence and load change show the effectiveness of the proposed method.

II. Small Power System

The concept of small power system in this paper is shown in Fig. 1. The small power system consists of the diesel generators and WF that generate power to supply the demand. In addition, the small power system is not connected to large power system which is different from micro-grid; it is assumed that the isolated island is always operated independently.

Small power system model, as referred to in [9], is shown in Fig. 2. As a frequency control method of power systems, the flat frequency control technique that is used in majority of stand alone power systems is adopted. In Fig. 2, P_L and P_d represent load and diesel generator output power, respectively. WF output power command system and WF system are described in Section III-IV.

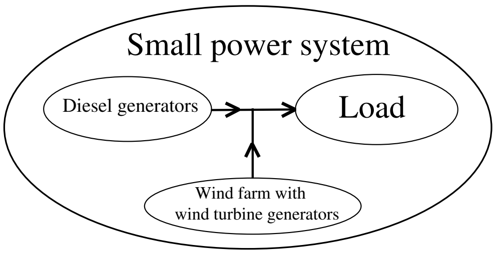

Fig. 1. Concept of power system.

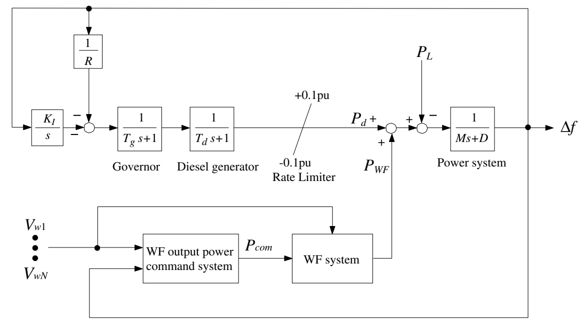

Fig. 2. Power system model.

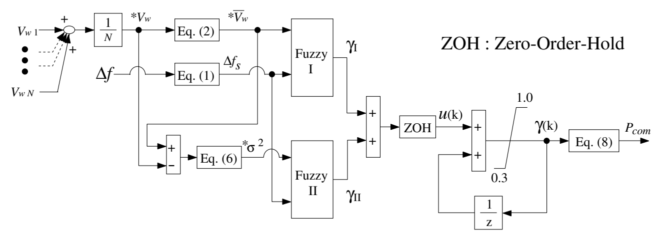

Fig. 3. Wind farm (WF) output power command system.

III. Wind Farm Output Power Command System

In order to control WF output power considering power system condition, WF output power command P_{com} is determined by WF output power command system in Fig. 3. WF output power command system consists mainly of two fuzzy reasoning, and the rate of rated output power for WF is determined by these fuzzy reasoning. Each fuzzy reasoning is described by a set of "if-then" rules based on fuzzy rules and do not need a deterministic model. In addition, fuzzy reasoning is effective when mathematical expressions are difficult by inherent complexity, nonlinearity, or unclarity.

Firstly, Fuzzy reasoning I is explained. There are two inputs of fuzzy reasoning I. One is absolute average of frequency deviation Δf_s, and the other is average wind speed ${}^*\bar{V}_w$. The former, which is an index to estimate power system condition, is expressed by

$$\Delta f_s = \frac{1}{T}\int_{t-T}^{t} |\Delta f| dt \tag{1}$$

where t is present time and T is integral interval. Since absolute value of frequency deviation Δf is used, absolute average of frequency deviation Δf_s increases or decreases with increase or decrease in frequency deviation Δf of the power system. Therefore, (1) indicates frequency deviation quantitatively at any given time. Average wind speed ${}^*\bar{V}_w$ is defined by

$${}^*\bar{V}_w = \frac{1}{T}\int_{t-T}^{t} {}^*V_w dt \tag{2}$$

where ${}^*V_w = \frac{1}{N}\sum_{N=1}^{N} V_{wN}$, N is number of WTG, V_{wN} is instantaneous wind speed for each WTG, ${}^*\bar{V}_w$ is summation of wind speed for each WTG divided by total number of WTG. WF output power control for power system condition is accomplished by using absolute average of frequency deviation Δf_s as an input of fuzzy reasoning. However, if wind speed condition is not considered, the generated power may decrease within that period. Thus, wind speed condition should be considered to determine WF output power command. Fuzzy rules and membership functions of Fuzzy reasoning I are shown in TABLE I and Fig. 4, respectively. There is need to prevent deviations of $\pm$0.3Hz for frequency deviation Δf with output power increase. Thus, membership functions are decided so that WF output power command decreases if power system frequency deviation increases. When frequency deviation Δf deviates by more than $\pm$0.2Hz at any given time, fuzzy rules and membership functions that yield a WF output power command to decrease WF output power are defined by trial-and-error. The ith of fuzzy rules is expressed as

$$\begin{aligned} &\text{Rule } i: \text{if } \Delta f_s \text{ is } L_x \text{ and } {}^*\bar{V}_w \text{ is } M_y \\ &\text{then } \gamma_{\rm I} \text{ is } Z_l \\ &x = 1, 2, \cdots, 7,\ y = 1, 2, \cdots, 7,\ l = 1, 2, \cdots, 7 \end{aligned} \tag{3}$$

where L_x, M_y denote the antecedents and Z_l are consequent part. Fuzzy reasoning $\gamma_{\rm I}$ is calculated by

$$\gamma_{\rm I} = \sum_{i=1}^{49} w_i Z_l \Big/ \sum_{i=1}^{49} w_i \tag{4}$$

where w_i denotes the grade for the antecedent and is obtained by

$$w_i = w_{\Delta f_s i} w_{{}^*\bar{V}_w i} \tag{5}$$

where $w_{\Delta f_s i}$ and $w_{{}^*\bar{V}_w i}$ are the grade of antecedents for each rule.

Absolute average of frequency deviation Δf_s and variance σ^2 of wind speed ${}^*V_w$ are used as inputs of Fuzzy reasoning II, where variance σ^2 is expressed as

$${}^*\sigma^2 = \frac{1}{T}\int_{t-T}^{t} ({}^*V_w - {}^*\bar{V}_w)^2 dt. \tag{6}$$

Output power command that depends on power system condition rather than wind speed condition is decided by using absolute average of frequency deviation Δf_s for both fuzzy reasoning I and fuzzy reasoning II as inputs. However, it is undesirable to increase output power command of WTG considerably by wind speed condition, because the probability of wind speed decrease at short periods is high as can be seen from the frequency distribution of wind speed. Therefore,

Table 1. Fuzzy rules of FuzzyI.

		Δf_s						
		NB	NM	NS	ZO	PS	PM	PB
$^*\bar{V}_w$	NB	ZO	NS	NM	NB	NB	NB	NB
	NM	PS	ZO	NS	NM	NB	NB	NB
	NS	PM	PS	ZO	NS	NM	NB	NB
	ZO	PB	PM	PS	ZO	NS	NM	NB
	PS	PB	PB	PM	PS	ZO	NS	NM
	PM	PB	PB	PB	PM	PS	ZO	NS
	PB	PB	PB	PB	PB	PM	PS	ZO

NB=Negative Big NM=Negative Medium NS=Negative Small
PB=Positive Big PM=Positive Medium PS=Positive Small
ZO=Zero

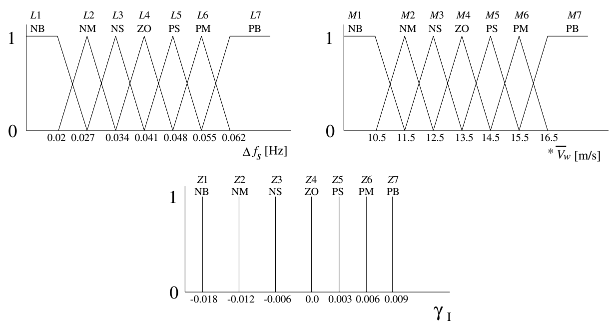

Fig. 4. Membership functions of FuzzyI.

Table 2. Fuzzy rules of FuzzyII.

		Δf_s						
		NB	NM	NS	ZO	PS	PM	PB
$^*\sigma^2$	NB	PB	PB	PB	PB	PM	PS	ZO
	NM	PB	PB	PB	PM	PS	ZO	NS
	NS	PB	PB	PM	PS	ZO	NS	NM
	ZO	PB	PM	PS	ZO	NS	NM	NB
	PS	PM	PS	ZO	NS	NM	NB	NB
	PM	PS	ZO	NS	NM	NB	NB	NB
	PB	ZO	NS	NM	NB	NB	NB	NB

NB=Negative Big NM=Negative Medium NS=Negative Small
PB=Positive Big PM=Positive Medium PS=Positive Small
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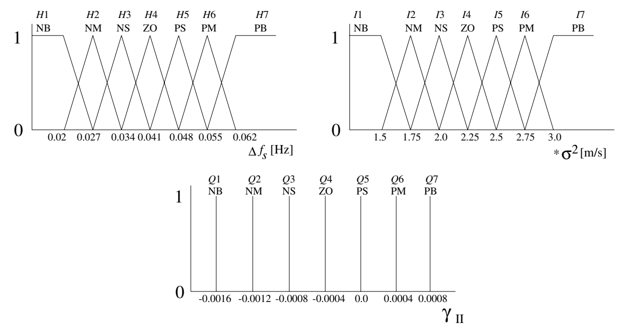


Fig. 5. Membership functions of FuzzyII.

it is desired to limit output power command using variance $^*\sigma^2$ in time with large fluctuation of wind speed. Fuzzy rules and membership functions of Fuzzy reasoning II are shown in TABLE II and Fig. 5, respectively. Setup of fuzzy rules and parameters of membership functions are determined by prioritizing to prevent increase of frequency deviation. The structure of the above fuzzy reasoning II is similar to that of fuzzy reasoning I, and it will not be discussed further.

As can be seen from Fig. 3, the discrete value $u(k+1)$ is obtained by the sums of output of Fuzzy reasoning I, $\gamma_{\rm I}$, and Fuzzy reasoning II, $\gamma_{\rm II}$, through zero-order-hold. Then, the discrete value $u(k+1)$ adds rate of WF rated output power $\gamma(k)$ of current time (k), and rate of WF rated output power $\gamma(k+1)$ of one sampling ahead $(k+1)$ which becomes WF output power command by the following equation:

$$\gamma(k+1) = \gamma(k) + u(k+1). \tag{7}$$

Moreover, since the rate obtained by (7) changes step, it is necessary to convert it into a smooth output power command. Continuous output power command P_{com} is obtained in each sampling time by using the following equation:

$$P_{com} = P_{rated}\left\{\gamma(k) + \frac{\gamma(k+1)-\gamma(k)}{T_s} f(t)\right\} \tag{8}$$

where P_{rated} is WF rated output power, T_s is sampling time, and $f(t)$ is a periodic function such that $f(t) = t$, for $(0 < t < T_s)$.

IV. Wind Farm System

The wind farm (WF) system is illustrated in Fig. 2. In Fig. 6 WF system has inputs which are WF output power command P_{com} and instantaneous wind speed for each WTG V_{wN}. In addition, WF output power P_{WF} is expressed as

$$P_{WF} = \sum_{N=1}^{N} P_{gN} \tag{9}$$

where P_{gN} is the output power for each WTG.

A. Coordination Control Method

Output power commands for each WTG P_{goN} are determined by WF output power command P_{com} and coordination control method. In order to identify WF output power P_{WF} to WF output power command P_{com}, coordination control method for each WTG is needed. If a WTG output power decreases with rapid decrease of wind speed, in order to compensate for shortage of power, other WTGs having more output power are controlled. Thus, the proposed coordination control method is different from the conventional method which achieves WF output power leveling by each WTG's output power leveling, WF output power leveling is achieved by changing output power for each WTG actively. Output power command for each WTG is obtained by

$$P_{goN} = P_{go\_maxN} \times \eta \tag{10}$$

$$\eta = \frac{P_{com}}{\sum_{N=1}^{N} P_{go\_maxN}} \tag{11}$$

$$P_{go\_maxN} = d_1 + d_2 V_{wN}^2 \tag{12}$$

where P_{go_maxN} is each WTG's output power corresponding to wind speed (0$\sim$1pu), η is rate of P_{go_maxN}, d_1 and d_2 are expressed as a function of the pitch angle β [5].

B. Wind Turbine Generator System

The WTG system using GPC for pitch angle control system [5] is shown in Fig. 7. Subtracting output power command

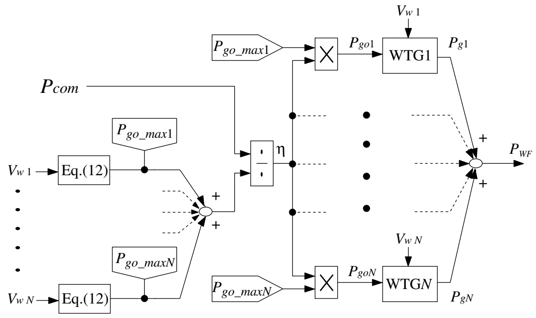


Fig. 6. Wind farm (WF) system.

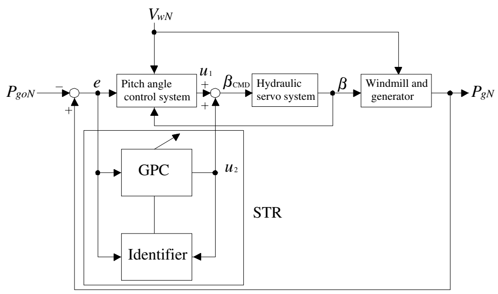


Fig. 7. Wind turbine generator (WTG) system.

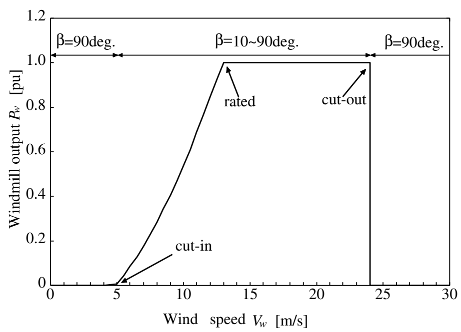


Fig. 8. Pitch angle control law for all operating regions.

P_{goN} from output power P_{gN} gives output power error e that evaluates pitch angle command β_{CMD} via pitch angle control system and GPC. Output power P_{gN} is smoothed by hydraulic servo system that drives the blades. In this paper, induction generator having advantages of low cost and robustness, is used. A detailed modeling of the WTG system and the GPC control rule is found in [5].

Conventional method for the pitch angle law is fixed between cut-in wind speed and rated wind speed so that the output power for WTG is proportional to the fluctuation of wind speed between cut-in wind speed and rated wind speed. Thus, in order to achieve output power control by coordination control for each WTG, pitch angle control law needs to be extended for all operating regions as shown in Fig. 8. In this paper, pitch angle control law for all operating regions as utilized in [5] is used.

Table 3. Simulation parameters.

Parameters of Small power system	
inertia constant M	0.1 puMW·sec/Hz
damping constant D	0.012 puMW/Hz
governor time constant T_g	0.1 sec
diesel generator time constant T_d	5.0 sec
Parameters of WTG system	
blade radius R	14 m
inertia coefficient J	62993 kg·m ^{2}
air density ρ	1.225 kg/m^3
rated output P_g	275 kW
phase voltage V	400 $\sqrt{3}$ V
stator resistance R_1	0.00397 Ω
stator reactance X_1	0.0376 Ω
rotor resistance R_2	0.00443 Ω
rotor reactance X_2	0.0534 Ω
Control parameters for GPC	
weighting factor Λ_2	diag{50(j)}
dead time order d	1
model order n	3
model order m	3
maximum costing horizon N	5
control horizon NU	1

V. Simulation Results

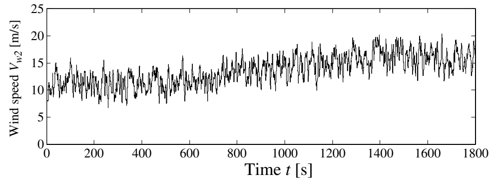
In this paper, the effectiveness of WF output power control for power system condition using the proposed method is evaluated by MATLAB/SIMULINK simulation with system model and parameters as mentioned in [4]. In order to use parameters for a real machine in [4], the rated output power of the WTG is 275kW (0.04pu), however the proposed method can also be applied to a large WTG. In the simulation, the proposed coordination control method is compared with the conventional method, and non-coordination control method, where each WTG is given output power command, which is WF output power command P_{com} divided by the number of WTGs, in non-coordination control system. In addition, the conventional control method described in [6] has constant output power command and fixed-pitch angle below rated wind speed region to get maximum captured power from wind. Simulation parameters of power system, windmill, induction generator, and controller are shown in TABLE III. Integral time T is 100s, sampling time T_s to obtain discrete value of output power command is 10s, sampling time of GPC is 1ms, and parameter Λ_2 of GPC, values of orders m and n, maximum costing horizon N, and control horizon NU are based on simulation results that achieve good performance. Output power error parameters used in GPC are unknown at initial condition. Unknown parameters are determined by least-square method [10], [11], and used to control pitch angle. Wind speed turbulence and load change (see Fig. 9) are equal in simulations of three cases with conventional method, coordination and non-coordination control.

A. Estimation of WF Output Power and Frequency Deviation

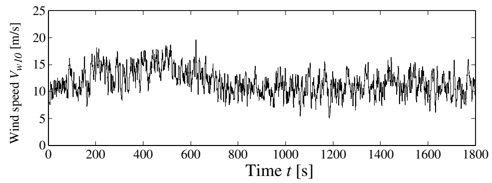
The effectiveness of the proposed method is estimated by WF output power and frequency deviation. WF output power error ΔP_e is defined by

$$\Delta P_e = P_{com} - P_{WF}. \quad (13)$$

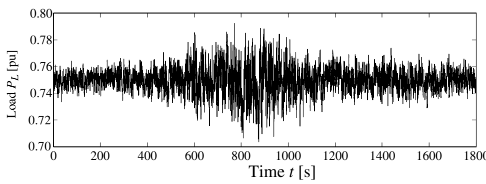
For WF output power P_{WF}, probability density of WF output power error ΔP_e is used to compare the all methods. WF



(a) Wind speed for WTG2.

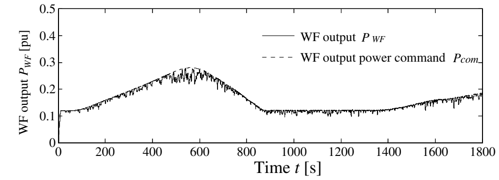


(b) Wind speed for WTG10.

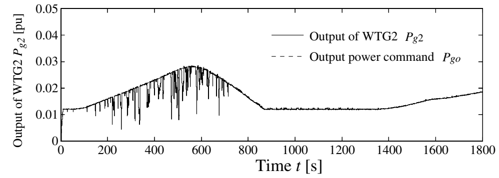


(c) Load.

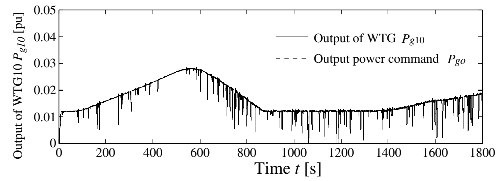
Fig. 9. Wind speed and load.



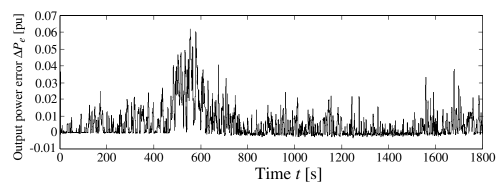
(a) Wind farm output power.



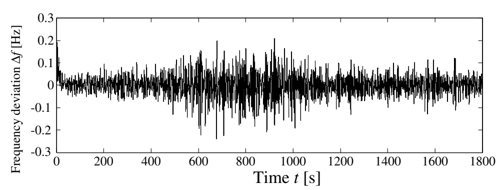
(b) Output power of WTG2.



(c) Output power of WTG10.



(d) Error of wind farm output power.



(e) Frequency deviation.

Fig. 10. Simulation results (non-coordination control).

output power command P_{com} is smooth, and has no harmful effects on power system frequency.

In addition, output power error ΔP_e and frequency deviation Δf are estimated by using probability density. Probability density distribution is expressed by

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] \quad (14)$$

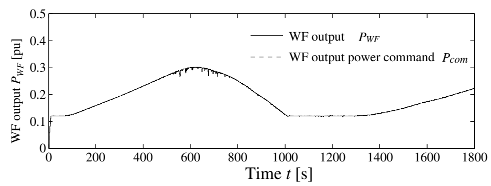
where σ is standard deviation (σ >0), x is sample (ΔP_e or Δf), and μ is average.

B. Discussion of Simulation Results

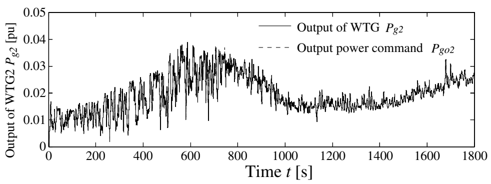
The simulation results with non-coordination control method are shown in Fig. 10. Fig. 10(a) shows WF output power P_{WF} Since WF output power command P_{com} is determined considering frequency deviation, at $t = 0 \sim 500$s, with small frequency deviation, WF output power command P_{com} increase. At $t = 500 \sim 900$s with increase of frequency deviation, WF output power command P_{com} decreases, and WF output power P_{WF} is leveling at $t = 900 \sim 1,300$s. However, as can be seen in Figs. 10(b) and 10(c), each WTG output power fluctuates, because coordination control method is not applied. Thus, WF output power P_{WF} fluctuates, too. WF output power error ΔP_e and frequency deviation Δf are shown in Figs. 10(d) and 10(e). WF output power error ΔP_e fluctuates, and frequency deviation Δf increases.

Fig. 11 shows simulation results with the proposed method. WF output power P_{WF} does not fluctuate rapidly at short time in Fig. 11(a), because each WTG is coordinated as shown in Figs. 11(b) and 11(c). In Fig. 11(d), WF output power error ΔP_e is small in whole compared with Fig. 10(d). Thus, frequency deviation Δf (see Fig. 11(e)) occurs by only load change, and frequency deviation Δf with coordination control method is smaller than Fig. 10(e). As can be seen in Figs. 10(a) and 11(a), coordination control method contributes an output power increase because frequency deviation becomes small. For example, at $t = 1,400 \sim 1,800$s with non-coordination control method, frequency deviation Δf increases by fluctuations in WF output power. As a result, WF output power command P_{com} is limited. However, in the above-mentioned time period with coordination control, frequency deviation does not increase with no fluctuation in WF output power. Thus, WF output power command P_{com} becomes large compared with output power command P_{com} for non-coordination control.

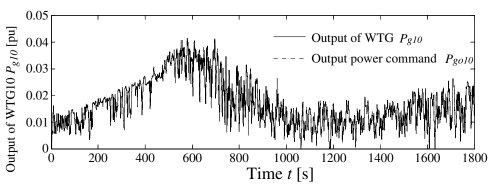
Probability density of output power error ΔP_e and frequency deviation Δf for the all method, are shown in Figs. 12, and 13, respectively. In Fig. 12, probability density of the proposed coordination control method has steep curve around



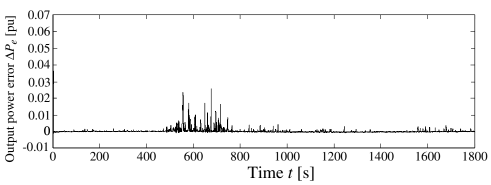
(a) Wind farm output power.



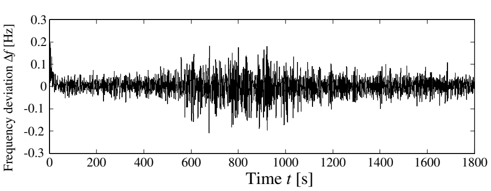
(b) Output power of WTG2.



(c) Output power of WTG10.



(d) Error of wind farm output power.



(e) Frequency deviation.

Fig. 11. Simulation results (coordination control).

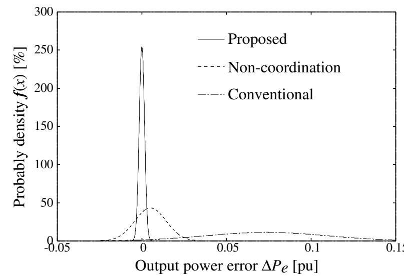


Fig. 12. Probably density of WF output power error.

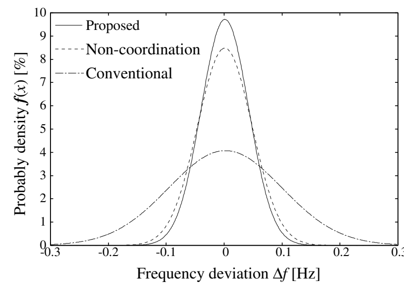


Fig. 13. Probably density of frequency deviation.

0 pu. Probability density of non-coordination control method has a gentler slope around 0.05 pu for same magnitude of standard deviation, σ. Therefore, non-coordination control method induces decrease of electric energy and increase of output power fluctuation. For probability density of frequency deviation, average μ is about 0 pu in all methods, however, standard deviation σ of coordination control method is smaller than non-coordination control method. Moreover, probability density of output power error ΔP_e and frequency deviation Δf becomes more large by the conventional control method (see Figs. 12 and 13).

VI. Conclusion

This paper presents WF output power control for power system condition. The proposed control is achieved by two strategies that determine output power commands for WF and each WTG. WF output power command is defined by fuzzy reasoning, and each WTG output power command is determined by coordination strategy. From the simulation results, the effectiveness of the proposed method is confirmed.

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