Voltage source control of offshore all-DC wind farm

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Abstract: The offshore all-DC wind farm with increasing capacity will bring problems such as the weakening of grid frequency stability and the increase of equivalent grid impedance. To overcome this, a coordinated control strategy for the offshore all-DC wind farm is proposed here with two salient features: better performance under weak grid condition and real-time frequency support from the wind farm. The control strategy consists of three parts: the inertia synchronising control of the receiving-end converter, the constant ratio control of the DC transformer and the frequency response of the wind farm. With the proposed strategy, the all-DC wind farm operates like a synchronous generator to the onshore grid, which provides fast frequency support when the onshore grid frequency changes. The effectiveness of the proposed method is validated in power systems computer aided design (PSCAD)/electromagnetic transients including DC (EMTDC) using a typical IEEE 9 bus system.

1 Introduction

Compared with conventional high voltage alternating current (HVAC) transmission systems, voltage source converter (VSC)-high voltage direct current (HVDC) has several superiorities such as lower losses and less capacitor charging effects; moreover, the flexibility of active and reactive power flow control makes VSC-HVDC an attractive means for offshore wind farms integration [1, 2]. However, the conventional AC collection of wind turbines are still causing higher power losses, particularly as the distance among wind turbines are likely to be increased due to increasing blade diameter for 10 MW+ offshore wind turbines. Accordingly, the concept of all DC wind farm, which utilises both DC collection and DC transmission, becoming the focus of recent studies [3, 4].

However, DC wind farms are immune to AC grid frequency variation under normal control method due to the decoupled feature from HVDC and medium voltage direct current (MVDC) side; such immunity has no inertial response towards AC grid, which will deteriorate frequency stability if wind power penetration is large enough. Therefore, to replace conventional power plants, the all-DC wind farms are required to provide ancillary services such as primary frequency regulation and inertia response to help maintain the stability of power grids.

Recent studies in terms of frequency support usually focused on the wind farm with AC collection. Inertial response and primary frequency regulation of the DC capacitors and wind turbines are discussed in [5–7]. A communication-free coordinate control strategy was proposed in [8–10] to allow the frequency support of both wind farm and HVDC system. However, few attempts have been made to achieve the frequency regulation service of the all-DC wind farm.

On the other hand, the increasing penetration of wind power has also increased the equivalent grid impedance, thus weakening the grid. Under this circumstance, the control capability may deteriorate when the receiving-end converter (REC) with conventional vector controller is utilised to integrate wind power [11, 12], thus resulting in the stability issues such as grid voltage distortions and harmonic oscillations. Applying voltage source control is an effective way to solve this problem. A typical example is the virtual synchronising generator (VSG) [13], which imitates the rotor motion equation of synchronous generator (SG) to realise self-synchronisation to replace phase-locked-loop (PLL). However, it is not suitable for REC, which delivers wind power since the output power of wind turbines are always changing.

Hence, a coordinated control strategy of the offshore all-DC wind farm is proposed in this paper, including the inertia synchronising control (ISC) of REC, the constant ratio control of DC transformers, and the frequency response of wind turbines. With this strategy, the AC-grid frequency information is transmitted to the DC wind turbine with little time delay. Therefore, the DC wind turbine may realise rapid inertial response and primary regulation. Finally, the all-DC wind farm performs as an SG to the onshore grid. A simulation model of the all-DC wind farm is constructed in a typical IEEE 9 bus system based on PSCAD/EMTDC and the effectiveness of the proposed control strategy is validated.

2 Benchmark of the all-DC wind farm and its voltage source control

A typical offshore all-DC wind farm is shown in Fig. 1. The system mainly consists of three parts: the DC wind turbines, the DC transformers, and the onshore REC. The DC turbines are built up with directly driven permanent magnetic and AC/DC converter. Usually, its output DC voltage is 30–60 kV. A cluster of DC turbines is parallel connected to the low-voltage side of a DC transformer. The high-voltage sides of DC transformers are connected to a DC bus (usually ±150–500 kV). Finally, the wind power is collected by DC transformers and transmitted to onshore converter station by HVDC line. In the proposed coordinated control strategy, DC voltage is chosen as the medium to transmit frequency information. The variation of onshore grid frequency is reflected in the HVDC voltage by the ISC of REC. The equivalent DC capacitor is controlled to simulate rotors of SG by utilising its natural response, achieving the capability of self-synchronising and accomplishing the real-time link between HVDC voltage and grid frequency. Moreover, the self-synchronising characteristic of ISC endows it with enhanced performance under weak grid condition.

At the same time, the constant ratio control is applied to DC transformers. The voltage of MVDC collection bus is regulated by DC transformers according to HVDC voltage, delivering the grid frequency information from HVDC side to MVDC collection bus.
Therefore, the wind turbines are able to obtain grid frequency variation by detecting the voltage of the MVDC collection bus.

For wind turbines, a combined frequency supporting strategy is proposed, including the rotor-speed-based inertial response and the pitch-angle-based primary frequency regulation.

Therefore, the all-DC wind farm operates like an SG, which has better performance under weak grid condition and real-time frequency support to the onshore grid.

3 Self-synchronising control of REC with DC droop characteristic

3.1 Basic principle of inertia synchronising control

Neglecting the loss of DC cable, the natural response of HVDC bus voltage to power variation can then be described as

\[
P_{WF} - P_{rec_grid} = CU_{dc} \frac{dU_{dc}}{dt},
\]

\[
P_{rec_grid} = \frac{U_{rec} U_g}{X \sin \delta} = \frac{\sqrt{3} m U_{dc} U_g}{2 \sqrt{2} X} \sin \delta,
\]

where \(P_{WF}\) is wind power, and \(P_{rec_grid}\) is the REC output power. \(U_{dc}\) is the DC voltage, and \(\omega\) is the equivalent DC bus capacitance. \(U_{rec}\) is the output RMS voltage of REC (line-to-line), and \(U_g\) is the RMS voltage of the AC grid (line-to-line). \(m\) is the modulation ratio, and \(\delta\) is the power angle. \(X\) is the sum of grid synchronous reactance, the leakage reactance of the transformer, and the transmission line reactance, whereas resistance is neglected because of high voltage and power level conditions.

Results indicated that (1) is similar to the motion equation of SG rotors

\[
P_m - P_e = J \omega_m \frac{d\omega_m}{dt},
\]

whereas (2) is similar to SG output power equation

\[
P_e = \frac{\sqrt{3} E_F U_g}{X} \sin \delta = \frac{\sqrt{3} m U_{dc} U_g}{\sqrt{2} X} \sin \delta.
\]

\(J\) is the moment of inertia of SG. As observed from (1) to (4), \(U_{dc}\) is equivalent to rotor speed \(\omega_m\), \(E_F\) is the electromotive force of the SG. Modulation ratio \(m\) is equivalent to air gap flux \(\psi\). \(P_{WF}\) and \(P_{rec_grid}\) are equivalent to SG's mechanical power \(P_m\) and electrical power \(P_e\).

To simulate the natural relationship between rotor speed \(\omega_m\) and electrical frequency \(\omega_e\) of SG, a link between \(U_{dc}\) and REC output frequency \(\omega_{rec}\) is established:

\[
K \frac{\omega_{rec} - \omega_{nom}}{\omega_{nom}} = \frac{U_{dc} - U_{dc_{nom}}}{U_{dc_{nom}}},
\]

\[
K \frac{\Delta \omega_{rec}}{\omega_{nom}} = \frac{\Delta U_{dc}}{U_{dc_{nom}}},
\]

where \(U_{dc_{nom}}\) and \(\omega_{nom}\) are the nominal values of \(U_{dc}\) and \(\omega_{rec}\), respectively. \(K\) is introduced to scale the coupling strength between DC bus voltage \(U_{dc}\) and REC output frequency \(\omega_{rec}\). Typically, the deviation of grid frequency is \(\pm 1\%\) (0.5 Hz), and the maximum deviation of DC voltage is \(\pm 5\%\). Hence, \(K\) can be chosen within the limit:

\[
\frac{5\%}{1\%} \geq K.
\]

The substitution of (5) into (1) combined with (2) presents the dynamics of REC with ISC by the following set of equations:

\[
\begin{align*}
\frac{KC U_{dc} \Delta U_{dc_{nom}}}{\omega_{nom}} \frac{d\omega_{rec}}{dt} &= P_{WF} - P_{rec_grid} \\
\frac{d\delta}{dt} &= \omega_{rec} - \omega_{grid} \\
P_{rec_grid} &= \frac{\sqrt{3} m U_{dc} U_g}{2 \sqrt{2} X} \sin \delta
\end{align*}
\]

Considering a small grid frequency variation, i.e. \(U_{dc} \rightarrow U_{dc_{nom}}\) has the following correlation:

\[
\omega_{grid} \uparrow \Rightarrow \delta \downarrow \Rightarrow P_{rec_grid} \downarrow \Rightarrow U_{dc} \uparrow \Rightarrow \omega_{rec} \uparrow.
\]
Thus, \( \omega_{\text{grid}} \) and \( U_{\text{dc}} \) are intrinsically coupled. As observed from (7) and (8), several beneficial characteristics are achieved in REC:

(i) Similar to SG rotor, DC bus voltage \( U_{\text{dc}} \) and REC output frequency \( \omega_{\text{out}} \) tend to track grid frequency autonomously. Given that the inertia of an equivalent DC bus capacitor is usually minimal, this tracking can be rapid.

(ii) The impedance of REC seen from PCC is purely inductive, and thus, the loop circuit has no resonance as the current-vector-based control method, i.e. enhanced stability performance under the weak grid.

### 3.2 Equivalent capacitance calculation of MMC-based DC system

As is mentioned above, the basic principle of ISC is the imitation of ISC of the SG rotor. Although there is no filter capacitor at DC side in MMC-based converter, the DC voltage is still coupled with average sub-module voltage (assuming that the voltages of sub-module capacitors are well balanced). It means that there will be an equivalent capacitor at DC side.

A typical topology half-bridge MMC converter is shown in Fig. 2. The number of inserted sub-modules in each phase (including both upper arm and lower arm) is constant, which is \( N \). Assuming the DC voltage is \( U_{\text{dc}} \), the voltage of the sub-module capacitor is \( U_{\text{SM}} = U_{\text{dc}} / N \). Therefore, the equivalent capacitance can be calculated by the energy equation as below:

The energy stored in all of the sub-module capacitors is

\[
W_{\text{cap}} = \sum_{n=1}^{6N} C_{\text{SM}} \left( \frac{U_{\text{dc}}}{N} \right)^{2} = \frac{1}{2} N C_{\text{SM}} U_{\text{dc}}^{2},
\]

while \( C_{\text{SM}} \) is the capacitance of sub-modules.

Suppose that there is an equivalent capacitor at DC side, its stored energy is

\[
W_{\text{cap}} = \frac{1}{2} C_{\text{eq}} U_{\text{dc}}^{2},
\]

Comparing (8) and (9), the equivalent capacitance \( C_{\text{eq}} \) is

\[
C_{\text{eq}} = \frac{6}{N} C_{\text{SM}}.
\]

The calculation of equivalent capacitance for MMC-based DC transformer is the same. Neglecting the resistance and reactance of the transmission line, the total capacitance of the HVDC bus is

\[
C_{\text{sum}} = \frac{6}{N_{\text{rec}}} C_{\text{SM,rec}} + C_{\text{line}} + \frac{6p}{N_{\text{rec}}} C_{\text{SM,dec}}
\]

while \( p \) is the number of DC transformers, \( C_{\text{line}} \) is the capacitance of transmission line.

### 3.3 Dynamic response analysis of the DC voltage to grid frequency variation

The accuracy and time delay are important indicators while delivering the grid frequency variation by DC voltage. Therefore, the transfer functions of the DC voltage to grid frequency are calculated by linearising (7) \( (U_{\text{dc}} - U_{\text{dc,nom}}) \rightarrow \omega_{\text{nom}} \)

\[
\Delta P_{\text{grid}} \rightarrow P_{\text{rec}} \rightarrow \omega_{\text{nom}} \rightarrow \delta_{0},
\]

while \( \Delta \omega_{\text{rec}} \) has been replaced by \( \Delta U_{\text{dc}} \) according to (5):

\[
\Delta P_{\text{grid}} = C_{\text{sum}} U_{\text{dc,nom}} \frac{d \Delta U_{\text{dc}}}{dt} + \frac{p}{2 N_{\text{rec}}^2} \frac{\Delta U_{\text{dc}}}{\omega_{\text{nom}}^2}
\]

Neglecting the fluctuating wind power and modulation ratio, i.e. \( \Delta P_{\text{in}} = 0, \Delta m = 0 \). Equation (13) can be written as below:

\[
\begin{aligned}
G(s) &= \frac{K \Delta \omega_{\text{g}}}{s (1/K)} = \frac{C_{\text{sum}} U_{\text{dc,nom}}^2 \delta_{0} / P_{\text{nom}}}{s^2 + (\delta_{0}/\omega_{\text{nom}})s + (1/K)}.
\end{aligned}
\]

\( G(s) \) is a typical second-order system, which has a damping ratio of

\[
\zeta = 1 - \frac{K P_{\text{nom}} \delta_{0}}{C_{\text{sum}} U_{\text{dc,nom}}^2 \omega_{\text{nom}}^2}.
\]

It can be observed from (15) that \( \zeta \) is proportional to \( \sqrt{P_{\text{nom}} \delta_{0}} \). The decline of \( P_{\text{nom}} \) will decrease the damping ratio, worsen the dynamic response of \( G(s) \) and increase response time.

Hence, a damping compensation unit is added to enhance the dynamic performance and reduce the response time. This damping compensation is realised by regulating the modulation ratio \( m \) (equivalent to the air gap flux \( \psi \) of SG), which is similar to the excitation control of the SG:

\[
\Delta m = M \frac{\Delta U_{\text{dc}}}{U_{\text{dc,nom}}}
\]

By substituting (16) into (13), the new transfer function \( G'(s) \) and damping ratio after compensation can be obtained:

\[
G'(s) = \frac{C_{\text{sum}} U_{\text{dc,nom}}^2 \delta_{0} / P_{\text{nom}}}{s^2 + (\delta_{0}/\omega_{\text{nom}})s + (1/K)}
\]

\[
\zeta' = \frac{1}{2} \frac{m_{\text{nom}} + M}{m_{\text{nom}}} \frac{K P_{\text{nom}} \delta_{0}}{C_{\text{sum}} U_{\text{dc,nom}}^2 \omega_{\text{nom}}^2}
\]

(17)
phase angle $\theta$ is the integration of $\omega_{rec}$. The modulation ratio $m$ is controlled by both reactive power loop and the damping compensation.

On the other side, $U_{abc\text{ ref}}$ is used to reduce the circulating current in MMC-based REC. $I_{zk}(k = a, b, c)$ is the common-mode component of arm current in each phase. After removing the DC component of $I_{zk}$, a PR controller is utilised to generate $U_{abc\text{ ref}}$.

Finally, the nearest-level modulation [14] is utilised to generate switching pulse according to the modulation wave and the sorting results of sub-modules.

4 Constant ratio control of the DC transformer

4.1 Basic control of the DC transformer

The DC transformer in the all-DC wind farm is made up of 2 MMC-based DC/AC converter and a medium-frequency AC transformer (see Fig. 4). Several different modulation strategies have been proposed for the DC transformer, including sinusoidal modulation [15], two-level modulation [16], and quasi two-level modulation [17]. In this article, a two-level modulation is utilised, which is similar to the control of the dual active bridge (DAB) converter. Two-level voltages are generated at both sides of the AC transformer, and the flow of active power is decided by the phase shift between them. Therefore, the voltage of DC collection bus can be controlled by regulating the phase shift angle $\theta$.

4.2 Constant ratio control

In the conventional control of all-DC wind farm, the voltage reference of the MVDC collection bus is constant. Therefore, it is decoupled with HVDC voltage, which represents the variation of grid frequency when inertial synchronising control is applied in REC. The proposed constant ratio control of the DC transformer will regulate the voltage reference of the MVDC collection bus according to HVDC voltage. Hence, the grid frequency information is delivered to wind turbines.

The block diagram of constant ratio control is shown in Fig. 4. The DC voltage of the HVDC side is measured as $U_{dc}$. In order to eliminate the influence of wind power fluctuation, the voltage drop on the HVDC transmission line is calculated based on the product of output current $I_{dc}$ and line resistance $R_L$ and added to $U_{dc}$. The result is then divided by a constant ratio $n$ and become the reference of MVDC collection bus voltage $U_{dc\text{ ref}}$.

4.3 Tracking of wind farm DC voltage to grid frequency variation

The transfer function from $\Delta \omega_g$ to $\Delta U_{dc}$ has been discussed in Section 3.3. While in the DC transformer, the transfer function from $\Delta U_{dc}$ to $\Delta U_{dc2}$ can be described as a first-order system (neglecting the time delay of $U_{dc}$ measurement), whose time constant is decided by the bandwidth $\omega_b$ of the DC-voltage control loop:

$$\Delta U_{dc2} = \frac{1}{1 + Ts} \Delta U_{dc, \text{ref}} = \frac{n}{1 + Ts} \Delta U_{dc}$$

$$T = \frac{1}{\omega_b}$$

Therefore, the transfer function from grid-frequency variation $\Delta \omega_g$ to the DC voltage of wind farm collection bus $\Delta U_{dc2}$ can be derived by combining (17) and (18):

$$\frac{\Delta U_{dc2}}{U_{dc2, \text{nom}}} = \frac{1}{1 + Ts} \frac{n \Delta U_{dc}}{U_{dc, \text{nom}}} = \frac{G(s)}{1 + Ts} \frac{\Delta \omega_g}{\omega_b}$$

Given that $K = 5, \omega_b = 10 \text{ rad/s}, P_0 = 0.7P_{\text{nom}}, M = 4$, the bode diagram of ($G(s)/(1 + Ts)$) is shown in Fig. 5 by substituting the parameters in Tables 1–4 into (19).

The process of a grid's typical inertial response usually lasts for 6 s. Assuming that the grid frequency changes according to the exponential function, the time constant of this process is $\sim 1.5$ s. The corresponding cut-off frequency is $0.67 \text{ rad/s}$. It can be observed from Fig. 5 that around the frequency of $0.67 \text{ rad/s}$, the amplitude is about 0 dB, and the phase delay is about $-4.23^\circ$, which means that there is no obvious time delay. Therefore, a real-time tracking of wind farm DC voltage to grid frequency is realised by the proposed strategy.

Fig. 3 Block diagram of ISC

Fig. 4 Block diagram of constant ratio control

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5.1 Basic control of the DC wind turbine

The AC output voltage of the PMSG is usually several kilovolts and its frequency is about 10 Hz. Since the voltage of the collection bus is MVDC level, an AC/DC converter is required. Different topologies and control strategies have been proposed for this kind of converter [18, 19]. In order to simplify the analysis, a two-level voltage source converter is utilised in this article (see Fig. 6).

5.2 Inertia response and primary frequency regulation from wind turbine

When the variation of the DC voltage is detected by the DC wind turbine, the grid frequency information can be derived by:

\[ \Delta U_{dc} = \frac{K U_{dc, nom}}{n \omega_{nom}} \Delta \omega_g \]

while \( n \) is the constant ratio of DC transformer, \( U_{dc} \) is the DC voltage of DC wind turbine, \( U_{dc, nom} \) is the DC voltage of the HVDC line. Hence, the inertial response and primary regulation can be realised by DC wind turbines.

The capability of wind turbines to provide an inertia response is investigated in [5]. An additional value associated with the rate-of-change-of-frequency (RoCoF) is attached to the active power reference \( P_{MPPT} \) given by the MPPT control. Additional power \( P_{add} \) is provided by accelerating or decelerating the wind turbine and utilising the kinetic energy stored in rotating blades. Assuming that the virtual inertia of a wind farm is \( H_{ WF} \), the value of additional power \( P_{add} \) is

\[ P_{add} = - H_{ WF} \frac{d \omega_g}{dt} = - 2 H_{ WF} \frac{K U_{dc, nom}}{\omega_{nom}} \frac{d \Delta U_{dc}}{dt} \]

Substituting (20) into (21), there is

\[ P_{add} = - 2 H_{ WF} \frac{K U_{dc, nom}}{\omega_{nom}} \frac{d \Delta U_{dc}}{dt} \]

Given that the kinetic energy stored in rotating blades is limited, if primary regulation of the wind farm is needed, then power source such as energy storage should be added. Another option is the utilisation of de-loading strategies by preserving a generation margin. Since the extra cost brought by an additional power source, especially for offshore all-DC wind farms, de-loading strategies are applied in the proposed strategy.

Two de-loading strategies have been discussed in [20, 21]: pitch-angle-based de-loading and rotor-speed-based de-loading. In order to decouple with the inertia response, which is rotor-speed-based, the pitch-angle-based de-loading strategy is utilised for

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**Table 1** Aggregated PMSG parameters

| Parameter                  | Value       |
|----------------------------|-------------|
| rated output voltage       | 50 kV       |
| rated power                | 50 MVA      |
| rated wind speed           | 11.4 m/s    |
| rotor speed                | 4.2–11.9 rad/s |
| \( x_d \)                  | 0.15 p.u.   |
| \( x_q \)                  | 0.1 p.u.    |
| blade equivalent inertia    | 5.54 s      |
| rotor inertia              | 0.84 s      |
| virtual inertia            | 6 s         |

**Table 2** DC Transformer parameters

| Parameter                              | Value       |
|----------------------------------------|-------------|
| rated power                            | 200 MVA     |
| rated HVDC voltage                     | ±100 kV     |
| rated MVDC collection bus voltage      | 50 kV       |
| amount of HVDC-side SMs per arm        | 100         |
| capacitance of HVDC-side SM capacitor  | 2 mF        |
| amount of DC collection-side SMs per arm| 25          |
| capacitance of DC collection-side SM capacitor| 8 mF|

**Table 3** Onshore REC parameters

| Parameter                  | Value       |
|----------------------------|-------------|
| rated active power         | 200 MW      |
| rated reactive power       | 0           |
| RMS value of grid voltage (line-to-line)| 100 kV   |
| rated grid frequency       | 50 Hz       |
| rated HVDC voltage         | ±100 kV     |
| rated MVDC collection bus voltage| 50 kV |
| rated RMS line-to-line voltage| 100 kV    |
| capacitance of SM capacitor| 8 mF        |
| amount of HV-side SMs per arm| 100        |
| coupling coefficient       | 5           |

**Table 4** DC transmission line parameters

| Parameter                  | Value       |
|----------------------------|-------------|
| resistance                | 0.0139 Q/km |
| capacitance               | 0.331 μF/km |
| inductance                | 159 μH/km   |
| length                    | 100 km      |

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**Fig. 5** Transfer function from grid frequency to DC voltage at wind farm side

**Fig. 6** Control block diagram of wind turbines with frequency response capability

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primary frequency regulation. The deviation of grid frequency can be achieved by (20).

The control block diagram of wind turbines with frequency response capability is shown in Fig. 6.

The inertia response is realised by the variation of rotor speed, an extra power \( P_{\text{add}} \) is calculated by (22) and added to the original power reference \( P_{\text{MPPT}} \), which is given by the MPPT control.

On the other side, the primary frequency regulation is realised by pitch angle control. Under normal circumstances, the wind turbine works under a small pitch angle to reserve part of the wind power. The amount of reserved power is decided by the demand of the local grid (usually 5–10%) [22–24]. When grid frequency variation is detected, wind turbines will change the pitch angle according to the deviation of grid frequency to its rated value.

6 Simulations

Simulations analysis are conducted in two different cases to achieve following objectives: (1) test effectiveness of the proposed method when applying to a complex power system, e.g. the IEEE 9-bus benchmark model; (2) test the performance of proposed method under a weak grid condition by adopting a simple power grid model. (Parameters of studied system are shown in Tables 1–4).

In addition, the conventional control strategy is also simulated in each case as a contrast. In the conventional control strategy [3], the REC performs the PLL-based constant HVDC voltage control. The bandwidths of its PLL, DC voltage loop, and inner current loop are 50, 20, and 200 Hz, respectively. The DC transformers perform the constant MVDC collection bus voltage control, the bandwidth of MVDC collection bus voltage control loop is 10 Hz. The DC wind turbines perform MPPT control.

6.1 Case1: effectiveness of the proposed method

In Case1, a 200 MW all-DC wind farm simulation model is established in PSCAD/EMTDC based on Fig. 1. There are four clusters in this model, and each cluster consists of 1 DC transformer and 10 permanent magnets SG (PMSG). The rated power of the wind turbine is 5 MW. Neglecting the voltage drop on the collection lines, wind turbines in each cluster can be equivalent to an aggregated 50 MW PMSG model.

For the AC side, a typical IEEE 9 bus system shown in Fig. 7 is utilised to simulate the power system. The all-DC wind farm integration is tied to Bus 6. Wind power is set to 160 MW. Since 10% of the rated power is reserved for primary frequency regulation, the output power of REC to the grid is 140 MW, i.e. 44% of the total load. The system simulation diagram is shown in Fig. 7.

Based on this model, the capability to provide inertial response and primary frequency regulation of the proposed control strategy is validated under two different scenarios.

Scenario I: A step increase of 20% active power and 5% reactive power of Load 1 is simulated at 2.0 s to cause a grid frequency drop. The simulation results are shown in Fig. 8.

Scenario II: A step decrease of 20% active power and 5% reactive power of Load 1 is simulated at 2.0 s to cause a grid frequency increase. The simulation results are shown in Fig. 9.

It can be observed from Figs. 8a and 9a that with the proposed control strategy, the grid frequency variation led by the sudden change of load can be delivered to wind turbines timely and precisely through HVDC voltage and MVDC collection bus voltage. However, because of decoupled control feature of the conventional strategy, the HVDC voltage and MVDC collection bus voltage are stable all the time. Thus, the grid frequency variation cannot be detected at wind farm side.

After detecting the deviation of grid frequency, the wind farm may realise fast inertial response and primary frequency regulation with the proposed control strategy (see Figs. 8b and 9b). At the beginning of grid frequency variation, the support power from a wind farm is dominated by the inertia response and is proportional to RoCoF. After \( t = 10 \) s, the grid frequency becomes stable. The supporting power is dominated by primary frequency regulation and is proportional to the deviation of the grid frequency. However, with the conventional control strategy, wind turbines cannot sense grid frequency deviation, thus providing no frequency support.

From Figs. 8a and 9a, the frequency nadir/peak and the RoCoF of the onshore grid are improved with the proposed control strategy, which has validated its effectiveness.
6.2 Case 2: performance of the proposed method under weak grid

Moreover, to validate the control effect of the proposed strategy under weak grid condition, a simple power grid model is constructed in Case 2 (see Fig. 10). The onshore power grid is equivalent to a single SG with a load of 500+j100 MVA. At $t = 2$ s, the AC grid load rises from 400 to 500 MW. The short-circuit ratio is set to 2.5, which represents a weak grid. The performance of conventional strategy and proposed strategy is shown in Fig. 11.

It can be observed from the left side of Fig. 11a that with the conventional control strategy, the HVDC voltage and the REC output power will oscillate under weak grid condition. By contrast, the proposed control strategy still perform well. The HVDC voltage shown in the right side of Fig. 11a follows the change of the grid frequency without apparent time delay, which helps wind farms realise inertia response ($t = 2–5$ s) and primary frequency regulation ($t = 5–20$ s). The frequency nadir increases by $\sim 0.1$ Hz compared with the conventional control strategy in Fig. 11b. However, for the conventional strategy, no frequency support is provided, and the grid frequency suffers from oscillation which is brought by the oscillation of REC output power.

7 Conclusion

A multi-timescale coordinated control strategy is proposed in this paper in order to realise the voltage source control of offshore all-DC wind farm, including the inertial synchronising control of REC, the constant ratio control of DC transformers, and the frequency response of wind turbines.

With the proposed control strategy, the REC of the all-DC wind farm will synchronise with grid autonomously without PLL, which means the system is more robust to grid impedances changes. Moreover, the grid frequency deviation is delivered to wind turbines through DC-link timely and precisely. Meanwhile, the rotor-speed-based inertial response and pitch-angle-based primary frequency regulation are applied in wind turbines.

Therefore, the all-DC wind farm operates like a SG to the onshore grid, which provides fast frequency support when the onshore grid frequency changes. The effectiveness of the proposed method is also validated by the simulation results.

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Fig. 9 Response of all-DC wind farm under Scenario II
(a) Response of grid frequency, HVDC voltage and MVDC collection bus voltage, (b) Response of REC output power

Fig. 10 System simulation diagram of Case 2

Fig. 11 Case 2 simulation results
(a) Response of HVDC voltage and REC output power, (b) Response of grid frequency
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