Unit Commitment with Tunable Frequency Response from Wind Turbine Generators

Juelin Liu¹, Juan Yu⁎, Song Rui², Junkai Huang,¹ Wang Xuebin², Wenyuan Li¹

¹ State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing University, Chongqing, 400044, China
² Electric Power Research Institute State Grid Qinghai Electric Power Corporation, Qinghai, 810008, China

⁎Corresponding author’s e-mail: yujuancqu@cqu.edu.cn

Abstract. Based on the natural inertia on the rotors, wind turbine generators can provide both inertia response and primary frequency response to support the system frequency stability. In this paper, by considering the coordinated optimization of frequency response, a unit commitment with tunable frequency response from wind turbine generators is proposed. The relationship between inertia response and primary frequency response is analyzed. A frequency response correlation constraint is proposed to eliminate the second frequency nadir. Considering the system frequency stability constraints and the feasible region of frequency response provided by wind turbine generators, a security-constrained unit commitment model with tunable frequency response is established. According to the actual operation mode of the power system, a bi-level algorithm is adopted to calculate the frequency response parameters of wind turbine generators. The simulation result of the GB 2030 system demonstrates that the proposed method can reduce operating costs while ensuring system stability.

1. Introduction

To operate the power system with low-carbon output, the generation mix has shifted to include a greater amount of renewable energy sources, such as wind power and photovoltaic power. Renewable energy generations generally work under the maximum power point tracking (MPPT) module, which cannot respond to the frequency fluctuation of the grid. The high penetration of non-synchronous energy sources brings a significant challenge to frequency security. Particularly, the frequency declines in the post-fault condition may cause a severe threat to the low-inertia power systems, leading to damages to power grids. The lack of frequency response in power grids also limits the maximum penetration ratio of non-synchronous generators and leads to the curtailment of renewable energy. Thus, renewable energy sources are expected to undertake the responsibility of providing frequency response support in future power grids.

Among the renewable energy sources, wind turbine generators (WTGs) are an appropriate choice to support the frequency stability considering the stored rotational energy on the rotor. Frequency response control has been adopted into WTGs to imitate the frequency response characteristic of synchronous generators, such as the inertial response (IR) and the primary frequency response (PFR). The frequency responses from WTGs are mainly provided by changing the machine rotor speed of WTGs to transfer mechanical energy to electrical energy and releasing the reserve capacity of WTGs.
When determining the unit commitment (UC) solution, the IR and the PFR from WTGs are expected to release the burden of the frequency regulation from synchronous generators. Relevant studies are briefly reviewed. In [3]-[4], considering the PFR constraint, the frequency-regulating reserve constrained UC is proposed. In [5], the constraints of IR are introduced into the UC model. In [6]-[7], the impact of wind uncertainty on the system inertia is considered in the frequency-constrained UC. However, the frequency responses in these papers are provided by conventional synchronous generators, which may not be sufficient for the system with high penetration of renewable energy sources. In [8], the inertia-dependent fast frequency response is introduced to support the frequency stability in stochastic scheduling. In [9] and [10], the fast frequency response provided by energy storage devices is included in the UC model with the constraints of the storage devices. The frequency response support from WTGs in the UC model also attracts attentions. In [11], the IR parameters of WTG are set as a constant in frequency-constrained UC. In [12], the aggregated parameters of IR and PFR from wind plants are optimized in the UC model to satisfy the frequency stability requirements and minimize operation cost.

The PFR control can be added independently to for each WTG or uniformly to the wind farm control centre. Due to the reserve for frequency regulation declines, the WTGs or wind plants need to work under the de-loading mode, which will cause wind power curtailment. The IR control is generally set at the WTGs. It does not need to keep a reserve, but its recovery process needs to absorb active power from the system, which may cause secondary frequency nadir. In [12], the additional PFR is added to reduce or eliminate the recovery effect.

We wonder that if the PFR control is set at a single WTG, the coordinated optimization of PFR and IR can effectively avoid the recovery effect without any additional PFR. To our best knowledge, the existing research on this issue has not been involved. Based on this basic idea, a frequency-constrained UC considering the coordination of IR and PFR from WTGs is proposed, which. The main contributions of this paper are as follows:

1) A frequency response correlation constraint of WTG is proposed to avoid the recovery effect of IR. To establish this constraint, the correlation between the IR and the PFR is analyzed.
2) Based on the frequency response correlation constraint, a UC model considering coordinated optimization of IR and PFR is proposed. The system frequency stability constraints and the constraints of frequency response from WTGs to keep the safe operation of WTGs are considered.
3) A hierarchical calculation model of the frequency response control parameters is proposed. Firstly, the frequency response required by the wind plants is obtained through the UC model. Then the frequency response is distributed to each unit based on the available power of WTGs. Finally, the frequency response parameters of WTGs can be obtained.

2. Modeling of Frequency Response from WTGs

![Figure 1. The power characteristic of WTG with the frequency response.](image)
2.1. Frequency Response model of WTGs

Under a certain wind speed, the power characteristic of WTG with frequency response is shown in Figure.1.

The mechanical power captured by WTG, which is denoted by $P_M$ (i.e., the black curve in Figure.1), can be generally expressed as a function of rotor speed $\omega_r$:

$$ P_M = f_M (\omega_r). \tag{1} $$

In this paper, the response time of the electrical converter and its controller is neglected, so that the electrical power of WTG is equal to the reference power for the active power controller. The reference power is generally determined by the control module. Under the MPPT control module, the reference power of WTG without frequency response, which is denoted by $P_{MPPT}$, can be expressed as follows:

$$ P_{MPPT} = K_{opt} \omega_r^3 \tag{2} $$

where $K_{opt}$ is the coefficient for MPPT. According to (1) and (2), there exists an optimal rotor speed $\omega_{wopt}$ and optimal reference power $P_{wopt}$ for each certain wind speed.

Similar to the synchronous generators, WTG needs to de-load from the optimal operating point by overspeeding to provide sufficient headroom for P-f droop control to be active when the system frequency decreases. The power-tracking feature of WTG under the de-loading module (i.e., the red curve in Figure.1) can be expressed as

$$ P_{DL} = K_{dl} \omega_r^3 \tag{3} $$

where $P_{DL}$ is the reference power with de-loading control; $K_{dl}$ is the de-loading coefficient. According to (1) and (3), the rotor speed $\omega_{w0}$ and reference power $P_{w0}$ under the de-loading module can be obtained.

The basic principle of frequency response control of WTG is to adjust the reference power of WTG according to the change of system frequency. Two main types of frequency response control schemes are designed to provide frequency response. One is the P-f droop control scheme, which is designed to provide PFR. Another is the virtual inertia control scheme, which is designed to support IR. The active power output of WTG $w$ for these two control schemes are expressed as

$$ \Delta P_{w_{PFR}} = -R_w \Delta f \tag{4} $$

$$ \Delta P_{w_{IR}} = -J_w \frac{d\Delta f}{dt} \tag{5} $$

where $\Delta P_{w_{PFR}}$ and $\Delta P_{w_{IR}}$ are the active power of WTG $w$ corresponding to the frequency change in form of PFR and IR, respectively; $R_w$ is the PFR coefficient of WTG $w$; $J_w$ is the IR coefficient of WTG $w$; $\Delta f$ is the frequency deviation of the power grid; $d\Delta f/dt$ is the rate of change of frequency (RoCoF). We focus on the frequency decline in this paper, but the proposed method is available for frequency increase.

Combining (3), (4) and (5), the reference power $P_w$ of the $w^{th}$ WTG (i.e., the blue curve in Figure.1) can be expressed as

$$ P_w(t) = K_{dl} \omega_r(t)^3 - J_w \frac{d\Delta f(t)}{dt} - R_w \Delta f(t) \tag{6} $$

Considering the power tracking curve (i.e., the red curve in Figure.1), the frequency response provided by WTGs $\Delta P_w$ can be expressed as

$$ \Delta P_w = P_w - P_{w0} \tag{7} $$

At the first instance following the contingency, PFR is still not activated, as the deviation of frequency is very small. The frequency deviation can be considered as $\Delta f = 0$. In this short interval, the frequency response from WTG should only include the IR $\Delta P_{w0}$.
At the steady-state, the frequency is not changed, i.e., $\frac{d\Delta f}{dt}=0$. The frequency response from WTG should only involve the PFR $\Delta P_{ws}$.

$$\Delta P_{ws} = K_{dl}\omega_{ws}^3 - J_w \left. \frac{d\Delta f}{dt} \right|_{\Delta f=0} - P_{w0} = -J_w \left. \frac{d\Delta f}{dt} \right|_{\Delta f=0}$$  \hspace{1cm} (8)$$

where $\omega_{ws}$ is the rotor speed of WTG at the steady-state.

2.2. The Correlation between IR and Primary Frequency Response

For the WTGs that IR and the PFR are unlinked, the transient response process of WTGs with IR is shown as the orange curve in Figure.2(a). When frequency declines, the rotor of WTG decelerates to transfer the rotational kinetic energy into electrical energy. This part of energy contributes to decreasing the power variation during the transient process and finally decreases the frequency fluctuation. When the grid frequency returns to the steady-state (i.e., $\frac{d\Delta f}{dt}=0$), the WTG experiences a recovery period to get back to the original operation point. During this period, the rotor accelerates and the WTG absorbs energy from the grid, the output may blow the original operation point ($\Delta P_{w}<0$), which is shown as the red box in Figure.2(b). The existing studies have observed that the recovery period may lead to the second frequency nadir.

When the WTGs provide both the IR and the PFR, the WTGs operate in the de-loading mode. The transient process of frequency response is shown as the green curve in Figure.2(b). When the grid frequency declines, the additional output of WTGs can be obtained by the kinetic energy from the rotor and the reserve. At the steady-state, the WTGs will reach a new operational point for the PFR control. Thus, the rotor does not need to experience the recovery period. Linking IR and PFR of WTGs helps avoid the second frequency nadir, to enhance the frequency stability.

The correlation constraint of IR and PFR of WTGs can be expressed as

$$\Delta P_{w0} \geq g(\Delta P_{w0})$$ \hspace{1cm} (10)$$

The $g(\cdot)$ is a complex function that relates to the transient process of WTGs, wind speed and, etc. The function $g(\cdot)$ is fitted by linear function for the following reasons: 1) Linear constraints can avoid introducing nonlinearity into the UC model and improve the calculation efficiency. 2) Linear constraints are easy to aggregate and decompose.

$$\Delta P_{ws} \geq k\Delta P_{w0}$$ \hspace{1cm} (11)$$

To ensure the WTGs will not absorb power from the grid, the parameter $k$ can be obtained by the following optimization model:
3. Unit Commitment Model with Frequency Responses from WTGs

A frequency-constrained UC model considering the frequency response from WTGs is proposed in this paper, which minimizes the expected system operation cost. This model includes the post-fault frequency stability constraint, the correlation constraint, and operational constraints of frequency response from WTGs and to ensure the secure operation of the grid and WTGs.

3.1. Post-Fault Frequency Stability Constraints

The time-domain evolution of frequency deviation following system disturbance $\Delta L$ can be described as follows:

$$
\frac{\partial}{\partial \Delta f} \Delta f = -R_G \Delta f + \frac{d \Delta f}{dt} + \sum_{j=1}^{N_p} n_j \Delta P_{f,j} = \Delta L
$$

where $D$ is load damping rate; $L$ is system load; $N_{wp}$ is the whole number of wind plants. In (13), the frequency response coefficients of synchronous generators $R_G$ and $H_G$ can be expressed as

$$
R_G = \sum_{g \in G} \frac{R_{gP_{\text{max}}U_g}}{f_0}
$$

(14)

$$
H_G = \sum_{g \in G} \frac{H_g p_{gP_{\text{max}}}}{f_0}
$$

(15)

where $G$ is the set of conventional units; $R_g=1/R_{\text{droop-g}}$, $R_{\text{droop-g}}$ is the P-f droop coefficient of the conventional unit $g$; $H_g$ is the inertia time constant of the conventional unit $g$; $P_{P_{\text{max}}}^{-}$ is the maximum output of the conventional unit $g$; $U_g$ is 0/1 variable denoting the off/on status of the conventional unit $g$.

In the UC optimization process, the aggregated parameters of wind plants are analyzed. The frequency responses from wind plants $\Delta P_{wp}$ are set as the optimization variable. It can be expressed as

$$
\Delta P_{wp} = \sum_{w \in W} \Delta P_w
$$

(16)

where $W$ is the set of WTGs in one wind plant. The expression of $\Delta P_w$ is shown in (7).

3.1.1. RoCoF Constraint

Generally, the highest value for $\text{RoCoF} \mid \left. \frac{d \Delta f}{dt} \right|_{\text{max}}$ achieves at the first instant after disturbance. In this short interval, the frequency deviation and the change of WTG rotor speed are very small and can be ignored (i.e., $\Delta f=0$ and $\omega_{w0} \approx \omega_{w0}$). According to (13), the time-domain evolution of frequency deviation at the first instant after disturbance should be

$$
\left. \frac{d \Delta f}{dt} \right|_{\text{max}} = \frac{\Delta L - \sum_{j=1}^{N_p} n_j \Delta P_{WP0,j}}{2H_G}
$$

(17)

where $\Delta P_{WP0} = \sum_{w \in W} \Delta P_{wp0}$.
To ensure the value of RoCoF will not exceed its threshold $RoCoF_{\text{max}}$, the largest value for RoCoF should obey the following constraint

$$\frac{\Delta L - \sum_{j=1}^{n_{w_0}} \Delta P_{WP_0,j}}{2H_G} \leq RoCoF_{\text{max}}$$

(18)

### 3.1.2. Frequency Deviation Constraint

Considering the correlation constraints of frequency response from WTGs, the WTGs do not need to experience the recovery process, which avoids the secondary frequency nadir. Considering a conservative constraint, ignoring the overshoot process of the synchronous units, the frequency deviation reaches the maximum value at the steady-state ($d\Delta f/dt=0$ and $\omega_r=\omega_{ws}$). According to equations (5), (7), and (11), the maximum value of frequency deviation can be expressed as

$$|\Delta f|_{\text{max}} = \frac{\Delta L - \sum_{j=1}^{n_{w_0}} \Delta P_{WP_0,j}}{DL + R_G}$$

(19)

where $\Delta P_{WP_0} = \sum_{w_{WP}} \Delta P_{w_0}$.

The $|\Delta f|_{\text{max}}$ should be lower than its threshold value $\Delta f_{\text{max}}$. Considering the frequency dead-band of governor $\Delta f_{\text{db}}$, the system frequency deviation constraint can be expressed as

$$\Delta f_{\text{db}} + \frac{\Delta L - \sum_{j=1}^{n_{w_0}} \Delta P_{WP_0,j}}{DL + R_G} \leq \Delta f_{\text{max}}$$

(20)

### 3.2. Operational Constraints of Frequency Response from WTGs

When the WTGs provide frequency response, its own safe and stable operation should be considered.

#### 3.2.1. Reserve Constraint

Similar to conventional plants, WTGs need to be de-loaded from the optimal operating point to provide sufficient headroom for the PFR to be active in under-frequency events. The output of WTGs at the original operational point cannot exceed the maximum value minus the curtailed part:

$$P_{w_0} \leq (1-a)P_{w_{\text{opt}}_0}$$

(21)

The corresponding constraint for wind plants should be

$$P_{WP_0} \leq (1-a)P_{WP_{\text{opt}}_0}$$

(22)

where $P_{WP_0} = \sum_{w_{WP}} P_{w_0}$; $P_{WP_{\text{opt}}_0} = \sum_{w_{WP}} P_{w_{\text{opt}}}$; coefficient $a$ is the proportion of curtailed wind that can contribute to frequency response provision.

The PFR from WTGs is limited by the curtailed wind power, which is shown as

$$\Delta P_{w_0} \leq P_{w_{\text{opt}}_0} - P_{w_0}$$

(23)

The corresponding constraint for wind plants should be

$$\Delta P_{WP_0} \leq P_{WP_{\text{opt}}_0} - P_{WP_0}$$

(24)
3.2.2. Capacity Constraint
At high wind speed, the frequency response from WTGs is limited by the capacity of converter. At low wind speed, the frequency response from WTGs is limited by the rotational kinetic energy stored on the rotor and the rotor speed. Thus, the capacity constraint for frequency response from WTGs can be expressed as

\[
\Delta P_{w0} \leq b_0 P_{wopt}
\]

\[
\Delta P_{ws} \leq b_s P_{wopt}
\]

where \(b_0\) and \(b_s\) are the coefficients for the largest value of frequency response from WTGs.

The corresponding constraints for wind plants are

\[
\Delta P_{WP0} \leq b_0 P_{WPopt}
\]

\[
\Delta P_{WP} \leq b_s P_{WPopt}
\]

3.3. Unit Commitment Model with Aggregated Frequency Response from Wind Plant

Set \(\Delta P_{WP0}, \Delta P_{WP}, \text{ and } P_{WP0}\) as optimal variables, the proposed UC, which considering the above three types of constraints is shown as (29)-(43).

**Objective Function:**
The objective of the UC problem is to minimize the operation cost, i.e., the sum of the fuel cost, on-off cost, and reserve cost.

\[
\min \sum_{i=1}^{T} \sum_{g \in G} \left[ \left( a_{g,i} P_{g,i}^2 + b_{g,i} P_{g,i} + c_{g} \right) + c_{sg}^w \left( U_{g,i} - U_{g,i-1} \right) + c_{USRg,i} \right]
\]

where \(T\) is optimization horizon, \(P_{g,i}\) is the output of the unit \(g\) at step \(i\); \(USR_{g,i}\) is the reserve capacity of unit \(g\) at step \(i\); \(a_{g,i}, b_{g,i}\) and \(c_{g}\) are the fuel cost coefficient for unit \(g\); \(c_{s}^w\) is the startup cost coefficient for unit \(g\); \(c_{USR}^w\) is reserve cost coefficient for unit \(g\).

**System Constraints:** \(i \in T\)

Power Flow Constraint

\[
\sum_{g \in G} P_{g,i} + \sum_{f=1}^{N_{nf}} \left( P_{w,if}^{\text{online}} \right) = L_i
\]

where \(P_{w,if}^{\text{online}} = \sum_{\text{w}} P_{w,if}^{\text{online}}\). \(P_{w,if}^{\text{online}}\) is the output of WTG \(w\).

Post-Fault Frequency Stability Constraints

\[
\frac{\Delta L_i - \sum_{j=1}^{N_{nf}} (\Delta P_{WP0,i,j})}{2H_{G,i}} \leq RoCoF_{\text{max}}
\]

\[
\frac{\Delta L_i - \sum_{j=1}^{N_{nf}} (\Delta P_{WP,i,j})}{D_i L_i + R_{G,i}} \leq \Delta f_{\text{max}}
\]

**Constraints of Synchronous Generators:** \(g \in G, i \in T\)
\[ P_{g,i}^{\max} = \min \left\{ \begin{array}{l}
U_{g,i} P_{g,i}^{\max} \\
U_{g,i+1} P_{g,i+1}^{\max} + R_{U,g} U_{g,i+1} \\
U_{g,i+1} + (1 - U_{g,i+1}) S_{D,g} \\
U_{g,i} + (1 - U_{g,i}) S_{U,g}
\end{array} \right\} \] (33)

\[ P_{g,i}^{\min} = \max \left\{ P_{g,i-1}^{\min} + U_{g,i} P_{g,i}^{\min} \right\} \] (34)

\[ P_{g,i}^{\min} \leq P_{g,i} \leq P_{g,i}^{\max} \] (35)

\[ 0 \leq \text{USR}_{g,i} \leq P_{g,i}^{\max} - P_{g,i} \] (36)

\[ \text{USR}_{g,i} \leq \kappa P_{g,i}^{\max} \] (37)

where \( P_{g,i}^{\max} \) and \( P_{g,i}^{\min} \) are the maximum and minimum generation of unit \( g \), respectively; \( R_{U,g} \) is the operational ramp rate of unit \( g \); \( S_{U,g} \) and \( S_{D,g} \) are the startup and shutdown ramp rate of unit \( g \), respectively; \( \kappa \) is the maximum proportion for reserve power.

**Constraints of Wind Plants:**

\( i \in T \)

\[ (P_{W,i}^{\text{line}}) \leq (P_{W,i}) \] \( j = 1, 2, ..., N_{wp} \) (38)

\[ (P_{W0,j}) \leq (1 - a_j) (P_{W0,j}) \] \( j = 1, 2, ..., N_{wp} \) (39)

\[ (\Delta P_{W0,j}) \leq (P_{W0,j}) - (P_{W0,j}) \] \( j = 1, 2, ..., N_{wp} \) (40)

\[ (\Delta P_{W0,j}) \geq b_{0,j} (P_{W0,j}) \] \( j = 1, 2, ..., N_{wp} \) (41)

\[ (\Delta P_{W0,j}) \leq b_{0,j} (P_{W0,j}) \] \( j = 1, 2, ..., N_{wp} \) (42)

According to (11), we can obtain:

\[ (\Delta P_{W0,j}) \geq k_j (\Delta P_{W0,j}) \] \( j = 1, 2, ..., N_{wp} \) (43)

3.4. The Calculation of WTG Parameters

We can obtain the aggregated parameters of wind plant \( \Delta P_{W0}, \Delta P_{W0}, \) and \( P_{W0} \) as well as \( d\Delta f/dt|_{t=0} \), \( \Delta f \) by the above UC model. \( \Delta P_{W0}, \Delta P_{W0}, \) and \( P_{W0} \) are distributed to each WTG by (44)-(46) to calculate the frequency response from WTGs.

\[ P_{w0} = \frac{P_{W0}}{P_{W0}} P_{w0} \] (44)

\[ \Delta P_{w0} = \frac{\Delta P_{W0}}{P_{W0}} P_{w0} \] (45)

\[ \Delta P_{ws} = \frac{\Delta P_{W0}}{P_{W0}} P_{w0} \] (46)

We can deduce that this \( P_{w0}, \Delta P_{ws}, \) and \( \Delta P_{w0} \) can satisfy the constraints (11), (21), (23), (25), (26).
We can obtain the IR parameter of WTG $J_w$ by substituting $\Delta P_{w0}$ and $d\Delta f/dt|_{t=0}$ into (8):

$$J_w = \frac{\Delta P_{w0}}{d\Delta f/dt|_{t=0}}$$  \hspace{1cm} (47)

At the steady-state, the rotor speed of WTG can be calculated by

$$f_{st}(\omega_s)|_{\omega_s} = P_{w0} + \Delta P_{ws}$$  \hspace{1cm} (48)

Substituting $P_{w0}, \Delta P_{ws}, \Delta f_s$, and $\omega_{ws}$ into (9), the PFR parameter of WTG $R_w$ can be obtained:

$$R_w = \frac{\Delta P_{ws} + P_{w0} - K_{di,ws} \omega_{ws}^3}{|\Delta f_s|}$$  \hspace{1cm} (49)

4. Simulation Results

4.1. Correlation Simulation Analysis of Frequency Response from WTG

Take a 1.5MW WTG as an example. Its wind speed is 9m/s, $d\Delta f/dt=0.5$Hz/s, and $\Delta f=0.5$Hz. The functional relationship $g$ between the PFR and the IR $\Delta P_{w0}$ is shown in the blue curve in Figure. 3. As shown in Figure.3, the linear function can effectively fit the function relationship $g$ within a rational fluctuation range of $\Delta P_{w0}$.

![Figure 3. The correlation analysis of frequency response from WTGs](image)

4.2. Test Systems and Tested Cases

The IEEE 39 bus system [13] and GB 2030 power system [10] are used to demonstrate the performance of the proposed model.

IEEE 39 bus system: For the synchronous generators, the inertia time constant is 7s, the droop coefficient is 1/15. The maximum capacity of the system is 665MW. The capacity of synchronous generators is 6.09GW, the capacity of WTGs is 6Gw, and the maximum demand is 6.9GW.

GB 2030 power system: For the synchronous generators, the inertia time constant is 4s, the droop coefficient is 1/10. The maximum capacity of the system is 1800MW. The capacity of synchronous generators is 63.2GW, the capacity of WTGs is 60Gw, and the maximum demand is 59.34GW.

The wind speed of WTGs is generated randomly by Weibull distribution. The marginal operating cost of wind power is 0. The coefficient $a=0.1$, $b_0=b_s=0.08$. Considering the typical N-1 security approach, the largest loss of power infeed is the sudden outage of the largest conventional generator. The RoCoF threshold is $RoCoF_{max}=0.5$Hz/s, the frequency deviation threshold is $\Delta f_{max} = 0.5$Hz, the frequency dead-band is $\Delta f_{db}=15$mHz, and the system load-damping coefficient is $D=1\%$/Hz.
In this paper, two methods are compared to demonstrate the effectiveness of the proposed method. M1: WTGs do not provide frequency response; M2: The proposed method considering the coordinated optimization of IR and PFR from WTGs.

4.3. Simulation Result

4.3.1. System Benefit of Frequency Response from WTG
The number of online synchronous units that are optimized by M1 and M2 are shown in Figure. 4. From Figure.4, if WTGs do not provide frequency support (M1), additional synchronous units need to be online to satisfy the system frequency stability constraints. Due to the minimum output constraint of synchronous units, these additional synchronous units will result in a large number of wind curtailment and high operation costs. If the WTGs can provide frequency response, the number of online synchronous units can be reduced, which reduces the wind curtailment and operation cost. The results of system operation cost and wind power utilization rate of M1 and M2 are shown in Table 1 and Table 2, respectively, which demonstrate that M2 can reduce the wind curtailment and operation cost.

![Figure 4. The number of online synchronous generators](image)

### Table 1. Operation cost comparison between M1 and M2.

| System     | M1      | M2      |
|------------|---------|---------|
| IEEE 39    | $7536041 | $3693668 |
| GB 2030    | $20978335 | $11866610 |

### Table 2. Wind curtailment ratio comparison between M1 and M2.

| System     | M1      | M2      |
|------------|---------|---------|
| IEEE 39    | 31.30%  | 7.90%   |
| GB 2030    | 10.28%  | 1.53%   |

4.3.2. Impact of Penetration Levels
Based on the IEEE 39 bus system, the impact of wind power penetration level on system benefit of frequency response from WTGs is shown in Figure.5 and Figure.6. For method M1, a sufficient number of online synchronous units must be guaranteed to satisfy the frequency stability requirements. When the penetration level of wind power is high, increasing the total capacity of wind power cannot reduce the operation cost of the system, and will greatly reduce the utilization rate of wind power. Considering only the frequency stability requirements of the system (assuming other security and stability requirements of the system can be satisfied), the frequency response provided by WTGs can relieve the pressure of frequency response provided by synchronous units. Thus, the online number and total output...
of synchronous units can be reduced. The system can accept a higher penetration of wind power resources and reduce the operation cost. It can be seen from Figure 5 that the system operation cost decreases with the increase of wind power penetration rate. Therefore, wind power frequency response has a higher economic value in the high penetration wind power system.

4.4. Impact of Primary Frequency Response on Recovery Process

Based on the IEEE 39 bus system, the first wind farm is taken as an example. The rated capacity of the WTG is 1.5MW, and the wind speed is 8.35m/s. For the first dispatch time, the results of parameter calculation are shown in Table 3. Based on DlgsILENT/PowerFactory software and a single-machine infinite system, we analyze the frequency response process of WTG. The output and rotor speed changes of WTG during frequency response are shown in Figure 7(a) and (b). The rotor operates at a new speed without returning to the initial speed. The WTG does not need to absorb power from the system. The output of WTG is always greater than the initial output, which can effectively support the frequency stability of the system.

Table 3. The calculation results of the frequency response parameters of WTG.

|     | Po | Pw0 | Pws | ∆Pw0 | ∆Pws | Jw | Rw |
|-----|----|-----|-----|------|------|----|----|
| MW  | MW | MW  | MW  | MW   | MW   | p.u.| p.u.|
| 0.695 | 0.648 | 0.695 | 0.055 | 0.044 | 4.432 | 24.952 |

Figure 7. The simulation of WTG frequency response provision in single-machine infinite system.
5. Conclusion

In this paper, considering the system frequency safety, as well as the correlation and operation safety of frequency response from the WTGs, a UC optimization model is proposed to evaluate the economic value of frequency response from WTGs.

1) Based on the proposed model, the frequency response provided by WTGs can relieve the pressure of the frequency response provision of synchronous units. The number of online synchronous units is reduced. Therefore, the system can accept a higher proportion of wind power resources and reduce the system operating costs.

2) Based on the correlation constraint of frequency response from WTGs, the recovery process caused by the IR can be effectively eliminated by coordinated optimization of IR and PFR of WTGs. Therefore, the system does not need to provide additional PFR to deal with the power interference caused by the recovery process. Thus, the operation cost can be reduced.

3) Based on the proposed hierarchical calculation, the proposed method can be used to guide the parameter setting of frequency response control of WTGs.

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