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RESEARCH ARTICLE

Coordinated Power Reserve Control of Wind Farm for Frequency Regulation

WEI CHEN[1], WENBIN YANG[1], HAIFENG QI[1], ZHAOHUI SHI[1], AND HUA GENG[2], (Fellow, IEEE)
[1]Key Laboratory of Far-Shore Wind Power Technology of Zhejiang Province, Powerchina Huadong Engineering Corporation Ltd., Hangzhou 311122, China
[2]Department of Automation, Tsinghua University, Beijing 100084, China

Corresponding author: Wei Chen (chen_w23@hdec.com)

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ABSTRACT With a higher wind power penetration level, the power system is facing more challenges in the aspects of active power balance and system frequency regulation. The power reserve control enables the wind farm (WF) to retain a certain available power as reserves, for participating in frequency regulation similarly to synchronous generators. In this paper, a coordinated power reserve control method of a WF for frequency regulation is proposed. By using the linear programming approach, the proposed method allocates the power reserve of each wind turbine generator (WTG) to maximize the kinetic energy of WTGs and minimize the blade pitch action of WTGs. A new coefficient to quantify the relation between the rotor speed variation and available power curtailment is defined for linear optimization. Based on the power reserve formed by the proposed method, the primary frequency control of a WF is achieved by determining the primary frequency control coefficients of WTGs. Finally, case studies based on EMTP-RV simulator are carried out to validate the proposed method. The results show that the proposed method can realize the power reserve control of a WF and improve the frequency regulation ability of a WF effectively.

INDEX TERMS Coordinated power reserve control, frequency regulation, linear programming, rotor overspeeding control, pitch angle control, wind farm.

I. INTRODUCTION

To address the climate problem, many countries promote a low-carbon energy system, an important way is to develop the renewable energy generation, such as wind power generation. According to "Global Wind Report 2023" issued by GWEC, the global wind power installed capacity has a growth of 77.6 GW in 2022 [1]. In China, total wind power installed capacity has reached to 380 MW by March 2023 [2].

With a higher wind power penetration level (WPPL), the power system is facing more challenges, especially in terms of active power balance and system frequency stability. Mainly, there are two reasons, firstly, due to the uncertain wind power generation, the electrical power balance shows a probabilistic trend, secondly, the wind energy conversion system connects to grids by power electronic equipment, which decouples the rotor speed and system frequency as well as decreases the system inertia. As a result, the system frequency changes more severely. In 2019, a serious power outage hit the Britain's power system, leaving more than a million power customers lack of electricity. The main cause is that the power reserve and system inertia are not enough, resulting in an insufficient frequency control ability [3].

In this context, transmission system operators (TSOs) wish that the wind power generation system, including wind turbine generators (WTGs) and wind farms (WFs) can make more contribution to the active power balance and system frequency control. In China, the new grid codes relevant to wind power generation includes the requirements of frequency control for WFs [4], [5], which specifies the inertia constant and primary frequency control coefficient of a WF.

Nowadays, wind power generation system usually performs the maximum power point tracking (MPPT) with no power reserves. As a result, after a power deficit event, wind power generation system cannot provide a long-term power support. Although WTGs can provide a temporary frequency

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support by utilizing the kinetic energy stored in the rotating masses [6], [7], [8], [9], the provided power support is very limited in order to avoid the over-deceleration. Besides, to recover the rotor speed as well as to return to the normal operation, WTGs should reduce the power output after the temporary frequency support, which can easily cause a worse secondary frequency dip [10]. Thus, to enable the wind power generation system to participate in a long-term frequency control, it is essential to perform power reserve control to retain a certain power reserve provision.

The power reserve control of a WF depends on the power reserve control of WTGs and the coordination among WTGs. The power reserve control of WTGs is to decrease the wind power coefficient, usually, there are two ways to achieve it [11], [12], one is so-called rotor overspeed control (ROC), the other is so-called pitch angle control (PAC). In existing literatures, there are many possible coordination ways of ROC and PAC to achieve the power reserve control of WTGs [13], [14], [15], [16], [17]. With respect to the coordination among WTGs, essentially, it is to allocate the power reserve of each WTG. Generally, the power reserve allocation is according to the available wind power of WTGs [18], [19], [20], a WTG with more available wind power will be responsible for more power reserve. Besides, load sharing is also considered in the power reserve allocation [21], [22], [23].

In this paper, a coordinated power reserve control method of a WF for frequency regulation is introduced. In order to maximize the kinetic energy (KE) of WTGs and minimize the blade pitch action of WTGs, the proposed method allocates the power reserve of each WTG based on the linear programming approach. A new coefficient to quantify the relation between the rotor speed variation and available power curtailment is defined for linear optimization. Based on the formed power reserve, the primary frequency control (PFC) of a WF can be achieved by determining the PFC coefficients of WTGs. In final, case studies based on EMTP-RV simulator are carried out to validate the proposed method. The results validate that the proposed method can realize the power reserve control of a WF and improve the frequency regulation ability of a WF.

II. ACTIVE POWER CONTROL OF A WTG

A. WIND TURBINE AERODYNAMICS

The captured mechanical power by a WTG is depicted as

$$P_m = \frac{1}{2}\rho S v^3 C_p(\lambda, \beta) \tag{1}$$

where ρ is air density, S is wind turbine swept area, v is wind speed, C_p is wind power coefficient, λ is tip speed ratio and β is pitch angle [24]. The tip speed ratio λ is defined as

$$\lambda = \omega_r r / v \tag{2}$$

where ω_r and r are the rotor speed and blade radius.

The wind power coefficient C_p is represented as

$$\begin{aligned} C_p(\lambda, \beta) &= 0.645\left(\frac{116}{\alpha} - 0.4(\beta + 2.5) - 5\right) e^{\frac{-21}{\alpha}} \\ \frac{1}{\alpha} &= \frac{1}{\lambda + 0.08(\beta + 2.5)} - \frac{0.035}{(\beta + 2.5)^3 + 1} \end{aligned} \tag{3}$$

In the optimal operation, the operation zone of a WTG can be divided into four parts, as shown in Figure 1, where v_{in}, $v_{\omega\text{max}}$, v_{nom} and v_{out} are the cut-in, maximum-rotor-speed-cut-in, nominal and cut-out wind speeds, respectively. In Zone 1, 3 and 4, the WTG is operated with its minimum rotor speed (ω_{min}) or maximum rotor speed (ω_{max}), the optimal rotor speed is outside the operation bound, and the maximum wind power coefficient cannot be achieved. In Zone 4, the pitch angle is increased to limit the available power not over the nominal value (P_{nom}). In Zone 2, the maximum wind power coefficient is achieved, the rotor speed is controlled at its optimal value and the pitch angle remains zero. Usually, the Zone 1, 2, 3 and 4 are so-called the start zone, MPPT zone, constant speed zone and constant power zone, respectively.

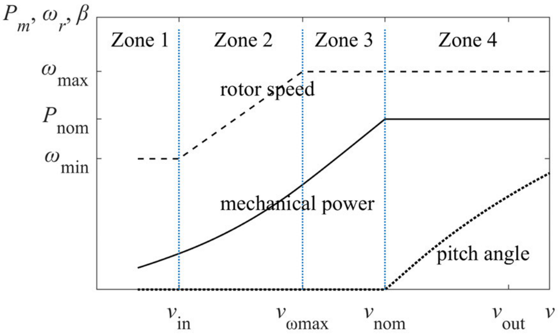


FIGURE 1. Mechanical power, rotor speed, pitch angle in the optimal operation.

B. POWER RESERVE CONTROL OF A WTG

The power reserve control of a WF depends on those of WTGs. Essentially, the power reserve control of a WTG is to decrease the wind power coefficient. Usually, there are two ways to achieve it, namely, ROC and PAC.

Further, there are many possible coordination ways of ROC and PAC for realizing the power reserve control of a WTG. In order to avoid the frequent action of blade pitch as well as to store the KE as much as possible, the ROC will be adopted preferentially if there is a rise margin for rotor speed. Once the rotor speed reaches the maximum, the PAC will be activated.

As shown in Figure 2, for a WTG operating in the MPPT zone, the rotor speed is regulated at its optimal value and lower than its maximum value, as represented by point A. Therefore, the mechanical power can be curtailed by ROC, which means the operation point will move from point A to point B along with the black solid line. Once the operation point reaches the point B, namely, the rotor speed reaches the maximum value, the PAC will be activated for curtailing the mechanical power continually. In this case, the operation point will move from point B to point C along with the blue dotted line. But for a WTG operating in the constant speed zone and constant power zone, since the rotor speed is regulated at its maximum value already, only PAC can be adopted to reduce the available wind power.

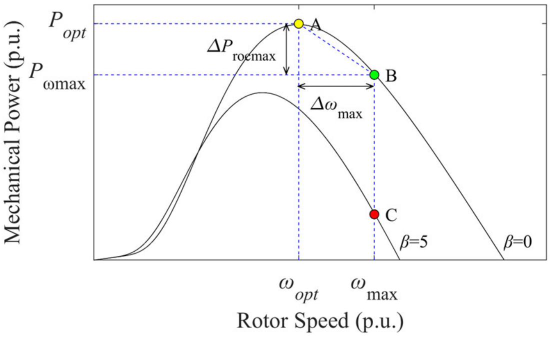


FIGURE 2. Coordination of ROC and PAC for power reserve control.

On the one hand, only if there is a rise margin for rotor speed, the ROC will be used in priority. Therefore, it is necessary to quantify the maximum rise margin for rotor speed, as

$$\begin{cases} \Delta\omega_{\max} = \omega_{\max} - \omega_{opt}, & v \leq v_{\omega\max} \\ \Delta\omega_{\max} = 0, & v > v_{\omega\max} \end{cases} \tag{4}$$

where $\Delta\omega_{\max}$ is the maximum rise margin for rotor speed, ω_{opt} is the rotor speed in the optimal operation. For example, ω_{opt} refers to point A in Figure 2, $\omega_{\max}$ refers to point B in Figure 2.

As shown in Figure 3, with wind speed increasing, ω_{opt} is closer to $\omega_{\max}$, resulting in the decrease of $\Delta\omega_{\max}$. Once v is higher than $v_{\omega\max}$, $\Delta\omega_{\max}$ will remain zero.

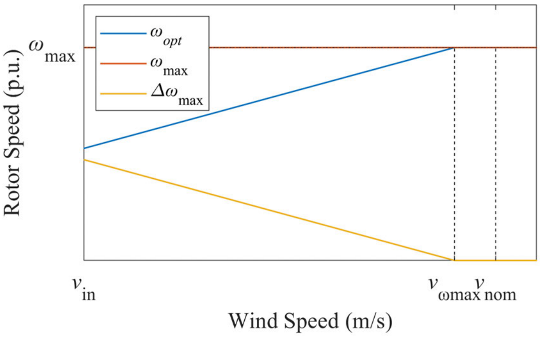


FIGURE 3. The variation of $\Delta\omega_{\max}$ with wind speeds.

On the other hand, only if the power reserve demand cannot be satisfied by ROC, the PAC will be activated coordinately. Therefore, it is necessary to quantify the maximum power reserve provided only by ROC, as

$$\begin{cases} \Delta P_{roc\max} = P_{opt} - P_{\omega\max}, & v \leq v_{\omega\max} \\ \Delta P_{roc\max} = 0, & v > v_{\omega\max} \end{cases} \tag{5}$$

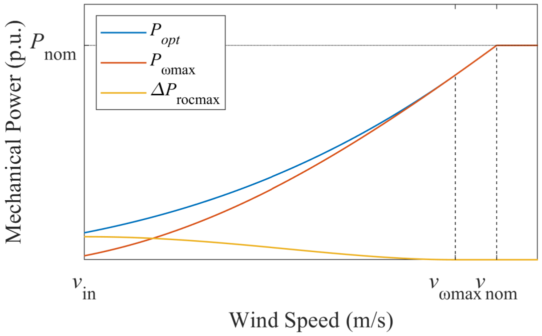


FIGURE 4. The variation of $\Delta P_{\omega\max}$ with wind speeds.

where $\Delta P_{roc\max}$ is the maximum power reserve provided only by ROC, P_{opt} is the maximum available power in the optimal operation, $P_{\omega\max}$ is the curtailed available power with the maximum rotor speed. For example, P_{opt} refers to point A in Figure 2, $P_{\omega\max}$ refers to point B in Figure 2.

As shown in Figure 4, with wind speed increasing, $P_{\omega\max}$ is closer to P_{opt}, resulting in the decrease of $\Delta P_{roc\max}$. Once v is higher than $v_{\omega\max}$, $\Delta P_{roc\max}$ will remain zero.

The relation between $\Delta\omega_{\max}$ and $\Delta P_{roc\max}$ can be described by a new coefficient α. The new coefficient α represents the average rate of change of rotor speed variation with respect to available power curtailment, as

$$\begin{cases} \alpha = \Delta\omega_{\max}/\Delta P_{roc\max}, & v \leq v_{\omega\max} \\ \alpha = 0, & v > v_{\omega\max} \end{cases} \tag{6}$$

Based on the new coefficient α, the power reserve provided by ROC can be approximatively represented as

$$\Delta P_{roc} = \alpha \cdot \Delta\omega, \quad 0 \leq \Delta\omega \leq \Delta\omega_{\max} \tag{7}$$

where ΔP_{roc} is the power reserve provided by ROC, $\Delta\omega$ is the rotor speed variation.

Once the rotor speed reaches the maximum, the PAC will be activated to provide the power reserve continually. In this case, the power reserve control of a WTG will be achieved by the coordination of ROC and PAC. The power reserve can be represented as

$$\begin{cases} \Delta P_{res} = \Delta P_{roc}, & \Delta P_{res} \leq \Delta P_{roc\max} \\ \Delta P_{res} = \Delta P_{roc\max} + \Delta P_{pac}, & \Delta P_{res} > \Delta P_{roc\max} \end{cases} \tag{8}$$

where ΔP_{res} is power reserve of a WTG, ΔP_{pac} is the power reserve provided by PAC.

Obviously, $\Delta P_{roc\max}$ is a key boundary value. If the required ΔP_{res} is less than $\Delta P_{roc\max}$, ΔP_{res} will be equal to ΔP_{roc}, which means the power reserve demand is able to be satisfied only by ROC. Otherwise, ΔP_{res} will be equal to sum of $\Delta P_{roc\max}$ and ΔP_{pac}, which means the power reserve demand is satisfied by the coordination of ROC and PAC.

C. PRIMARY FREQUENCY CONTROL OF A WTG

The power reserve control enables WTGs to retain a certain available power as reserve for participating in the frequency

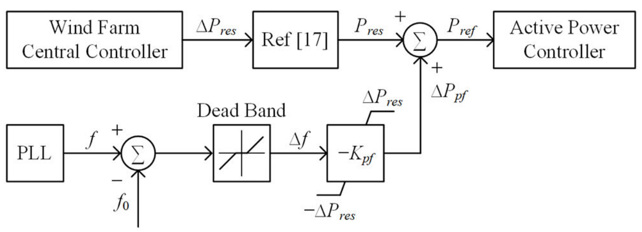


FIGURE 5. The control block diagram of primary frequency control.

regulation. By adding the additional droop control loop to the active power control loop, WTGs are able to provide a similar PFC capacity as synchronous generators. The detailed control block is presented in Figure 5. The total active power reference (P_{ref}) consists of two components, one is responsible for the power reserve control (P_{res}) and the other is for the PFC (ΔP_{pf}). Further, P_{res} is determined based on the required ΔP_{res} and by using the method presented in Ref [17], ΔP_{pf} is generated by multiplying the frequency deviation (Δf) and the negative PFC coefficient (K_{pf}). It is worthy noted that, ΔP_{pf} cannot be over ΔP_{res}. In addition, Δf is obtained by considering the dead band to avoid unnecessary activation of PFC, as

$$\begin{cases} \Delta f = f - f_0 + \Delta f_{db}, & f - f_0 \le -\Delta f_{db} \\ \Delta f = 0, & -\Delta f_{db} < f - f_0 < \Delta f_{db} \\ \Delta f = f - f_0 - \Delta f_{db}, & \Delta f_{db} \le f - f_0 \end{cases} \tag{9}$$

where f is the frequency produced from phase-locked loop (PLL), f_0 is the nominal frequency, Δf_{bd} is the dead band of frequency deviation.

III. COORDINATED POWER RESERVE CONTROL OF A WF FOR FREQUENCY REGULATION

In this section, a coordinated power reserve control method of a WF is introduced to improve the frequency regulation capacity of a WF. The proposed method allocates the power reserve of each WTG by using the linear programming method, so as to maximize the KE of WTGs and minimize the blade pitch action of WTGs. Besides, the PFC method of a WF is presented, which determines the PFC coefficients of WTGs, in order to satisfy the PFC requirements of a WF by TSO.

A. COORDINATED POWER RESERVE CONTROL OF A WF

In order to achieve the power reserve control of a WF, it is necessary to determine the allocated power reserve of each WTG. The total power reserve of a WF is the sum of power reserve of each WTG, as

$$\Delta P_{res,wf} = \sum_{i=1}^{n} \Delta P_{res,ithwtg} \tag{10}$$

where n is the number of WTGs in a WF, $\Delta P_{res,wf}$ is the total power reserve of a WF, $\Delta P_{res,ithwtg}$ is the power reserve of the *ith* WTG.

To maximize the KE of WTGs and minimize the blade pitch action of WTGs, the power reserve should be preferentially provided by ROC. Therefore, it is necessary to quantify the maximum power reserve of a WF provided only by ROC, as

$$\Delta P_{\mathrm{rocmax},wf} = \sum_{i=1}^{n} \Delta P_{\mathrm{rocmax},ithwtg} \tag{11}$$

where $\Delta P_{\mathrm{rocmax},wf}$ is the maximum power reserve of a WF provided only by ROC, $\Delta P_{\mathrm{rocmax},ithwtg}$ is the maximum power reserve of the *ith* WTG provided only by ROC.

It is worthy noted that, $\Delta P_{\mathrm{rocmax},wf}$ is a key boundary value. If $\Delta P_{res,wf}$ is less than $\Delta P_{\mathrm{rocmax},wf}$, the power reserve demand of a WF will be satisfied only by ROC. If $\Delta P_{res,wf}$ is more than $\Delta P_{\mathrm{rocmax},wf}$, the power reserve demand of a WF will be met by the coordination of ROC and PAC.

The following discussions is presented according to above two scenarios.

If $\Delta P_{res,wf}$ is less than $\Delta P_{\mathrm{rocmax},wf}$, the power reserve demand of a WF will be met only by ROC. Therefore, $\Delta P_{res,wf}$ can be represented as

$$\begin{cases} \Delta P_{res,wf} = \sum_{i=1}^{n} \Delta P_{res,ithwtg} = \sum_{i=1}^{n} \Delta P_{roc,ithwtg} \\ \Delta P_{res,ithwtg} = \Delta P_{roc,ithwtg} \end{cases} \tag{12}$$

where $\Delta P_{roc,ithwtg}$ is the power reserve of the *ith* WTG provided by ROC.

The determination of $\Delta P_{roc,ithwtg}$ is to maximize the total KE of WTGs. For the *ith* WTG, the KE variation is represented as

$$\begin{aligned} \Delta KE_{ithwtg} &= H_{ithwtg}[(\omega_{opt,ithwtg} + \Delta\omega_{ithwtg})^2 - \omega_{opt,ithwtg}^2] \\ &= H_{ithwtg}(2\omega_{opt,ithwtg}\Delta\omega_{ithwtg} + \Delta\omega_{ithwtg}^2) \end{aligned} \tag{13}$$

where ΔKE_{ithwtg} is the KE variation of the *ith* WTG, H_{ithwtg} is the inertia time constant of the *ith* WTG, $\omega_{opt,ithwtg}$ is the rotor speed in the optimal operation of the *ith* WTG, $\Delta\omega_{ithwtg}$ is the rotor speed variation of the *ith* WTG.

Ignore the higher order item and substitute (7) into (13), the following can be obtained.

$$\begin{aligned} \Delta KE_{ithwtg} &= H_{ithwtg}(2\omega_{opt,ithwtg}\Delta\omega_{ithwtg} + \Delta\omega_{ithwtg}^2) \\ &\approx 2H_{ithwtg}\omega_{opt,ithwtg}\Delta\omega_{ithwtg} \\ &\approx 2H_{ithwtg}\omega_{opt,ithwtg}\alpha_{ithwtg}\Delta P_{roc,ithwtg} \end{aligned} \tag{14}$$

where α_{ithwtg} is the α of *ith* WTG.

Based on (14), assuming that WTGs are identical types, the KE variation of a WF can be represented as

$$\begin{aligned} \Delta KE_{wf} &= \sum_{i=1}^{n} \Delta KE_{ithwtg} \\ &\approx 2H_{wtg} \sum_{i=1}^{n} \omega_{opt,ithwtg}\alpha_{ithwtg}\Delta P_{roc,ithwtg} \end{aligned} \tag{15}$$

where ΔKE_{wf} is the KE variation of a WF, H_{wtg} is the same inertia time constant of WTGs.

Thus, the determination of $\Delta P_{roc,ithwtg}$ is to maximize ΔKE_{wf}, which can be solved based on linear programming, as follows.

The decision variables are $\Delta P_{roc,ithwtg}$, respectively.

The objective function is to maximize the KE of a WF, as

$$\max \{\Delta KE_{wf} = 2H_{wtg}\sum_{i=1}^{n}\omega_{opt,ithwtg}\alpha_{ithwtg}\Delta P_{roc,ithwtg}\} \quad (16)$$

The constraint conditions mainly cover $\Delta P_{roc,ithwtg}$, as

$$\text{s.t.}\begin{cases} 0 \leq \Delta P_{roc,ithwtg} \leq \Delta P_{\text{rocmax},ithwtg} \\ \sum_{i=1}^{n}\Delta P_{roc,ithwtg} = \Delta P_{res,wf} \end{cases} \quad (17)$$

The above is a typical linear programming problem, which can be solved by using function *linprog* in Matlab software.

If $\Delta P_{res,wf}$ is more than $\Delta P_{\text{rocmax},wf}$, the power reserve demand of a WF will be satisfied by the coordination of ROC and PAC. Therefore, $\Delta P_{res,wf}$ can be represented as

$$\begin{cases} \Delta P_{res,wf} = \sum_{i=1}^{n}\Delta P_{res,ithwtg} \\ \qquad\quad = \sum_{i=1}^{n}(\Delta P_{\text{rocmax},ithwtg} + \Delta P_{pac,ithwtg}) \\ \Delta P_{res,ithwtg} = \Delta P_{\text{rocmax},ithwtg} + \Delta P_{pac,ithwtg} \end{cases} \quad (18)$$

where $\Delta P_{pac,ithwtg}$ is the power reserve of the *ith* WTG provided by PAC.

The determination of $\Delta P_{pac,ithwtg}$ is to ensure a safe operation of WTGs. When a high $\Delta P_{pac,ithwtg}$ is allocated to a WTG with a low available power, the WTG will be operated with a lower power state, which may pose a threat to the normal operation of the WTG. To this end, the determination of $\Delta P_{pac,ithwtg}$ takes the available power of WTGs into consideration, as

$$\Delta P_{pac,ithwtg} = (\Delta P_{res,wf} - \Delta P_{\text{rocmax},wf})\frac{P_{opt,ithwtg}}{\sum_{i=1}^{n}P_{opt,ithwtg}} \quad (19)$$

where $P_{opt,ithwtg}$ is the maximum available power of *ith* WTG in the optimal operation.

Essentially, the coordinated power reserve control of a WF is to allocate the power reserve of WTGs, in order to maximize the KE of WTGs and minimize the pitch action of WTGs. The overall flowchart of the coordinated power reserve control of a WF is shown in Figure 6.

Once receiving the power reserve order ($\Delta P_{res,wf}$) from TSO dispatching center, the WF central controller will collect some important information from WTGs, including α_{ithwtg}, $\omega_{opt,ithwtg}$, $P_{opt,ithwtg}$ and $\Delta P_{\text{rocmax},ithwtg}$. Then, the power reserve of every WTG, $\Delta P_{res,ithwtg}$, will be determined and sent to every WTG controller.

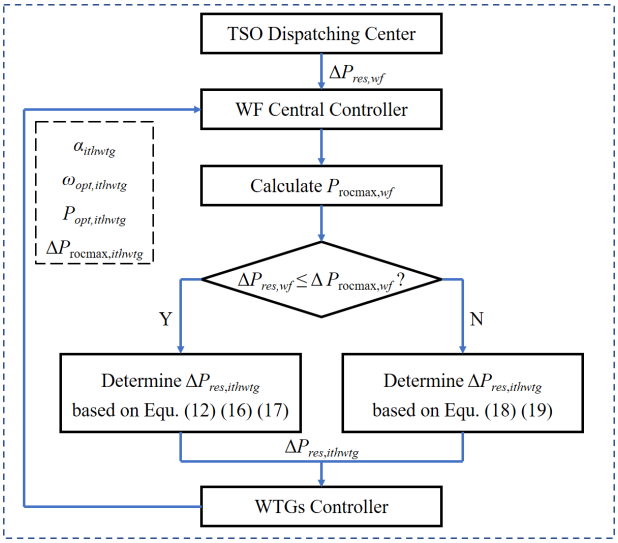


FIGURE 6. Flowchart of the coordinated power reserve control of a WF.

The determination of $\Delta P_{res,ithwtg}$ can be summarized as

$$\begin{cases} \Delta P_{res,ithwtg} = \Delta P_{roc,ithwtg}, \quad \Delta P_{res,wf} \leq \Delta P_{\text{rocmax},wf} \\ \Delta P_{res,ithwtg} = \Delta P_{\text{rocmax},ithwtg} + \Delta P_{pac,ithwtg}, \quad \Delta P_{res,wf} > \Delta P_{\text{rocmax},wf} \end{cases} \quad (20)$$

In (20), if $\Delta P_{res,wf}$ is less than $\Delta P_{\text{rocmax},wf}$, $\Delta P_{res,ithwtg}$ will be determined based on (12), (16) and (17), which is to maximize the KE of WTGs and minimize the pitch action of WTGs. Else, if $\Delta P_{res,wf}$ is more than $\Delta P_{\text{rocmax},wf}$, $\Delta P_{res,ithwtg}$ will be determined based on (18) and (19), which is to avoid the unsafe operation of WTGs.

B. PRIMARY FREQUENCY CONTROL OF A WF

Usually, the TSO puts forward the specific requirements of PFC in WF level rather than WTG level. Whereas the PFC of a WF is realized by those of WTGs. Therefore, the key is how to coordinate the PFC of WTGs so as to make the WF satisfy the PFC requirements by TSO.

For the PFC, the critical parameter is the PFC coefficient, which decides the extra active power support. Thus, the most important thing is to determine the PFC coefficient of WTGs so that the equivalent PFC coefficient of a WF can satisfy the relevant requirements by TSO.

The PFC power provided by a WF is required as

$$\Delta P_{pf,wf} = -K_{pf,wf}\cdot\Delta f\cdot P_{\text{nom},wf} \quad (21)$$

where $\Delta P_{pf,wf}$ is the PFC power provided by a WF, $K_{pf,wf}$ is the PFC coefficient of a WF with the unit of p.u./Hz, Δf is defined as (8) which has considered the frequency dead band, $P_{\text{nom},wf}$ is the nominal power of a WF.

A typical PFC curve of a WF is shown in Figure 7, which is usually specified in the grid codes related to WFs. With the frequency dip, the PFC power will increase, and vice versa.

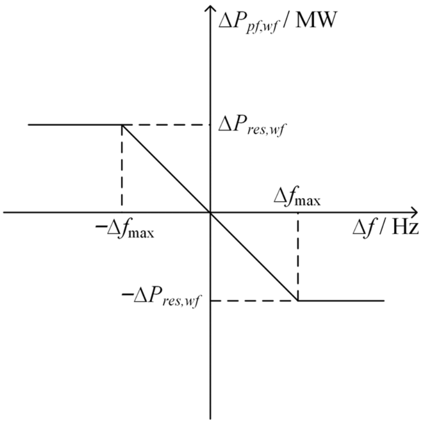


FIGURE 7. Primary frequency control curve of a WF.

Obviously, $\Delta P_{pf,wf}$ cannot exceed $\Delta P_{res,wf}$, thus, $K_{pf,wf}$ can be represented by

$$K_{pf,wf} = \frac{\Delta P_{res,wf}}{P_{\text{nom},wf} \cdot \Delta f_{\max}} \tag{22}$$

where $\Delta f_{\max}$ is the frequency deviation corresponding to the maximum PFC power.

Considering that the PFC of a WF relies on those of WTGs, $\Delta P_{pf,wf}$ can also be represented as

$$\Delta P_{pf,wf} = \sum_{i=1}^{n} \Delta P_{pf,ithwtg} = \sum_{i=1}^{n} -K_{pf,ithwtg} \cdot \Delta f \cdot P_{\text{nom},ithwtg} \tag{23}$$

where $\Delta P_{pf,ithwtg}$ is the PFC power provided by the *ith* WTG, $K_{pf,wf}$ is the PFC coefficient of the *ith* WTG with the unit of p.u./Hz, $P_{\text{nom},ithwtg}$ is the nominal power of the *ith* WTG.

Similar to (22), $K_{pf,ithwtg}$ can be represented by

$$K_{pf,ithwtg} = \frac{\Delta P_{res,ithwtg}}{P_{\text{nom},ithwtg} \cdot \Delta f_{\max}} \tag{24}$$

Assuming that all WTGs are identical types, $P_{\text{nom},wf}$ can be represented as

$$P_{\text{nom},wf} = n \cdot P_{\text{nom},wtg} \tag{25}$$

where $P_{\text{nom},wtg}$ is the same nominal power of WTGs.

By incorporating (21), (23) and (25), the following equation can be obtained.

$$K_{pf,wf} = \frac{1}{n} \sum_{i=1}^{n} K_{pf,ithwtg} \tag{26}$$

In other words, only if (26) is satisfied, the WF will satisfy the PFC requirements by TSO.

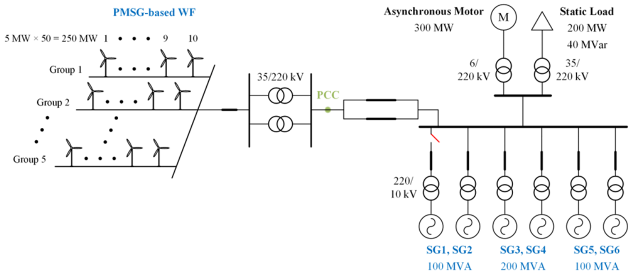


FIGURE 8. Model system for case studies.

By substituting (22) and (24) into (26), it can be proved that (26) is satisfied, the proving process is as

$$\begin{aligned} \frac{1}{n} \sum_{i=1}^{n} K_{pf,ithwtg} &= \frac{1}{n} \sum_{i=1}^{n} \frac{\Delta P_{res,ithwtg}}{P_{\text{nom},ithwtg} \cdot \Delta f_{\max}} \\ &= \frac{\sum_{i=1}^{n} \Delta P_{res,ithwtg}}{n \cdot P_{\text{nom},wtg} \cdot \Delta f_{\max}} \\ &= \frac{\Delta P_{res,wf}}{P_{\text{nom},wf} \cdot \Delta f_{\max}} = K_{pf,wf} \end{aligned} \tag{27}$$

In summary, by determining PFC coefficient of WTGs as (24), the desired PFC coefficient of a WF can be realized. That is to say, relying on the PFC provided from WTGs, the WF can meet the PFC requirements by TSO.

IV. CASE STUDIES

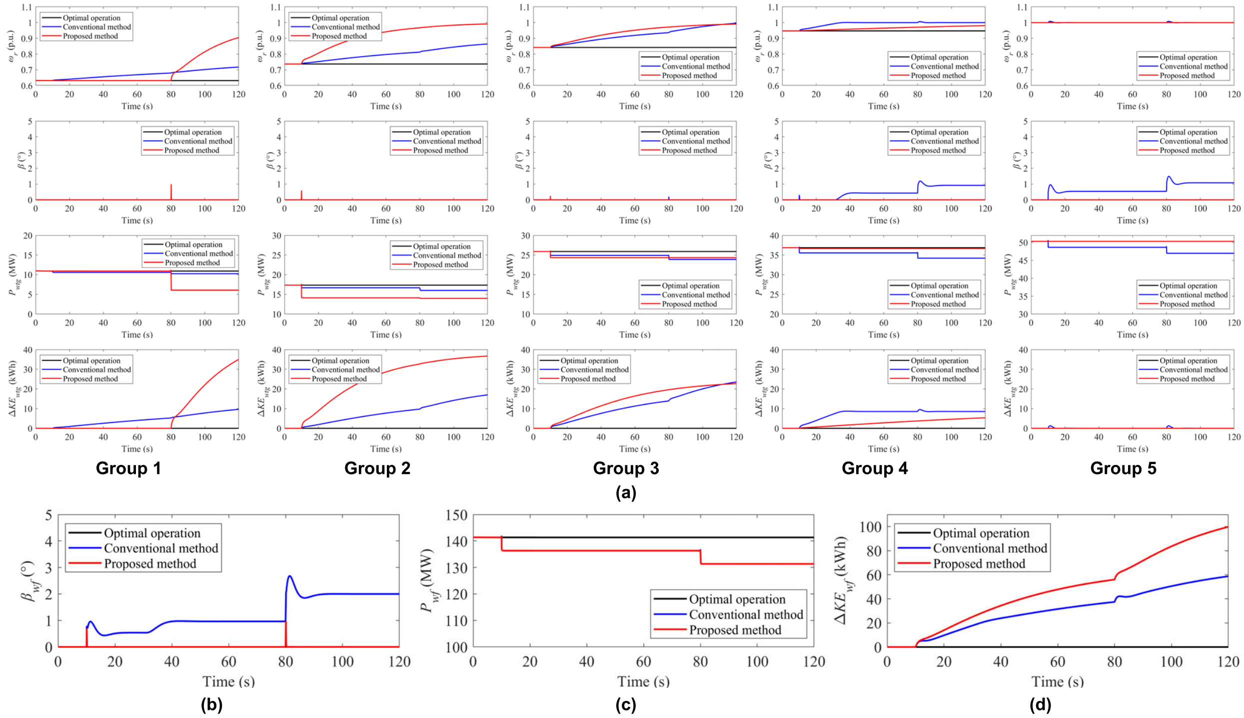
As shown in Figure 8, a model system, which comprises of six synchronous generators, a static load of 200 MW and 40 MVar, an asynchronous motor load of 300 MW and a PMSG-based WF of 250 MW, is built to validate the performance of the proposed method. In the WF, fifty PMSG-based WTGs are averagely distributed on the five power collection feeders. To improve the simulation speed, the wind speeds of WTGs on one row are assumed to be same, thus, ten WTGs on one row are aggregated into one WTG with a larger capacity. The wind speed of each group is 6 m/s, 7 m/s, 8 m/s, 9 m/s and 10 m/s.

A. COORDINATED POWER RESERVE CONTROL OF A WF

In this section, the simulation results for the power reserve control of a WF under the proposed method are presented, for comparison, the results for the power reserve control of a WF under the conventional method [18] together with the results for the optimal operation of a WF are also given, as shown in Figure 9.

In Figure 9(a), the WTG level responses, including the rotor speed, pitch angle, active power output and KE variation of each WTG, are presented. Besides, the total pitch angle, active power output and KE variation of a WF are shown in Figure 9(b), Figure 9(c) and Figure 9(d), respectively.

At 10 s, the power reserve demand of 5 MW occurs. Under the conventional method, the power reserve is allocated to



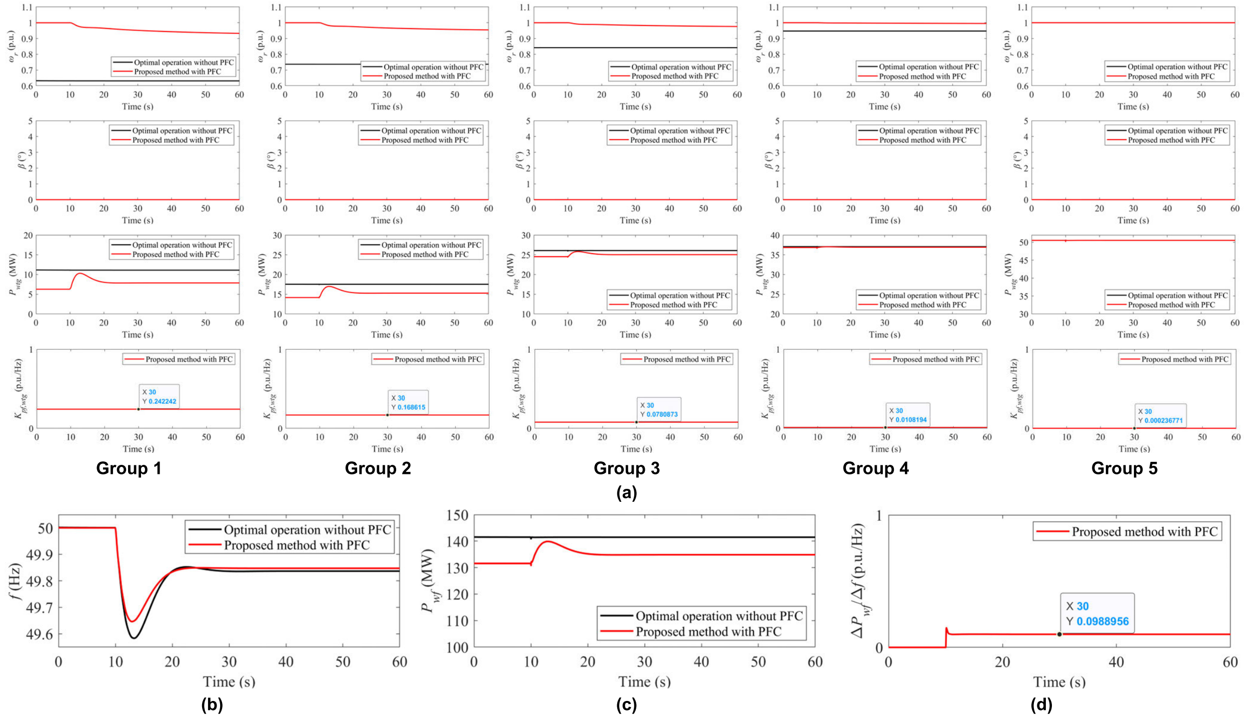
(a)

(b)

(c)

(d)

FIGURE 9. Power reserve control of a WF. (a) WTG-level: rotor speed, pitch angle, active power output, and KE variation. (b) WF-level: total pitch angle. (c) WF-level: total active power output. (d) WF-level: total KE variation.



(a)

(b)

(c)

(d)

FIGURE 10. Primary frequency control of a WF. (a) WTG-level: rotor speed, pitch angle, active power output, and primary frequency control coefficient. (b) System-level: frequency. (c) WF-level: total active power output. (d) WF-level: increased active power output divided by frequency deviation.

each WTG based on wind speeds. The higher wind speed, the larger allocated power reserve. Thus, after 10 s, the rotor speed or the pitch angle of WTGs are increased. Under the proposed method, the power reserve is only allocated to WTG 2, WTG 3 and WTG 4. In this case, the power reserve demand can be satisfied only by ROC. Thus, the rotor speed of WTG 2, WTG 3 and WTG 4 is increased, and no PAC is activated. After 80 s, the power reserve demand is changed to 10 MW. Similarly, the conventional method distributes a larger power reserve to the WTG with a higher wind speed. For the proposed method, since the power reserve demand is over the maximum power reserve provided only by ROC, the allocated power reserve of each WTG is enough to maximize the rotor speed.

In terms of the WF-level responses, both the conventional method and the proposed method can realize the power reserve control of a WF, as depicted in Figure 9(c). Compared to the conventional method, the proposed method leads a lower pitch angle increase but a larger KE variation, the total pitch angle action keeps zero and the total KE variation is 1.67 times that of the former, as depicted in Figure 9(b) and Figure 9(d). In a word, the proposed method achieves the power reserve control of a WF with maximum KE and minimum pitch angle action.

B. PRIMARY FREQUENCY CONTROL OF A WF

In this section, the simulation results for the PFC of a WF under the proposed method are presented, for comparison, the results for the optimal operation of a WF without PFC are also included, as shown in Figure 10.

In Figure 10(a), the WTG level responses, which covers the rotor speed, pitch angle, active power output and determined PFC coefficient of each WTG, are shown. Besides, the system frequency, the active power output and increased active power output divided by frequency deviation of a WF are shown in Figure 10(b), Figure 10(c) and Figure 10(d), respectively.

The PFC requirements of a WF are specified as follows, the retained power reserve of a WF is 10 MW, the frequency dead band is 0.02 Hz, the maximum frequency deviation of PFC is 0.4 Hz. As a result, the PFC coefficient of a WF is desired as 0.1 p.u./Hz, where the nominal power of a WF (250 MW) is used as the base value.

Before 10 s, the proposed method enables the WF to retain a power reserve of 10 MW, correspondingly, the rotor speed of each WTG is higher than that under the optimal operation and the active power output of each WTG is less than that under the optimal operation. At 10 s, SG6 is tripped to emulate a frequency disturbance, causing a power deficit of 50 MW. Under the optimal operation, since no power reserve is kept, the WF cannot provide any frequency support and the active power output maintains invariant. Under the proposed method, the retained power reserve is released to provide the PFC, and the active power output is increased with the frequency drop. The PFC coefficient of each WTG is determined based on the retained power reserve, the WTG with a larger power reserve has a higher PFC coefficient, thus provides a stronger power support. With the frequency support provided by the proposed method, the system frequency nadir is improved from 49.58 Hz to 49.65 Hz and the quasi-steady-state frequency deviation is decreased by 0.01 Hz. Besides, the increased active power output divided by frequency deviation is close to the expected.

In summary, the proposed method enables a WF to provide the effective PFC based on the retained power reserve, which similar to synchronous generators. With the provided PFC, the system frequency response is improved in terms of frequency nadir and quasi-steady-state frequency deviation.

V. CONCLUSION

In the power system with a higher WPPL, it is necessary for a WF to retain a certain power reserve for frequency regulation. In this paper, a coordinated power reserve control method of a WF for frequency regulation is shown. The proposed method allocates the power reserve of each WTG by using the linear programming method, in order to maximize the KE of WTGs and minimize the pitch action of WTGs. A new coefficient to quantify the relation between the rotor speed variation and available power curtailment is defined for linear optimization. Based on the retained power reserve, the PFC of a WF is achieved by determining the PFC coefficients of WTGs. The case studies validate that the proposed method can realize the power reserve control of a WF and improve the frequency regulation ability of a WF, effectively.

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WEI CHEN was born in Anhui, China, in 1994. He received the B.S. degree in electrical engineering and automation from Ningbo University, in 2016, and the Ph.D. degree in electrical engineering from Zhejiang University, in 2022. He is currently a Postdoctoral Researcher with Powerchina Huadong Engineering Corporation Ltd. His main research interest includes the frequency control of new energy generation.

WENBIN YANG was born in Zhejiang, China, in 1979. He received the B.S. and M.S. degrees in electrical engineering from Zhejiang University, in 2002 and 2009, respectively. He is currently the Executive President of the Renewable Energy Engineering Institute, Powerchina Huadong Engineering Corporation Ltd., Hangzhou, China. His current research interest includes renewable energy power generation.

HAIFENG QI is currently with Powerchina Huadong Engineering Corporation Ltd., Hangzhou, China.

ZHAOHUI SHI received the B.S. degree in electrical engineering from Northeast Electric Power University, in 2005. He is currently the Vice President of the Renewable Energy Engineering Institute, Powerchina Huadong Engineering Corporation Ltd., Hangzhou, China. His current research interests include renewable energy power generation and transmission system design.

HUA GENG (Fellow, IEEE) received the B.S. degree in electrical engineering from the Huazhong University of Science and Technology, Wuhan, China, in 2003, and the Ph.D. degree in control theory and application from Tsinghua University, Beijing, China, in 2008. From 2008 to 2010, he was a Postdoctoral Research Fellow with the Department of Electrical and Computer Engineering, Ryerson University, Toronto, ON, Canada. In 2010, he joined the Department of Automation, Tsinghua University, where he is currently a Professor. His current research interests include advanced control of power electronics and renewable energy conversion systems.

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