Leader-Following Diffusion-Based Reactive Power Coordination and Voltage Control of Offshore Wind Farm

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ABSTRACT This paper proposed a distributed reactive power coordination and voltage control of offshore wind farm based on the leader-following diffusion algorithm. Designating several wind turbine generators (WTGs) as the leaders to receive the information of voltage at point of common coupling (PCC), the reactive power generations required to minimize the voltage deviation could be computed by these leaders. The required reactive power generations are diffused throughout all WTGs by the diffusion algorithm, resulting in the coordinated operation of WTGs to regulate the PCC voltage. The proposed offshore wind farm controller is based on the hierarchical control strategy, which consists of primary and secondary layers. The primary layer is responsible for the inner current, voltage or power regulations whereas the secondary layer is based on the proposed diffusion algorithm to achieve the coordinated operation among WTGs. The proposed strategy could maintain accurate reactive power sharing among WTGs and regulate the PCC voltage. A comparison study with the conventional consensus-based control is presented to show the effectiveness of the proposed diffusion controller. The comparison results show the better performance of the proposed method in terms of dynamic responses of PCC voltage and reactive power coordination. Simulation scenarios of constant wind speed, variable wind speed, and voltage sag in the utility grid are carried out to evaluate the performance of proposed method. The proposed diffusion control is tested either in a small or large offshore wind farm systems. Effect of communication delay on the performance of proposed diffusion control is also described. An experiment of the small-scale wind farm system is conducted to show the feasibility of proposed diffusion strategy.

INDEX TERMS Distributed control, diffusion algorithm, voltage control, wind farm control.

I. INTRODUCTION

The offshore wind energy has been becoming prominent due to the restriction of the land availability for onshore installation [1], [2]. The wind powers are transferred to the utility grid by the high voltage direct current (HVDC) or high voltage alternative current (HVAC) transmissions. The choice between HVAC and HVDC is based on the break-even distance that is determined by the technical and economic analysis. The capacity of the offshore wind farm has a significant impact on the break-even distance; for example, in [3], it is about 120 km to 160 km for the 1 GW wind farm.

The HVAC technology is still preferable for the transmission of bulk power in a short distance.

The uses of AC-based grid connection of offshore wind farm have introduced challenges to both offshore wind farm and system operations. The fluctuations in wind powers cause the variation of voltage at point of common coupling (PCC) and the disturbance of utility grid voltage directly affects to the operation of wind farm system. Since the capacity of offshore wind farm has grown rapidly, the offshore wind farm is required to participate in the reactive power compensation to improve the grid voltage. Typically, the passive devices such as SVCs or STATCOM were used to compensate for reactive power and reduce the voltage variation [4]–[6]. However, these solutions are costly due to the needs of
additional devices. Instead of using these passive devices, the coordinated reactive power control in wind farm could deal with the problem [7]. Most of the wind farm controllers were based on the centralized control strategies, in which a central controller gathers all information to decide the reactive power generations and controls the PCC voltage. The secondary voltage controls based on the PI regulator or V/Q-droop approach were proposed in [8]–[11] to counteract the changes of reactive power flow, resulting in the improvement of PCC voltage. In these methods, the control performance relies on the central PI regulator. Thus, the selection of the PI parameters, which is based on the linearized wind farm model, plays a vital role in the design of these central controllers. However, the characteristic of offshore wind farm system is nonlinearity due to the inclusion of power converters, which leads to the difficulty of designing PI parameters. Low-frequency oscillation of power and voltage could exist if the PI parameters were not properly chosen.

On the other hand, the central controllers could be developed by various optimization techniques. In [12], the optimal tracking secondary voltage control based on the voltage deviation identifier was proposed to improve the PCC voltage. The integer optimization problem was proposed in [13] to mitigate the voltage dip induced by frequency excursion. Recently, model predictive control (MPC) techniques were applied for the central controllers of wind farms [14]. Based on the state-space model of wind farm, the future dynamic behavior of voltage and reactive power were predicted. The control actions were found by solving the pre-defined cost functions. Nonlinear constraints or additional control variables could be involved in the cost function of the MPC techniques [15]. The proposed MPC strategy in [16] could minimize the voltage variations and fluctuation in reactive power output. In [17], the proposed MPC controller was used to optimize the reactive power distribution in order to maximize the reactive power reserve. However, the main drawback of the MPC-based or optimization-based central control strategies is the computational burden in the central controller, especially in case the size of wind farm system significantly increases.

To avoid the computational burden in the central controller, the distributed control strategies based on the consensus algorithm were proposed [18]–[21]. The offshore wind farm system could be considered as a multiagent system, in which each wind turbine generator (WTG) is an agent. The dynamic average consensus algorithm is used to obtain the average of a set of initial values of all agents. By interchange the information of reactive power generations of all WTGs, the average value of reactive power generations could be achieved. Each WTG can regulate its reactive power generation following to the average value, resulting in the accurate reactive power sharing among WTGs [22], [23]. Voltage control layer could be added in addition to the reactive power control to restore the system voltage [24]–[26]. The distributed controls based on consensus algorithms were discussed extensively in the microgrid (MG) system [27]–[31]. However, these strategies for MG system focused on the regulation of voltage at each distributed generation instead of PCC voltage.

A few studies on the application of distributed control for the wind farm system was found. In [20], three strategies for PCC voltage regulation were discussed and an improved voltage control was proposed. However, a central voltage control was required in these approaches. The consensus-based distributed voltage controls of large-scale wind farm were proposed in [21], [32]. However, the distributed cooperation was only applied for sub-wind farm clusters whereas a central controller was used to manage the reactive powers of WTGs in each cluster.

This paper proposes a distributed control of offshore wind farm system based on the leader-following diffusion algorithm. Unlike existing distributed controllers of wind farm system, the proposed method could maintain the reactive power coordination and control the PCC voltage in fully distributed manner. By designating some WTGs as the leaders to receive the PCC voltage information, the leader WTGs are involved in minimizing the PCC voltage deviation by adjusting their reactive power generations. The following WTGs, which are the neighbors of the leader WTGs, receive the new information from the leaders and update their reactive power generations accordingly. Other following WTGs sequentially update their reactive power. Thus, the reactive power required to minimize the PCC voltage deviation is diffused throughout the offshore wind farm system. The PCC voltage could be regulated in fully distributed manner by using the proposed leader-following diffusion control strategy. Compared to the existing consensus or leader-based distributed strategies, the proposed leader-following diffusion strategy estimates the future value of each agent based on the present and past values. The convergence speed of the proposed strategy is outperformed by iteratively updating each agent value with the negative gradient at each step, which results in better performance of reactive power coordination and voltage regulation. A comparison study with the consensus-based control strategy is presented in this study to show the effectiveness of the proposed leader-following diffusion strategy.

Various simulation and experiment scenarios are carried out to validate the feasibility and effectiveness of the proposed diffusion control strategy. Firstly, a simple offshore wind farm system consisting one radial feeder with five WTGs is conducted to demonstrate the operation of proposed diffusion control method. A large-scale wind farm system with twenty WTGs dividing into four feeders is used to verify the scalability of the proposed control. Effects of communication topologies and communication delay are also discussed. An experiment of small wind farm is conducted to verify the feasibility of the proposed diffusion algorithm.

The rest of this paper is organized as follows. Section II presents the proposed hierarchical control of offshore wind farm system, including the leader-following diffusion control strategy. Simulation results are provided in Section III. The experiment of small-scale wind farm system is presented in
Section IV. Finally, the main conclusion is summarized in Section V.

II. DISTRIBUTED CONTROL OF OFFSHORE WIND FARM SYSTEM

The distributed control scheme of offshore wind farm shown in Fig. 1 consists of primary control (PC) and secondary control (SC) layers. PC layer utilizes local information of WTG such as voltage or current to regulate output power and ensure the stability of WTG. SC layer is responsible for the power quality improvement such as accurate reactive power sharing and PCC voltage improvement. Communication network is employed in the SC layer to interchange information among WTGs. For example, at time instant $t$, WTG$_i$ broadcasts local information ($x_i,t$) and receives information from its neighbors ($x_{j,i},t$) through the communication network. Based on the local and received information, set-point signals ($x_i,s$) for the local control (LC) layer are computed by the proposed leader-following diffusion algorithm.

The control diagram of WTG$_i$ is shown in Figs. 2. The WTG is controlled by a back-to-back (BTB) converter that includes of a machine-side converter (MSC) and a grid-side converter (GSC). The BTB controller consists of PC and SC layers. There are two control loops in the PC layer, which are the inner current control loop and the outer power or voltage control loop. The current control loop, which is based on dq-decoupling control strategy, is used in both MSC and GSC. The maximum power point tracking (MPPT) scheme is used in the MSC to capture maximally wind power, whereas the controls of the dc-link voltage of the BTB converter and the reactive power generation are applied to the GSC. The conventional proportional-integral (PI) regulators are used in the PC layer.

A. PRIMARY CONTROL OF WTG

Output power of WTG based on permanent magnet synchronous generator (PMSG) is controlled by MSC that consists of the current and power control loops. Dynamic model of PMSG in dq-reference frame is shown in (1) and (2).

$$L_{di} \frac{di_{mdi}}{dt} = v_{mdi} - w_{ri}L_{qi}i_{mqi} - R_{mi}i_{mdi}$$  \hspace{1cm} (1)

$$L_{qi} \frac{di_{mqi}}{dt} = v_{mqi} - w_{ri}L_{di}i_{mdi} - w_{ri}\lambda_{PM}$$  \hspace{1cm} (2)

where $i$ denotes the WTG$_i$; $L_{di}$ and $L_{qi}$ are the dq-inductance of stator; $R_{mi}$ is the stator resistance; $\omega_{qi}$ is the angular frequency of PMSG; $i_{mdi}$ and $i_{mqi}$ are the dq-stator currents; $\lambda_{PM}$ is the magnet flux of PMSG; $v_{mdi}$ and $v_{mqi}$ are the stator voltages that are calculated by the modulation signals ($m_{mdi}$ and $m_{mqi}$) given by (3) and (4).

$$v_{mdi} = \frac{m_{mdi}v_{dci}}{2}$$ \hspace{1cm} (3)

$$v_{mqi} = \frac{m_{mqi}v_{dci}}{2}$$ \hspace{1cm} (4)

where $v_{dci}$ is the DC-link voltage of the BTB converter.

It could be seen that the dynamic coupling between dq stator currents in (1) and (2) exists. To decouple such dynamic of the dq stator currents, the modulation signals are chosen by (5) and (6).

$$m_{mdi} = \frac{2}{v_{dci}} \left( -w_{ri}L_{qi}i_{mqi} + k_{p}(i_{mdi} - i_{mdi}) + k_{i} \int (i_{mdi} - i_{mdi}) dt \right)$$ \hspace{1cm} (5)

$$m_{mqi} = \frac{2}{v_{dci}} \left( w_{ri}\lambda_{PM} + w_{ri}L_{di}i_{mqi} + k_{p}(i_{mqi} - i_{mqi}) + k_{i} \int (i_{mqi} - i_{mqi}) dt \right)$$ \hspace{1cm} (6)

where $k_{p}$ and $k_{i}$ are the PI gains; $i_{mqi}^{*}$ and $i_{mdi}^{*}$ are the reference currents that are given by the outer control loop.

Based on (5) and (6), the schematic diagram of the MSC current controller is shown in Fig. 3a. Current reference $i_{mqi}^{*}$ is provided by the maximum power point tracking (MPPT) controller whereas $i_{mdi}^{*}$ is set to zero.

Since the responsibility of the GSC is to regulate the DC link voltage $v_{dci}$ and output reactive power $Q_{di}$, the GSC is based on current-mode converter with output inductance $L_f$.
filter. Dynamic equation of GSC with $L_f$ filter is shown in (7) and (8).

$$L_f \frac{di_{gdi}}{dt} = w_{gi} L_f i_{gqi} + v_{gdi} - v_{gdi} \tag{7}$$

$$L_f \frac{di_{gqi}}{dt} = -w_{gi} L_f i_{gdi} + v_{gqi} - v_{gqi} \tag{8}$$

where $w_{gi}$ is the angular frequency of the AC grid; $v_{gdi}$ and $v_{gqi}$ are the $dq$ terminal converter voltages of GSC; $v_{gdi}$ and $v_{gqi}$ are the $dq$ output filter voltages; $i_{gdi}$ and $i_{gqi}$ are the output filter currents.

The modulation signals of GSC are given by (9) and (10), which consists of decoupling terms to improve the performance of the current controller.

$$m_{gdi} = \frac{2}{v_{di}} \left( v_{gqi} - w_{gi} L_f i_{gqi} + k_p (i_{gdi}^* - i_{gdi}) \right) + k_i \int (i_{gdi}^* - i_{gdi}) dt \tag{9}$$

$$m_{gqi} = \frac{2}{v_{qi}} \left( v_{gdi} + w_{gi} L_f i_{gdi} + k_p (i_{gqi}^* - i_{gqi}) \right) + k_i \int (i_{gqi}^* - i_{gqi}) dt \tag{10}$$

where $i_{gdi}^*$ and $i_{gqi}^*$ are the reference currents that are given by the outer DC-link voltage and reactive power control loops, as in (11) and (12).

$$i_{gdi}^* = k_p (v_{dc}^* - v_{dc}) + k_i \int (v_{dc}^* - v_{dc}) dt \tag{11}$$

$$i_{gqi}^* = k_p (Q_i^* - Q_i) + k_i \int (Q_i^* - Q_i) dt \tag{12}$$

where $v_{dc}^*$ is the dc voltage reference; $Q_i^*$ is the reactive power reference provided by the secondary diffusion control loop.

Based on (9) to (12), the schematic diagram of the GSC controller is shown in Fig. 3b.

**B. SECONDARY CONTROL BASED ON LEADER-FOLLOWING DIFFUSION ALGORITHM**

The offshore wind farm system consists of multiple feeders and wind powers are often collected to the PCC bus. The PCC voltage is controlled by adjusting total reactive power generation of offshore wind farm. The leader-following diffusion strategy is proposed to achieve the reactive power coordination and PCC voltage control of offshore wind farm system. Selecting WTGs that are near the PCC bus to receive the PCC voltage information, the leader WTGs are involved in deciding required reactive power to minimize the PCC voltage deviation. The leader WTGs adjust their reactive power generations when the PCC voltage deviates from its nominal value. The updated information of reactive power generations are sent to the following WTGs that are the neighbors of the leader WTGs. These following WTGs adjust their reactive power generations according to the distributed averaging rule. Other following agents sequentially update their reactive power generations. Therefore, required reactive power generation to minimize the PCC voltage deviation is diffused throughout the wind farm system. The proposed leader-following diffusion strategy utilizes the communication network to interchange the reactive power information among WTGs. The graph theory in the following section is used to represent the communication network of the wind farm system.

1) **GRAPH THEORY**

The communication network between WTGs can be represented as an undirected graph $G = (V, E)$, consisting of the set of nodes $V = \{1, 2, \ldots, n\}$ that represents the $n$ WTGs, and the set of edges $E \subseteq V^2$ representing communication links between these WTGs. The edge $E(i,j)$ in the edge set $E$ indicates that WTG $i$ communicates with WTG $j$. The adjacency matrix associated with the undirected graph $G$ is the $n \times n$ matrix $A = \{a_{ij}\}_{i,j=1,...,n} \in \mathbb{R}^{n\times n}$, and its element is defined in (13).

$$a_{ij} = \begin{cases} 1 & \text{if } E(i,j) \in E \\ 0 & \text{if } E(i,j) \notin E \text{ and } i = j \end{cases} \tag{13}$$

The Laplacian matrix $L = \{l_{ij}\}_{i,j=1,...,n} \in \mathbb{R}^{n\times n}$, which is a matrix representation of graph $G$, is given by (14).

$$l_{ij} = \begin{cases} \sum_{j=1,j\neq i}^{n} a_{ij} & \text{for } i = j \\ -a_{ij} & \text{for } i \neq j \end{cases} \tag{14}$$

2) **LEADER-FOLLOWING DIFFUSION STRATEGY**

The secondary control is responsible for the reactive power coordination and PCC voltage control of the offshore wind farm system. The sparse communication network represented by the graph theory is used to interchange information of
reactive power generations among WTGs. Each WTG maintains a table that stores its reactive power information and its neighbors’ information, initializing with its reactive power generation only. At each iteration, each WTG interchanges the table information with its neighbors according to the distributed linear iteration. After a number of iterations, the average value of reactive power generations could be found. The distributed averaging algorithm implemented in WTG$_i$ is given by (15),

$$Q_{i,k+1} = w_{ii}Q_{i,k} + \sum_{j \in V_i} w_{ij}Q_{j,k}$$

(15)

where $w_{ij}$ is the weight on WTG$_j$ at WTG$_i$ and $w_{ii}$ is the self-weight on WTG$_i$; $V_i$ is the set of neighbors of WTG$_i$.

The convergence of the distributed averaging algorithm is guaranteed by choosing proper weights $w_{ii}$ and $w_{ij}$. A simple approach is to set the all the edge weights $w_{ij}$ equal to a constant $\alpha$ while the self-weight $w_{ii}$ is selected to satisfy the condition (16),

$$w_{ii} = 1 - \alpha \sum_{j=1}^{n} w_{ij}$$

(16)

These weights could be represented by a matrix form $W = \{w_{ij}\}_{i,j=1,...,n} \in \mathbb{R}^{n \times n}$. The selection of these weights is based on the Laplacian matrix, as in (17),

$$W = I - \alpha L$$

(17)

where $I$ is the identity matrix of size $n$; $\alpha$ is a positive constant, which is chosen based on eigenvalues of the Laplacian matrix $L$ to ensure fast convergence speed [33], as in (18),

$$\alpha = \frac{2}{\lambda_1(L) + \lambda_{n-1}(L)}$$

(18)

where $\lambda_i(\cdot)$ represents the $i$th largest eigenvalue of $L$.

The distributed averaging algorithm in (15) could maintain accurate reactive power sharing among WTGs. In order to involve the reactive power coordination in the PCC voltage regulation, several WTGs are designated as the leader WTGs to compensate for the voltage fluctuation. By broadcasting the PCC voltage information to the leader WTGs, the reactive powers required to compensate for the voltage deviation are computed and diffused throughout all WTGs. The following WTGs sequentially adjust their reactive power generations when they detect the change of reactive powers of leader WTGs. Thus, the distributed reactive power coordination for the PCC voltage regulation is achieved. The iterative form of the leader-following algorithm is given by (19),

$$Q_{i,k+1} = w_{ii}Q_{i,k} + \sum_{j \in V_i} w_{ij}Q_{j,k} + b_i(V_{pcc,k} - v^*)$$

(19)

where $b_i$ equals 1 if WTG$_i$ is the leader and equals 0 otherwise, $V_{pcc,k}$ is the PCC voltage measured at time $k$; $v^*$ is the PCC voltage reference.

The aim of proposed approach in (19) is to assign the leader WTGs react firstly to the change of PCC voltage. Then, the following WTGs sequentially adjust their reactive power generations to reduce the burden in the leader WTGs. Thus, the distributed control with fast convergence speed brings a positive impact on the dynamic performance of the control system. In order to improve the convergence speed, the diffusion algorithm is employed, resulting in the form of leader-following diffusion algorithm given by (20). In the proposed leader-following diffusion algorithm, an additional table of reactive power deviations of all WTGs is used to improve the convergence speed of distributed control.

$$\begin{align*}
\phi_{i,k+1} &= w_{ii}Q_{i,k} + \sum_{j \in V_i} w_{ij}Q_{j,k} \\
&+ b_i(V_{pcc,k} - v^*) \\
Q_{i,k+1} &= \phi_{i,k+1} - \mu(\phi_{i,k+1} - \phi_{i,k})
\end{align*}$$

(20)

where $\phi_{i,k}$ is the intermediate variables of WTG$_i$ at time $k$; $\mu$ is the constant edge satisfying $0 < \mu < 1$.

Considering the reactive power constraints, the reference reactive power $Q^*_i$ for the PC loop is given by (21),

$$Q^*_{i,k+1} = \begin{cases} Q_{i,\min} & \text{if } Q_{i,k+1} \leq Q_{i,\min} \\ Q_{i,k+1} & \text{if } Q_{i,\min} < Q_{i,k+1} \leq Q_{i,\max} \\ Q_{i,\max} & \text{if } Q_{i,k+1} \geq Q_{i,\max} \end{cases}$$

(21)

Vector representation of the proposed diffusion algorithm (20) is shown in (22). It could be seen that if the coefficient $\mu$ in (22) is equal to zero, (22) becomes the conventional leader-following consensus algorithm. The leader-following diffusion algorithm is implemented in each WTG by the Algorithm II-B2.

$$\begin{align*}
\Phi_{k+1} &= W\Phi_k + B(V_{pcc,k} - v^*) \\
\Phi_{k+1} &= \Phi_{k+1} - \mu(\Phi_{k+1} - \Phi_k)
\end{align*}$$

(22)

where $\Phi_k = \{Q_{1,k}; Q_{2,k}; \ldots; Q_{n,k}\}$, $B = \{b_1; b_2; \ldots; b_n\}$, $\Phi_k = \{\phi_{1,k}; \phi_{2,k}; \ldots; \phi_{n,k}\}$.

III. SIMULATION RESULT

A. SIMPLE WIND FARM SYSTEM

The real-time simulation using OP5600 of OPAL-RT technologies is presented to evaluate the performance of proposed control strategy. A simple wind farm system shown in Fig. 4, which consists of one radial feeder with 5 WTGs. The WTGs are connected in series by 22.9 kV normal cable with a length of 2 km. Each WTG includes a permanent magnet synchronous generator (PMSG), a back-to-back converter and a step-up transformer. Detailed parameters of the WTGs are given in Table 1.

In the secondary layer, the communication network with line-connection topology is used, as shown in Fig. 4. The Laplacian matrix of the communication network is given by (23). Based on (18), the constant edge weight $\alpha$ is chosen by 0.5 to achieve fast convergence speed. Coefficient $\mu$ is chosen from experience by gradually increasing $\mu$ from
Algorithm 1 Proposed Diffusion Algorithm Implemented in WTG for PCC Voltage Control

Input: \( Q_{i,k} \); \( \forall Q_{j,k} \in V_i \); \( v_{pcc,k} \) if WTG \( i \) is the leader.

Output: \( Q_{i,k+1}^{o} \)

Initialization:
\[
Q_k = [0; 0; \ldots 0]_{n \times 1}; \quad \Phi_k = [0; 0; \ldots 0]_{n \times 1};
\]
\[
B = [0; 0; \ldots 0]_{n \times 1};
\]
\[
B(i) = 1 \text{ if WTG}_i \text{ is the leader;}
\]
calculate \( W; \)

1: for \( m = 1 \) to \( n \) do
2: \[ Q_k(m) = Q_{i,k}; \]
3: else if \( m = j \) then
4: \[ Q_k(m) = Q_{j,k}; \]
5: end if
6: end for
7: \[ \Phi_{k+1} = WQ_k + B(v_{pcc,k} - v^*); \]
8: \[ Q_{k+1} = \Phi_{k+1} - \mu(\Phi_{k+1} - \Phi_k); \]
9: if \( |Q_{k+1}(i)| \geq Q_{i,max} \) then
10: \[ Q_{i,k+1}^o = \text{sign}(Q_{k+1}(i)) \ast Q_{i,max}; \]
11: else
12: \[ Q_{i,k+1}^o = Q_{k+1}(i); \]
13: end if
14: Update table information:
15: \[ Q_k = Q_{k+1}; \quad \Phi_k = \Phi_{k+1}; \]
16: return \( Q_{i,k+1}^o \)
17: Wait for next sampling instant

TABLE 1. WTG parameters.

| Symbol | Parameter | Value |
|--------|-----------|-------|
| \( S \) | Nominal power | 10 MW |
| \( v \) | phase voltage of PMSG | 6.6 kV |
| \( TR \) | Step-up transformer | 6.6 kV / 22.9 kV |
| \( v_{DG} \) | Grid phase voltage | 22.9 kV |
| \( v_{DC} \) | DC-link voltage | 12 kV |
| \( C \) | DC capacitor | 2000 \( \mu F \) |
| \( f \) | Grid synchronous frequency | 60 Hz |
| \( \omega_x \) | Mean wind speed | 11.4 m/s |

0 to 1. In this case, coefficient \( \mu \) is chosen by 0.85.

\[
L = \begin{bmatrix}
1 & -1 & 0 & 0 & 0 \\
-1 & 2 & -1 & 0 & 0 \\
0 & -1 & 2 & -1 & 0 \\
0 & 0 & -1 & 2 & 0 \\
0 & 0 & 0 & -1 & 1
\end{bmatrix}
\] (23)

A comparison study with the consensus strategy is presented to show the effectiveness of the proposed controller. The convergence speed of two approaches is shown in Fig. 5, in which the WTG1 is considered as the leader. It is assumed that the initial reactive power outputs of five WTGs are 0.8, \(-0.25, 0.2, 1.5, \) and \(-0.5 \) MVAR. Suppose the reactive power output of the leader WTG1 is controlled at 1 MVAR. It could be seen that the reactive power outputs of all WTGs reach to the leader value of 1 MVAR. The diffusion reaches the same level of precision with a much smaller number of iterations compared to the consensus algorithm.

The effectiveness of the controller is evaluated by the mean square error (MSE) of the PCC voltage \( v_{pcc,k} \) and reactive power that are defined by (24) and (25).

\[
\text{MSE}(v_{pcc,k}) = (v_{pcc,k} - v^*)^2 
\] (24)

\[
\text{MSE}(Q_{i,k}) = \frac{1}{n} \sum_{i=1}^{n} \left( Q_{i,k} - \frac{1}{n} \sum_{i=1}^{n} v_{pcc,k} \right)^2 
\] (25)

where \( v_{pcc,k} \) is the measured PCC voltage at time \( k; \) \( v^* \) is the reference voltage; \( Q_{i,k} \) is the measured reactive power of WTG \( i \) at time \( k; \) \( n \) is the number of WTGs.

1) CONSTANT WIND SPEED

The constant wind speed of 8 m/s is used to test the performance of the proposed controller. The waveforms of terminal voltages of WTGs and output reactive powers are shown in Fig. 6. The proposed controller is activated at 12 s, leading to the reduction of the terminal voltages and the accurate reactive power sharing among WTGs. The PCC voltage under...
two distributed controllers is restored to 1 pu, as shown in Fig. 7. The comparison between the proposed diffusion strategy and consensus strategy clearly shows that the performance of the proposed diffusion controller is superior to the consensus-based controller. The MSEs of voltage and reactive power shown in Fig. 8 indicates the faster response of the proposed diffusion control compared to the consensus strategy.

2) VARIABLE WIND SPEED

The fluctuations in wind power shown in Fig. 9 cause the variation of PCC voltage. The proposed controller could reduce the variation of PCC voltage, as shown in Fig. 10. The proposed controller maintains accurate reactive power sharing among WTGs in the wind farm system and reduces the variation of PCC voltage. The output reactive powers of WTGs in cases of proposed diffusion and consensus controllers are shown in Figs. 10(c) and (d). Since the convergence speed of the diffusion strategy is much quicker than the consensus, the difference between output reactive powers of WTGs in the case of diffusion-based controller is smaller than the case of using consensus strategy. The PCC voltage response under two distributed controllers is shown in Fig. 11.
The MSEs of leader voltage and reactive powers shown in Fig. 12 indicates the better performance of the proposed diffusion-based controller.

3) UTILITY VOLTAGE SAG
The wind farm system could support the reactive power for the utility grid during voltage sag. The performance of the proposed controller during grid voltage sag is shown in Fig. 13. It is assumed that the grid voltage sag occurs during 10 s (from 40 s to 50 s). It can be seen that all WTGs are coordinated to restore the PCC voltage during disturbance. Since the WTG1 is designated as the leader, the response of WTG1 is fastest compared to other WTGs, as shown in Figs. 13 (c) and (d). The following WTGs adjust their reactive power generations sequentially to support for the leader WTG1. In case of the diffusion strategy, the voltage and output reactive power reaches the steady-state values after 3 s whereas it is 6 s in case of consensus-based controller. The use of proposed diffusion-based controller offers the fast convergence speed compared to the consensus-based controller, which leads to the fast response of PCC voltage during disturbance, as shown in Fig. 14. The MSEs of the PCC voltage and reactive power are shown in Fig. 15. It is observed that the response of the diffusion-based controller is quicker than the consensus strategy.

B. LARGE WIND FARM SYSTEM
An offshore wind farm system with 20 WTGs is used to evaluate the scalability of the proposed diffusion strategy.
The tested offshore wind farm system consists of four radial feeders, in which each feeder includes five WTGs. Four topologies of communication network shown in Fig. 16 are used to evaluate the performance of distributed control. It is assumed that the WTG10 and WTG15 are chosen as the leaders.

The reactive power generations is shown in Fig. 17 and the voltage response of WTGs under conventional consensus and proposed diffusion strategies is shown in Fig. 18. The PCC voltage is shown in Fig. 19. It is assumed that the communication network is ideal with delay time \( \tau \) equal to zero. Initially, the reactive power outputs of WTGs are equal and the PCC voltage is stable at 1 pu. The disturbance at 25 s causes voltage drop from 1 pu to 0.9 pu. All WTGs increase their reactive power to recover the PCC voltage. Two leader WTGs response quickly to the change of PCC voltage, resulting in the fastest response of reactive power outputs. The output reactive power of two leaders reach to their limits of 5 MVar in case the network communication is tree or ring. The convergence speed of the reactive powers in case of using tree or ring connection is slow, resulting in the slow recovering of the PCC voltage. It could be seen that the uses of cross or full connection performs better voltage response or convergence speed compared to the tree or ring connections.

The comparison results with the conventional consensus method show that the convergence speed of the proposed diffusion-based voltage controller is much faster than the conventional method. A comparison on the convergence time between two methods is shown in Table 2. It could be seen
that, in case of tree connection, the convergence time of diffusion control is 80% smaller than the consensus control (40.6 s compared to 208.1 s). The convergence speed has a significant impact on the dynamic performance of the wind farm system. When the convergence speed is slow, the leader WTGs experience very high reactive power supplies. When the convergence speed is improved, the reactive power required to reduce the PCC voltage variation would be shared quickly by other following WTGs, resulting in the improvement of voltage responses, as seen in Figs. 18 and 19.

It could be seen in Figs. 19 that the PCC voltage response with the proposed method under the tree connection is still faster than that of the conventional consensus method with full connection. The comparison between the proposed diffusion strategy and consensus strategy clearly shows that the performance of the proposed diffusion controller is superior to the consensus-based controller.

The communication delay, which could be caused by the processing, propagation, or malicious activity, is unavoidable in the communication network. The secondary distributed controller should be stable in case of worst communication delay. This section evaluates the effect of communication delay on the control performance of the proposed control strategy. The delay time $\tau$ of 300 ms, which could be considered as the worst case of communication delay [34], is used in this study. Responses of voltages and reactive powers under condition of communication delay are shown in Figs. 20, 21, and 22. The communication delay has a negative impact on the convergence speed of the distributed controllers. The convergence speed comparison between the consensus and proposed diffusion controller is shown in Table 2. It could be
seen that the proposed diffusion strategy still performs better performance compared to the consensus method.

C. DISCUSSION ON THE SELECTION OF LEADER WTG

The typical configuration of the offshore wind farm system is shown in Fig. 23, which consists of several radial feeders. Any WTG in the offshore wind farm system could be chosen as the leader in the proposed strategy. It is recommended that the WTGs near to the PCC bus should be designated as the leader to reduce the cost of the communication network. Fig. 23 shows the potential WTG to become the leader.

The reliability of the proposed control strategy is affected by the number of leaders. It could be seen that if only one WTG is designated as the leader, the wind farm system would be uncontrolled when the failure occurs in the communication link to the leader. The problem is addressed in the proposed strategy by choosing multiple leaders. Fig. 24 shows the performance of the proposed strategy for the offshore wind farm system with 20 WTGs, in which the ring communication topology in Fig. 16b is employed and two WTGs are chosen as the leaders. The voltage disturbance occurs at 25 s and the failure of one leader occurs at 30 s. It can be seen that the failure of one leader has a slight impact on the voltage response and reactive power control. The proposed strategy could improve the reliability of the wind farm system.

The number of leaders has an impact on the performance of the proposed controller. Fig. 25 shows the performance of PCC voltage restoration under different number of leaders. The increase in the number of leaders leads to the increase of PCC voltage response. It can be explained that the more WTGs are designated as the leaders, the quicker diffusion of reactive power generation required to compensate for the voltage disturbance. It is also observed that there is a slight difference in voltage response between the cases of three and four leaders. Thus, the number of leaders could be chosen by analyzing the performance of the PCC voltage response.

IV. EXPERIMENTAL VERIFICATION

Various experiments are conducted to verify the feasibility of the proposed diffusion control strategy. Due to the hardware limitation, a small-scale wind farm system with three WTGs is conducted, as shown in Fig. 26. The experimental setup includes a cable simulator, three back-to-back (BTB) converters that simulate three WTGs, and an OP4510 simulator that models the diffusion-based secondary control layer. The primary control layer is implemented in the digital signal processor (DSP) TMSF28335.

The BTB converter is based on the two-level three-phase voltage source converter (VSC). The controllers of two VSCs in the BTB converter are modified to simulate WTG, in which the VSC1 regulates the dc-link voltage and the VSC2 controls the output real and reactive powers of the BTB converter, as shown in Fig. 27. The real power reference $P_i^*$ is given to the VSC2 to model the output power of the WTG. The reactive power reference $Q_i^*$ is provided by the secondary control layer that is implemented in the OP4510.

The proposed diffusion control strategy is tested in the condition of constant output wind power. The experimental results in Fig. 28 show the waveforms of voltages and output reactive powers of three WTGs. Before 27 s, the reactive powers of three WTGs are uncontrolled, and the voltages are higher than the nominal values. The controller activates at 27 s, resulting in the decrease of output reactive powers to
regulate the PCC voltage, as shown in Fig. 29. The reactive powers are shared equally among three WTGs.

The MSE of the PCC voltage is illustrated in Fig. 30(a). The controller activates at 27 s, resulting in the reduction of the MSE of the PCC voltage. It can be seen that the MSE of the PCC voltage under the diffusion strategy is overall smaller than the consensus. The MSEs of the output reactive powers shown in Fig. 30(b) indicate the quicker response of the proposed diffusion strategy. Although both diffusion and consensus strategies could stably control the wind farm system, the responses of voltages and reactive powers under the proposed diffusion strategy are approximately twice as fast to the consensus-based controller.

The proposed controller is verified in the condition of the fluctuation in output wind powers. Fig. 31 shows the
FIGURE 31. Fluctuations in wind powers.

FIGURE 32. Waveforms of voltage and reactive power generations.

FIGURE 33. Waveform of PCC voltage.

FIGURE 34. MSE of PCC voltage and reactive power generations.

V. CONCLUSION

The leader-following diffusion control strategy of offshore wind farm system has been proposed to regulate PCC voltage and achieve accurate reactive power sharing among WTGs. The comparison study with the conventional consensus algorithm showed the superior performance of the proposed diffusion strategy. Various simulation scenarios and experiments showed the effectiveness and feasibility of the proposed method. It was shown that the convergence speed of the distributed reactive power control has an impact on the response of PCC voltage. The proposed diffusion algorithm involving the gradient of each reactive power generation resulted in quicker convergence speed compared to the conventional consensus algorithm, which improved the dynamic response of the PCC voltage and accuracy of the reactive power sharing among WTGs. The proposed diffusion strategy could regulate the PCC voltage and achieve the reactive power coordination in fully distributed manner, which could be considered as a promising solution for coordination control of the large-scale wind farm system.

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