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Hierarchical Energy Control of MMC-MTDC System Integrated with Offshore Wind Farms for Optimal Frequency Support Provision

Haobo Zhang, Wang Xiang, Senior Member, IEEE, Yining Wang, Yan Xu, Senior Member, IEEE, Jinyu Wen, Senior Member, IEEE

Abstract—This paper proposes an energy coordination control scheme for offshore wind farms (OWFs) integrated modular multilevel converter-based multi-terminal direct current (MMC-MTDC) system towards enhanced grid frequency support. First, a two-layer hierarchical energy control framework is established. At the lower layer, a local energy coordination controller is designed to directly regulate OWF rotor kinetic energy and MMC capacitor energy by using local measurements, eliminating energy utilization errors. At the upper layer, an energy optimization method is developed to dispatch multiple energy for achieving optimal energy utilization and minimizing grid frequency deviations. In addition, a multi-stage energy recovery strategy is designed, ensuring frequency stability during the recovery process and enabling the OWFs-MTDC system to support multiple successive frequency events. Finally, the effectiveness and robustness of the proposed method are verified in a test system jointly built in PSCAD/EMTDC and MATLAB.

Index Terms—Offshore wind, modular multilevel converter, energy coordination, frequency support, model predictive control.

I. INTRODUCTION

With the increasing integration of offshore wind farms into modern power grids, the MMC-MTDC system is emerging as a flexible solution for large-scale OWF integration into onshore AC systems. However, due to the reduced grid inertia, the OWFs-MTDC system is also expected to provide frequency support to the connected power grids [1]-[3].

Considering the need for high power generation efficiency, OWFs do not work under deloading operation conditions, resulting in no power reserve in the system [4]. In this scenario, energy reserves such as the kinetic energy of OWFs and the capacitor energy in the MTDC system can be leveraged to participate in grid frequency response. References [5]-[7] proposed a coordinated control method between kinetic energy and capacitor energy using a dual droop control (f_g - V_{dc} - f_{off}). This method adjusts the DC link voltage (V_{dc}) to link changes in onshore grid frequency (f_g) to offshore frequency shifts (f_{off}), enabling MTDC systems to utilize capacitor energy and OWFs

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Haobo Zhang, Wang Xiang, Yining Wang and Jinyu Wen are with the School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, 430074, Wuhan, China, and also with the State Key Laboratory of Advanced Electromagnetic Technology, Huazhong University of Science and Technology, 430074, Wuhan, China (e-mail: zhanghaobo9902 @foxmail.com; xiangwang1003@hust.edu.cn; wangyining0712@foxmail.com; jinyu.wen@hust.edu.cn).

Yan Xu is with the School of Electrical and Electronic Engineering, Nanyang Technological University, 639798, Singapore (xuyan@ntu.edu.sg).

to release rotor kinetic energy for frequency regulation.

To utilize the kinetic energy in OWFs, the frequency-power (f_g-P) droop control and the virtual inertia $(df_g/dt-P)$ control have been added to the MPPT controller to change output power during frequency variation [8][9]. [10] proposed a preset power based droop control scheme, which can effectively improve the frequency response performance. Referring to grid code regulations, reference [11] further designed rotor speed-power (ω_m-P) control. However, since the setpoint power of MPPT is the cube of the rotor speed, rotor speed deviation from the initial point will cause a counter-effect of the MPPT controller, leading to the OWF support power being less than the desired power [12]. Consequently, the rotor kinetic energy may not be fully utilized, diminishing the frequency support.

For capacitor energy utilization in MTDC systems, the aforementioned references regulated the DC link voltage to use the MMC capacitor energy. Nevertheless, as pointed out in [13], a narrow range of DC link voltage variation can limit capacitor energy utilization, thereby reducing the effectiveness of frequency support. To enhance the efficiency of MTDC capacitor energy utilization, references [14] and [15] developed several frequency-energy droop control schemes that directly regulate capacitor energy for frequency support. Nonetheless, these methods did not consider coordination with OWF kinetic energy, and their effectiveness depends on the actual system frequency. If the energy utilization reaches its limits during certain grid frequency events, the MTDC system may abruptly stop providing support, leading to further frequency drops [16].

In addition to the limitations in energy utilization, it is important to note that the energy coordination methods for OWFs-MTDC systems discussed above rely on traditional droop and proportional-integral (PI) controllers. Specifying constant control gains prevents the system from offering maximum frequency support in various grid disturbances, such as AC load disturbances, wind speed changes, etc. Although different adaptive control methods [16] and [17] are respectively introduced to optimize MMC capacitor energy utilization and OWF kinetic energy utilization for improving grid frequency regulation, various constraints cannot be dealt with simultaneously with classic PI controllers, e.g., power, DC voltage and energy limits in OWFs-MTDC systems.

To achieve optimal frequency response, online optimization techniques are typically applied in frequency support control while accounting for various constraints. For OWFs-MTDC systems, various types of model predictive control (MPC)-based frequency support control schemes have been studied, including centralized MPC [18], mixed centralized/

decentralized MPC [19], and distributed MPC [20]-[24]. However, these methods primarily focus on power coordination and depend on the availability of power reserves in deloaded OWFs and asynchronous grids. For instance, reference [18] designed a centralized MPC controller to coordinate the operations of synchronous generators (SGs) and the deloaded OWFs, minimizing frequency deviations in each grid. References [19]-[24] implemented independent MPC controllers at each converter to regulate the output power of MMCs for optimal frequency regulation separately. Nevertheless, these studies assumed that sufficient power sources were available in the test systems.

In scenarios without power reserves, reference [25] explored the optimal utilization of wind farms' kinetic energy for frequency regulation using nonlinear MPC. On this basis, references [26] and [27] examined the MPC-based energy coordination between OWFs and battery storage systems, as well as between OWFs and offshore DC collection grid capacitors. However, the optimal coordination between OWF kinetic energy and MMC capacitor energy in the OWFs-MTDC system has not yet been investigated. Therefore, key challenges that need to be addressed include 1) how to flexibly regulate these two types of energy; 2) how to optimize their utilization to enhance frequency support. Additionally, the energy recovery after frequency support should be considered.

Therefore, a two-layer hierarchical energy control framework is developed for the OWFs-MTDC system to efficiently coordinate the utilization of OWF kinetic energy and MMC capacitor energy for enhancing frequency support. The main novelty and contributions of this paper are listed:

- A local energy coordination control scheme is devised as the lower-layer controller. This scheme directly regulates multiple energy sources by incorporating rotor speed control of OWFs and active energy control of MMCs. Unlike conventional coordinated control, this approach mitigates the problem of insufficient energy utilization.
- A distributed MPC-based energy utilization method is proposed as the upper-layer controller to dispatch OWF kinetic energy and MMC capacitor energy, ensuring enhanced frequency response and smooth energy recovery with less communication dependence.

This paper is organized as follows. Section II describes the test system and the equivalent frequency response model. Section III analyzes the limitations of the conventional energy coordination scheme. Section IV proposes a hierarchical energy control framework of the OWFs-MTDC system, including the designed energy coordination control and distributed MPC-based energy utilization method, also considering energy recovery. The effectiveness and robustness of the proposed method are verified by simulations in Section V. Finally, conclusions are drawn in Section VI.

II. SYSTEM DESCRIPTION AND MODELING

A. System Description

Fig. 1 illustrates the investigated four-terminal MMC-HVDC system integrating with OWFs. OWF1 and OWF2 are the same

OWFs in different regions, and the capacity is 1100MW. The mechanical parameters of the wind turbine are according to the GE benchmark model, as listed in Table A I [28]. In the MTDC system, master-slave control is adopted. MMC1 and MMC3 are the DC voltage station and power station, respectively. MMC2 and MMC4 are AC voltage stations. And all MMCs adopt half-bridge sub-modules (SMs). The detailed parameters of MMC stations are shown in Table A II. In this work, the SM capacitance is designed following the practical projects, with an energy storage time constant of about 40ms.

The topology and line parameters of the onshore AC grid refer to reference [16]. All SGs are represented by the subtransient model and equipped with governor control (steam turbine). The basic and control parameters of SGs are listed in Table A III and Table A IV, respectively.

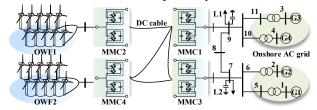


Fig. 1. The investigated OWFs-MTDC system.

B. System Frequency Response Model

According to SGs' model, the frequency response model of a large AC grid can be obtained by the methods in [29][30], as shown in Fig. 2. Thus, the expression can be derived as [14]:

$$2H_s \Delta \dot{f}_{onpu} = \Delta P_m - \Delta P_L + \Delta P_{WF1} + \Delta P_{WF2} + \Delta P_{MTDC} \tag{1}$$

where the dot "·" above a variable denotes the derivative with respect to time. H_s is the equivalent inertia constant of the AC grid. ΔP_m is the supplementary mechanical power of SGs, offered by the governor and reheat turbine, as shown in the shaded box in Fig. 2. The aggregated gains (R, K_3, K_4, K_5) and time constants $(T_1, T_2, T_3, T_4, T_5)$ are defined in Table A IV.

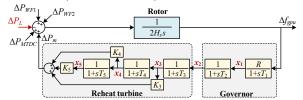


Fig. 2. The aggregated frequency response model of the AC grid.

Besides, ΔP_L is the load disturbance power. ΔP_{MTDC} denotes the support power using the capacitor energy stored in the MMC-MTDC system. ΔP_{WFi} (i=1, 2) denotes the support power provided by the rotor kinetic energy of the ith OWF, respectively. Notably, the above power is in per-unit value, while the base value is the total capacity of SGs, namely S_G . Thus, the different support power can be obtained as:

$$\Delta P_{MTDC} = -\frac{W_{C0}}{S_G} \cdot \frac{dW_{Cpu}}{dt} \tag{2}$$

$$\Delta P_{WFi} = -\frac{E_{k0i}}{S_G} \cdot \frac{dE_{kpui}}{dt} + \frac{\Delta P_{Wmi}}{S_G} \quad (i = 1, 2)$$
 (3)

where subscript "i" denotes the variables associated with the *i*th OWF. W_{Cpu} and W_{C0} are the MTDC capacitor energy in per-unit value and its rated value. E_{kpui} and E_{k0i} denote the kinetic energy

in per-unit value and its rated value of the *i*th OWF. ΔP_{Wmi} is the mechanical power variation of the *i*th OWF. Then, E_{kpui} can also be calculated by rotor speed, that is:

$$E_{kpui} = \omega_{mi}^2 \tag{4}$$

where ω_{mi} is the rotor speed of the *i*th OWF in per-unit value. In (3), ΔP_{Wmi} is expressed as:

$$\Delta P_{Wmi} = \frac{1}{2} \rho \pi r^2 C_{pi} \left(\lambda_i \left(\omega_{mi}, w_{si} \right), \beta_i \right) w_{si}^3 - P_{Wm0}$$
 (5)

where mechanical power variation P_{Wm0} denotes the mechanical power of the OWF under rated conditions. ρ is the air density. r is the radius of the turbine blade. w_{si} is the wind speed of the ith OWF. C_{pi} is the power coefficient for the given pitch angle β_i and the tip-speed ratio λ_i . Considering the overload of OWFs is slight and short-term during frequency support, the pitch angle control can be assumed as inactive, and β_i is regarded as 0.

III. CONVENTIONAL ENERGY COORDINATION SCHEME

Fig. 3 shows the conventional coordinated frequency control scheme for OWFs-MTDC systems in [4]-[6]. The red arrows show the traditional dual droop $(f_g$ - V_{dc} - f_{off}) control applied in onshore and offshore MMCs, which enables OWFs to sense changes in onshore frequency f_g .

The OWF control is shown in the blue cube in Fig. 3. The support power ΔP_{add} is generated by frequency control and added to the MPPT setpoint power. Considering the controller can well track the power reference, the actual support power ΔP_{WF} of OWF is expressed as:

$$\Delta P_{WF} = \Delta P_{MPPT} + \Delta P_{add} \tag{6}$$

where ΔP_{MPPT} is the variation in the MPPT setpoint.

When the grid frequency decreases, the OWF kinetic energy is released for support. As the rotor speed decreases, ΔP_{MPPT} is always minus since P_{MPPT} is approximately proportional to the cube of the rotor speed. Thus, ΔP_{WF} will be less than the desired power ΔP_{add} , and the kinetic energy cannot be used effectively.

The control of onshore DC voltage MMC is presented in the green cube in Fig. 3. The MMC control with two modulation ratios (M_d and M_q) is adopted. Since the SM capacitor voltage is proportional to the DC link voltage, the frequency control is

applied to utilize the MMC capacitor energy by regulating the DC link voltage. However, the allowable DC voltage variation is ± 0.2 p.u., much less than [-0.232p.u., 0.5p.u.] of capacitor voltage variation [16]. Hence, the DC voltage-based energy regulation method limits capacitor voltage (energy) utilization.

To sum up, the conventional energy coordination method indirectly regulates energy, with the problem of insufficient energy utilization. Meanwhile, the control coefficients of k, D and H in frequency control are usually fixed, also making it hard to achieve optimal energy coordination under various scenarios.

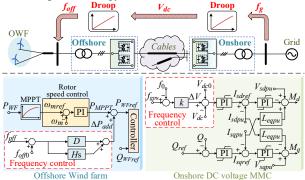


Fig. 3. Conventional coordination control method.

IV. PROPOSED ENERGY COORDINATION METHOD

A. Hierarchical Energy Control Framework

Fig. 4 illustrates the proposed hierarchical energy control framework for efficiently coordinating energy reserves in OWFs and MMCs. The proposed framework consists of lower-and upper-layer controllers. The lower-layer controller aims to directly regulate kinetic and capacitor energy, containing rotor speed control in OWFs and energy control in MMCs, as shown in red cubes in Fig. 4. The upper-layer controller utilizes two types of energy for optimal frequency support, where the distributed MPC controllers, e.g., onshore and offshore MPCs, are designed to generate control references for the lower-layer control, as shown in yellow boxes in Fig. 4. To ensure the generated control references by different MPCs are consistent, MPC controllers in all MMCs are the same.

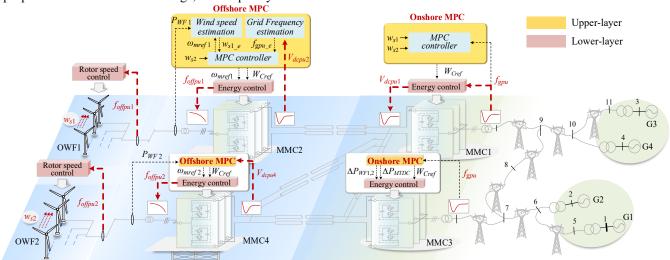


Fig. 4. The proposed hierarchical energy control framework for OWFs-MTDC system.

When implementing MPC controllers, the grid frequency f_{gpu} and wind speeds of OWFs (w_{s1} and w_{s2}) are required. For onshore MPCs, the grid frequency is measured at the AC side of onshore MMCs. The wind speeds are received by satellite communication.

For the offshore MPC, two estimators are designed to estimate the grid frequency f_{gpu_e} and the wind speed of the connected OWF (e.g., w_{s1_e} and w_{s2_e}) using local measurements (DC voltage and OWF output power). Satellite communication is also used to get the other OWF wind speed.

Although satellite communication is involved in the proposed method, the communication volume is much less than the centralized MPC methods. For instance, the common centralized MPC method in [18] requires the communication of mass control references, causing a very high data traffic. In contrast, the distributed method only requires communication of wind speeds. Due to the slow time scale of wind speed changes, there is no need for frequent communication.

B. Lower-layer Energy Coordination Control Design

Different from the indirect energy coordination control scheme in Fig. 3, a direct energy coordination control strategy is first employed in the lower-layer controller, as follows:

- Regarding the OWFs, the control structure is shown in the blue cube in Fig. 5. Since the kinetic energy is the square of the rotor speed, the rotor speed control is switched from MPPT mode to regulate kinetic energy during frequency response.
- For the MMCs, as shown in the gray cube in Fig. 5, the active energy control structure containing AC modulation ratios(M_d , M_q), DC modulation ratios (M_{dc}) and capacitor voltage modulation ratios (M_C) is adopted [13], enabling MMC to regulate the SM capacitor voltage independently. Then, the capacitor energy control of different MMCs is designed, as shown in green blocks in Fig. 5. Regarding the DC voltage station (MMC1), energy control is implemented by AC current control [31]. For other MMCs, energy

regulation is achieved by DC current control.

Then, to achieve energy coordination among all MMCs, the traditional f_g - V_{dc} droop control in Fig. 3 is introduced in the DC voltage station MMC1, which is expressed as:

$$V_{dcref} = V_{dc0} + k_f (f_{gpu} - f_{g0})$$
 (7)

where V_{dcref} is the DC voltage control reference. f_{gpu} is the grid frequency in per-unit value. Subscript "0" is used to indicate the rated value. And k_f is a droop gain. With (7), other MMCs can sense grid frequency changes by measuring DC link voltage, and then regulate capacitor energy synchronously.

Meanwhile, a method of regulating OWF kinetic energy by offshore MMC is developed. Unlike the V_{dc} - f_{off} droop in Fig. 3, a ω_m - f_{off} droop control is designed for offshore MMCs to couple the offshore frequency f_{off} with the desired OWF rotor speed ω_m . The expression of the ω_m - f_{off} droop control in offshore MMCs is written as:

$$f_{offref i} = f_{off 0} + k_{\omega} \left(\omega_{mref i} - \omega_{m0} \right) \tag{8}$$

where the subscript "i" denotes the control reference of the MMC integrated with the ith OWF, respectively. f_{offref} is the control reference of the frequency control. f_{off0} and ω_{m0} represent the rated values. And k_{ω} is the droop gain.

Then, a coordinated control is advised for the *i*th OWFs to generate the rotor speed reference ω_{mrefi} from their own offshore frequency f_{offi} . The expression is obtained by (8):

$$\omega_{mref i} = \frac{1}{k_{o}} \left(f_{offpu i} - f_{off 0} \right) + \omega_{m0} \tag{9}$$

where f_{offpui} is the offshore frequency measures at the *i*th OWF. Thus, the obtained ω_{mrefi} can be imported into the rotor speed control of the *i*th OWF, achieving rotor kinetic regulation.

As shown in Fig. 5, MMC3 is the constant power station. If the power of MMC3 remains fixed, the total support power ΔP_{tot} (= ΔP_{MTDC} + ΔP_{WF1} + ΔP_{WF2}) will flow through the DC voltage station MMC1, causing overload in MMC1. Hence, power-sharing control is proposed for MMC3 to share the total support power, which can be expressed as:

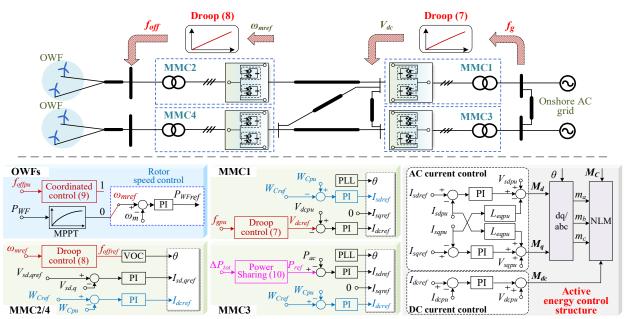


Fig. 5. The proposed energy coordination control structure of the OWFs-MTDC system.

$$P_{ref} = K \cdot \Delta P_{tat} + P_{ref\,0} \tag{10}$$

where P_{ref0} is the power control reference under normal conditions. K is the distribution coefficient.

As analyzed above, all the MMCs and OWFs are connected by local measurements, facilitating flexible regulation of various energies. Meanwhile, the local-based control also decreases the communication pressure of the whole system.

C. Upper-layer Energy Optimization Control Design

For dynamically optimal frequency response, the MPC controller is a promising solution to coordinate the energy in MMC capacitors and OWF rotors. Since the various types of energy can be represented by corresponding support power, as expressed in (2) and (3), the optimization of energy is equivalent to the optimization of support power in Fig. 2.

Firstly, based on the frequency response model shown in Fig. 2, the state-space equations can be obtained as:

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{A}_0 \mathbf{x} + \mathbf{B}_0 \mathbf{u} + \mathbf{R}_{L0} \mathbf{z} \\ \mathbf{v} = \mathbf{C} \mathbf{x} \end{cases}$$
 (11)

where state vector $\mathbf{x} = [\Delta f_{gpu}, x_1, x_2, x_3, x_4, x_5]^T$. Input vector $\mathbf{u} = [\Delta P_{WF1}, \Delta P_{WF2}, \Delta P_{MTDC}]^T$, which are variables required to be optimized. The disturbance vector $\mathbf{z} = [\Delta P_L]$. In addition, the output of the system is defined as the grid frequency variation. Thus, the output vector $\mathbf{y} = [\Delta f_{gpu}]$. \mathbf{A}_0 , \mathbf{B}_0 , \mathbf{R}_{L0} and \mathbf{C} are the state matrix, input matrix, disturbance matrix and output matrix, which can be calculated according to Fig. 2.

Using the Zero-Order Hold discretization technique, a discrete-time prediction model can be obtained from (11). It yields,

$$\begin{cases}
\mathbf{x}_{k+1} = (\mathbf{I} + T_s \mathbf{A}_0) \mathbf{x}_k + \underbrace{T_s \mathbf{B}_0}_{\mathbf{B}} \mathbf{u}_k + \underbrace{T_s \mathbf{R}_{L0}}_{\mathbf{R}_L} \mathbf{z}_k \\
\mathbf{y}_k = \mathbf{C} \mathbf{x}_k
\end{cases} \tag{12}$$

where I is the identity matrix. T_s is the sampling period, and the subscript k is the time step. A, B and R_L are discretized statespace matrices.

From (12), we see that solving the MPC problem also requires the load disturbance power ΔP_L , which cannot be measured in general. In this paper, the method of moving horizon estimation (MHE) is employed to estimate the state of ΔP_L . The details about the MHE are referred to [24]. The prediction model (12) can be modified as:

$$\begin{bmatrix}
\begin{bmatrix} \mathbf{x}_{k+1} \\ \mathbf{z}_{k+1} \end{bmatrix} = \begin{bmatrix} \mathbf{A} & \mathbf{R}_{L} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{x}_{k} \\ \mathbf{z}_{k} \end{bmatrix} + \begin{bmatrix} \mathbf{B} \\ 0 \end{bmatrix} \mathbf{u}_{k} + \begin{bmatrix} 0 \\ T_{s} \end{bmatrix} \delta_{k}^{L} \\
\mathbf{y}_{k} = \begin{bmatrix} \mathbf{C} & 0 \end{bmatrix} \begin{bmatrix} \mathbf{x}_{k} & \mathbf{z}_{k} \end{bmatrix}^{T} + \delta_{k}^{f}$$
(13)

where x_k is the modified state vector at the k time step. A', B' and C' are the modified matrices. Both δ_k^L and δ_k^L are independent Gaussian white-noise processes.

Then, based on the prediction model, the cost function has to be specified to obtain the time series of the optimal input vector \boldsymbol{u} . For improving the grid's frequency stability, the primary objective of the designed MPC is to suppress the system output \boldsymbol{y} (i.e., frequency deviations Δf_{gpu}). Moreover, to avoid

exceeding the energy utilization limit, magnitudes of the input u (i.e., support power ΔP_{WF1} , ΔP_{WF2} and ΔP_{MTDC}) should be restricted. Therefore, the cost function is designed as:

$$\min_{u_{k}} J:= \sum_{h=0}^{N_{p}-1} \left((y_{k+h} - y_{ref})^{T} Q(y_{k+h} - y_{ref}) + u_{k+h}^{T} R u_{k+h} \right)$$

$$+ (y_{k+N_{n}} - y_{ref})^{T} F(y_{k+N_{n}} - y_{ref})$$
(14)

where N_p is the prediction and control horizon. \mathbf{y}_{ref} is the desired output reference, which is normally 0 for maximum frequency support. \mathbf{Q} and \mathbf{R} are the weighting matrices corresponding to the future predicted frequency deviations and control input signals, respectively. Meanwhile, the $(\mathbf{y}_{k+Np}$ - $\mathbf{y}_{ref})$ is the terminal cost. \mathbf{F} is the corresponding weighting matrix [25].

Finally, considering the limits of OWF rotor speed and MMC capacitor energy, the constraints on the control input vector \boldsymbol{u} can be designed.

1) Constraints on OWF support power: As presented in [32], the OWF rotor speed must be within a safe range. Combining and discretizing (3)-(5), the relationship between support power ΔP_{WFi} and rotor speed ω_{mi} can be calculated as (i=1,2):

$$\underline{\Delta P_{WFi}(k)} = -\frac{2E_{k0}}{S_G T_s} \omega_{mi}(k) \left[\omega_{mi}(k) - \omega_{mi}(k-1) \right] + \frac{\rho \pi r^2 w_{si}^3}{2S_G} \left[C_{pi} \left(\omega_{mi}(k), w_{si} \right) - C_{p0i} \right]$$
(15)

where $u_k(i)$ is the *i*th element of the input vector u at the *k*th time step. C_{p0i} is the nominal power coefficient, which can be determined by the initial rotor and wind speed. Considering the rotor speed limits of $\omega_m^{lim} = [\omega_m^{min}, \omega_m^{max}]$, the constraints on the OWF support power can be obtained as [27]:

$$\left. \boldsymbol{u}^{\min}(i) \right|_{\boldsymbol{\omega}_{mi}(k) = \boldsymbol{\omega}_{m}^{\max}} \le \boldsymbol{u}_{k}(i) \le \left. \boldsymbol{u}^{\max}(i) \right|_{\boldsymbol{\omega}_{mi}(k) = \boldsymbol{\omega}_{m}^{\min}} \quad (i = 1, 2) \quad (16)$$

2) Constraints on MTDC support power: according to (2), the discrete equation of MTDC support power can be written as:

$$\underline{\Delta P_{MTDC}(k)}_{u_{k}(3)} = -\frac{W_{C0}}{S_{G}T_{s}} \left[W_{Cpu}(k) - W_{Cpu}(k-1) \right]$$
 (17)

Considering the MMC capacitor energy limit of $W_C^{lim} = [W_C^{min}, W_C^{max}]$, the constraints can be yielded:

$$\mathbf{u}^{\min}(3)\Big|_{W_{Cm}(k)=W_{C}^{\max}} \le \mathbf{u}_{k}(3) \le \mathbf{u}^{\max}(3)\Big|_{W_{Cm}(k)=W_{C}^{\min}}$$
(18)

Combining the prediction model (13), cost function (14), constraints (16) and (18), time series of the optimal support power output (ΔP_{WF1} , ΔP_{WF2} , and ΔP_{MTDC}) can be obtained. On this basis, the time series of OWFs rotor speed $\omega_{mi}(k)$ and MMC capacitor energy $W_{Cpu}(k)$ can be further calculated from (15) and (17), using the MPC power outputs together with the previous-step state variables (k-1). Then, they are used as the control references of the lower-layer energy control (i.e., ω_{mref1} , ω_{mref2} and W_{Cref}). Notably, the wind speed w_{si} should be known when calculating ω_{mrefi} by (15). Thus, communication is adopted in MMCs to receive wind speed information.

Moreover, as presented in Fig. 4, the estimations of the connected OWF wind speed and onshore grid frequency are required for offshore MMCs to implement the proposed MPC controller. Due to the relationship between the DC link voltage and grid frequency in (7), the grid frequency can be estimated

by detecting the local DC voltage. The details of the frequency estimation can be found in [9].

In addition, the relationship between the connected OWF support power ΔP_{WFi} , rotor speed ω_{mi} and wind speed w_{si} satisfies the equation (15). Where the ΔP_{WFi} can be directly measured. Assuming the rotor speed control can accurately track control references, the ω_{mi} can be regarded as the ω_{mrefi} generated by offshore MPC controllers. As a result, the wind speed can be estimated by solving (15).

To better illustrate the operating mechanism of the upperlayer MPC controller in different MMCs, Fig. 4 is expanded and detailed as Fig. 6. As shown, all MMCs adopt the same MPC controller, as the required information and outputs are consistent across controllers, as shown in the gray boxes in Fig. 6. The required information includes wind speeds from OWFs (w_{s1}, w_{s2}) and the grid frequency f_{gpu} . Moreover, the outputs of the MPCs consist of the desired supporting power from OWFs and MMCs: ΔP_{WF1} , ΔP_{WF2} , and ΔP_{MTDC} .

The differences lie in the source of the input information and the utilization of the output signals for each MMC. Taking onshore MMC3 for example, both wind speeds of OWF1 and OWF2 are obtained via communication, while the grid frequency is measured locally. The MPC outputs are used for power-sharing control (equation (10)) and for generating the lower-layer capacitor energy control reference W_{Cref} through equation (17). For offshore MMC2, only the wind speed w_{s2} of the non-directly connected OWF2 needs to be obtained via communication; all other required information can be derived through local estimators (e.g., w_{s1} e and f_{gpu} e). Moreover, the output ΔP_{WF1} , combined with the estimated w_{s1} e, is converted into the rotor speed control reference ω_{mref1} by equation (15). The third output ΔP_{MTDC} is used to generate W_{Cref} by (17). The control references generated in MMC4 follows a similar principle to that of MMC2.

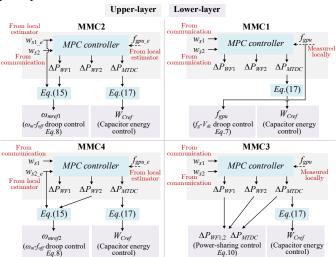


Fig. 6. Diagram of the implementation of MPC controllers in different MMCs.

D. Energy Recovery Strategy

As analyzed above, the MPC output reference y_{ref} (frequency deviation Δf_{gpu}) is set to 0, which can utilize energy to minimize frequency deviation as much as possible. However, during the primary frequency regulation period, there will be a steady state frequency deviation Δf_{steady} . Therefore, consistently setting the

 y_{ref} to 0 may lead to energy overutilization, which is not conducive to energy recovery. Regarding this issue, y_{ref} is designed to change from 0 to Δf_{steady} , that is:

$$\mathbf{y}_{ref} = \begin{cases} 0, & t \le t_{nadir} \\ \Delta f_{steady} \cdot \min \left\{ k_{re} \left(t - t_{nadir} \right), 1 \right\}, & t > t_{nadir} \end{cases}$$
(19)

where t_{nadir} is the time at the frequency nadir, which can be determined by monitoring the rate of change of frequency (RoCoF). And k_{re} is the change slope of y_{ref} , here is 0.5. Therefore, the output reference y_{ref} will be adjusted to Δf_{steady} after 2s. According to Fig. 2, the Δf_{steady} can be calculated by letting s=0 in the governor and reheat turbine loops, yielding:

$$\Delta f_{steady} = \frac{\Delta P_L}{R} \tag{20}$$

In addition, to avoid serious second frequency dips during energy recovery, a multi-stage recovery strategy is developed. Taking the load increase as an example, the proposed energy recovery strategy after energy utilization is depicted in Fig. 7. Defining the disturbance occurrence time as 0, the strategy consists of four stages, as outlined below.

- a) Stage I (t_1 - t_2 after disturbances): The energy recovery strategy is enabled at t_1 after the disturbance. Within this stage, the rotor speeds of all the OWFs remain unchanged. And the capacitor energy is still utilized to suppress frequency variation.
- b) **Stage II** (*t2-t3* **after disturbances**): Considering the frequency deviation is still quite large during this stage, the OWF with a smaller rotor speed deviation is controlled to restore linearly. Meanwhile, the capacitor energy utilization for frequency support is still in operation.
- c) Stage III and IV (t3-t4 and t4-t5 after disturbances):

 During stage III, the other OWF recovers rotor speed linearly. In stage IV, MMC capacitor energy is restored to its rated value following a quadratic curve, with the slope set to 0 at t5 for smooth recovery.

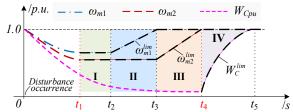


Fig. 7. Illustration of the multi-stage energy recovery method.

To achieve the coordinated recovery of rotor kinetic energy and capacitor energy at the above stages, the distributed MPC controllers are also utilized. By changing the limits in constraints (16) and (18) along the preset black dotted curves in Fig. 7, the desired control references can be generated to realize the sequential energy recovery. It should be noted that limit changes are only carried out during energy recovery periods.

V. SIMULATION TESTS

To verify the effectiveness of the proposed method, the electromagnetic transient model of the OWFs-MTDC system in Fig. 1 is built in PSCAD/EMTDC. Details of the tested system parameters are presented in the Appendix. The designed MPC

algorithm is implemented on the MATLAB platform. In the PSCAD platform, the simulation time step is set to $50\mu s$. To not affect simulation speed, the frequency of calling the MPC algorithm is selected to 100 Hz. Thereby, the sampling period T_s of the MPC controller is set to 10 ms in MATLAB. Meanwhile, the prediction and control horizon N_p is set to 20, i.e., 200ms.

Considering the energy recovery strategy, rotor speed and capacitor energy limits of the proposed method can be concluded in Table I. Referring to [32], the normal range of the rotor speed is [0.7p.u., 1.2p.u.]. For the MMC capacitor energy, our previous work [16] points out that its lower limit depends on the DC voltage, and the normal range is $[(0.5V_{dcpu}+0.368)^2, 2.25]$ in per-unit value. During the energy recovery stages, the limits are switched to the corresponding curves shown in Fig. 7.

LIMITS FOR THE PROPOSED MPC CONTROLLERS

Limits	Normal ranges	Energy recovery period
WF1 rotor speed $\omega_{m1}^{lim}/\text{p.u.}$	[0.7, 1.2]	Curves of stage I to IV
WF2 rotor speed $\omega_{m2}^{lim}/\text{p.u.}$	[0.7, 1.2]	in Fig. 7
Capacitor energy W_C^{lim} /p.u.	$[(0.5V. \pm 0.368)^2 \ 2.25]$	Curve in stage IV
Capacitor energy W _c /p.u.	$[(0.37_{dcpu}, 0.308), 2.23]$	in Fig. 7

A. Parameter Settings

1) Control parameters:

The control parameters (k_{ω} , k_f and K) should be determined to implement the proposed local energy coordination control. For the f_g - V_{dc} droop control of MMC1, the droop gain k_f is designed by considering the DC voltage and frequency deviation limit. As stated in [33], the statutory limits Δf_{lim} in most countries are ± 0.01 p.u. with a nominal frequency of 50Hz. Meanwhile, the DC voltage variation limit ΔV_{dclim} is ± 0.2 p.u [16]. To ensure the DC voltage is within the allowable range at maximum frequency variation, k_f should satisfy:

$$k_f \le \frac{\Delta V_{dclim}}{\Delta f_{lim}} = 20 \tag{21}$$

As shown in Table I, the larger the DC voltage drops, the lower the capacitor energy limit. Thus, k_f is set to 20 for a large capacitor utilization margin.

Regarding the gain k_{ω} in the ω_{mref} - f_{off} droop control of offshore MMCs, the limits of the WF rotor speed and offshore frequency are considered. Since the offshore frequency has a wide range of variations, k_{ω} is set to 1.

Moreover, the distribution coefficient *K* is determined as:

$$K = \frac{S_{MMC3}}{S_{MMC1} + S_{MMC3}} = 0.364 \tag{22}$$

where S_{MMC1} and S_{MMC3} are the rated capacities of MMC1 and MMC3, respectively. Therefore, the support power flowing through MMC1 and MMC3 can be proportional to their capacity without the risk of overload.

2) Time points:

Additionally, the time points for energy recovery need to be determined in Fig. 7. Considering the primary frequency response is within 20 seconds [34], the total recovery time t_5 is set to 20s to enable rapid recovery in response to successive system disturbances. Since the critical first swing of a frequency drop/rise lasts about 2-5 seconds [32], the OWFs can stop utilizing kinetic energy after 5 seconds to avoid a severe

second frequency dip during recovery. Therefore, t_1 is set to 5s. The rotor speeds are held constant for an additional 3 seconds, with t_2 set to 8s. This allows the system to stabilize and ensures that the frequency deviation is sufficiently regulated before energy recovery. Finally, the energy recovery time for each component (OWF1, OWF2, and the MTDC system) is evenly divided into three parts for a total of the remaining 12 s.

3) Weighting matrices:

The control roles and tuning impacts of MPC parameters (i.e., weighting matrices) are summarized in Table II. As shown, parameter selection involves a trade-off between improving the frequency nadir and mitigating the second frequency dip. Therefore, the parameters should be chosen through a reasonable trade-off and iterative testing process. Specifically, set Q=2, R=diag(0.1, 0.1, 0.2), and F=50. Although the weighting matrices in the cost function (14) can be further optimized for better frequency support, the focus of this paper is to validate the capability of the proposed hierarchical energy control framework in fully utilizing multiple energy. Parameter optimization can be further explored in future research.

TABLE II
IMPACT OF MPC PARAMETERS ON FREQUENCY RESPONSE

IWI ACT OF WITC TARAWETERS ON TREQUENCT RESPONSE			
MPC Parameter	Control Role	Tuning Impact	
Q (scalar)	Penalizes frequency deviation Δf_{gpu}	Larger <i>Q</i> : improves frequency nadir; may worsen second frequency dip	
$R=diag(R_{11},R_{22},R_{33})$	Penalizes supporting power of OWF1&2, and MTDC system	Larger <i>R_{ii}</i> : mitigates second frequency dip; may reduce frequency nadir	
F (scalar)	Penalizes terminal prediction state	Larger F: improves frequency nadir; may worsen second frequency dip	

B. Validations of the Proposed Method

1) Performance of the estimators:

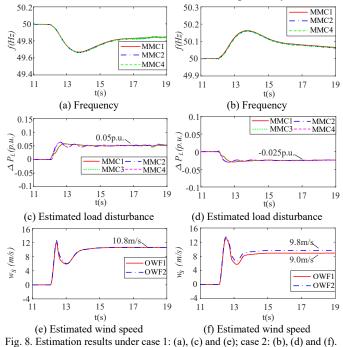
To test the correctness of the designed estimators, some simulation cases are carried out below.

- Case 1: a 160MW load increase (ΔP_L =5%) is applied at bus 7, with wind speeds of OWF1 and OWF2 being 10.8m/s.
- Case 2: an 80MW load decrease (ΔP_L =-2.5%) is applied at bus 7, with wind speeds of 9.0 m/s and 9.8 m/s for OWF1 and OWF2, respectively.

It should be pointed out that the proposed energy recovery control is not activated in these cases. The simulation results are shown in Fig. 8. Fig. 8 (a), (c) and (e) depict the estimated frequency, load disturbance power and wind speed under case 1. In Fig. 8 (a), the grid frequency measured by MMC1 and the estimated frequency by MMC2 and MMC4 are almost coincidental, demonstrating the frequency estimat in offshore MMCs is precise. In Fig. 8 (c), the load disturbance powers estimated by all the MMCs are about 0.05p.u., corresponding to the preset conditions. Although there will be some prediction error in the early period after the disturbance occurs, it will be corrected to the exact value within 2s. Hence, the correctness of load disturbance estimator in (13) is verified. Moreover, the wind speeds of OWF1 and OWF2 can also be correctly estimated at about 10.8m/s, as shown in Fig. 8 (e).

Regarding case 2, the estimated results are presented in Fig. 8 (b), (d) and (f). The frequency estimations in offshore MMCs are also accurate. The estimated load disturbance power is -

0.025p.u., in accord with the actual load disturbance. In addition, the wind speeds of the two OWFs are also accurately estimated, which are 9.0m/s and 9.8m/s, respectively.



2) Performance of the proposed distributed MPC method:

To verify the effectiveness of the proposed distributed MPC-based energy coordination method, a 160MW load increase (ΔP_L =5.0%) is applied in bus 7, with the wind speeds of OWF1 and OWF2 being 10.8m/s. Meanwhile, to highlight the merits of the proposed method, three different control schemes are compared in the following simulations, they are:

- **D-MPC** (method in this paper): The proposed distributed MPC-based energy utilization method.
- C-MPC: The proposed energy utilization method using the centralized MPC (all MMCS and OWFs are controlled by one main MPC controller).
- **D-MPC-noMMC**: The proposed energy utilization and recovery strategies with the designed distributed MPC, considering only OWF rotor kinetic energy as [25].
- D-MPC-noRotor: The proposed energy utilization and recovery strategies with the designed distributed MPC, considering only the MMC capacitor energy.

Fig. 9 compares the frequency response using various control schemes. As shown in the red and blue curves, the frequency response using the *D-MPC* is almost the same as *C-MPC*. Thus, the proposed distributed method can effectively provide frequency support even with additional processes of measurement and estimation. Compared to the *D-MPC-noMMC* method, the proposed *D-MPC* method improves the frequency nadir by 8%, verifying the enhanced effect by coordinating MMC energy. Meanwhile, the proposed *D-MPC* method improves the frequency nadir by 27% than the *D-MPC-noRotor* method, demonstrating the enhanced effectiveness of utilizing the rotor kinetic energy of OWFs. Additionally, although the frequency drops many times due to the energy recovery, the maximum frequency drop does not exceed the

frequency nadir. Thereby, the properness of the energy recovery strategy is verified.

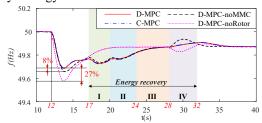


Fig. 9. Comparison of the frequency responses using different methods.

Fig. 10 depicts the control performance using the *D-MPC* method. Fig. 10 (a) and (b) show the control references generated by onshore MPC (e.g., MMC1) and offshore MPC (e.g., MMC4), respectively. As can be seen, different MPCs operate in coordination, ensuring the generated control references are consistent. Meanwhile, the control references match the preset curves in Fig. 7 very well. At 17s, both the OWF1 and OWF2 stop reducing their rotor speed and recover rotor speed linearly at 20s and 24s, respectively. Then, MMCs start to recover capacitor energy with a quadratic curve at 28s.

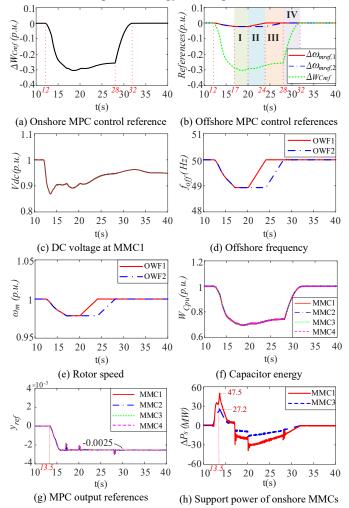


Fig. 10. Performance of the proposed method under a 160MW load increase.

Fig. 10 (c) and (d) show the DC voltage at MMC1 and offshore frequency at the AC side of the two OWFs. The DC voltage changes with the grid frequency variation, and the offshore frequency follows the rotor speed references generated

by offshore MPC. Thus, the dual droop control in the proposed local energy control performs well for energy coordination. The actual rotor speed and MMC energy are presented in Fig. 10 (e) and (f), which can track the control references precisely. Meanwhile, the capacitor energy in all MMCs can be utilized synchronously.

Fig. 10 (g) depicts the MPC output reference y_{ref} in different MMCs. It can be observed that y_{ref} changes at 13.5s, from 0 to Δf_{steady} =-0.05/20=-0.0025p.u. As a result, the support power injected into the grid can be quickly reduced to avoid excessive energy utilization, as shown in Fig. 10 (h). Meanwhile, the support power of MMC1 and MMC3 is approximately proportional to their rated capacities, following equation (22).

In summary, the proposed distributed MPC method achieves the same frequency response as the centralized MPC method. Both OWF kinetic energy and MMC capacitor energy are flexibly utilized and recovered as planned.

C. Robustness Analysis

1) Successive load disturbances:

To test the performance of the proposed D-MPC method under successive load disturbances, two different load disturbances are considered in this case. A 180MW load increase(ΔP_L =5.6%) at bus 7 and a 90MW load decrease (ΔP_L =-2.8%) at bus 9 are applied at t=12s and t=52s, respectively. The comparative results of the frequency response using different control methods are depicted in Fig. 11.

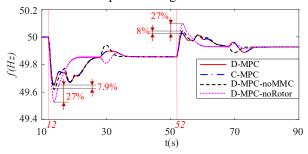


Fig. 11. Comparisons of the frequency responses using different methods.

As can be seen, the *D-MPC* method consistently has the same frequency support performance as the *C-MPC*. Moreover, compared to the *D-MPC-noMMC*, the maximum frequency deviation using the *D-MPC* method is reduced by 7.9% and 8% during the two successive frequency support periods, respectively. In comparison with the *D-MPC-noRotor* method, the reductions are even more significant, reaching 27% in both periods. In addition, the proposed energy recovery strategy also ensures that the maximum frequency deviation during energy recovery is no more than the first frequency deviation.

The control performances of the proposed *D-MPC* method are shown in Fig. 12. Fig. 12 (a) presents the estimated load disturbance power by different distributed MPCs. It can be seen that all MPCs can precisely estimate the two load disturbance powers, which are 5.6% and -2.8%, respectively. Control references and the actual values of the OWF rotor speed and MMC capacitor energy are shown in Fig. 12 (b)-(d). The rotor speed and capacitor energy can follow their references precisely. Meanwhile, the capacitor energy of all MMCs is also utilized consistently. Therefore, the energy coordination capability of

the proposed method is still valid even under two successive load disturbances.

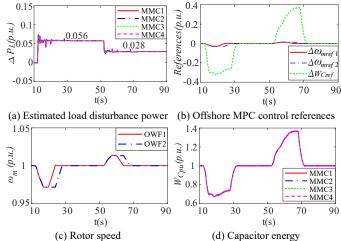


Fig. 12. Performance of the proposed method under successive disturbances.

2) Wind speed variations:

Changing the wind speed of OWF1 from 10.8m/s to 10.3m/s at t=12s, the performances of the proposed distributed method are shown in Fig. 13. Fig. 13 (a) compares the frequency responses of three different control methods. The proposed *D-MPC* method has the same frequency support effect as the *C-MPC* method and improves the frequency nadir by 10% through the utilization of MMC capacitor energy, and by 26% through the utilization of rotor kinetic energy. Meanwhile, there is no severe frequency drop during energy recovery.

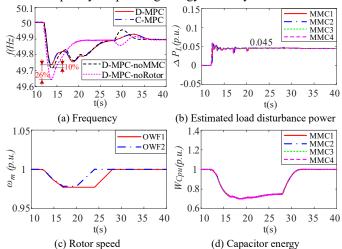


Fig. 13. Performance of the proposed method under wind speed variation.

Fig. 13 (b) shows the estimated power shortage caused by the wind speed change of OWF1, about 4.5%. On this basis, coordinated energy utilization and recovery are also achieved as expected, as shown in Fig. 13 (c) and (d). In summary, the proposed method is still effective in energy coordination and frequency support under wind speed change.

3) Communication time delays:

According to Fig. 4, satellite communication is employed in the proposed *D-MPC* method to sense OWF wind speeds. To test the robustness of the proposed method to communication time delays, two delays of 200ms and 500ms are considered during frequency support. At t=12s, a 180MW load increase is

applied at bus 7. Wind speeds of both OWFs are set to 10.8m/s. To imitate the communication delays process, the wind speed information in the communication system is initially 0m/s at t=12s, then updated to 10.8m/s after delays. As a comparison, the same time delays are also applied when using the C-MPC method.

Fig. 14 (a) and (b) depict the frequency responses under the two methods. As can be seen, since control references are communicated when using the *C-MPC* method, time delays in control references will cause energy utilization errors and affect the frequency support effect, as shown in Fig. 14 (a). However, in Fig. 14 (b), the proposed *D-MPC* method shows robustness against different time delays in communication. That is because for offshore MMCs, the rotor speed control reference of the connected OWF is generated using the estimated wind speed, independent of communications. As a result, time delays in wind speeds will not affect the rotor speed regulation in OWFs, as shown in Fig. 14 (c) and (d).

Although the time delays in communicating wind speeds may cause an error in MPC constraint (15), the delay duration is much smaller than the time required for the rotor speed to reach its limit (up to the second level). Therefore, the safe utilization of the rotor kinetic energy can still be guaranteed.

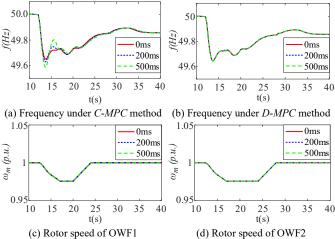


Fig. 14. Performance of the proposed method under communication delays.

VI. CONCLUSION

For OWFs-MTDC systems, this paper proposes a hierarchical energy control framework that utilizes OWF kinetic energy and MMC capacitor energy to optimize grid frequency response. At the upper-layer, the distributed MPC based energy utilization method is developed to optimally dispatch kinetic and capacitor energies. At the lower-layer, an energy coordination control scheme is designed to enhance energy utilization for frequency support, even without extra power reserves.

Simulation results shows that the designed estimators in distributed MPC controller can precisely calculate the grid frequency, load disturbance power, and wind speed. Thus, it causes that the proposed distributed MPC method has the same frequency support effect as the centralized method. Meanwhile, the proposed energy coordination control can reduce frequency deviations by at least 8%. Moreover, the designed energy

recovery strategy ensures that the frequency deviations during the energy recovery are less than the first deviation.

Robustness analysis demonstrates that under two successive load disturbances and wind speed variations, the proposed method is still available to improve the frequency support effect by coordinating multiple energies. Moreover, communication time delays do not affect the frequency support performance of the proposed distributed method.

Although the proposed MPC-based method has demonstrated good performance in this study, future work will focus on further optimizing MPC parameters to improve adaptability and control effectiveness under varying operating conditions.

VII. APPENDIX

TABLE A I

MECHANICAL PARAMETERS OF WIND TURBINE

Parameters	Symbol	Value
Rated wind speed/m·s ⁻¹	W_{s}	10.8
Rated rotor speed/p.u.	ω_m	1.0
Air density/kg·m ⁻³	ho	1.225
Inertia time constant/s	T_{j}	4
turbine blade radius /m	r	63
Number of pole-pairs	N_p	60

TABLE A II
BASIC PARAMETERS OF MMCS

Parameters	MMC1	MMC3	MMC2, MMC4
Rated capacity/MVA	1400	800	1100
Rated DC voltage/kV	± 400	± 400	± 400
Number of SM per arm	400	400	400
SM capacitance/mF	12.27	6.54	9.0
Voltage ratio (line-to-line)/kV	230/416.41	230/416.41	230/416.41
Leakage reactance uk/%	15	15	15

TABLE A III
BASIC PARAMETERS OF SYNCHRONOUS GENERATORS

	Capacity	Inertia constant /s	Terminal voltage	Transformer
	/MW		/kV	ratio
G1~G4	800	3.2	13.8	13.8/230

TABLE A IV
CONTROL PARAMETERS OF SYNCHRONOUS GENERATORS

Elements	Parameters	Symbol	Value
	Inverse of droop /p.u.	R	-20
Governor	Speed relay time constant /s	T_1	0.1
	Servo-motor time constant /s	T_2	0.3
	Steam chest time constant /s	T_3	0.3
	Reheater time constant /s	T_4	10
Turbine	Cross-over constant /s	T_5	0.4
Turbine	K_3 fraction /p.u.	K_3	0.3
	K_4 fraction /p.u.	K_4	0.4
	K_5 fraction /p.u.	K_5	0.3

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BIOGRAPHIES



Haobo Zhang received his B.Eng. and PhD degrees both in electrical engineering from Huazhong University of Science and Technology (HUST), China in 2020 and 2025 respectively. He was a visiting PhD student at the Nanyang Technological University (NTU) from 2023 to 2024. Currently, he is a Research Associate at Cardiff University, UK. His research interests include protection and control of MMC-HVDC and DC grids.



Wang Xiang (S'16-M'17-SM'25) received his B.Eng. and PhD degrees both in electrical engineering from Huazhong University of Science and Technology (HUST), China in 2012 and 2017 respectively. He was a visiting PhD student at the University of Aberdeen and the University of Strathclyde in 2014 and 2016 respectively. He was with the University of Strathclyde from 2018 to 2021. Currently, he is a Professor at School of Electrical and Electronics Engineering, Huazhong University of Science and Technology, China.

His main research interests include MMC-HVDC, high power DC/DC converters, DC grids and offshore wind power integration.



Yining Wang received the B.Eng. degree in electrical engineering and automation from Hunan University (HNU), Changsha, China, in 2022, and she is currently working toward the Ph.D. degree in Huazhong University of Science and Technology (HUST). Her research interests include the grid-forming converter control technology.



Yan Xu (S'10-M'13-SM'19) received the B.E. and M.E. degrees in electrical engineering from the South China University of Technology, Guangzhou, China, in 2008 and 2011, respectively, and the Ph.D. degree in electrical engineering from the University of Newcastle, Callaghan NSW, Australia, in 2013. After the postdoctoral training with the University of Sydney Postdoctoral Fellowship, he joined Nanyang Technological University (NTU) with the Nanyang Assistant Professorship. He was an Associate Professor in 2021, and the Cham Tao Soon Professor in

Engineering (an endowed professorship named after the founding president of NTU) in 2024. He is currently the Director with Center for Power Engineering (CPE), and Co-Director with Singapore Power Group-NTU Joint Lab, with NTU. His research interests include power system stability and control, microgrids, and data-analytics for smart grid applications. Dr Xu was the recipient of the Nanyang Research Award (Young Investigator) by NTU, and the Outstanding Engineer Award by IEEE Power & Energy Society (PES) Singapore Chapter. He is an Associate Editor for IEEE TRANSACTIONS on SMART GRID and IEEE TRANSACTIONS on POWER SYSTEMS, Chairman of IEEE PES Singapore Chapter (2021 and 2022), and the General Co-Chair of the 11th IEEE ISGT Asia Conference in 2022.



Jinyu Wen (M'10-SM'25) received his B.Eng. and Ph.D. degrees all in electrical engineering from Huazhong University of Science and Technology (HUST), Wuhan, China, in 1992 and 1998, respectively. He was a visiting student from 1996 to 1997 and research fellow from 2002 to 2003 all at the University of Liverpool, UK, and a senior visiting researcher at the University of Texas at Arlington, USA in 2010. From 1998 to 2002 he was a director engineer in XJ Electric Co. Ltd. in China. In 2003 he joined the HUST and now

is a Professor at HUST. His current research interests include renewable energy integration, energy storage application, DC grid, and power system operation and control.