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 harmfuly 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],[8], 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.

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.
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 $\Delta_f$, and the other is average wind speed $\bar{V}_w$. The former, which is an index to estimate power system condition, is expressed by

$$\Delta_f = \frac{1}{T} \int_{t-T}^{t} |\Delta f| dt \quad (1)$$

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

$$\bar{V}_w = \frac{1}{T} \int_{t-T}^{t} V_w dt \quad (2)$$

where $V_w = \frac{1}{N} \sum_{i=1}^{N} V_{w,i}$, $N$ is number of WTG, $V_{w,i}$ 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 $\Delta_f$ 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 $\pm 0.3$Hz for frequency deviation $\Delta f$ 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 $\Delta f$ deviates by more than $\pm 0.2$Hz 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

Rule $i$ : if $\Delta_f$ is $L_x$ and $\bar{V}_w$ is $M_y$ then $\gamma_i$ is $Z_l$ \quad (3)

where $L_x, M_y$ denote the antecedents and $Z_l$ are consequent part. Fuzzy reasoning $\gamma_i$ is calculated by

$$\gamma_i = \frac{\sum_{i=1}^{49} w_i Z_l}{\sum_{i=1}^{49} w_i} \quad (4)$$

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

$$w_i = w_{\Delta_f,i} w_{\bar{V}_w,i} \quad (5)$$

where $w_{\Delta_f,i}$ and $w_{\bar{V}_w,i}$ are the grade of antecedents for each rule.

Absolute average of frequency deviation $\Delta_f$ and variance $\sigma^2$ of wind speed $\bar{V}_w$ are used as inputs of Fuzzy reasoning II, where variance $\sigma^2$ is expressed as

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

Output power command that depends on power system condition rather than wind speed condition is decided by using absolute average of frequency deviation $\Delta_f$ 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,
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, $\gamma_I$, and Fuzzy reasoning II, $\gamma_{II}$, 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:

$$\gamma(k+1) = \gamma(k) + u(k+1).$$

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:

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

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 $V_{w,N}$. In addition, WF output power $P_{WF}$ is expressed as

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

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

$$P_{goN} = P_{go,maxN} \times \eta$$

$$\eta = \frac{P_{com}}{\sum_{N=1}^{N} P_{go,maxN}}$$

$$P_{go,maxN} = d_1 + d_2 V_{w,N}^2$$

where $P_{go,maxN}$ is each WTG’s output power corresponding to wind speed (0~1pu), $\eta$ is rate of $P_{go,maxN}$. $d_1$ and $d_2$ are expressed as a function of the pitch angle $\beta$ [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...
wind speed between cut-in wind speed and rated wind speed.

Thus, in order to achieve output power control by coordination

between cut-in wind speed and rated wind speed so that the
output power for WTG is proportional to the fluctuation of

wind speed. Conventional method for the pitch angle law is fixed be-

 tween wind speed and cut-in wind speed. In this paper, induction

generator having advantages of low cost and robustness, is

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

In addition, output power error $\Delta P_e$ and frequency deviation $\Delta f$ are estimated by using probability density. Probability density distribution is expressed by

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

where $\sigma$ is standard deviation ($\sigma > 0$), $x$ is sample ($\Delta P_e$ or $\Delta f$), and $\mu$ 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 $P_{com}$ increases. 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 $\Delta P_e$ and frequency deviation $\Delta f$ are shown in Figs. 10(d) and 10(e). WF output power error $\Delta P_e$ fluctuates, and frequency deviation $\Delta f$ 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 $\Delta P_e$ is small in whole compared with Fig. 10(d). Thus, frequency deviation $\Delta f$ (see Fig. 11(e)) occurs by only load change, and frequency deviation $\Delta f$ 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 $t = 1,400 \sim 1,800$ with non-coordination control method, frequency deviation $\Delta f$ 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 $\Delta P_e$ and frequency deviation $\Delta f$ 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
and each WTG. WF output power command is defined by strategies that determine output power commands for WF system condition. The proposed control is achieved by two ∆ becomes more large by the conventional control method (see Figs. 12 and 13).

Standard deviation, average deviation, average output power fluctuation. For probability density of frequency, the probability density of non-coordination control method is smaller is about 0 pu in all methods, however, probability density of output power error ∆e and frequency deviation ∆f 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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