Two-Level Combined Control Scheme of VSC-MTDC Integrated Offshore Wind Farms for Onshore System Frequency Support

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Abstract—This paper proposes a two-level combined control (TLCC) scheme of voltage source converter-based multi-terminal high-voltage direct current (VSC-MTDC) integrated offshore wind farms to provide frequency support onshore system. The proposed TLCC scheme consists of two levels, which are the step start-up and adaptive inertial droop control of the offshore wind turbine level, and the communication-free allocation control of the onshore VSC station level. On the first level, each wind turbine adopts the inertial and droop control with adaptive coefficients, and all wind turbines (WTs) work at the maximum power point tracking (MPPT) mode without energy reserve. To reduce the second frequency drop (SFD), the WT clusters are divided into different clusters according to their rotor speed, and a step start-up control scheme is adopted for the WT clusters to provide frequency support sequentially. On the system level, the communication-free allocation control strategy is proposed using local frequency signal of onshore VSC stations to share the active power among onshore VSC stations reasonably. The proposed TLCC scheme can provide onshore system frequency support and reduce the SFD simultaneously, while all WTs work at MPPT mode. Case studies are carried out on a 3-area 4-terminal VSC-MTDC based offshore wind farms (OWFs). Simulation results demonstrate the effectiveness and universality of the proposed TLCC scheme under different scenarios.

Index Terms—VSC-MTDC, offshore wind farm, two-level combined control (TLCC) scheme, second frequency drop, frequency support.

I. INTRODUCTION

ARGE-SCALE offshore wind farms (OWFs) integrated with voltage source converter-based multi-terminal high-voltage direct current (VSC-MTDC) system has gradually attracted much attention in recent years [1]–[3]. Owing to the decoupled control between the mechanical and electrical system, VSC-MTDC integrated OWFs cannot respond to the onshore system frequency change directly, and the rate of change of system frequency (RoCoF) during first few seconds grows rapidly with the increase of the OWF penetration. Once the frequency deviation and RoCoF of onshore AC system exceed the limits defined by the system, it will trigger under-frequency load shedding or over-frequency generator tripping events, or even lead to more serious cascading outages. Therefore, to maintain the stability of onshore AC system, VSC-MTDC integrated OWFs are required to provide frequency support [4]–[7].

The frequency regulation control strategies of OWFs integrated via high-voltage alternating current system are similar to onshore wind farms, such as the kinetic energy control strategy [8]–[12], the de-loading control strategy [13], [15]–[18]. To realize the kinetic energy control scheme, additional control strategies, like inertial control and droop control, should be added to the maximum power point tracking (MPPT) control scheme [8], to achieve the inertial control, two additional loops for the inertial control, the RoCoF loop and droop loop, are implemented in the controller of each DFIG in [9], [10]. And an algorithm is proposed to estimate and control the quantity of extractable kinetic energy stored in a wind farm during frequency drops in [11]. In addition, to reduce the high-dimensional problem in wind farm power control and numerical simulation, different clustering algorithms are proposed to divide wind turbines into several groups in [13], [14]. The de-loading control can be realized by controlling the pitch angle or accelerating the rotor speed in [15], [16]. A method to evaluate the capability of providing inertia and primary frequency support is proposed in [17]. However, the de-loading control will reduce the economic effectiveness of the wind farms, and temporary frequency support strategies may cause a secondary frequency drop (SFD) of the system [19]. After the frequency regulation period, the rotor speed needs to be recovered to its initial operating state. If there is no other power injection to offset the corresponding power shortage, a serious SFD may occur or even be worse than the first frequency drop (FFD). Meanwhile, with the proliferation of wind generation integration, the SFD turns to be important for the practical deployment of rotor speed recovery. Consequently, the trade-off between reducing frequency nadir and the SFD appears necessary [20]. To mitigate the SFD, an extended state observer-based inertia emulation controller for DFIG-based wind turbine in [20]. A two-stage variable
proportion coefficient-based controller is proposed for DFIG-based wind turbine in [21]. However, the effectiveness of this two-stage control scheme relies on the predetermined training with the fuzzy controller, which should be re-determined under different situations.

Large-scale OWFs are usually far away from the onshore power system and more economical to be integrated via VSC-HVDC systems. Frequency regulation control strategies for VSC-HVDC systems are investigated in [22]–[31]. In [22]–[24], electrostatic energy stored in the converter capacitors is used for frequency support, and similar coordinated control strategies are proposed in [26], [27], which use both the electrical energy of the DC capacitor and the kinetic energy of wind turbines (WTs) to provide frequency support. However, the large enough DC capacitors are required for this frequency support scheme, and it will increase the investment of VSC stations. Furthermore, similar communication-free control schemes are proposed in [29]–[31], which convert the frequency deviation into the DC voltage change. However, if the output power of the wind farm varies to provide frequency support, the DC voltage of the offshore VSC station will also vary with the conventional voltage-frequency control. Consequently, the frequency deviation will not be fully reflected by the DC voltage deviation, and the effectiveness of these communication-free control schemes will be affected.

As for VSC-MTDC integrated OWFs, WTs can release kinetic energy for frequency support during frequency events. Furthermore, if the frequency support power can be allocated reasonably among onshore VSC stations, the frequency support performance can be improved. Similar power sharing control strategies are proposed to optimize the sharing power among onshore VSC stations and improve the frequency regulation performance in [32]. To reduce the SFD, an adaptive frequency regulation method is presented using the releasable kinetic energy in WTs and the electrostatic energy in VSC stations in [19]. However, WTs are required to reserve much power with a de-loading strategy to increase the instantaneous power injection, which will decrease the economic efficiency of OWFs [19].

To coordinate the VSC-MTDC system with OWFs, the control strategy of the converter stations in a multi-terminal DC (MTDC) grid to provide frequency support for the surrounding AC systems is the subject matter in [33], but the coordinate control between the MTDC system and the OWFs is lacked. In [34], the primary frequency support to asynchronous AC areas through an MTDC grid using a minimal-communication scheme is proposed, an improved pilot voltage droop based control for the MTDC systems is illustrated in [35], and a control strategy for the provision of inertial and primary frequency support through MTDC grid connecting asynchronous AC areas and OWFs is presented in [36]. Among these control schemes, the rotor speed recovery control and the potential risk of SFD are not studied. Furthermore, a stability-constrained adaptive droop approach is proposed for autonomous power sharing following the outage of a converter in an MTDC grid in [37]. A unified reference controller is proposed for primary control of MTDC grids as a step towards more flexible operation in [38], and the VSC stations can work in different operation modes based on this strategy. As for the MTDC grid droop control design, a calculation method is presented for droop coefficients in the case of outage or power step disturbance on any converter station in [39], and it can minimize the DC voltage deviation between pre- and post-disturbance. The requirements of power distribution, DC voltage control and system stability are considered for designing MTDC droop coefficients in [40]. A method used for choosing the droop gains of droop controlled converters is developed based on the dc voltage transient and steady-state dynamics in [41]. Different control schemes using adaptive droop coefficients are proposed to ensure the control capability of the whole MTDC system in [42], [43]. However, some of these droop parameter design methods need complex calculation, the others may not take the AC system characteristics (for example, the frequency) into consideration. Besides, as for system operators, it is a little difficult to get the proper droop coefficients of every VSC station via complex calculation.

In general, to achieve the satisfactory performance of frequency support and reduce the SFD, the following two key issues must be taken into account: (1) how to make good use of the kinetic energy of WTs and reduce SFD while less WTs work in the de-loading condition for economic performance; (2) how to coordinate OWFs with VSC-MTDC system to allocate the frequency regulation power reasonably. To address the above two issues, this paper proposes a two-level combined control (TLCC) scheme of VSC-MTDC integrated OWFs, which can adaptively coordinate the VSC stations with OWFs to provide onshore AC system with frequency support, and reduce the SFD when WTs recover to their own initial operating states. Different with [19], the proposed TLCC scheme can allocate power reasonably among onshore VSC stations without energy reserve, which will increase the economic effectiveness of OWFs.

The main contributions of this paper are listed as:

- This paper proposes a two-level combined control (TLCC) scheme of VSC-MTDC integrated OWFs for onshore frequency support, which can combines the WTs and the VSC-MTDC system to provide onshore AC system with frequency support. The proposed TLCC scheme is a trade-off between reducing the frequency nadir and the SFD.
- On the wind turbine level, adaptive inertial and droop control is adopted with all wind WTs working at the MPPT mode. WTs are divided into different clusters according to their rotor speed. Different with [13] and [14], WT clusters participate in frequency regulation in sequence to reduce SFD with the step start-up control strategy in the proposed TLCC scheme.
- On the VSC station level, the proposed communication-free control scheme can allocate frequency support power between onshore VSC stations reasonably using local frequency signal during frequency events. It can avoid large scale power flow change of the onshore AC system to decrease the RoCoF of the onshore AC system.

The remainder of this paper is organized as follows. Section II proposes the basic structure of the TLCC scheme for VSC-MTDC based OWF participating in onshore frequency support. Section III presents the controller designed for the test system. Case studies are carried out to verify the effectiveness of the proposed TLCC scheme in Section IV. Finally, conclusions are drawn in Section V.
II. STRUCTURE OF THE PROPOSED TLCC SCHEME

A. Overview of the Proposed TLCC Scheme

The proposed TLCC scheme consists of the step start-up and adaptive inertial droop control on the wind turbine level, and the communication-free allocation control strategy of onshore VSC station on the VSC station level, the basic structure of the proposed TLCC scheme is depicted in Fig. 1. It can be seen from Fig. 1 that the droop coefficients of onshore VSC stations will recover to their initial value after $\Delta t_{\text{fin}}$.

On the wind turbine level, adaptive inertial droop control is adopted with all WTs working at MPPT mode, and WTs are divided into different clusters according to their rotor speed. It is worth to point out that the number of clusters depends on the real situation, to elaborate the detailed process of the proposed control scheme, the WTs in an OWF are divided into two clusters in this paper. In order to reduce both the frequency nadir and the second frequency drop, WTs are sorted by their rotor speed. The 60% top-ranked WTs are ranked as the first cluster, while the rest 40% WTs are ranked as the second cluster in the load increase frequency events, and the critical rotor speed is named as $\omega_d$. (For example, if there are 25 WTs in an offshore wind farm, the top 15 WTs are ranked as the first cluster, while the rest 10 WTs are ranked the second cluster, referred to Fig. 2). WTs ranked in different clusters participate in frequency regulation with different time delay in this proposed TLCC scheme. According to [1], the inertial frequency support usually works during 0-5 seconds after the frequency events. Therefore, when the first cluster WTs recover their rotor speed, the second cluster WTs are settled to participate into frequency support to reduce the SFD with 5 seconds delay. The main target of WTs in Cluster 1 is to reduce the frequency nadir. When the WTs in Cluster 1 recover to their initial condition, the WTs in Cluster 2 are participated into frequency regulation with a certain time delay (5 seconds in this paper) to reduce the SFD.

On the VSC station level, onshore VSC stations adopt power-voltage droop control, the droop coefficient of each onshore VSC station is adaptively changed using local frequency signals, which are different on account of the different electrical distance defined in [44], [45], to the disturbance bus node. Therefore, the frequency support power provided by OWFs can be allocated reasonably among different VSC stations. The closer to the disturbance bus node the station is, the more power will be transmitted by this onshore VSC station, thus, the power flow change of onshore AC system can be controlled to a small range, which is benefit to the frequency recovery. The start-up sequence of the TLCC scheme is shown as Fig. 2. It can be seen from Fig. 2 that the $\Delta P_{\text{WT}}$ of WTs in different clusters will recover to its initial condition after frequency support.

B. The First Level: The Step Start-Up Adaptive Inertial and Droop Control Strategy

WTs can provide frequency support by releasing kinetic energy. During the recovery time, if there is no other offset power
Algorithm 1: Processes of the Step Start-UP Adaptive Inertial and Droop Control on the WTs Level.

**Input:** The rotor speed of WT$i$, $\omega_{r,i}$; The frequency of onshore AC system, $f_{ac}$; The maximum and minimum rotor speed limit of WTs, $\omega_{r,max}$ and $\omega_{r,min}$; The initial value of inertial and droop coefficients, $k_{win,i,0}$ and $k_{wdr,i,0}$; The slope of inertial and droop coefficients, $k_2$ and $k_3$.

**Output:** The frequency regulation power provided by the inertial and droop control, $\Delta P_{win,i}$ and $\Delta P_{wdr,i}$;

1. Dividing WTs into two clusters according to their rotor speed, the WTs whose rotor speed is larger than the critical rotor speed $\omega_d$ ($\omega_d = 0.9pu$ in this article) are the first cluster, and the rest WTs belong to the second cluster;
2. When the onshore AC system frequency $f_{ac}$ exceeds the threshold ($f_{ac} \geq 50.1Hz$ or $f_{ac} \leq 49.9Hz$ in this paper), the WTs in Cluster 1 participate in frequency support and release their kinetic energy without time delay;
3. When the rotor speed of WTs in Cluster 1 change, the inertial and droop coefficients change adaptively to ensure the rotor speed remaining in the safe range (0.9pu-1.2pu);
4. When WTs in Cluster 1 recover their rotor speed after 5 seconds, WTs in Cluster 2 begin to provide frequency support and release the kinetic energy. Owing to the frequency support power provided by WTs in Cluster 2, the SFD caused by WTs in Cluster 2 will be reduced.
5. return $\Delta P_{win,i}$ and $\Delta P_{wdr,i}$;

To integrate into the onshore AC system, the SFD may occur. If the recovery time and control strategy are not settled suitably, the SFD will be even larger than the FFD. In order to reduce the SFD, the step start-up adaptive inertial and droop control is proposed for the wind turbine level. The logical scheme of the step start-up adaptive inertial and droop control is shown as Fig. 1. WTs working at the MPPT point are divided into two clusters according to their different rotor speed, and participate in frequency support with different time delay. In this paper, there are 25 equivalent WTs in an OWF, and the critical rotor speed $\omega_d$ is settled as 0.9pu. Therefore, the WTs whose rotor speed is larger than 0.9pu are the first cluster, and the rest WTs belong to the second cluster. The WTs in Cluster 1 provide frequency support immediately once the frequency exceeds the threshold, and the WTs in Cluster 2 participate in frequency regulation after 5 seconds to reduce the SFD during the recovery time of Cluster 1 WT. It is worth to point out that WTs are divided into two clusters in this paper, and more clusters can be divided according to the real situations.

C. The Second Level: The Communication-Free Allocation Control Strategy of Onshore VSC Stations

VSC-MTDC based large-scale OWFs can be integrated into the onshore system via two or more onshore VSC stations because of the huge transmission power. Taking Fig. 1 as an example, the OWF1 is integrated into the AC system via two onshore VSC stations. When there is load increase in an AC bus, the frequency deviation measured by different onshore VSC stations should be allocated reasonably between onshore VSC stations to avoid large scale power flow change of onshore AC system. In order to achieve the better frequency support performance, more frequency support power should be injected into onshore AC system via the VSC station, which is closer to the disturbance bus.

$$k_{win,i} = k_{win,i,0} + k_2 \frac{\omega_{r,i}^2 - \omega_{r,min}^2}{\omega_{r,max}^2 - \omega_{r,min}^2}$$

$$k_{wdr,i} = k_{wdr,i,0} + k_3 \frac{\omega_{r,i}^2 - \omega_{r,min}^2}{\omega_{r,max}^2 - \omega_{r,min}^2}$$
Therefore, the communication-free allocation control strategy of onshore VSC stations is proposed in this section. The block diagram of this control strategy is depicted in Fig. 1. In Fig. 1, $f_{\text{VSC}_1}$ and $f_{\text{VSC}_1,\text{ref}}$ represent the measured frequency value and the reference value of onshore station VSC$_1$, $k_{\text{dr},0}$ represents the initial value of power-voltage droop coefficients. The $\Delta k_{\text{dr},i}$ represents the change value of $k_{\text{dr},i,0}$ during the frequency event, which is obtained by $k_1$ multiplying the integration of the deviation between $f_{\text{VSC}_i}$ and $f_{\text{VSC}_i,\text{ref}}$ during 0.01 seconds (referred to Eq. (5)). The adaptive droop coefficient $k_{\text{dr},i}$ is the sum of $k_{\text{dr},0}$ and $\Delta k_{\text{dr},i}$, which can change adaptively during the frequency event. For (VSC$_1$ and VSC$_2$), the $k_1$ and $k_{\text{dr},0}$ is settled as the same value (referred to Table II), but the deviation value $\Delta k_{\text{dr},i}$ is different from each other because of the different electrical distance to the disturbance bus. Thus, the frequency support power can be allocated between different onshore VSC stations more reasonably than conventional constant droop control. The calculation process of the adaptive droop coefficient value $k_{\text{dr},i}$ and the injected power of onshore station VSC$_i$ is shown as follows.

$$k_{\text{dr},i} = k_{\text{dr},0} + \int_{t_1}^{t_1+\Delta t_s} k_1 dt \times (f_{\text{VSC}_i,\text{ref}} - f_{\text{VSC}_i}(t)) + \int_{t_1}^{t_1+\Delta t_s} k_1 dt \times \left( U_{\text{dec},\text{ref}} - U_{\text{dec}} \right)$$

In (5) and (6), $t_1$ represents the start time when the onshore AC system frequency change exceeds the dead threshold. $\Delta t_s$ represents the integral time and is chosen as 0.01 seconds in this paper. It can reflect the electrical distance between different onshore VSC stations and the disturbed bus, and change the droop coefficients as soon as possible after the frequency event occurs. Note that the integration only lasts 0.01 s and the zero steady-state error of the frequency need not be achieved in the primary frequency response timescale. $k_1$ and $k_{\text{dr},0}$ represent the adaptive value and the initial value of power-voltage droop coefficients in different onshore VSC stations. $f_{\text{VSC}_1}$ and $f_{\text{VSC}_1,\text{ref}}$ represent the measured frequency and reference value of onshore station VSC$_1$, $P_{i,\text{ref}}$ and $P_{i,\text{ref}}$ represent the reference value and the initial value of injected active power for VSC$_1$, $U_{\text{dc},\text{ref}}$ and $U_{\text{dc}}$ represent the reference value and the measured value of the DC voltage, respectively.

It can be found from Fig. 1 that the droop coefficients of each onshore VSC stations remain constant in a normal situation. During frequency events, the droop coefficients $k_{\text{dr},1}$, $k_{\text{dr},2}$ of onshore station VSC$_1$ and VSC$_2$ will adaptively change because of the different measured frequency. Therefore, the
frequency regulation power provided by OWFs will be allocated reasonably, and more power will be injected into the onshore system via the VSC stations which is closer to the disturbance bus. During the whole control process, the local measured frequency signal is required only, therefore, the proposed strategy is communication-free. The detailed control processes of the proposed communication-free allocation control strategy can be shown as Algorithm 2, and the overall flow chart of the proposed TLCC scheme is shown as Fig. 4.

III. CONTROLLER DESIGN

A. Test System

The 3-area 4-terminal VSC-MTDC based offshore wind farm and onshore AC system model shown in Fig. 5 is used as the test system.

In Fig. 5, Area 1 is onshore AC system, which includes 4 synchronized generators (G1-G4), and there are 11 bus nodes and 10 lines in this area, and the rated voltage of the onshore AC system is 220 kV, the rated frequency is 50 Hz. Area 2 and Area 3 are offshore wind farms, there are 5 equivalent wind turbine models in both areas (G5-G9 in area 1 and G10-G14 in area 2), each equivalent wind turbine model represents 20 2 MW wind turbines. All equivalent wind turbines work at the MPPT mode, and only WTs in Area 2 participate into frequency support.

The offshore wind farms are connected with the onshore AC system with a DC grid, which includes 2 offshore VSC stations and 2 onshore VSC stations. The VSC1 and VSC2 stations adopt the voltage-active power droop control strategy, and the VSC3 and VSC4 stations adopt the AC voltage magnitude control. Only the OWF1 participates in onshore frequency regulation. Owing to the different wind speed settlement, the initial steady-state rotor speed of G5-G9 in OWF1 are 0.9pu, 0.95pu, 0.85pu, 1.0pu, 1.05pu. Therefore, G6, G8, G9 are the Cluster 1, and G5, G7 are the Cluster 2 in steady-state time. Other parameters are given in Table I.

B. Controller Parameter Design

The controller parameter design is referred to [19] and based on the trial and error method. The offshore wind turbines adopt the step start-up adaptive inertial and droop control to provide the frequency regulation power during the onshore AC system frequency events, and the control parameter design can be seen as (1)-(4). The onshore VSC stations adopt the communication-free onshore VSC stations coordinated control strategy to allocate the frequency regulation power between onshore VSC stations reasonably, and the droop coefficient is decided by (5). The controller parameters and their description are shown as Table II.

As is shown in Fig. 6, the integral coefficient $k_1$ is the same value in all onshore VSC stations, and it is the adaptive droop coefficient value $k_{dr,i}$, which will affect the transmission power of different onshore station VSC$_i$. In order to prove the influence
of \( k_{\text{dr,1}} \), small-signal analysis is adopted with different droop coefficient value \( k_{\text{dr,1}} \) and \( k_{\text{dr,2}} \) respectively in VSC\(_1\) and VSC\(_2\) under nominal operation of the system. The changing trajectory of the eigenvalues with different value of \( k_{\text{dr,1}} \) and \( k_{\text{dr,2}} \) can be shown as Fig. 6. It can be found that the eigenvalues will change with the variation of the droop coefficient values. However, the damping ratios (DR) of the critical eigenvalues are larger than 0.1 when \( k_{\text{dr,1}} \) and \( k_{\text{dr,2}} \) change from 0-120, it proves the adaptability of the value range.

IV. SIMULATION VERIFICATION

To illustrate the effectiveness and universality of the proposed TLCC scheme, the 3-area 4-terminal VSC-MTDC based offshore wind farm and onshore AC system model referred to [46], [47] is proposed and tested on the MATLAB/Simulink platform. In this model, the electromechanical transient model is used to represent the two-level VSC-based converter stations, and the type 3 DFIG model is used for WTs. A standard vector control strategy with inner current control loops is assumed. The AC and DC transmission lines are modeled using \( \pi \)-section equivalent circuit. All synchronous generators are represented by sixth-order sub-transient models equipped with type AC-4 A excitation systems. Loads are represented by the constant impedance model. For further details of the system modeling and parameters, it can refer to the Appendix and [46], [47].

Different frequency events are simulated with different control schemes in the 3-area 4-terminal VSC-MTDC based OWFs system (shown as Fig. 5). Among these control schemes, WTs do not participate into frequency regulation in Control scheme 1 (which is defined as NO FSC); in Control scheme 2, WTs take the inertial and droop control with constant parameters to provide frequency support (defined as CIDC); in Control scheme 3, WTs take the conventional inertial and droop control with 10% de-loading to provide frequency support referred to [19] (defined as CIDC&DL); in Control scheme 4, WTs take the proposed TLCC scheme to provide frequency support. All frequency events occur in Bus 7 at \( t = 5 \) s, the time delay for frequency signal transmitted to the OWFs is 200 ms in all scenarios, and the Matlab/Simulink package is employed for these simulation studies.

A. Load Increase

In this scenario, a 200 MW load increase in Bus 7 occurs at \( t = 5 \) s. The initial steady-state rotor speed of G5-G9 in OWF1 are 0.9pu, 0.95pu, 0.85pu, 1.0pu, 1.05pu. Therefore, WTs G6, G8, G9 are Cluster 1, which participate into frequency regulation immediately after the frequency events, and G5, G7 are the Cluster 2, which release their kinetic energy when Cluster 1 WTs recover to their initial state to reduce SFD. The four different control schemes are tested in this scenario.

The frequency measured at the VSC\(_1\) station, the transmitted power by VSC\(_1\) and VSC\(_2\) are shown as Fig. 7. It can be found from Fig. 7(a) that when there is 200 MW load increase in Bus 7 at \( t = 5 \) s, the frequency nadirs of VSC\(_1\) are 49.78 Hz, 49.78 Hz, 49.83 Hz, 49.85 Hz with NO FSC scheme, CIDC scheme, CIDC&DL scheme, and the proposed TLCC scheme, respectively. Moreover, there is an SFD problem when WTs participate in frequency regulation with CIDC scheme, CIDC&DL scheme and the proposed TLCC scheme, but the proposed TLCC scheme can reduce the SFD. The nadir of the SFD with Control scheme 2-4 are 49.81 Hz, 49.83 Hz, 49.85 Hz, respectively. Since WTs do not participate into frequency regulation under the NO FSC control strategy, the SFD will obviously not occur due to no WTs recovery process. It can also be seen from Fig. 7(b) and (c) that more frequency support power is injected into the onshore AC system by VSC\(_1\) with the TLCC scheme during the frequency event. The transmission power peak of VSC\(_1\) is 410 MW with the proposed TLCC scheme, and 380 MW with the CIDC scheme, and 355 MW with the CIDC&DL scheme. During the recovery time, the power drop of VSC\(_1\) is 82 MW with the proposed TLCC scheme, 45 MW with the CIDC scheme, and 32 MW with the CIDC&DL scheme. More frequency support power is integrated via VSC\(_1\) with the proposed TLCC scheme, thus, the large-scale power flow change can be avoided and SFD will be reduced. The third frequency drop in Fig. 7(a) is caused by the recovery of WTs in the Cluster 2, and can be restrained quickly.

Compared with other three control schemes, the proposed TLCC scheme can adaptively change the inertial and droop coefficients of WTs to make full use of the kinetic energy, and reasonably share frequency support power among onshore VSC stations to reduce the power flow change of the onshore system. Therefore, although there are more WTs participating into frequency regulation with the CIDC scheme, the control performance of the proposed TLCC scheme is still better than that of the CIDC scheme. As for the CIDC&DL scheme, because the droop coefficients of onshore stations are constant, the frequency regulation power can not be shared reasonably between onshore VSC stations, which will affect the frequency regulation performance. Furthermore, it can be found from Fig. 7 that the third frequency droop caused by rotor speed recovery of WTs in Cluster 2 is small, which can be restrained quickly. If the third frequency droop is big enough, more clusters can be divided to reduce it.
Fig. 8. The changes of coefficients with the proposed two level control strategies (with load increase 200 MW): (a) The rotor speed of WTs in WF1; (b) The active power of WTs in WF1; (c) The adaptive droop coefficients of WTs in WF1; (d) The adaptive inertial coefficients of WTs in WF1; (e) The adaptive voltage droop coefficients of VSC1 and VSC2 stations; (f) The DC voltage of VSC1 and VSC2 stations.

Fig. 9. The simulation results of different control schemes (with load decrease 200 MW): (a) The measured frequency in VSC1 station; (b) The transmitted active power of VSC1 station; (c) The transmitted active power of VSC2 station.

To elaborate on the detailed control process of the proposed TLCC scheme, the rotor speed, the active power, the adaptive droop coefficients and the adaptive inertial coefficients of WTs in area 1 are shown in Fig. 8(a)–(d), respectively. It can be found that the rotor speeds of G6, G8, G9 which belong to the Cluster 1 decrease to release the kinetic energy from \( t = 5 \) s to \( t = 10 \) s. After \( t = 10 \) s, the rotor speeds of WTs in Cluster 1 begin to recover and WTs in Cluster 2 (G5, G7) start to release their kinetic energy. After that, it can be found from Fig. 8(a) that the rotor speed of all WTs will be recovered to their initial state. Owing to the step start-up control strategy, WTs in OWF1 can participate into frequency regulation and reduce SFD without de-loading reserve. Moreover, it can also be found that the droop and inertial coefficients of WTs in Area 1 can be changed adaptively in Fig. 8(c)–(d). Consequently, the rotor speed of WTs can be limited to a safe range. Fig. 8(c) indicates that the power-voltage droop coefficients of VSC1 and VSC2 can also be changed adaptively to allocate the frequency support power among onshore VSC stations during the frequency event, which will reduce the power flow change of onshore AC system.

B. Load Decrease

In order to elaborate on the effectiveness of the proposed control scheme in load decrease situation, in this scenario, there is a 200 MW load decrease in Bus 7 at \( t = 5 \) s. During the load decrease moment, the WTs need to reduce their output power. Different with the load increase event, the 60% top-ranked WTs sorted by the rotor speed from small to big are the Cluster 1. Therefore, G5, G6, G7 are the Cluster 1 and G8, G9 are the Cluster 2 in this scenario.

The frequency measured at the VSC1 is shown as Fig. 9(a). It can be found that with four different control schemes, the frequency of onshore system will increase to 50.35 Hz, 50.25 Hz, 50.31 Hz, 50.23 Hz, respectively. By adopting the proposed TLCC scheme, the second frequency increase will be restrained to a smaller value, which is 50.29 Hz with the CIDC scheme and 50.24 Hz with the proposed TLCC scheme in Fig. 9(a). The transmitted power by VSC1 and VSC2 are shown as Fig. 9(b) and (c). The transmission power valley of VSC1 is 202 MW with the proposed TLCC scheme, and 242 MW with the CIDC scheme, and 271 MW with the CIDC&DL scheme. Owing to the quick reduction of power output, the frequency increase can be constrained to a lower value with the proposed TLCC scheme. However, on account of the only two divided clusters, the third frequency increase of the proposed TLCC scheme after \( t = 15 \) s is 50.24 Hz, which can be restrained quickly. In order to reduce the third frequency increase, more clusters can be employed in real situations, which is the future research and not involved in this paper.

C. Partial Outage of the Generator

In this scenario, a 250 MW partial outage at G2 in Area 1 occurs at \( t = 5 \) s. The initial steady-state rotor speed of G5-G9
in OWF1 are 0.9pu, 0.95pu, 0.85pu, 1.0pu, 1.05pu. Therefore, WTs G6, G8, G9 are ranked as Cluster 1 to participate into frequency regulation immediately after the frequency events, while G5, G7 are ranked as the Cluster 2 to release their kinetic energy to reduce SFD after Cluster 1 WTs recover to their initial state.

Four different control schemes are tested in this scenario. The frequency measured at the VSC1 station, the transmitted power by VSC1 and VSC2 are shown as Fig. 10. It can be found from Fig. 10(a) that, under 250 MW partial outage in G2 at $t=5$ s, the frequency nadirs of VSC1 are 49.68 Hz, 49.74 Hz, 49.76 Hz, 49.78 Hz with NO FSC scheme, CIDC scheme, CIDC&DL scheme, and the proposed TLCC scheme, respectively. Moreover, there is an SFD problem when WTs participate in frequency regulation with CIDC scheme, CIDC&DL scheme, and the proposed TLCC scheme, respectively. Moreover, there is an SFD problem when WTs participate in frequency regulation with CIDC scheme, CIDC&DL scheme, and the proposed TLCC scheme, but the proposed TLCC scheme can reduce the SFD. The nadir of the SFD with Control scheme 2-4 are 49.76 Hz, 49.78 Hz, 49.80 Hz, respectively. It can also be seen from Fig. 10(b) and (c) that more frequency support power is injected into the onshore AC system by VSC1 with the TLCC scheme during the frequency event. The transmission power peak of VSC1 is 450 MW with the proposed TLCC scheme, and 420 MW with the CIDC scheme, and 380 MW with the CIDC&DL scheme. Consequently, the large-scale power flow change can be avoided and the SFD will be reduced.

### D. Performance Comparison of Different Schemes

In order to elaborate the universality of the proposed TLCC scheme, different load-increasing scenarios are carried out, and different control schemes are also compared in these scenarios. For Control scheme 3, WTs take the conventional inertial and droop control with 10% de-loading to provide frequency support (defined as CIDC&DL). For Control scheme 4, WTs adopt the proposed methods in [38] (defined as URC). These frequency events are 600 MW, 500 MW, 400 MW, 300 MW, 200 MW load increase at bus 7, and the system response to the frequency events with different control schemes are shown as Table III.

It can be found that the FFD and the SFD are the smallest with the proposed TLCC scheme, which indicates the better frequency support performance of the TLCC scheme than other three compared schemes. For the 500 MW and 400 MW load increasing scenarios, although the SFD of the proposed TLCC scheme is the same as that of the CIDC&DL scheme, the FFD of the proposed scheme is smaller than that of the CIDC&DL scheme. On the other hand, WTs are required to reserve much power with the CIDC&DL scheme, which may cause the loss in revenue of OWFs due to the de-loading control [16]. In contrast, the proposed TLCC scheme can reduce the SFD without energy reserve, which is economical for OWFs. As for the CIDC scheme, it cannot make the best use of kinetic energy in different WTs with constant inertial and droop coefficients, therefore, its control effect is not as good as the proposed TLCC scheme. With the control performance comparison in different frequency events, the effectiveness and universality of the proposed TLCC scheme can be proved. Since the frequency support power under URC scheme cannot be allocated to different VSC stations reasonably, its frequency regulation performance is worse than that of the TLCC scheme.

### V. Conclusion

This paper proposes a two-level combined control scheme to coordinate the OWFs with the VSC-MTDC system for onshore frequency support, which can reduce SFD while all WTs work at MPPT point. The proposed TLCC scheme contains two levels, the step start-up and adaptive inertial and droop control on the offshore wind turbine level, and the communication-free allocation control on the onshore VSC station level.

Compared with other control schemes, the proposed TLCC scheme can reduce the frequency deviation at both the load increasing and the load decreasing situations. With the adaptive inertial and droop control, WTs whose rotor speed are high will...
release more kinetic energy. Consequently, the proposed TLCC scheme has better frequency support performance than that of the control scheme with constant inertial and droop coefficients. Moreover, with the step start-up control, the WTs in Cluster 2 can provide power support during WTs in Cluster 1 recovering their rotor speed. Furthermore, with the communication-free allocation control strategy, the frequency support power can be allocated reasonably between different onshore VSC stations during frequency events, which will do benefit to reduce power flow change of onshore AC system, and decrease the RoCoF. Different case studies also prove the effectiveness and universality of the proposed TLCC scheme.

It is worth to point out that the proposed TLCC scheme is beneficial when the wind speed and the rotor speed of WTs are big enough to provide the kinetic energy for frequency support. The disadvantages of this scheme lie in that the WTs are divided into different clusters, which can reduce the SFD but will affect the effectiveness of the reduction of the frequency nadir slightly. More clusters can be employed according to the real situation. Besides, the time delay for Cluster 2 to participate in frequency regulation is a constant value (5 seconds). Since this paper focuses on the proposed two-level control scheme, the optimized cluster number and time delay will be studied in future work. Furthermore, the asynchronous interconnection in the onshore system will also be considered.

**APPENDIX**

### TABLE A1

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### REFERENCES


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