A Grouping-Based Frequency Support Scheme for Wind Farm Under Cyber Uncertainty

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\textbf{ABSTRACT} The injection of a significant amount of wind power tends to increase the difficulty of the grid frequency control. Therefore, wind farm (WF) has to have the ability to participate in system frequency support. However, during the frequency control process in a large WF, individual wind generators may prone to instability due to possible over-deceleration. In addition, the deeply-intertwined cyber physical power system (CPPS) has gradually replaced the traditional grid due to the development of information and communication technology. However, CPPS also introduces cyber uncertainties that have a significant negative impact on the real-time control of power system. To address above issues, this paper considering possible cyber uncertainty, and proposes a grouping-based hierarchical frequency support scheme for WF. In the proposed scheme, the variable speed wind turbines (VSWTs) are clustered into several groups, according to their wind profiles at first, by dispatching the same control commands to the VSWTs belonging to the same group. As a result, the number of the VSWTs and control variables reduces significantly. Then, a hierarchical control scheme based on virtual inertial control is proposed with consideration of possible cyber uncertainty. The top-layer controller determines whether cyber uncertainty exists, and calculates power increment based on frequency deviation and cyber uncertainty. The bottom-layer controller coordinates the power increment distribution on the basis of ensuring the safe operation of all VSWTs. By do this, it is expected to achieve not only optimal frequency response but also wind generator stability. The effectiveness of proposed scheme is verified on a simulation platform built using MATLAB.

\textbf{INDEX TERMS} Wind farm, cyber physical power system, frequency support, clustering grouping control, cyber uncertainty.

\textbf{NOMENCLATURE AND ABBREVIATION}

\begin{tabular}{ll}
\textbf{V}\textsubscript{j} & The wind speed of \textit{j}-th DFIG \\
\textbf{V\textsubscript{base}} & The ambient wind speed \\
\textbf{C\textsubscript{T},i} & Thrust coefficient of \textit{i}-th DFIG \\
\textbf{\lambda} & Tip-speed ratio \\
\textbf{\beta} & Pitch angle \\
\textbf{\alpha} & Axial interference factor \\
\textbf{x} & Distance between DFIGs with the wind direction \\
\textbf{\alpha} & Decay coefficient \\
\textbf{A\textsubscript{0}} & Sweep area of DFIGs \\
\textbf{A\textsubscript{x}} & Shadowed area of DFIGs \\
\textbf{P\textsubscript{m},i} & Mechanical power of \textit{i}-th DFIG \\
\end{tabular}

\begin{tabular}{ll}
\textbf{\rho} & Air density \\
\textbf{r\textsubscript{0}} & Blade length \\
\textbf{V\textsubscript{wind},i} & Wind speed of \textit{i}-th DFIG \\
\textbf{C\textsubscript{p},i.(\lambda\textsubscript{i}, \beta\textsubscript{i})} & An aerodynamic power coefficient \\
\textbf{T\textsubscript{m},i} & Mechanical torque of \textit{i}-th DFIG \\
\textbf{T\textsubscript{e},i} & Electromagnetic torque of \textit{i}-th DFIG \\
\textbf{\omega\textsubscript{r},i} & Rotation speed of \textit{i}-th DFIG \\
\textbf{J\textsubscript{c}} & Combined inertia of wind turbine and generator \\
\textbf{C\textsubscript{p},i,max} & The maximum value of \(C\textsubscript{p},i(\lambda\textsubscript{i}, \beta\textsubscript{i})\) when \(\beta\textsubscript{i} = 0\) \\
\textbf{\lambda\textsubscript{i, opt}} & Optimal value of \(\lambda\textsubscript{i}\) \\
\textbf{C\textsubscript{T,group},i} & The thrust coefficients of DFIG in area \textit{i} \\
\textbf{H\textsubscript{sys}} & The equivalent inertia of power system with WECS
\end{tabular}
In recent years, wind energy has been widely used due to its clean, green, and renewable advantages [1]. In wind power generation technology, VSWT is active in various fields by virtue of its wide range of applications and high efficiency advantages [2]. However, with the popularization of VSWT-based WECS, traditional power plants have been gradually replaced; the frequency control of power systems faces new challenges [3]. The reason for these challenges is that VSWTs usually operate in the MPPT mode, which essentially does not respond to the system frequency [4]. Therefore, the integration of large-scale wind power will reduce the equivalent inertia of the system, which brings challenges to the temporary primary frequency control [5]. In view of this, it is absolutely necessary to develop frequency support schemes that enable the WECS to improve FN and reduce the ROCOF.

In response, many researchers have reported on the frequency control schemes, which allowed WECSs to participate in the grid frequency support. These methods are mainly divided into the following types in principle: virtual inertia control, deloading control, charging and discharging control [6]. Virtual inertia control utilizes the rotational kinetic energy of VSWTs to support system primary frequency [7]. The paper [8] developed a nonlinear dynamic model for the DFIG’s output power integrated into the dynamic model of power grid. A state feedback controller is proposed by considering whether DFIGs participate in the frequency regulation task or not. In this paper, two control schemes are proposed on the basis of modulating the inertia gains, one is a dynamic equation-based scheme and other is an adaptive fuzzy-based scheme. The proposed schemes modulate the gains of inertia controls dynamically for a wide range of wind speeds on the perspectives of wind turbine stability and frequency security [9]. A primary frequency control strategy based on fuzzy logic, designed for VSWTs has been proposed in [10]. This methodology to implement in real time, the fuzzy logic supervisor has been proposed to reduce the computation time. In [11], a distribute newton method is developed for primary frequency support in WECSs. This process uses a state of energy index to assign the power to be dispatched from WECS to the grid. Deloading control allows VSWTs to have power margin at steady state and be released in frequency events [12].

The study in [13] proposed a new integrated frequency regulator for DFIG, in which the initial pitch angle and deloading level are first theoretically calculated based on VSWTs generation characteristics, and the pitch angle is then adjusted based on the varying rotor speed in frequency event. Vidyanandan et al. mooted a droop deloading control method to improve the frequency control stability with time-varying wind speed [14]. The third type of method utilizes charging/discharging control of energy storage devices to assist WECS for frequency control [15]. A new collaborative controller that considers the variability of wind energy and the state of charge of capacitor was developed to accelerate frequency recovery of power systems [16]. Masoud et al. proposed strategy for adjusting microgrid parameters to determine the inertia constant of the microgrid with energy storage equipment to optimize the frequency response of the microgrid [17].

To the best knowledge of the authors, these methods shared a common limitation, that they studied the WECS frequency support problem from the perspective of either an individual VSWT model or an equivalent VSWT model. Specifically, the operating status differences among individual VSWTs were completely ignored. However, with the scale of WECS continues to increase, the interaction of a single VSWT should be considered in design of frequency support scheme. This is because in WECS, the geographic location and wind direction of VSWTs will cause wake effect, which results in the upstream VSWTs, which will affect the wind speed experienced by the downstream VSWTs [18]. It has been reported that wake effect within a WECS has significant impact on

\[ D \] Load damping coefficient
\[ P_g \] Power generated by conventional generators
\[ P_{WECS} \] Power generated by conventional generators
\[ P_l \] Load consumptions
\[ \Delta f \] Deviation of frequency
\[ J_i \] The moment of inertia of \( i \)-th traditional generator
\[ S_{sys} \] The rated generation capacity of the power system
\[ \omega_{m,i} \] The rated mechanical angular of the \( i \)-th traditional generator.
\[ \Delta P_{WECS} \] Power increment of the WECS
\[ K_1, K_2 \] The adaptive gain of \( \Delta f \) and \( \Delta f_h \)
\[ \kappa_1, \kappa_2 \] Coefficients of \( \Delta f \) and \( \Delta f_h \)
\[ \Delta f_h \] Frequency difference between two adjacent time steps
\[ k \] \( k \)-th time step
\[ \tau \] Equivalent network delay
\[ \Delta P_{WECS, max} \] Maximum kinetic energy available for WECS
\[ \Delta P_{m,m} \] Power increment of the \( m \)-th group
\[ \delta \] Relaxation coefficient
\[ d\% \] Degree of deloading control
\[ P_{de} \] Output power of DFIG in deloading control
\[ \omega_{min} \] Minimum rotation speed
\[ P_{max} \] Maximum power
\[ WF \] Wind farm
\[ VSWT \] Variable speed wind turbine
\[ WECS \] Wind energy conversion system
\[ MPPT \] Maximum power point tracking
\[ FN \] Frequency nadir
\[ ROCOF \] Rate of change of frequency
\[ DFIG \] Double-fed induction generator
\[ CPPS \] Cyber physical power system
WECS frequency support [19]. Therefore, the VSWTs should be coordinated for frequency support of WECS. For example, Z. Wang et al. in [11] proposed a distributed Newton method, which realized fast active power distribution among multiple VSWTs during the frequency events. S. Ghosh et al. proposed a control framework for inertial and primary frequency response for a high wind integrated power system. In this scheme, an online reduced-order model based integrated controller allows for coupled control of torque and pitch angle at all speed range of DFIG’s [20]. However, among the above methods, when the number of VSWTs is large, there are many variables that need to be coordinated, and the control scheme will become very time-consuming. Therefore, it is necessary to design a more comprehensive frequency support scheme in consideration of the operating status differences among individual VSWTs and complexity of the method.

In addition to that, due to the large amount of information exchange is required; cyber uncertainty also needs to be considered in control scheme design. In fact, with the rapid development of information and communication technology, the CPPS that composed of analog, interactive digital, power supply systems and artificial components designed by integrated logic and physical functions has gradually replaced the traditional power grid and constituted the basis of the smart grid [21]. However, since CPPS relies heavily on the network, it brings convenience to the power system and also introduces cyber uncertainty [22]. These cyber uncertainties such as network induces delay and packet loss have a significant impact on the real-time control of the power grid [23]. For example, an advanced damping control based on Q-learning is proposed in [24] to reduce the impact of cyber uncertainty on the stability of closed-loop control of wide-area power systems. Similarly, during a frequency event, the possible cyber uncertainty will reduce the control performance of the frequency support scheme [25]. However, the research on this topic received little attention. Therefore, there is an urgent need to conduct and deep investigation on WECS frequency support in consideration of cyber uncertainty.

This paper aims to fill the above-mentioned problems, and takes into account the possible cyber uncertainty, proposes a grouping-based hierarchical frequency support scheme. Compared with other frequency support article, the main contributions of this paper are: (1) establish a CPPS model and use this model to quantify the specific adverse effects of cyber uncertainty on the frequency support scheme. (2) A clustering method based on wake effect is used to group WECS into groups. VSWTs belong to the same group are assigned the same control commands. In this way, the number of signal transmissions and the cost of calculation in the system are greatly reduced. (3) A hierarchical frequency support scheme is proposed based on virtual inertial control and deloading control. In the scheme, the top-layer controller determines the WECS power reference to fulfill the frequency support capability. The controller considers the possible existence of cyber uncertainty, and calculates the active power increment based on the system frequency. The bottom-layer controller takes the grouped result after clustering as the control object, considers the operating status of each group of VSWTs, and coordinates the power increment amount generated by top-layer controller. The salient feature of proposed scheme is that, by incorporating the dynamics and local wind conditions of each individual VSWT’s, it achieves the objectives of optimal frequency response and stable operation. Finally, the effectiveness of proposed scheme is verified on the MATLAB simulation platform.

II. SYSTEM DESCRIPTION AND MODELING

A. CPPS MODEL

In CPPS, WECS not only needs to exchange various signals with the external power system, but also needs to realize the transmission of control and feedback signals with its internal DFIGs. Figure 1 shows the closed-loop control framework of common WECS participating in frequency support. As shown, the sensor first measures and samples the system frequency in a given sampling step, and then packages the sampled frequency signal into a data packet. These data packets are transmitted to the corresponding controller by the communication network, and are processed to generate control signals. The control signal is followed by transmitting to the corresponding actuator of DFIGs, which realizes the closed-loop control.

![FIGURE 1. Framework of the closed-loop control for WECS in CPPS.](image)

Obviously, the communication network plays a very important role in this closed-loop control. Nevertheless, due to external factors or internal network fluctuations, cyber uncertainty may occur in the communication network. These uncertainties will affect the quality of signal transmission, which in turn reduces the control performance of the frequency support scheme. For example, assuming that cyber uncertainty such as network delay exists, the signal received by the WECS controller at time $k$ is not a real-time signal transmitted from the sensor, but a lagging signal with the network delay. Similarly, cyber uncertainty also exists in the feedback communication channel from the controller to...
the actuator. Therefore, it is a pressing need to consider the possible cyber uncertainty in the frequency support process.

### B. WAKE EFFECT MODEL

In WECS, due to wake effect, the wind speed faced by the upstream DFIGs is greater than the downstream DFIGs. This paper uses the Jensen model [18] to illustrate wake effect because just the basic idea of clustering based coordinated control is mainly discussed. Figure 2 shows the Jensen model for wake effect. From the Figure 2, the wind speed \( V_j \) of \( j \)-th DFIG is:

\[
V_j = V_{\text{base}} \left[ 1 - \sum_{i=1}^{n-1} (1 - \sqrt{1 - C_{T,i}}) \frac{A_{\text{s}}}{A_0} \xi_{i,j} \right] \tag{1}
\]

\[
C_{T,i} = 4a(1-a)
\tag{2}
\]

\[
\xi_{i,j} = \left( \frac{r_0}{r_0 + \alpha x} \right)^2 \tag{3}
\]

**FIGURE 2. Illustration of wake effect.**

\( C_{T,i} \) is determined by \( \lambda \) and \( \beta \). \( x \) is the distance between the upstream DFIG and the downstream DFIG along with the wind direction. The affected area in downstream increases according to decay coefficient \( \alpha \). \( A_0 \) and \( A_{\text{s}} \) are determined by the geographical location and the wind direction.

### C. DFIG MODEL

This paper selects the DFIG model which is adopted by most large-scale WECS as the research object. A typical structure of a DFIG includes wind turbine, shafting model, generator, converter and controller. The stator of DFIG is directly connected to the grid, while the rotor is connected to the grid through a converter. The converter decouples the rotor speed from the grid frequency to maximize the efficiency of DFIG in capturing wind energy.

For the \( i \)-th DFIG in WECS, its mechanical dynamics model, can be described as:

\[
P_{m,i} = \frac{1}{2} \rho \pi r_0^2 C_{p,i} (\lambda_i, \beta_i) V_{\text{wind},i}^3 \tag{4}
\]

\( C_{p,i}(\lambda_i, \beta_i) \) denotes an aerodynamic power coefficient that is a nonlinear function of tip-speed ratio \( \lambda_i \) and blade pitch angle \( \beta_i \), given as

\[
C_{p,i}(\lambda_i, \beta_i) = 0.645 \left\{ 0.00912 \lambda_i + \frac{-5 - 0.4(2.5 + \beta_i) + 116 \lambda_i}{e^{21\lambda_i}} \right\} \tag{5}
\]

\[
\lambda_1 = \frac{1}{\lambda_i + 0.08(2.5 + \beta_i)} - \frac{0.035}{1 + (2.5 + \beta_i)^3} \tag{6}
\]

\[
\lambda = \frac{\omega_{r,i} r_0}{V_{\text{wind},i}} \tag{7}
\]

The shafting model transfers \( P_{m,i} \) to the generator and drives the generator to rotate. Under the shafting model applied in this paper, the dynamic relationship between the mechanical torque \( T_m \) of the wind turbine and the electromagnetic torque \( T_e \) of the generator can be expressed as:

\[
\frac{d\omega_{r,i}}{dt} = \frac{1}{J_c} (T_{m,i} - T_{e,i}) = \frac{1}{J_c} \left( \frac{P_{m,i}}{\omega_{r,i}} - \frac{P_{r,i}}{\omega_{r,i}} \right) \tag{8}
\]

In general, DFIG operates in MPPT mode to achieve maximum wind capture. The output power in MPPT mode can be described as:

\[
P_{\text{MPPT},i} = \frac{1}{2} \rho \pi r_0^2 \left( \frac{\omega_{r,i} r_0}{\lambda_{i,\text{opt}}} \right)^3 C_{p,i,\text{max}} \tag{9}
\]

In this paper, \( C_{p,i,\text{max}} \) is the maximum value of \( C_{p,i}(\lambda_i, \beta_i) \) when \( \beta_i = 0 \) and is set to 0.5; \( \lambda_{i,\text{opt}} \) is the optimal value of \( \lambda_i \) and is set as 9.95.

### III. FREQUENCY SUPPORT SCHEME BASED ON GROUPING

#### A. SCHEME DESCRIPTION

To arrest the system frequency decline, the proposed frequency support scheme should immediately releases the kinetic energy stored in the DFIGs. More importantly, due to the existence of wake effect, the operating states of DFIGs are different; the control scheme should also ensure the safe operation of all DFIGs during frequency support. Therefore, DFIGs should be coordinated to participate in system frequency support. Coordinated control means that suited DFIGs are given more responsibility. However, the number of control variables is large in large-scale WECS, so the solution of coordinated control will be time-consuming and the results may not be satisfactory.

In order to accomplish these objectives, this paper proposes a two-layer frequency support scheme, which is conceptually represented in Figure 3. The proposed scheme clusters all DFIGs into groups at first. DFIGs in the same group are assigned the same control signals. Consequently,
the number of variables and the complexity of communication are significantly reduced. The top-level controller (T-controller) considers various factors and calculates WECS-level power increment reference. Under the premise of safe operation of each DFIG, the bottom-level controller (B-controller) coordinates all DFIGs to realize the power increment reference.

**B. WECS CLUSTERING GROUPING**

In the control process, the results of WECS grouping will be calculated first and will be continuously updated according to wind speed and other information. The most critical feature of WECS grouping is the wind speed. Because the Jensen model assumes that DFIGs in WECS are regular layout, the wind direction, the distance, and the working states of the upstream DFIGs all affect the downstream DFIGs. Due to the working states of DFIGs are controllable [26], the geographical information of DFIGs is selected as the clustering index in this paper.

The applied grouping method clusters DFIGs into groups according to the clustering index, and ensures that there is no wake effect between each DFIG in the same group. Therefore, DFIGs in the same group have similar wind speeds so that every group can be replaced by an equivalent DFIG model. The combination of all groups can approximately represent the output power of the whole WECS. The details of the applied grouping method are demonstrated as follows:

(1) Divide WECS into several areas, i.e., area \( I \), area \( 2 \), \( \ldots \), area \( n \). The principle of area division is that there is no mutual shadowed of DFIGs in the same area. First, the DFIG in area \( I \) is not shadowed by other DFIGs. DFIGs in the area \( n \) are shadowed by the DFIGs in all previous areas.

(2) DFIGs in \( n \) areas are divided into several groups in order. First, cluster all DFIGs in area \( I \) into group \( I \), and the wind speed of group \( I \) is the base wind speed \( V_{\text{base}} \). The DFIGs in area \( 2 \) are only affected by area \( I \), and the thrust coefficients \( C_{T,\text{group1}} \) of DFIGs in area \( I \) are same. So, the wind speed of DFIGs in area \( 2 \) is described as:

\[
V_{j,\text{Zone2}} = V_{\text{base}}[1 - (1 - \sqrt{1 - C_{T,\text{group1}}}) \phi(1, j)]
\]

(10)

\[
\phi(m, j) = \sum_{i = \text{group } m} \frac{A_i S_i}{A_0} \phi_i
\]

(11)

In area \( 2 \), \( \phi(1, j) \) is the only variable that causes differences in the wind speed of DFIGs. Therefore, \( \phi(1, j) \) is selected as the feature vector for DFIGs clustering in area \( 2 \). Therefore, the DFIGs in area \( 2 \) are reasonably divided into several groups, and the DFIGs in the same group have similar wind speeds. In this paper, the machine learning method \( k\text{-means} \) implements clustering [27].

(3) Suppose area \( I \) to area \( k - 1 \) has been clustered into group \( (k) \) groups. For area \( k (k > 2) \), the wind speeds of DFIGs are:

\[
V_{j, \text{Zone} k} = V_{\text{base}}[1 - \sum_{m = 1}^{\text{group}(k)} [(1 - \sqrt{1 - C_{T,\text{groupm}}}) \cdot \phi(m, j)]
\]

(12)

Since the DFIGs of area \( k \) are affected by wake effects from area \( I \) to area \( k - 1 \), clustering in area \( k \) needs to consider more complex feature vectors. In this paper, the applied feature vectors are:

\[
[\phi(1, j), \phi(2, j), \ldots, \phi(m, j)]_{\text{group}(k) \times 1}
\]

(13)

where \( \phi(m, j) \) only determined by the geographical location and wind direction.

Finally, all DFIGs with the same wind conditions in WECS are clustered into the same group. DFIGs in a same group have the same wind speed and receive the same control signals, which significantly simplify the control scale of WECS.

**C. DESIGNING OF T-CONTROLLER**

In a steady-state power system, the system frequency is closely related to the output power of the system. Once the system is disturbed, the dynamic balance will be broken. This dynamic model can be described as [28]:

\[
2H_{\text{sys}} \frac{d\Delta f}{dt} + D\Delta f = P_g + P_{\text{WECS}} - P_l
\]

(14)

\[
H_{\text{sys}} = \sum_{i = 1}^{n} (J_i \omega_{m,i}^2/2)/S_{\text{sys}}
\]

(15)

where \( \Delta f \) is the deviation of frequency, with Hz as the unit. The unit of \( P_g, P_{\text{WECS}} \) and \( P_l \) are MW; \( n \) is the number of conventional generators.

From (14), we can actively increase the output power of WECS to achieve frequency support. Therefore, the T-controller based on equation (14-15) proposes an adaptive virtual inertial control scheme, which calculates the power increment reference for the WECS. In this scheme, not only the ROCOF is considered in the gain, but also the cyber uncertainty. The proposed adaptive scheme can be expressed...
where \( \Delta f_k \) is the frequency difference between two adjacent time steps, which is used to describe the ROCOF in CPPS; \( k \) denotes the \( k \)-th time step. The units of \( \Delta P_{WECS} \), \( \Delta f \), \( \Delta f_k \) and \( \tau \) are MW, Hz, Hz and s, respectively. \( \Delta P_{WECS,\text{max}} \) is determined by wind speed.

The proposed scheme considers the cyber uncertainty of CPPS and uses the equivalent network delay \( \tau \) to quantify the system uncertainty. This is because within a certain range, the equivalent delay can be used to quantify the time delay and packet loss [24]. Because this paper adopts a clustering method based on a wake model in advance to control the DFIGs in WECS, the number of communication signals in WECS is greatly reduced. Considering that the signal transmission from the sensor to the controller in CPPS is much more complicated than the process from the controller to its actuator, and the clustering method is used to control the WECS in groups, which greatly reduces the number of communication signals. Therefore, this paper mainly considers the cyber uncertainty of the forward channel. For the calculation of \( \tau \), this paper uses timestamp technology based on TrueTime Toolbox [29]. First, record the corresponding time while the sensor sampling the frequency and then send the frequency signal and its corresponding timestamp to the controller of each WECS. Finally, the controller calculates \( \tau \) by comparing the current time with the received timestamp signal.

Equations (16) shows that \( \Delta P_{WECS} \) depends on the gain coefficients \( K_1 \) and \( K_2 \), which adaptively changes based on \( \Delta f_k \) and \( \tau \). At the beginning of the frequency event, \( \Delta f_k \) has a large value, so \( K_1 \) has a large value. Subsequently, as WECS supports the system frequency, the gain \( K_1 \) will gradually decrease. Obviously, if there is cyber uncertainty during the frequency support process, \( K_1 \) and \( K_2 \) will also change accordingly, and the greater the cyber uncertainty, the greater the coefficients. This shows that the proposed scheme can make up for the cyber uncertainty in the communication network.

### D. DESIGNING OF B-CONTROLLER

In the frequency event, DFIGs release the kinetic energy of the rotor to increase the output power with short-term. However, excessive release may cause the output power of DFIG to drop sharply or even stop [28]. Therefore, it is necessary to reasonably allocate \( \Delta P_{WECS} \) based on the wind speed and rotor speed of each group.

On the basis of clustering, B-controller assigns \( \Delta P_{WECS} \) according to the wind speed of each group, which can be achieved by minimizing the objective function:

\[
\min \ J = \alpha \sum_{m=1}^{n} (R_m - \Delta P_{e,m})^2 + (1 - \alpha)\delta^2 \tag{19}
\]

\[
R_m = \Delta P_{WECS} \cdot V_{wind,m}^3 / \sum_{m=1}^{n} V_{wind,m}^3 \tag{20}
\]

where \( n \) is the total number of groups after clustering. \( \Delta P_{e,m} \) is the power increment of the \( m \)-th group. The relaxation coefficient \( \delta \) is introduced to soften the constraints to cope with the problem that \( \sum_{m=1}^{N} \Delta P_{e,m} \) cannot be perfectly matched with \( \Delta P_{WECS} \) due to the case of low wind speed.

In addition, DFIG operates in deloading mode in B-controller [30]. Deloading control indicates that DFIG runs at a specific operating condition at steady states, in which its output power is lower than the maximum available power. This condition provides a power margin for frequency support. As shown in Figure 4, the deloading control changes the rotor speed or pitch angle so that DFIG operates in the area on the right side of the MPPT characteristic curve (red solid line). Moreover, the rotor speed is higher at lower-middle wind speeds, and DFIGs have more kinetic energy that can be utilized. The output power of DFIG in deloading control can be described as:

\[
P_{de} = (1 - d\%) P_{MPPT} \tag{21}
\]

![FIGURE 4. Turbine power characteristics (pitch angle beta = 0).](image)

Below the rated wind speed, the output power is reduced by increasing the rotor speed, while above the rated wind speed; the power is controlled by the pitch angle. From the perspective of WECS economic, the degree of deloading should be limited to a small value.

In the rotor-side controller of DFIG, \( \Delta P_{e,m} \) and \( P_{de} \) are added to obtain the reference power \( P_{ref,m} \) of each group:

\[
P_{ref,m} = P_{de} + \Delta P_{e,m} \tag{22}
\]

However, while pursuing \( P_{ref,m} \), it is necessary to ensure the steady-state operation of DFIG. The corresponding constraints should be added to the solution of \( \Delta P_{e,m} \). The constraints are as follows:

1) Regardless of the value of \( P_{ref,m} \), \( \omega_r,m \) should always be in a stable range:

\[
\omega_r,m \geq \omega_{min} \tag{23}
\]
2): The power output of a DFIG is not higher than the maximum power value $P_{\text{max}}$:

$$P_{e_{\text{ref},m}} \leq P_{\text{max}} \quad (24)$$

3): The pitch angle is kept within the set range.

In general, the proposed scheme can not only quickly calculate the optimal $\Delta P_{\text{WECs}}$ based on $\Delta f_{\text{h}}, \Delta f$ and the network equivalent delay $\tau$ in the initial frequency event. The existence of B-Controller also ensures that each group of DFIGs can adaptively participate in system frequency support under the premise of stability, and maximize the utilization efficiency of WECS. By doing so, both objectives of optimal frequency response and DFIG stability are expected to be achieved.

IV. CASE STUDIES

A. SIMULATION SETUP

To assess the performance of the proposed scheme, case studies are carried out in MATLAB/Simulink. A simulation system consisting of a classic four-machine two-area power system and a regular WECS was established. The configuration of the simulation system is shown in Figure 5. The system parameters of traditional generators and transmission lines can be found in [31], and traditional power plants G1~G4 are equipped with power system stabilizers. L1 and L2 are load sides of the power system. This paper assumes that a frequency event occurs when the frequency deviation $|\Delta f|$ exceeds 0.02 Hz.

In this paper, in order to verify the superiority of the proposed scheme, MPPT control and common virtual inertial control scheme are selected as the benchmark scheme. The common virtual inertial control (C-VIC) scheme is based on frequency deviation $\Delta f$ and ROCOF multiplied by a proportional coefficient [32]. In this paper, ROCOF is replaced by $\Delta f_{\text{h}}$.

The WECS, which consists of 5 rows of DFIGs and each row has 8 DFIGs is used to validate the proposed method. The parameters of WECS and DFIG are shown in Table 1. The communication part of CPPS is realized based on TrueTime Toolbox. The parameters of the communication network are shown in Table 2. As described in [33], there is generally a certain inherent response delay, when measuring frequency using a phase-locked loop, so the sampling interval of the sensor is set to 0.09 s.

### TABLE 1. WECS and DFIG parameters.

| Variable                      | Quantity | unit |
|-------------------------------|----------|------|
| Distance                      | 630      | m    |
| Turbine radius                | 63       | m    |
| Deficit factor                | 0.075    |      |
| Rated active power            | 5        | MW   |
| Nominal stator voltage        | 0.69     | kV   |
| Number of pole pairs          | 3        |      |
| DC capacitor                  | 1.2      | kV   |
| Rated rotational speed        | 1.2      | pu   |
| Base, cut-in, and cut-out wind speeds | 12, 6, 20 | m/s  |
| Speed lower limit             | 0.7      | pu   |
| Speed upper limit             | 1.26     | pu   |
| Pitch upper limit             | 45       | deg. |
| $d\%$                         | 5%       |      |

### TABLE 2. Parameters of the communication network.

| Variable                  | Quantity | unit |
|---------------------------|----------|------|
| Sampling time             | 0.09     | s    |
| Network Type              | Ethernet |      |
| Package Size              | 80       | bits |
| Transmission Rate         | 80000    | bit/s|

B. RESULTS OF WECS GROUPING

1): case 1: This section explores the results of WECS clustering in different wind directions. In this case, the base wind speed $V_{\text{base}}$ is set to 12m/s. Since DFIGs in WECS are regularly distributed, the number of groups is set to 5 groups, which is the same as the number of rows in WECS. The results of WECS clustering under different wind directions (0°, 15°, 32°, and 315°) are shown in Table 3.

### TABLE 3. Results of WECS clustering with different wind directions.

| Grouping Results | 0° | 15° | 32° | 315° |
|-----------------|----|-----|-----|------|
|                 |    |     |     |      |
| Group 1         | 1-8 | 1-16 | 1-16 | 1-9   |
| Group 2         | 9-16| 18-24| 18-24| 10-16 |
| Group 3         | 17-24| 26-32| 26-32| 19-24 |
| Group 4         | 25-32| 34   | 34   | 28-32 |
| Group 5         | 33-40| 36-40| 36-40| 37-40 |

After clustering, the DFIGs in the same group have similar wind profiles and same wind conditions. Actually, how many groups will the clustering algorithm obtain depends on the clustering indices.
C. IMPACT OF CYBER UNCERTAINTY ON CONTROL SCHEME

This section uses C-VIC as the basic control scheme to analyze the specific impact of cyber uncertainty on the frequency support scheme. In order to highlight the cyber uncertainty, the wind speed of all groups is set to 10 m/s. The frequency event is simulated by L1 by increasing the power consumption 110 MW at 30s. The comparison between the frequency signal received by the controller and the actual frequency of the power grid is given in Fig 6. As can be seen from Fig. 6, the existence of cyber uncertainties such as time delay and packet loss makes the frequency signals received by the controller have hysteresis and incompleteness.

FIGURE 6. The Comparison of real and received frequency signal.

1): case 2: Only the packet loss is considered and the packet loss rate is 0, 0.1, 0.2, and 0.3, respectively, and no other types of cyber uncertainty are involved. The results of C-VIC with different packet loss rates are shown in Fig 7. Due to the increase in packet loss rate, more and more data packets are lost in the communication network, and the controller can’t get correct feedback in time, which will cause a decrease in FN within a certain range.

FIGURE 7. The Control performance of case 1 with different package dropout rate.

2): case 3: This case also doesn’t involve other cyber uncertainties, only the network time delay is considered and it is assumed to be 0 s, 0.18 s and 0.36 s in extreme cases, respectively. The control performances of C-VIC in case 3 are shown in Fig 8. As seen from Fig 8, as the network time delay increases from 0 s to 0.36 s, the signal received by the controller becomes more and more lagging and the FN will continue to decrease from 59.697Hz to 59.678Hz.

Case 2 and case 3 show that different types of cyber uncertainties have different degrees of impact on the frequency support scheme. In addition, it can be seen from case 2 that the impact of packet loss is similar to the impact of network time delay on the control performance. Therefore, it is feasible to use the equivalent time delay $\tau$ to measure the cyber uncertainty in the communication network as mentioned. In summary, cyber uncertainties such as packet loss and the network time delay will have a bad influence on the control performance of the frequency support scheme, and the network time delay occupies a dominant position.

D. PERFORMANCE OF THE PROPOSED SCHEME

In order to evaluate the control performance of the proposed frequency support scheme in frequency events, this section simulates the cases of WECS responding to frequency events under different operating conditions. For this reason, the load L1 increases the active power consumption 100MW at 20s to simulate a frequency event. If WECS does not participate in the frequency support of the system, this under-frequency event will cause the FN of the grid frequency to drop to nearly 49.625 Hz.

1) CASE 4 MIDDLE-HIGH WIND SPEED WITH CYBER UNCERTAINTY

In this case, the network equivalent delay is set to 0.36s to simulate the cyber uncertainty under extreme conditions. The base wind speed $V_{base}$ is 12m/s and the wind direction is 0°, after the applied clustering scheme, the downstream wind speeds experienced by the representative Group 2, Group 3, Group 4 and Group 5 can be computed according to the wake model. That is, 10.53, 10.4, 10.25 and 10.18 m/s, respectively, i.e., below the $V_{base}$. The control results for this case are shown in Fig. 9.

In Fig. 9(a), The FN of MPPT, C-VIC and the proposed scheme are 59.624 Hz at 22.9 s, 59.697 Hz at 22.8 s, and 59.753 Hz at 22.7 s, respectively. As can be seen from Fig. 9(b), the response of C-VIC with cyber uncertainty is slower than that without it, resulting in WECS’s power increment becomes less, and FN decreases from 59.710 Hz to 59.696 Hz. However, even with cyber uncertainty, the
proposed scheme not only effectively improves FN, but also has a small frequency deviation after stabilization. There are three reasons why the proposed scheme has robust control performance: (1) In the T-controller, a compensation link is set for the cyber uncertainty, so that regardless of whether the cyber uncertainty exists, WECS can always respond quickly to frequency changes, and the larger the network equivalent delay, the larger the coefficient of the compensation link. (2) In B-controller, based on clustering grouping, DFIGs of different groups get different control signals, so that the groups with high wind speed assume more responsibility. (3) DFIG initially operates in deloading mode. As shown in Fig 9(c)-(d)-(f), the increase in rotor speed gives DFIG more kinetic energy for system frequency support. In addition, after the speed recovery phase of the proposed scheme, the rotor speed and active power output of DFIG will not drop much, so it has the ability to cope with the next frequency event.

2) CASE 5 LOW-MIDDLE WIND SPEED WITHOUT CYBER UNCERTAINTY
This case is set for the problem of the rotor speed of DFIG at low-medium wind speeds. When the DFIG rotor speed is low, excessive deceleration of the rotor may occur during frequency event. In this situation, the output power of DFIG will change drastically and even make DFIG unstable. In case 5, the base wind speed $V_{base}$ is set to 10 m/s and the wind direction is $0^\circ$. After clustering grouping, the downstream wind speeds experienced by the representative Group 2, Group 3, Group 4 and Group 5 are 8.82, 8.68, 8.60 and 8.51 m/s, respectively. The existence of cyber uncertainty is not considered, and the corresponding control results are given in Fig 10.

It can be clearly seen from Fig. 10(a) that the C-VIC (blue solid line) has a second frequency drop, and the two FNs are 59.686 Hz and 59.732 Hz, respectively. This is because Group 2, Group 3, Group 4 and Group 5 under the C-VIC scheme over-utilize the kinetic energy in the rotor. As shown in Fig. 10(d)-(f), the initial speed of the four groups is low and reaches 0.7 pu in turn after participating in system frequency support. This caused the power increment of WECS to fall four times to a negative value in a short time (Fig. 10(b)). However, the proposed scheme not only didn’t have a second frequency drop, but also maintained a well frequency support effect (59.724 Hz). This is mainly because in the B-controller, the controller distributes the control signals reasonably according to the wind speed of each group. Therefore, the proposed scheme not only can reasonably achieve the power increment index delivered by the T-controller, but also ensure the stable operation of the DFIGs within each group. Fig. 10(c)-(e) also verifies that WECS under the proposed scheme achieves the aim of more output from capable DFIG and less output from DFIG with low wind speed.

Obviously, regardless of case 4 or case 5, the proposed frequency support scheme has the best control effect. In addition, the proposed scheme considers the possible existence of cyber uncertainty and sets up corresponding compensation link, so that WECS can always participate in the system
frequency support well. Therefore, this scheme has a high practical application potential.

V. CONCLUSION

Frequency support scheme of large scale WECS considers wake effect and cyber uncertainty is studied in this paper. A clustering based grouping method is applied to coordinate all the DFIGs so that the WECS could optimally work at the ideal operating state. By clustering the WECS into groups, numbers of variables to be optimized are significantly reduced.

Cyber uncertainty has a negative impact on WECS participating in power system frequency support. This paper proposes a grouping-based frequency support scheme for WECS. The proposed frequency support scheme combines the deloading control and adaptive virtual inertial control. T-controller can enable each WECS to quickly respond to the system frequency change in the frequency event, entirely consider the cyber uncertainty, and determine the power increment of each WECS. B-controller ensures the stable operation of DFIGs in each group and as far as possible to achieve $\Delta P_{WECS}$. The obtained simulation results show that the proposed scheme can effectively improve the control performance of WECS for frequency support under various wind speeds. The main advantage of the proposed scheme is hierarchical control, which converts the frequency support control of WECS into two subsystem problems, so that both objectives of optimal frequency response and DFIG stability are expected to be achieved.

REFERENCES

[1] H. Wang, Z. Lei, X. Zhang, B. Zhou, and J. Peng, “A review of deep learning for renewable energy forecasting,” Energy Convers. Manage., vol. 198, Oct. 2019, Art. no. 111799.
H. Wang, Y. Liu, B. Zhou, C. Li, G. Cao, N. Voropai, and E. Barakthenko, “Taxonomy research of artificial intelligence for deterministic solar power forecasting,” *Energy Convers. Manage.*, vol. 214, Apr. 2020, Art. no. 112909.

F. R. Badal, P. Das, S. K. Sarker, and S. K. Das, “A survey on control issues in renewable energy integration and microgrid,” *Protection Control Mod. Power Syst.*, vol. 4, no. 1, pp. 87–113, Dec. 2019.

H. Z. Wang, G. B. Wang, G. Q. Li, J. C. Peng, and Y. T. Liu, “Deep belief network based deterministic and probabilistic wind speed forecasting approach,” *Appl. Energy*, vol. 182, pp. 80–93, Nov. 2016.

D. Xu, Q. Wu, B. Zhou, C. Li, L. Bai, and S. Huang, “Distributed multi-energy operation of coupled electricity, heating and natural gas networks,” *IEEE Trans. Sustain. Energy*, early access, Dec. 23, 2019, doi: 10.1109/TSTE.2019.2961432.

P. Li, W. Hu, R. Hu, Q. Huang, J. Yao, and Z. Chen, “Strategy for wind power plant contribution to frequency control under variable wind speed,” *Renew. Energy*, vol. 130, pp. 1226–1236, Jan. 2019.

S. G. Varzaneh, M. Abedi, and G. B. Gharehpetian, “A new simplified model for assessment of power variation of DFIG-based wind farm participating in frequency control system,” *Elect. Power Syst. Res.*, vol. 148, pp. 220–229, Jul. 2017.

M. Toulabi, S. Bahrami, and A. M. Ranjbar, “An input-to-state stability approach to inertial frequency response analysis of doubly-fed induction generator-based wind turbines,” *IEEE Trans. Energy Convers.*, vol. 32, no. 4, pp. 1418–1431, Dec. 2017.

C. Pradhan, C. N. Bhende, and A. K. Samanta, “Adaptive virtual inertia-based frequency regulation in wind power systems,” *Renew. Energy*, vol. 115, pp. 558–574, Jul. 2018.

M. El Mokadem, V. Courtecuisse, C. Saudemont, B. Robyns, and I. Deuse, “Fuzzy logic supervisor-based primary frequency control experiments of a variable-Speed wind generator,” *IEEE Trans. Power Syst.*, vol. 24, no. 1, pp. 407–417, Jan. 2009.

Z. Wang and W. Wu, “Coordinated control method for DFIG-based wind farm to provide primary frequency regulation service,” *IEEE Trans. Power Syst.*, vol. 33, no. 3, pp. 2644–2659, May 2018.

R. G. de Almeida and J. A. Pecas Lopes, “Participation of doubly fed induction wind generators in system frequency regulation,” *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 944–950, Aug. 2007.

Y. Fu, X. Zhang, Y. Hei, and H. Wang, “Active participation of variable speed wind turbine in inertial and primary frequency regulations,” *Electr. Power Syst. Res.*, vol. 147, pp. 174–184, Jun. 2017.

K. V. Vidyamantid and N. Senroy, “Primary frequency regulation by delayed wind inertial response using variable droop,” *IEEE Trans. Power Syst.*, vol. 28, no. 2, pp. 837–846, May 2013.

J. MacDowell, S. Dutta, M. Richwine, S. Achilles, and N. Miller, “Serving the future: Advanced wind generation technology supports ancillary services,” *IEEE Power Energy Mag.*, vol. 13, no. 6, pp. 22–30, Nov./Dec. 2015.

Y. Li, L. He, F. Liu, Y. Tan, Y. Cao, L. Luo, and M. Shahidehpour, “A dynamic coordinated control strategy of WTG-ES combined system for short-term frequency support,” *Renew. Energy*, vol. 119, pp. 1–11, Apr. 2018.

M. Hajiakbari Fini and M. E. Hamedani Golshan, “Determining optimal virtual inertia and frequency control parameters to preserve the frequency stability in islanded microgrids with high penetration of renewables,” *Electr. Power Syst. Res.*, vol. 154, pp. 13–22, Jan. 2018.

S. Kuenzel, L. P. Kunjumuhammed, B. C. Pal, and I. Erlich, “Impact of variable-speed wind farm inertial response,” *IEEE Trans. Sustain. Energy*, vol. 5, no. 1, pp. 237–245, Jan. 2014.

A. S. Ahmadzad and G. Verbic, “Exploring wake interaction for frequency control in wind farms,” in *Proc. 13th Wind Integ. Workshop*, Berlin, Germany, 2016, pp. 551–557.

S. Ghosh, S. Kamalasadan, N. Senroy, and J. Enslin, “Doubly fed induction generator (DFIG)-based wind farm control framework for primary frequency and inertial response applications,” *IEEE Trans. Power Syst.*, vol. 31, no. 3, pp. 1861–1871, May 2016.

H. Wang, J. Ruan, B. Zhou, C. Li, Q. Wu, M. Q. Raza, and G.-Z. Cao, “Dynamic data injection attack detection of cyber physical power systems with uncertainties,” *IEEE Trans. Ind. Informat.*, vol. 15, no. 10, pp. 5505–5518, Oct. 2019.

M. Cui, J. Wang, and M. Yue, “Machine learning-based anomaly detection for load forecasting under cyberattacks,” *IEEE Trans. Smart Grid*, vol. 10, no. 5, pp. 5724–5734, Sep. 2019.

R. Javed, G. Mustafa, A. Q. Khan, and M. Abid, “Networked control of a power system: A non-uniform sampling approach,” *Electr. Power Syst. Res.*, vol. 161, pp. 224–235, Aug. 2018.

J. Duan, H. Xu, and W. Liu, “Q-learning-based damping control of wide-area power systems under cyber uncertainties,” *IEEE Trans. Smart Grid*, vol. 9, no. 6, pp. 6408–6418, Nov. 2018.

A. B. Attya and T. Hartkopf, “Wind farms dispatching to manage the activation of frequency support algorithms embedded in connected wind turbines,” *Int. J. Electr. Power Energy Syst.*, vol. 53, pp. 923–936, Dec. 2013.

T. S. L. V. Ayyarao, “Modified vector controlled DFIG wind energy system based on barrier function adaptive sliding mode control,” *Protection Control Mod. Power Syst.*, vol. 4, no. 1, pp. 34–41, Dec. 2019.

F. Vallez, G. Brunieu, M. Pirlot, O. Dobelecker, and J. Lobry, “Optimal wind clustering methodology for adequacy evaluation in system generation studies using nonsequential Monte Carlo simulation,” *IEEE Trans. Power Syst.*, vol. 26, no. 4, pp. 2173–2184, Nov. 2011.

G. Xu and L. Xu, “Improved use of WT kinetic energy for system frequency support,” *IET Renew. Power Gener.*, vol. 11, no. 8, pp. 1094–1100, Jun. 2017.

A. Cervin, D. Henriksen, and M. Ohlin, “TRUETIME 2.0—Reference manual,” Lund Univ., Lund, Sweden, Tech. Rep., 2016.

Y. Fu, Y. Wang, and X. Zhang, “Integrated wind turbine controller with virtual inertia and primary frequency responses for grid dynamic frequency support,” *IET Renew. Power Gener.*, vol. 11, no. 8, pp. 1129–1137, Jun. 2017.

P. Kundur, *Power System Stability and Control*. New York, NY, USA: McGraw-Hill, 1993.

H. Karimi, M. Karimi-Ghartemani, and M. R. Iravani, “Estimation of frequency and its rate of change for applications in power systems,” *IEEE Trans. Power Del.*, vol. 19, no. 2, pp. 472–480, Apr. 2004.

G. Xu, F. Liu, J. Hu, and T. Bi, “Coordination of wind turbines and synchronous generators for system frequency control,” *Renew. Energy*, vol. 129, pp. 225–236, Dec. 2018.

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