

Multi-source Communication-less Coordinated Frequency Support of DRU-HVDC-based Offshore Wind Power Integration Systems

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Abstract—This paper presents a frequency support strategy for the diode rectifier unit (DRU)-high-voltage direct current (HVDC)-based offshore wind power integration system, which coordinates multiple power sources without communication to reduce receiving grid frequency fluctuations. First, based on the deduced DRU's frequency transfer characteristic, a fine-designed ripple carrying frequency information is superimposed on the HVDC link, transferring the onshore frequency to offshore wind turbines (WTs) via the DC ripple and coupled AC harmonic without communication. Second, multiple power sources are utilized for frequency support, including HVDC capacitance and grid-forming WTs combined with energy storage systems, and appropriate sources are activated in the order specified by the designed thresholds. Finally, the effectiveness of the proposed frequency support strategy is verified by simulations in PSCAD/EMTDC.

Index Terms—Diode rectifier unit, frequency support, grid-forming wind turbine, high voltage direct current transmission, offshore wind farm.

I. INTRODUCTION

EXPLOITING superior wind resources of distant offshore projects requires reliable and economical grid integration technologies [1], [2]. To date, offshore wind farms over 80 km are integrated mainly by the modular multilevel converter (MMC)-based high voltage direct current (HVDC) system [3]. The offshore MMC is a voltage source converter (VSC) and serves as an offshore AC voltage source [4]–[6]. In this way, wind turbines (WTs) operate in conventional grid-following mode and maintain synchronization by the phase-locked loop (PLL). However, the MMC-HVDC scheme has the disadvantage of a huge and costly offshore MMC platform [7]. With the continuous growth in transmission capacity and distance, the

scale and construction difficulty of offshore MMC platforms are increasing, posing economic and technical challenges for distant offshore wind power development.

Recently, light-weight and low-cost offshore converters have become a research hotspot [8]–[10]. Suggested as a feasible alternative to the offshore MMC, the diode rectifier unit (DRU) offers the advantages of higher reliability, smaller loss, and lower cost [11]. By replacing the MMC rectifier with the DRU, the volume and cost of the offshore platform can be significantly reduced by 80% and 30% [12]. Thus, the DRU-HVDC scheme becomes a promising solution for large-capacity long-distance offshore wind power integration. However, the line-commutated DRU requires an external AC voltage source and lacks active control. To establish offshore AC voltage, one technical approach is to install voltage-source equipment to provide centralized support for offshore AC voltage [13]–[17], but the additional device may diminish the economic benefits of the DRU. To maintain the lightweight of the DRU platform, WTs are converted to grid-forming mode to achieve decentralized control of offshore AC voltage [18]–[24], including PLL-based and reactive power-frequency droop-based grid-forming strategies.

With the increasing capacity of grid-connected wind farms, the inherent intermittency and randomness of wind power bring challenges to the frequency stability of the onshore receiving AC grid. Since the WT mechanical side is decoupled from the receiving grid by the WT converter and the HVDC system, the WT mechanical inertia is imperceptible to the receiving grid. Thus, as wind farms replace fossil-fuel power plants, the overall inertia of the future power grid will decrease. As a result, the grid frequency variation will be larger than before if WTs provide no frequency support, and unacceptable frequency offsets beyond the specified tolerance can occur. Therefore, wind farms are expected to provide frequency support services for the receiving grid.

With appropriate additional controls, it is possible to force the HVDC-connected wind farm to contribute to grid inertia. A frequency support strategy of HVDC-connected WTs was first proposed in [25], [26], where the receiving grid frequency is transmitted to WTs by communication. To avoid remote communication, several communication-less frequency-support strategies for VSC-HVDC-based wind farms were proposed in [27]–[29]. Despite subtle differences, these communication-less strategies share a core feature: the

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wind farm frequency is controlled by the VSC rectifier in response to the HVDC voltage amplitude, which is in turn controlled by the VSC inverter in response to the receiving grid frequency. In this way, remote WTs can sense the receiving grid frequency locally without communication or active power control to achieve frequency support.

However, existing communication-less frequency-support methods for VSC-HVDC-transmitted wind farms are unsuitable for DRU-HVDC scenarios due to fundamental differences between the DRU and the VSC. Unlike the VSC, the line-commutated DRU has no active control ability. Thus, although the onshore frequency can be transferred to the DRU platform via the controlled HVDC voltage amplitude, the uncontrollable DRU cannot further transmit frequency information to each WT.

To achieve frequency support for the DRU-HVDC-based offshore wind farm, communication is required in existing methods. Reference [30] directly communicated the onshore frequency to offshore WTs. To reduce reliance on communication, the onshore frequency was transmitted via fluctuations in the HVDC voltage amplitude [31], [32] or the AC voltage amplitude [33]. In this way, communication from the onshore grid to the offshore platform was eliminated, but offshore communication from the offshore platform to each WT was still necessary. Besides, the offshore AC voltage amplitude in the DRU-based system varied with the varying wind active power and could not accurately convey frequency information [34]. The above methods based on hundreds of kilometers of communication challenge the real-time property, reliability, and cost of frequency support. Especially for long-distance large-capacity offshore wind power scenarios, a reliable and efficient solution is essential for frequency support. To improve timeliness and reliability, [35] used a small disturbance voltage to deliver onshore frequency without communication. However, the selection of an appropriate small disturbance frequency is not considered, and only the WT rotor's kinetic energy is used for inertia support.

To fill the research gap, a multi-source communication-free coordinated frequency-support strategy for a DRU-HVDC-based offshore wind power integration system is proposed for the first time in this paper. The main contributions of this study are summarised as follows.

1) Based on the deduced frequency transfer characteristic of the DRU, a communication-less frequency transfer strategy is proposed by superimposing a ripple current reflecting onshore frequency on the HVDC link, thereby transferring onshore frequency to offshore WTs via DC ripple and coupled AC harmonic. The ripple current frequency is fine-tuned to account for attenuation and inherent frequencies.

2) A multi-source coordinated frequency support strategy is proposed to fully utilize frequency support capabilities of the HVDC capacitance and grid-forming WTs combined with energy storage systems. By designing thresholds, multiple sources can participate in frequency support in an orderly manner according to the receiving grid's disturbance level, ensuring offshore wind energy utilization while providing frequency support.

The remainder of this paper is organized as follows. In Section II, the topology of DRU-HVDC-based offshore wind power integration is described. The communication-less frequency transfer strategy is proposed in Section III. Section IV presents the multi-source coordinated frequency support strategy. The simulation verification is performed in Section V. Section VI summarizes the findings.

II. TOPOLOGY OF DRU-HVDC-BASED OFFSHORE WIND POWER INTEGRATION SYSTEM

The offshore wind farm integrated via the DRU-based HVDC system is illustrated in Fig. 1. The large-capacity offshore wind farm includes numerous WTs. Offshore wind power is gathered to the point of common coupling (PCC) through AC collecting submarine cables and transmitted to the onshore grid via the DRU rectifier, long-distance HVDC submarine cables, and the MMC inverter.

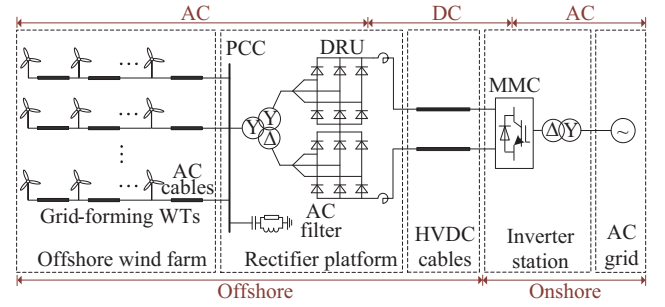


Fig. 1. Topology of DRU-HVDC-based offshore wind power integration.

Since the DRU is uncontrollable and requires an external AC voltage source to provide commutation voltage, WTs operate in grid-forming mode to control the AC voltage amplitude and frequency of the offshore system. In the DRU-based offshore wind farm scenario, the grid-forming WT employs two control couplings, namely active power-voltage amplitude and reactive power-frequency. This special collocation of control variables can be selected by sensitivity analysis of the WT control variables [34]. The MMC controls the DC voltage of the HVDC system.

III. COMMUNICATION-LESS FREQUENCY TRANSFER STRATEGY

A. Frequency Transfer Characteristic of DRU

Modulation theory can be utilized to calculate the frequency transfer characteristic of the converter [36], [37]. By modulating the DC current with the switching function, the three-phase AC current of the DRU can be obtained as follows:

$$\begin{cases} i_a = i_{dc} S_a \\ i_b = i_{dc} S_b \\ i_c = i_{dc} S_c \end{cases} \quad (1)$$

where i_a , i_b , and i_c are each phase of the AC current of the DRU; i_{dc} is the DC current instantaneous value of the DRU; S_a , S_b , and S_c are each phase of the switching function.

The switching function is related to the conducting state of each phase diode. If the overlap angle is ignored, the switching function is a series of square waves, whose amplitude varies from 1 to 0 when the diode switches from on to off. Considering the commutation process, the switching function of a 6-pulse DRU can be simply modified as slash lines during commutation as plotted in Fig. 2. Therein, f_{off} is the fundamental frequency of the offshore AC system, and μ is the overlap angle of the DRU.

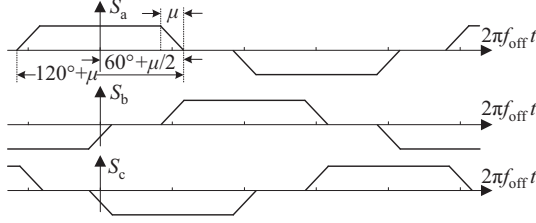


Fig. 2. Switching function of a 6-pulse DRU with commutation overlap.

The 12-pulse DRU, consisting of two 6-pulse DRUs with a phase difference of 30° on the AC side, as shown in Fig. 1, is adopted to reduce characteristic harmonics. Based on Fig. 2, the Fourier series of the switching function of the 12-pulse DRU can be expressed as follows:

$$\begin{cases} S_a = \sum_{n=1}^{\infty} A_n \cos n2\pi f_{\text{off}} t \\ S_b = \sum_{n=1}^{\infty} A_n \cos n \left(2\pi f_{\text{off}} t - \frac{2\pi}{3} \right) \\ S_c = \sum_{n=1}^{\infty} A_n \cos n \left(2\pi f_{\text{off}} t + \frac{2\pi}{3} \right) \end{cases} \quad (2)$$

where the Fourier coefficient A_n satisfies

$$A_n = \frac{4}{\pi} \frac{1}{n} \sin \frac{n\pi}{2} \cos \frac{n\pi}{6} \frac{\sin(n\mu/2)}{n\mu/2} \cdot \left(\frac{1}{2} + \frac{1}{\sqrt{3}} \cos \frac{n\pi}{6} \right) \quad (3)$$

In general, the DC current instantaneous value i_{dc} of the DRU can be described as follows:

$$i_{\text{dc}} = I_{\text{dc}} + \sum_{h=1}^{\infty} i_{\text{dch}} = I_{\text{dc}} + \sum_{h=1}^{\infty} I_{\text{dch}} \cos(2\pi f_{\text{dch}} t + \phi_{\text{dch}}) \quad (4)$$

where I_{dc} is the smoothing DC component of the DC current; i_{dch} is the h^{th} ripple current in the DC current; I_{dch} , f_{dch} , and ϕ_{dch} are the amplitude, frequency, and initial phase of i_{dch} , respectively.

Submitting (2)–(4) into (1), the phase-a AC current of the DRU is calculated as follows:

$$\begin{aligned} i_a = & I_{\text{dc}} \sum_{n=1}^{\infty} A_n \cos n2\pi f_{\text{off}} t \\ & + \sum_{h=1}^{\infty} \sum_{n=1}^{\infty} \frac{I_{\text{dch}} A_n}{2} \{ \cos[2\pi(f_{\text{dch}} + n f_{\text{off}})t + \phi_{\text{dch}}] \\ & + \cos[2\pi(f_{\text{dch}} - n f_{\text{off}})t + \phi_{\text{dch}}] \} \end{aligned} \quad (5)$$

The first term of (5) represents the fundamental and characteristic harmonics of the AC current. It is noticed from (3) that A_n is not 0 only if $n = 12k \pm 1$ ($k = 0, 1, 2, \dots$). Thus,

the orders of the characteristic harmonic AC currents of the 12-pulse DRU are $12k \pm 1$. The second term of (5) contains non-characteristic harmonic AC currents, which are generated by ripples in the DC current and transferred from the DC side to the AC side through the DRU. The frequencies of non-characteristic harmonic AC currents are $|f_{\text{dch}} \pm (12k \pm 1) f_{\text{off}}|$. Therein, it is obvious that only the first term with frequencies of $|f_{\text{dch}} \pm f_{\text{off}}|$ is notable, while the other higher harmonics are too small to be noticed. Therefore, the coupled harmonic AC current transferred from the h^{th} DC side ripple can be simplified as follows:

$$\begin{cases} i_{ha} = k_{\text{dc-ac}} I_{\text{dch}} \{ \cos[2\pi(f_{\text{dch}} + f_{\text{off}})t + \phi_{\text{dch}}] \\ \quad + \cos[2\pi(f_{\text{dch}} - f_{\text{off}})t + \phi_{\text{dch}}] \} \\ i_{hb} = k_{\text{dc-ac}} I_{\text{dch}} \{ \cos[2\pi(f_{\text{dch}} + f_{\text{off}})t + \phi_{\text{dch}} - 2\pi/3] \\ \quad + \cos[2\pi(f_{\text{dch}} - f_{\text{off}})t + \phi_{\text{dch}} + 2\pi/3] \} \\ i_{hc} = k_{\text{dc-ac}} I_{\text{dch}} \{ \cos[2\pi(f_{\text{dch}} + f_{\text{off}})t + \phi_{\text{dch}} + 2\pi/3] \\ \quad + \cos[2\pi(f_{\text{dch}} - f_{\text{off}})t + \phi_{\text{dch}} - 2\pi/3] \} \end{cases} \quad (6)$$

where i_{ha} , i_{hb} , and i_{hc} are each phase of the harmonic AC current i_h transferred from i_{dch} . The amplification factor of current amplitude $k_{\text{dc-ac}}$ satisfies

$$k_{\text{dc-ac}} = \frac{2\sqrt{3} \sin(\mu/2)}{\pi \mu} \quad (7)$$

As can be seen from (6), the h^{th} ripple current on the DC side will generate two dominant non-characteristic harmonic currents on the AC side of the DRU; one is positive-sequence with the frequency of $(f_{\text{dch}} + f_{\text{off}})$, and the other is negative-sequence with the frequency of $|f_{\text{dch}} - f_{\text{off}}|$. The amplitudes of two dominant non-characteristic AC harmonics are equal and do not vary with the frequency of the DC side ripple. The amplification factor $k_{\text{dc-ac}}$ of the harmonic current amplitude from the DC side to AC side is 0.55 approximately.

B. Frequency Transfer Strategy

Since the offshore wind farm is decoupled from the onshore receiving grid via the HVDC system, it is essential to transfer the onshore frequency to the offshore WTs manually. To avoid the defects of timeliness, reliability, and economy associated with long-distance communication, electrical quantities in the HVDC link can be used to carry frequency signals.

Based on the deduced frequency-transfer characteristic of the DRU, a frequency-transfer strategy without communication can be achieved by superimposing an appropriately small-ripple current with frequency information on the DC current. The frequency of the ripple current i_{dch} is set as $k_f f_{\text{on}}$, where k_f is the proportional coefficient of the ripple frequency to the onshore frequency f_{on} . According to (6), the DC ripple current i_{dch} can be transferred through the DRU to the AC side and causes the harmonic AC current i_h with frequencies of $|k_f f_{\text{on}} \pm f_{\text{off}}|$. This harmonic AC current carrying onshore frequency information can spontaneously transmit throughout the offshore wind farm. Therefore, each WT can detect corresponding harmonic voltage u_h with frequencies of $|k_f f_{\text{on}} \pm f_{\text{off}}|$ at the WT AC port and obtain the onshore frequency locally. By this means, the onshore frequency can be transferred to offshore WTs through the DC side ripple and AC side harmonic as illustrated in Fig. 3.

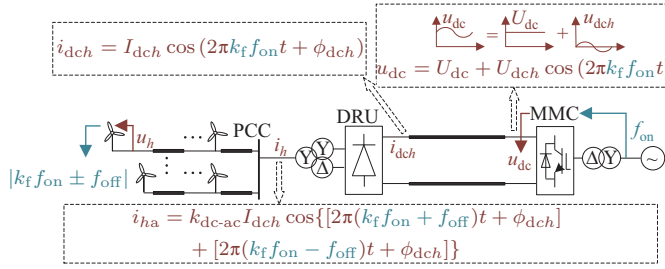


Fig. 3. Process of communication-less onshore frequency transfer.

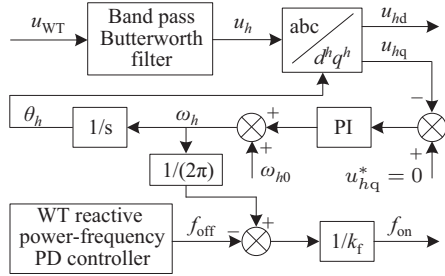


Fig. 4. Block diagram of onshore frequency extraction of WT.

The method of extracting the onshore frequency f_{on} from the AC voltage u_{WT} at the WT AC port is presented in Fig. 4. First, the harmonic voltage u_h is extracted from the WT AC port voltage u_{WT} through a band-pass filter. Second, the $abc-d^h q^h$ reference frame transformation is adopted, transforming the harmonic voltage from the three-phase static reference frame to the $d^h q^h$ reference frame rotating at the speed of ω_h , which is the harmonic angular frequency of u_h . By the $abc-d^h q^h$ transformation, only the h^{th} harmonic component with the frequency of ω_h can be transformed into the DC component in the $d^h q^h$ reference frame, while the other components become AC components. Third, by controlling the output harmonic phase θ_h , the q^h -axis harmonic component u_{hq} keeps track of its reference value u_{hq}^* of 0 under proportional-integral (PI) control, thereby locking the angular frequency ω_h of the harmonic voltage space vector. The rated harmonic angular frequency ω_{h0} is added to accelerate the phase locking speed. Finally, the detected harmonic frequency comprises both the offshore and transferred onshore frequencies, so the onshore frequency can be obtained by subtracting the offshore frequency. It should be noted that the offshore frequency f_{off} is controlled by the reactive power-frequency proportional-differential (PD) controller of the grid-forming WT, and f_{off} fluctuates slightly rather than being fixed at the rated value.

To generate the DC ripple current, a DC ripple voltage is added to the HVDC voltage controlled by the MMC. As illustrated in Fig. 5, the MMC measures the AC voltage u_{mmc} and obtains the onshore frequency f_{on} through the PLL. Considering that the offshore wind farm does not need to participate in onshore frequency support when frequency fluctuations are very small, an acceptable frequency deviation is set as ε_{dc} . If the frequency deviation from the rated onshore frequency f_{on0} exceeds $(-\varepsilon_{dc}, \varepsilon_{dc})$, the ripple voltage u_{dch} is added to the modulation loop. In this way, the MMC can control both the DC voltage-smoothing component and the

onshore frequency information carried by the DC ripple. The controlled HVDC voltage can be described as follows:

$$u_{dc} = U_{dc} + u_{dch} = U_{dc} + U_{dch} \cos(2\pi k_f f_{on} t) \quad (8)$$

where u_{dc} is the HVDC voltage instantaneous value; U_{dc} is the smoothing DC component; u_{dch} and U_{dch} are the instantaneous value and amplitude of the ripple voltage, respectively.

In Fig. 5, u_{pj}^* and u_{nj}^* ($j = a, b, c$) are three-phase voltage references of the upper arm and the lower arm of the MMC, respectively; u_{comj}^* and u_{diffj}^* ($j = a, b, c$) are three-phase common-mode and difference-mode voltage references, respectively; U_{dc}^* is the reference of the smoothing DC component of the HVDC voltage.

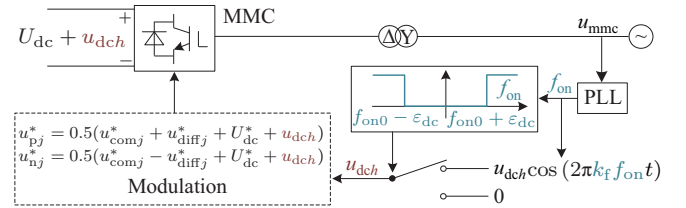


Fig. 5. Frequency transfer control strategy of MMC.

C. Design of Additional Ripple

According to the proposed communication-less frequency transfer strategy, the onshore frequency is transferred by the DC ripple and the corresponding AC harmonic. To achieve accurate frequency transfer and minimize impact on the system's normal operation, it is necessary to design the additional ripple's frequency appropriately.

First of all, to avoid being affected by inherent frequency components, the ripple frequency should not be close to the fundamental and characteristic harmonic frequencies of the DRU-based offshore system, as listed below.

1) The wind active power varies slowly when wind speed changes, causing the amplitudes of the DC current and offshore AC current to fluctuate at low frequencies. Thus, the frequency $k_f f_{on}$ of the DC ripple should not be too low.

2) The DRU and WTs are AC harmonic sources. The characteristic harmonics of WTs mainly include 2nd, 3rd, 5th, and 7th [38], and the DRU generates $(12k \pm 1)^{\text{th}}$ characteristic harmonics. Therefore, the frequency $|k_f f_{on} \pm f_{off}|$ of the AC harmonic raised by the DC ripple should be away from the 2nd, 3rd, 5th, 7th, and $(12k \pm 1)^{\text{th}}$ harmonic frequencies.

Besides, since the capacitance of cables is generally 20 to 40 times larger than that of overhead lines, while the series impedance of cables is only 50% to 100% of that of overhead lines [38], cables exhibit a strong capacitive character. As frequency increases, the cable capacitance remains unchanged, while its shunt reactance decreases. Thus, the ripple current at a higher frequency is more easily grounded through the cable's distributed capacitance. Taking a typical submarine cable of 250 km in the case system's HVDC link as an example, when the ripple voltage of different frequencies is added on the inverter side, the ratio of the amplitude of the ripple currents on the rectifier and inverter side is plotted in Fig. 6. It can be seen that the higher the ripple frequency, the more obvious

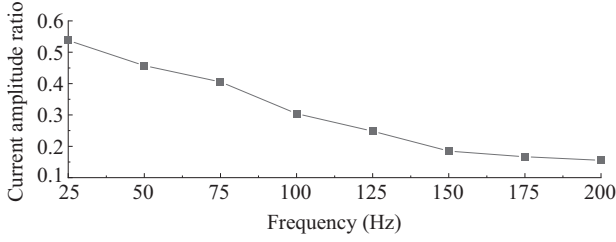


Fig. 6. Amplitude ratio of ripple currents on the rectifier and inverter side.

the filtering effect of the distributed capacitance, and the more significant the attenuation of the ripple current in the cable. Therefore, to avoid significant attenuation of the ripple current-carrying frequency information and to ensure that WTs detect sufficient harmonics, the frequency of the additional ripple current is preferably small.

In summary, the ripple frequency should be small and far from fundamental and characteristic harmonic frequencies, so it is selected as 25 Hz here. Since the ripple current attenuation is small at the optimized ripple frequency, the ripple voltage amplitude required to generate the ripple current can be set to 0.01 p.u. (with the base value of rated HVDC voltage) to minimize the impact on system operation.

IV. MULTI-SOURCE COORDINATED FREQUENCY SUPPORT STRATEGY

To maximize the frequency-support capability of the DRU-HVDC-based offshore wind power integration system, multiple power sources with frequency-support capacity can be fully utilized, including HVDC link capacitance, grid-forming WTs, and energy storage systems. Besides, only local signals are needed to determine the onshore frequency for these sources. Further, a coordination strategy is proposed to orderly activate frequency supports from each source to improve reliability and economy.

A. Inertia Support from HVDC Link Capacitance

The DRU-HVDC link contains a large amount of capacitance, mainly including the distributed capacitance in HVDC cables and submodule capacitors in the MMC. The HVDC link capacitance can store electrostatic energy. The dynamic of the HVDC capacitance can be described as follows:

$$C_{dc}U_{dc}\frac{dU_{dc}}{dt} = P_{in} - P_{out} = \Delta P_{dc} \quad (9)$$

where C_{dc} is the total capacitance of the HVDC link; P_{in} and P_{out} are the input and output active powers of the HVDC link, respectively; ΔP_{dc} is the power absorbed or released by the capacitance during voltage changes. It is indicated that the stored energy in capacitance varies with the HVDC voltage.

It is well known that a synchronous generator can spontaneously absorb or release rotor kinetic energy to smooth frequency fluctuations. This process is expressed as follows:

$$\frac{2H_{SG}}{f_{on0}}\frac{df_{on}}{dt} = P_T - P_E = \Delta P_{SG} \quad (10)$$

where H_{SG} is the inertia time constant of the generator; P_T and P_E are the mechanical and electric powers of the

generator, respectively; ΔP_{SG} is the changing kinetic power during the dynamic.

By analogy with (9) and (10), the dynamic of the electrostatic energy stored in HVDC capacitance is similar to the dynamic of the kinetic energy stored in the mechanical rotor. Specifically, the HVDC input power is analogous to the generator mechanical power, the HVDC output power is analogous to the generator electromagnetic power, and the changing HVDC voltage corresponds to the changing rotor speed. Equating the available powers in (9) to (10) yields

$$C_{dc}U_{dc}\frac{dU_{dc}}{dt} = \frac{2H_{dc}}{f_{on0}}\frac{df_{on}}{dt} \quad (11)$$

where H_{dc} is the equivalent inertia constant of the HVDC link capacitance. Integrating both sides of (11) yields

$$\int_{U_{dc0}}^{U_{dc}} C_{dc}U_{dc}\frac{dU_{dc}}{dt} = \int_{f_{on0}}^{f_{on}} \frac{2H_{dc}}{f_{on0}}\frac{df_{on}}{dt} \quad (12)$$

$$\frac{C_{dc}}{2}(U_{dc}^2 - U_{dc0}^2) = \frac{2H_{dc}}{f_{on0}}(f_{on} - f_{on0}) \quad (13)$$

where U_{dc0} is the rated value of the HVDC voltage.

Transforming (13) to obtain the voltage reference U_{dc}^* for the MMC controller yields

$$U_{dc}^* = \sqrt{\frac{4H_{dc}}{C_{dc}}\left(\frac{f_{on}}{f_{on0}} - 1\right) + U_{dc0}^2} \quad (14)$$

In (14), the onshore frequency is measured by the PLL of the MMC. By controlling the HVDC voltage amplitude according to the onshore frequency, the stored energy in HVDC link capacitance is utilized. A larger inertia constant H_{dc} can mobilize more capacitance energy but causes larger HVDC voltage variation. In practice, the HVDC voltage can only vary within a small range, for example $\pm 10\%$ around the rated value. Thus, the capacitance energy is limited and can only provide short-term inertia support for the onshore grid.

B. Inertia Support from Grid-Forming WTs

The full-rated converter type WT, with a permanent magnet synchronous generator (PMSG), a machine-side converter (MSC), and a grid-side converter (GSC), is currently the mainstream choice for distant offshore wind farms. For WTs operating in the conventional grid-following mode or the grid-forming mode in [35], the MSC controls the output active power, and the DC voltage of WT converters is controlled by the GSC. By this means, the output active power is controlled on the mechanical side and then transmitted to the grid side by maintaining the DC voltage constant, resulting in slower active power control. By altering the MSC's active power reference, the rotor speed is adjusted to release or absorb kinetic energy. However, the DC capacitor of WT converters does not participate in frequency support.

According to (11), the electrostatic energy stored in the WT DC capacitor can also be used to support inertia. To take full advantage of frequency support resources in the WT, for the grid-forming WT in this paper, the output active power control function is moved from the MSC to the GSC, while the MSC undertakes DC voltage control. In this way, the output

active power is directly controlled on the grid side, with faster response. What is more, by controlling the GSC's active power in response to frequency variations, both the rotor speed and the DC voltage of the WT are adjusted, thereby releasing or absorbing part of the turbine rotor's kinetic energy and the DC capacitor's electrostatic energy. The comparison of the frequency-support power sources for grid-following and grid-forming WTs is shown in Fig. 7.

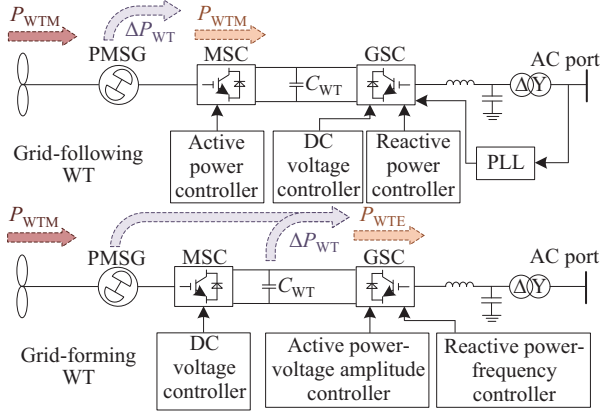


Fig. 7. Frequency support sources of grid-following and grid-forming WTs.

In Fig. 7, P_{WTM} and P_{WTE} are the input mechanical and output electric powers, respectively; ΔP_{WT} is the available inertia support power from WT; C_{WT} is the DC capacitor of WT converters. The dynamic of the grid-forming WT, whose output active power is controlled by the MSC, can be described as follows:

$$\frac{2H_{WTM}}{\omega_{WTM0}} \frac{d\omega_{WTM}}{dt} + C_{WT} U_{WTdc} \frac{dU_{WTdc}}{dt} = P_{WTM} - P_{WTE} = \Delta P_{WT} \quad (15)$$

where H_{WTM} is the inertia time constant of the turbine rotor; ω_{WTM} and ω_{WTM0} are the actual and rated values of the turbine rotor speed, respectively; U_{WTdc} is the DC voltage of the WT converters. Combining (10) and (15) yields

$$\frac{2H_{WTM}}{\omega_{WTM0}} \frac{d\omega_{WTM}}{dt} + C_{WT} U_{WTdc} \frac{dU_{WTdc}}{dt} = \frac{2H_{WT}}{f_{on0}} \frac{df_{on}}{dt} \quad (16)$$

where H_{WT} is the equivalent inertia constant of the WT.

To maximize the use of captured wind energy, WTs mainly operate in maximum power point tracking (MPPT) mode and provide no reserve capacity. Under the premise of maintaining the efficient MPPT mode, the original active power reference P_{MPPT}^* generated by the MPPT strategy is retained, and an auxiliary active power reference P_{WTF}^* in response to frequency variations is added to P_{MPPT}^* . The modified active power reference P_{WTE}^* is expressed as follows:

$$P_{WTE}^* = P_{MPPT}^* + P_{WTF}^* \quad (17)$$

From the controller perspective, to emulate both the inertial response and speed governor response of synchronous generators for better frequency support effect, the auxiliary power

reference P_{WTF}^* is generated by combining the inertia control and the droop control as follows:

$$P_{WTF}^* = -k_{iW} \frac{df_{on}}{dt} - k_{dW} (f_{on} - f_{on0}) \quad (18)$$

where k_{iW} and k_{dW} are proportional coefficients of the inertia and droop control, respectively. Based on the proposed communication-less frequency transfer strategy, the onshore frequency in (18) is detected from the specific harmonic voltage at the WT AC port.

In this way, by mobilizing the turbine rotor's kinetic energy and the DC capacitor's electrostatic energy, grid-forming WTs can provide fast, short-term inertia support under MPPT mode, without wind power curtailment to retain reserve capacity. To achieve primary frequency regulation by WTs, it is necessary to retain long-term reserve capacity by de-loading control, primarily overspeed de-loading and variable-pitch de-loading. However, de-loading operations cause WTs to deviate from the MPPT state and reduce the economic benefits of long-term operation. Besides, constrained by inevitable changes in wind speed, the reliability of variable-speed WTs participating in primary frequency regulation is poor. To address this limitation, energy storage technology can serve as an auxiliary frequency support method for wind farms due to its accurate power tracking and fast response, as discussed in the following section.

C. Inertia Support and Primary Frequency Regulation from Energy Storage Sources in WTs

There is a growing desire to integrate energy storage systems (ESSs) with large-capacity wind farms [39], as ESSs can improve wind power integration performance to meet grid code requirements and provide the essential black-start energy for DRU-based grid-forming WTs. In terms of frequency support, the ESS can enhance the frequency support capability and maintain the operation efficiency of wind farms.

Compared with the centralized ESS on the offshore platform, distributed ESSs installed in WTs offer flexible modular control and better offshore AC fault ride-through capability, without increasing the offshore platform volume. Due to its high power density, fast response, and easy maintenance, the supercapacitor energy storage system (SCESS) is a type of ESSs suitable for remote offshore wind power applications [40]. Since the supercapacitor is charged and discharged in DC, the SCESS is preferable to connect to the DC bus of WT back-to-back converters through a DC/DC converter.

Since the MSC continuously controls the DC voltage of WT back-to-back converters, the SCESS can operate in active power control mode to achieve accurate, fast power tracking. The active power controller adopts proportional-integral control to track active power and generate the voltage reference for modulation. To provide both inertia support and primary frequency regulation, the active power reference P_{SC}^* of the SCESS is designed as follows:

$$P_{SC}^* = -k_{iS} \frac{df_{on0}}{dt} - k_{dS} (f_{on} - f_{on0}) \quad (19)$$

where k_{iS} and k_{dS} are proportional coefficients, which represent the active power distribution for inertia support and

primary frequency regulation, respectively. The onshore frequency is transferred to WT AC port without communication. In the valve control layer, the state of charge of the SCESS should be considered to avoid overcharging or overdischarging, which has been widely studied and will not be covered here.

D. Multi-source Coordinated Strategy

As discussed before, frequency support sources in the DRU-based offshore wind power integration system include the HVDC link capacitance, grid-forming WTs, and SCESSs. The multi-source control strategy is elaborated in Fig. 8. Therein, P_{MMC} , Q_{MMC} , and i_{MMC} are the output active power, reactive power, and AC current of the MMC, respectively; P_{WTE} and Q_{WTE} are output active and reactive powers of the WT, respectively; u_{WT} is the voltage at the WT AC port; u_v and i_v are the voltage and current on the AC side of GSC, respectively; u_g and i_g are the voltage and current on the AC side of MSC, respectively; θ_v and θ_g are phases of the GSC and MSC, respectively; the superscript * denotes the reference values; and subscripts d and q denote the d -axis and q -axis components, respectively.

As shown in Fig. 8, the basic function of the onshore MMC is to maintain the HVDC voltage and output reactive power. To exploit the inertia support capability of the HVDC capacitance, the HVDC voltage reference of the MMC is set to change with the onshore frequency as in (14). To achieve frequency transfer without communication, the DC ripple voltage in (8) is added to the modulation loop of the MMC. As for the WT GSC, the active power-voltage amplitude controller uses proportional-integral control to track the active power reference accurately, and the additional active power reference in (18) is added to the MPPT reference to provide inertia support. Since grid-forming WTs serve as reactive power balancing nodes in the DRU-based offshore system, the reactive power-frequency loop of the WT GSC is designed as a proportional-differential controller, so the WT reactive power can fluctuate to maintain the offshore reactive power balance under varying active power levels. The MSC controls the DC voltage of the WT converters. The SCESS tracks its output active power reference as in (19) to provide inertia support and primary frequency

regulation. The control parameters for these frequency-support strategies for multiple sources are listed in Table I.

TABLE I
CONTROL PARAMETERS OF THE MULTI-SOURCE FREQUENCY SUPPORT STRATEGY

Parameters	Values (p.u.)
Equivalent inertia constant of HVDC capacitance H_{dc}	0.8
Proportional coefficient of inertia control of WT k_{iW}	0.1
Proportional coefficient of droop control of WT k_{dW}	0.2
Proportional coefficient of inertia support of SCESS k_{iS}	0.1
Proportional coefficient of primary frequency regulation of SCESS k_{dS}	0.2

To activate these frequency support sources, one strategy is to enable them simultaneously once frequency deviations occur. Although this strategy can fully leverage all frequency support capabilities, the offshore wind farm and HVDC system would be often involved in frequency support even for small disturbances. As a result, the operating condition of the wind power transmission system is constantly deviating from the stable operating point, damaging the economy and stability of the system operation.

To solve the aforementioned problem, a coordination strategy that can orderly activate each frequency support source is proposed as shown in Fig. 9, where Δf_{on} is the onshore frequency deviation; ε_{dc} , ε_{WT} , and ε_{SC} are start-up thresholds of the HVDC link, WT, and SCESS participating in frequency support, respectively; T_{dc} and T_{WT} are the time of active power rise during inertia support of the HVDC link and WT, respectively; T_{SC} is the time of active power rise during primary frequency regulation of the SCESS. Based on cascading start-up thresholds and the locally measured frequency deviation, each frequency support source can assess the disturbance level of the receiving grid and then provide frequency support accordingly. In this way, it not only improves the frequency stability of the receiving grid but also ensures the operational stability and economic efficiency of the wind power transmission system.

As elaborated in Fig. 9, considering economy and transmission distance, the electrostatic energy stored in HVDC link capacitance is firstly utilized for onshore grid inertia support. If the onshore frequency deviation still exceeds the threshold,

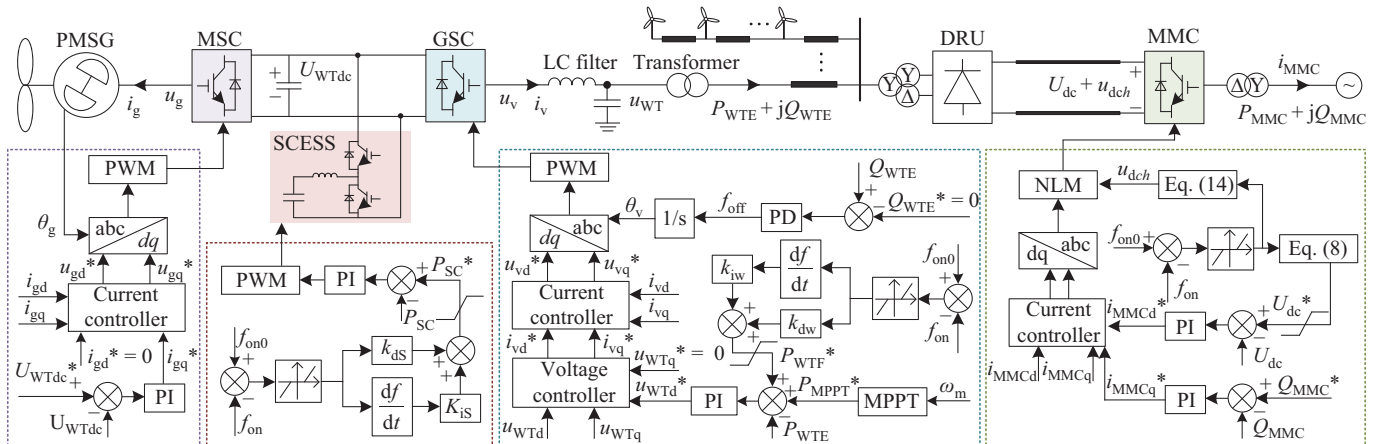


Fig. 8. Control block diagram of multi-source frequency support of the DRU-HVDC-based offshore wind power system.

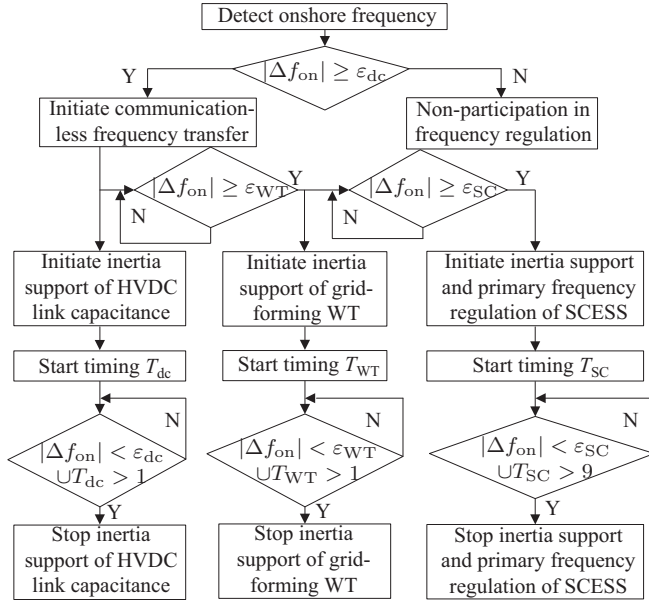


Fig. 9. Flow chart of multi-source coordinated frequency support.

then WT inertia is exerted. The inertia capacity of the HVDC link capacitance and the WT is limited. Finally, the SCESS is activated, providing inertia support and smooth primary frequency regulation after the HVDC link capacitance and WT inertia supports, and avoiding a secondary frequency dip during the recovery of the DC voltage and the WT rotor speed. The equivalent inertia constant of the SCESS is denoted as H_{SC} , and the overall virtual inertia constant H_{WS} of the DRU-HVDC-based offshore wind power integration system is given as follows:

$$H_{WS} = \begin{cases} 0, & |\Delta f_{on}| < \varepsilon_{dc} \\ H_{dc}, & \varepsilon_{dc} \leq |\Delta f_{on}| < \varepsilon_{WT} \\ H_{dc} + H_{WT}, & \varepsilon_{WT} \leq |\Delta f_{on}| < \varepsilon_{SC} \\ H_{dc} + H_{WT} + H_{SC}, & |\Delta f_{on}| \geq \varepsilon_{SC} \end{cases} \quad (20)$$

According to the China grid code for connecting wind farms to the power system, the deadband for inertia support and primary frequency regulation from the wind farm integration system is recommended to be between 0.03 Hz and 0.1 Hz. Thus, ε_{dc} , ε_{WT} , and ε_{SC} are set as 0.03 Hz, 0.05 Hz, and 0.1 Hz here, respectively. The time limits for active power during inertia support and for primary frequency are set to 1 s and 9 s, respectively. Besides, the recommended increase in active power for primary frequency regulation is 6% of the wind active power, so the capacity of the SCESS is set to 0.1 p.u. of the WT capacity.

V. CASE STUDY

A. System Configuration

To verify the effectiveness of the proposed multi-source communication-less coordinated frequency support strategy, electromagnetic transient simulations are performed in PSCAD/EMTDC. The simulation model is presented in Fig. 10, and its parameters are listed in Table II. Offshore wind

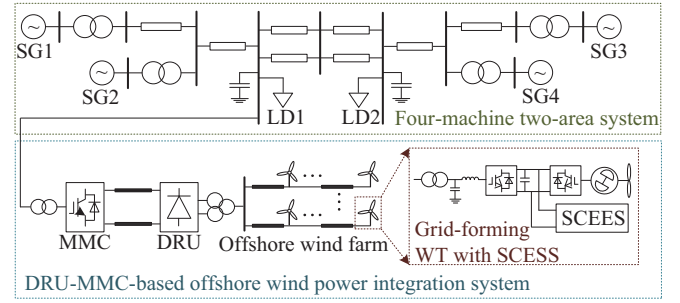


Fig. 10. Four-machine two-area case system with DRU-HVDC-based offshore wind power integration.

TABLE II
MAIN CIRCUIT PARAMETERS

Items	Parameters	Values
Wind turbines	Total installed capacity	1000 MW
	Rated power of single WT	10 MW
	Rated frequency	50 Hz
	Rated DC voltage	1.2 kV
DRU station	Transformer rated capacity	2×550 MVA
	Transformer ratio	66 kV/257 kV
	AC filter reactive capacity	300 Mvar
	Smoothing inductance	100 mH
DC Cable	Line resistance	0.056 Ω /km
	Line inductance	0.227 mH/km
	Line capacitance	0.181 μ F/km
	Cable length	250 km
MMC inverter	Transformer rated capacity	1100 MVA
	Transformer ratio	500 kV/320 kV
	Rated DC voltage	± 320 kV
	Submodules per arm	350
	Submodule capacitor	11.4 mF
Receiving grid	Arm inductor	77.8 mH
	Rated frequency	50 Hz
	Rated voltage	230 kV

power is transmitted via the DRU-HVDC system to a classical four-machine, two-area system. The active power of the load LD1 and load LD2 is 1800 MW and 1700 MW, respectively.

B. Sudden Load Increase

The sudden load increase event is simulated, in which the active power of LD1 increases by 350 MW at $t = 20$ s. First, to verify the effectiveness of the proposed communication-less frequency transfer strategy, the onshore frequency detected by the onshore MMC's PLL and the transferred onshore frequency detected by the offshore WT are compared as shown in Fig. 11. When the load increases causing a shortage of active power, the onshore frequency decreases. Once the onshore frequency deviation exceeds the threshold, the communication-less frequency transfer is initiated. It can be seen that the actual onshore frequency and the transferred onshore frequency are basically consistent. Despite passing through long transmission lines over 250 km, offshore WTs can still obtain the onshore frequency in time and accurately.

The system responses under the proposed multi-source coordinated frequency support strategy are plotted in Fig. 12. Once the onshore frequency drops below 0.03 Hz, controlled by the MMC, the HVDC voltage amplitude is reduced to release the HVDC capacitance's stored energy. Meanwhile, the small ripple is injected into the HVDC voltage, generating

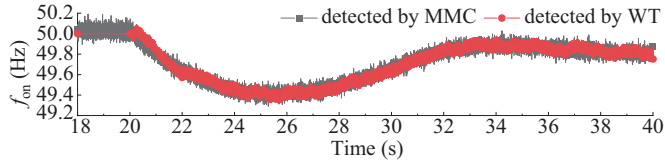


Fig. 11. Comparison of onshore frequency detected by MMC and transferred onshore frequency detected by offshore WT.

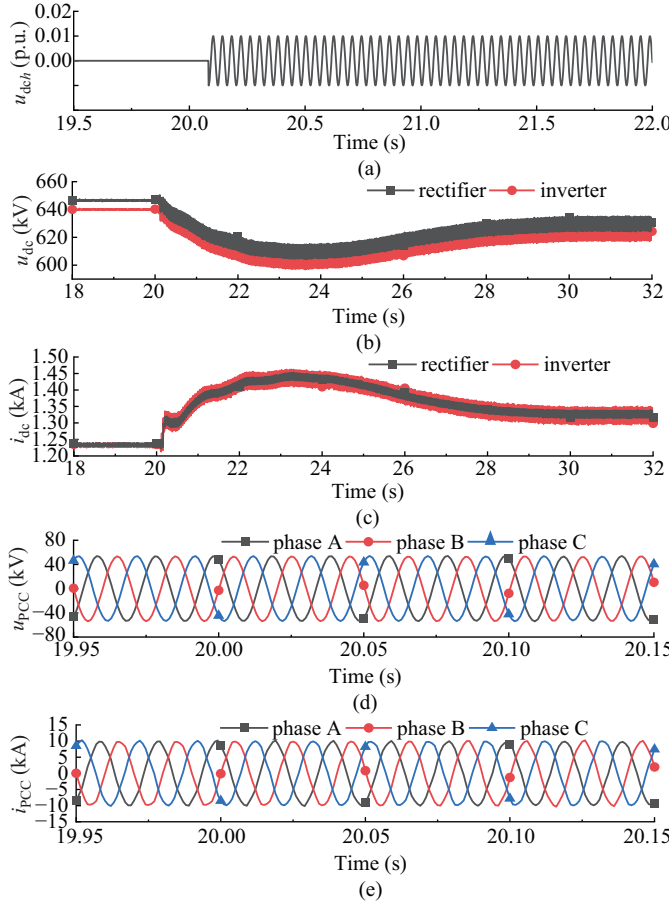


Fig. 12. Responses to sudden load increase under proposed multi-source coordinated frequency support. (a) Ripple voltage. (b) DC voltage on the rectifier and inverter sides. (c) DC current on the rectifier and inverter sides. (d) AC voltage at PCC. (e) AC current at PCC.

the ripple current to transfer the onshore frequency. The ripple current is attenuated from the inverter side to the rectifier side due to the filtering effect of cable capacitance. The small ripple causes no noticeable distortion of the offshore AC voltage and AC current, and will not affect the normal operation of the wind power transmission system.

The effects of different frequency support sources are compared in Fig. 13. The inertia support capability of the HVDC capacitance is limited and only slightly decreases the rate of change of frequency (ROCOF). WTs can release inertia support power from the turbine rotor's kinetic energy and the DC capacitor's electrostatic energy for a short time, thereby decreasing the ROCOF. However, the recovery process of the DC voltage and WT rotor speed consumes active power, which is not conducive to subsequent frequency recovery. The

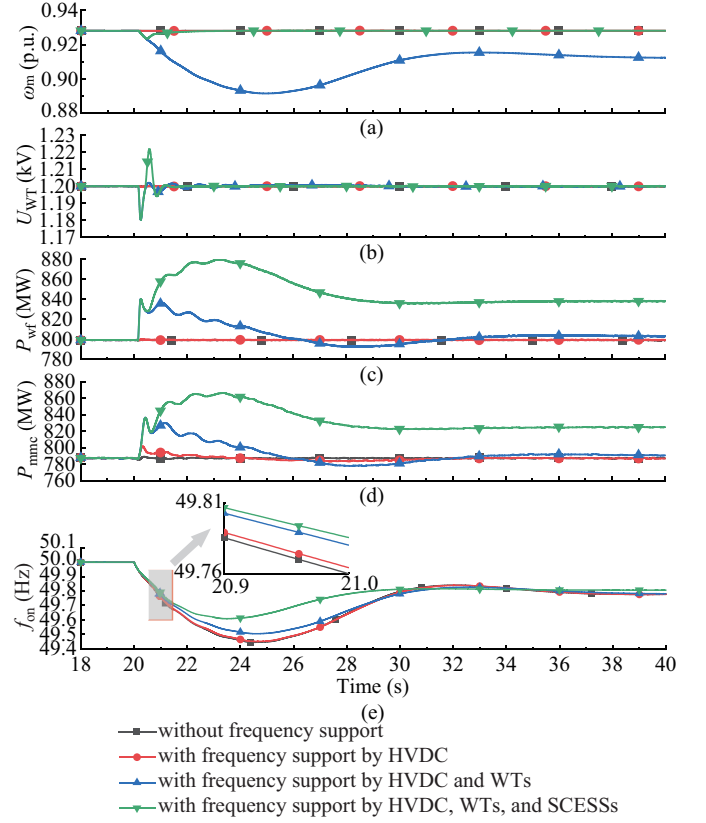


Fig. 13. Responses to sudden load increase under frequency support from different power sources. (a) Rotor speed of WT. (b) DC voltage of WT. (c) Active power of the wind farm. (d) Active power of MMC. (e) Onshore frequency.

SCESSs can provide continuous primary frequency regulation, raise both the minimum and steady frequencies, and avoid secondary frequency dips caused by inertia exhaustion.

C. Sudden Load Decrease

The effects of different frequency support strategies are compared during the sudden load decrease event, including the communication-less simultaneous, communication-based coordinated, and communication-less coordinated multi-source frequency support strategies. The simulation results when the active power of LD1 decreases by 350 MW at $t = 20$ s are plotted in Fig. 14.

Latency in communication over hundreds of kilometers from onshore to distant offshore can be as high as 1 second. Although pessimistic, the high latency is considered to demonstrate the effect of latency on frequency support from remote offshore wind farms. Communication delay will obviously affect the frequency support speed of distant offshore WTs and SCESSs, thereby weakening the frequency support effect. Compared with the communication-less simultaneous method, the proposed communication-less coordinated method can achieve an approximate frequency support effect, while avoiding offshore wind farms from participating in frequency support too frequently under small frequency offset.

D. Wind Speed Variation

Figure 15 shows the effectiveness of the proposed frequency

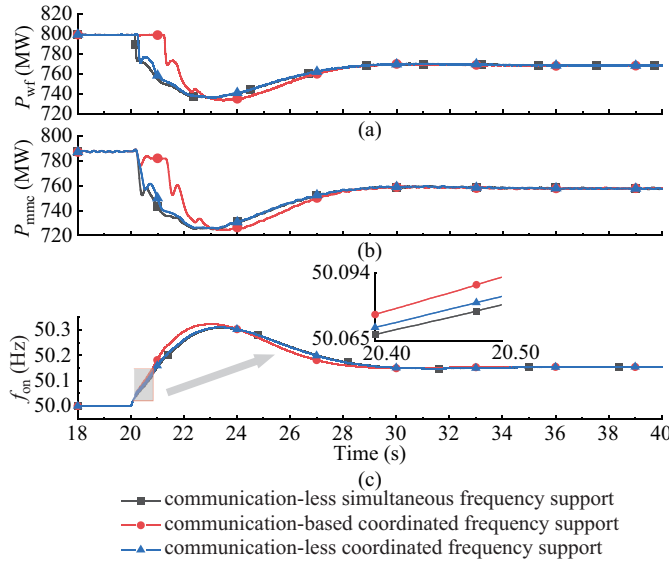


Fig. 14. Responses to sudden load decrease under communication-less simultaneous frequency support, communication-based coordinated frequency support, and communication-less coordinated frequency support. (a) Active power of wind farm. (b) Active power of MMC. (c) Onshore frequency.

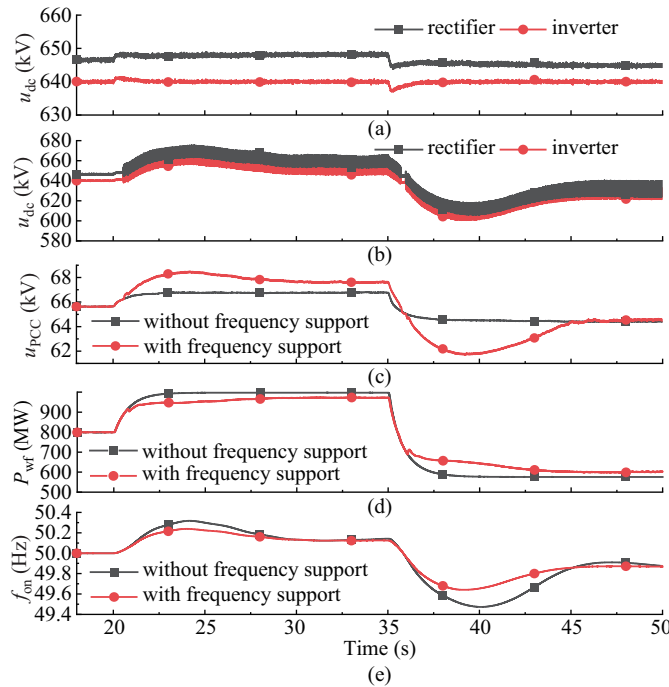


Fig. 15. Responses to wind speed variations with and without frequency support. (a) DC voltage without frequency support. (b) DC voltage with frequency support. (c) AC voltage of PCC. (d) Active power of the wind farm. (e) Onshore frequency.

support strategy under wind active power fluctuations, where the offshore wind speed is set to 11.15 m/s, then to 12 m/s, and finally to 10 m/s. As shown in Fig. 15(a)–(d), the DC and AC voltage amplitudes of the DRU are coupled, and the voltage amplitudes are strongly related to the transmitted active power. The HVDC voltage amplitude fluctuation is limited to $\pm 10\%$. With the additional frequency control, the active power fluctuations of offshore wind farms under

wind speed variations are appropriately suppressed, which is beneficial to the frequency stability of the onshore receiving grid.

VI. CONCLUSION

This paper proposes a communication-less multi-source coordinated frequency support strategy for the DRU-HVDC-based offshore wind power integration system to help reduce frequency fluctuations of the onshore receiving grid. The conclusions can be summarized as follows.

1) The ripple current on the DC side of the DRU can spontaneously convert to the AC side and become harmonic currents with the frequency of $|k_f f_{on} \pm f_{off}|$. By superimposing DC ripple current, each offshore WT can locally obtain the onshore frequency by detecting the corresponding harmonic at its AC port. The ripple frequency is preferably small and far from fundamental and characteristic harmonic frequencies.

2) The frequency support capabilities of multiple sources are exploited, including the inertia support of the HVDC link capacitance and grid-forming WTs, and the inertia support and primary frequency support of WT-combined SCESSs. Each source can locally sense the degree of the receiving grid disturbance and provide coordinated frequency support according to cascading start-up thresholds.

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