Parallel operation of diode-rectifier based HVDC link and HVAC link for offshore wind power transmission

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Abstract

This paper investigates the integration of large offshore wind farms using parallel HVAC and diode-rectifier based HVDC (DR-HVDC) systems. Three different operation modes, i.e. HVAC operation mode, DR-HVDC operation mode and parallel operation mode are investigated. A wind turbine control scheme including distributed control and centralized control is proposed to ensure the stable operation of the offshore wind farms under different operation modes. The proposed control requires no switching of the distributed control strategy when operation mode is changed. Moreover, power flow between the DR-HVDC link and HVAC link under parallel operation can be well controlled with the centralized control. Simulation results in PSCAD/EMTDC verify the proposed control during transition among the three operation modes.

1 Introduction

Wind energy is now the major renewable source in Europe. Large offshore wind farms have been developed because of higher offshore wind speed and limited suitable onshore sites. With the increase of the distance between offshore wind farms and onshore grid, power transmission technology is playing a more and more important role. For the long-distance offshore wind farms, high voltage direct current (HVDC) is a preferred technology [1-3].

Voltage source converters (VSC) have been successfully used in HVDC links for offshore wind power transmission. Due to the offshore frequency and AC voltage control by the offshore VSC [4], same wind turbine (WT) control developed for the AC connection can also be applied when WTs are connected with VSC-HVDC.

Recently, diode-rectifier based HVDC (DR-HVDC) is considered as a potential solution to transmit offshore wind power. It provides some attractive advantages, such as higher reliability, higher efficiency and lower cost [5-6], when compared with VSC-HVDC. However, the use of diode-rectifier in the HVDC link also leads to some challenge due to its uncontrollability. The DR-HVDC rectifier cannot control the offshore AC network frequency and voltage as the VSC-HVDC does. Thus the WT converters have to take these responsibilities.

In [7-10], a frequency and voltage control of WT converters connected with DR-HVDC link is proposed which requires communication due to its measurement of the offshore PCC voltage. In [11], a distributed PLL based control of WT converter connected with DR-HVDC link is proposed without the use of communication.

On the other hand, there is an increasing interest in the parallel operation of DR-HVDC link and HVAC link. The research motivations mainly include:

- Due to the unidirectional power transmission of DR-HVDC, AC cables are connected in parallel with DR-HVDC link to energize the offshore network and diode rectifier during the start-up [6].
- Parallel operation of DR-HVDC and HVAC links also provides a more reliable solution to transmit the offshore wind power. If one link is disconnected with offshore wind farms, the wind power can still be transmitted to onshore grid without interruption.

Therefore, this paper is to investigate the operation of offshore wind farms under the following three operation modes:

- HVAC operation mode: The offshore wind farm is only connected with HVAC link while DR-HVDC link is disconnected.
- DR-HVDC operation mode: The offshore wind farms are only connected with DR-HVDC link while HVAC link is disconnected.
- Parallel operation mode: The offshore wind farms are connected with both DR-HVDC link and HVAC link, offshore wind power can be transmitted through both links.

The main objective of this paper is to propose a WT control method, which ensures the stable operation of the wind farm under the three operation modes including the smooth transition during the transition of the three operation modes.

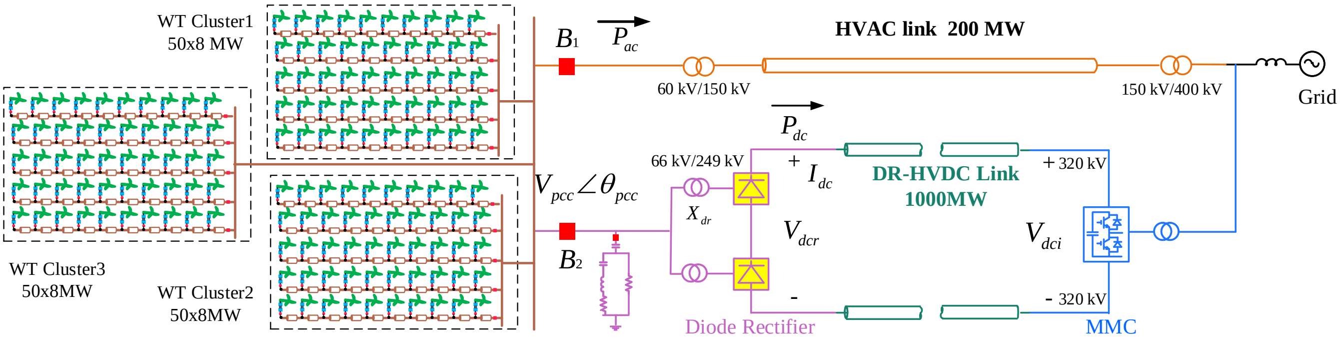

Fig. 1. Diagram of the offshore wind farms connected with DR-HVDC and HVAC transmission system

2 System structure

Fig.1 shows the considered 1200 MW offshore wind farms, which consist of 3 WT clusters. Each cluster is made up of 5 strings with a total of fifty 8 MW WTs. A 200 MW HVAC link and a 1000 MW DR-HVDC link are used to transmit the wind power to onshore grid. The 150 kV HVAC link is connected with the 66 kV offshore network via a step-up transformer. The DR-HVDC link uses a 12-pulse diode as the offshore rectifier and a modular multilevel converter (MMC) based on half-bridge submodules as the onshore inverter. As the offshore diode rectifier is uncontrollable, the onshore MMC is assigned to control the DC link voltage.

3 Control requirements of WT converters

To ensure stable operation of wind farms under the three operation modes previously described, WT converter control strategies should be well designed according to the requirements under different operation modes.

3.1 WT converter control requirements under HVAC operation mode and DR-HVDC operation mode

Assuming that the WT generator-side converters control the WT DC voltage [7], the control requirements of WT line-side converters on HVAC operation mode include:

- Active power control to transmit active power based on WT operation conditions, e.g. maximum power point tracking.
- Reactive power control to exchange reactive power with offshore network.
- Current control to prevent the WT converter from overcurrent during fault.

When on DR-HVDC operation mode, in addition to the control requirements mentioned above, WT line-side converters also need to provide:

- AC voltage control to ensure the offshore AC voltage is within a certain range [11].
- Frequency control to regulate the offshore network frequency.

These control requirements can be fulfilled by the distributed WT control, as the control objectives are local variables.

3.2 Control requirements of WT converter under AC and DC parallel operation mode

In order to alleviate the disturbance during the transition from HVAC operation mode to parallel operation mode, it is important to ensure that no power is transferred from HVAC link to DR-HVDC link when DR-HVDC is connected.

Moreover, after the connection of DR-HVDC link, the offshore wind power flow between two links needs to be controlled to avoid any circulating power. To reduce transmission loss, HVAC link transmitted active power is preferred to be controlled at 0 MW under parallel operation mode when the DR-HVDC link is not overloaded. When the total wind turbine generated active power is higher than DR-HVDC link rated power, the excessive wind power should be transmitted through HVAC link while DR-HVDC link transmitted active power is controlled at its rated value. Thus, the control requirements on parallel operation is described as

$$\begin{cases} P_{dc} = 0, & \textit{when } \text{DR-HVDC is first connected} \\ P_{ac} = 0, & \textit{when } P_{wt} \le P_{dcrated} \\ P_{dc} = P_{dcrated}, & \textit{when } P_{wt} > P_{dcrated} \end{cases} \tag{1}$$

Due to the uncontrollability of the diode rectifier, these control requirements should be implemented by all the WT converters. However, the power transmitted through the HVAC or DR-HVDC link are not local variables to the WT converters, thus part of the control is designed in a centralized controller, whose output will then be sent to all the WT distributed controllers by low bandwidth communication.

4 Control of WT converters

4.1 Distributed control of WT line-side converters

On HVAC operation mode, the offshore WT line-side converters can be controlled as current sources to inject appropriate active and reactive power [12]. But this control method is not suitable for the WTs on DR-HVDC operation mode, as diode rectifier cannot provide the offshore network with constant frequency like the onshore grid does.

Thus the WT line-side converters are controlled to emulate voltage sources rather than current sources. The PLL based frequency control, active power control and reactive power

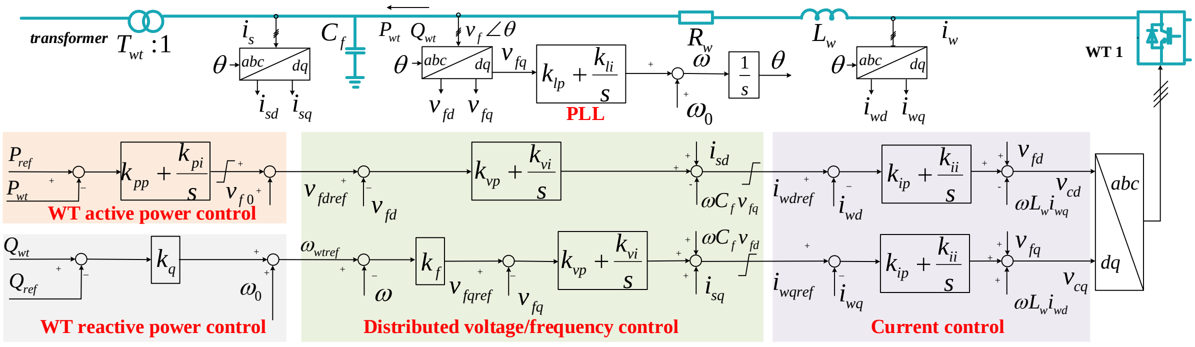

Fig. 2. Distributed control of WT line-side converter connected with DR-HVDC link and HVAC link

sharing control of WT converter proposed in [11] are implemented here. The WT active power P_{wt} is controlled through the adjustment of WT converter filter d-axis voltage v_{fd}, while the frequency ω is controlled through the adjustment of q-axis voltage v_{fq}. The reactive power sharing Q_{wt} is realized by the reactive power frequency droop control. With such distributed control method, the WT converters can operate under different operation modes without the need of distributed control method switching. The overall distributed control of WT line-side converter connected with DR-HVDC link and HVAC link is illustrated in Fig. 2 [11].

4.2 Centralized control of WT line-side converters

Considering the DC link voltage at the onshore MMC terminal is controlled at a constant value by the onshore converter, the transmitted active power via DR-HVDC is decided by the DC voltage produced by the diode-rectifier, expressed as

$$\begin{aligned} V_{dcr} &= 2(1.35nV_{pcc} - 3X_{dr}I_{dc}/\pi) \\ I_{dc} &= \left(V_{dcr} - V_{dci}\right)/R_{dc} \end{aligned} \tag{2}$$

where X_{dr} and n are reactance and voltage ratio of the diode rectifier transformer, I_{dc} and R_{dc} are DC current and DC resistance ,V_{dcr} and V_{dci} are the DC voltages at the offshore and onshore of the DR-HVDC link respectively. Thus, DR-HVDC transmitted active power can be controlled by regulating the offshore PCC voltage V_{pcc}. When the offshore PCC voltage is lower than $V_{dci}/2.7n$ (0.95 pu in this paper), the offshore PCC voltage will not be high enough to trigger the conduction of the diode rectifier after DR-HVDC connection. Thus, disturbance during the connection can be alleviated.

On the other hand, as the offshore PCC voltage is related to WT reactive power output on HVAC operation mode, the offshore PCC voltage control (designed to control DR-HVDC link power) is implemented through the adjustment of the WT reactive power reference Q_{ref}. The offshore PCC voltage control shown in Fig. 3 is expressed as

$$Q_{ref} = k_{dcp}\left(V_{pccref} - V_{pcc}\right) + k_{dci}\int\left(V_{pccref} - V_{pcc}\right)dt + Q_0 \tag{3}$$

where k_{dcp} and k_{dci} are the control parameters of offshore PCC voltage control, V_{pccref} and V_{pcc} are the reference and measured voltages at the offshore PCC . The common reactive power reference is then sent to all the WT converters by low bandwidth communication to adjust each converter's output reactive power. The communication delay used in this paper is 80 ms.

When HVAC link transmitted power P_{ac} needs to be decreased to 0 after the connection of DR-HVDC link, it can be achieved by regulating offshore PCC voltage phase angle, which is affected by WT output frequency. Due to the reactive power frequency droop control in the distributed controller, HVAC link power can also be controlled by the adjustment of WT reactive power reference Q_{ref}, expressed as

$$Q_{ref} = k_{acp}\left(P_{ac} - P_{acref}\right) + k_{aci}\int\left(P_{ac} - P_{acref}\right)dt + Q_0 \tag{4}$$

where k_{acp} and k_{aci} are the control parameters of the HVAC link active power control, P_{acref} and P_{ac} are the HVAC link active power reference (0 MW) and the measured active power.

To achieve smooth transition between offshore PCC voltage control and HVAC link power control, the output of the offshore PCC voltage control is used as the upper limit of the HVAC link power control, as shown in Fig. 3. When WT generated active power is less than 1000 MW, HVAC link power is controlled at 0. Meanwhile, the offshore PCC voltage control is saturated because the offshore PCC voltage is lower than its maximum value of 1.045 pu. With the increase of DR-HVDC transmitted active power, offshore PCC voltage increases according to (2). When it reaches the maximum value, offshore PCC voltage control is no longer saturated, leading to the reduction of the upper limit of the HVAC link power control. As a result, HVAC link power control is saturated and the offshore PCC voltage is controlled at 1.045 pu to ensure the constant DR-HVDC transmitted active power at 1000 MW. The operating principle of the centralized control is described in Table 1.

	Offshore PCC voltage control	**HVAC link power control**
HVAC operation mode before DR-HVDC connection	enabled, offshore PCC voltage controlled at 0.95 pu	saturated
Parallel operation mode when $P_{wt} \leq$ 1000 MW	saturated, offshore PCC voltage reference at 1.045 pu (maximum value)	enabled, HVAC link power at 0
Parallel operation mode when $P_{wt} >$ 1000 MW	enabled, offshore PCC voltage controlled at 1.045 pu	saturated

Table 1: Parameter of the tested system

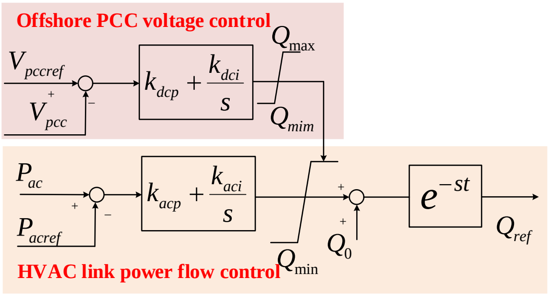

Fig. 3. Centralized offshore PCC voltage control and HVAC power control

5 Simulation result

The system shown in Fig. 1 is simulated in PSCAD/EMTDC to verify the proposed control of WTs under the three operation modes. The offshore wind farm is simplified with three 400 MW aggregated wind turbine converters. The detailed system parameters are presented in Table 2.

Components	Parameters	Values
DR-HVDC link	Power	1000 MW
	DC voltage	±320 kV
	DR transformer (Y/Y/Δ) Leakage inductance	66 kV/249 kV/249 kV, 0.18 pu
	DR reactive power compensation	0.3 pu
	MMC submodule	2.5 kV×256
HVAC link	Power	200 MW
	HVAC link transformer	60 kV/150 kV 150 kV/400 kV
	HVAC cable length	50 km
WT converters	Rating of aggregate WTs	400 MW×3
	Transformer (Y/Δ) Leakage inductance	0.69 kV/66 kV 0.08 pu
	Filter capacitor C_f	0.1 pu
	Converter reactance L_w and resistance R_w	0.1 pu 0.01 pu
	AC cable length (for each aggregated converter)	5 km, 7 km, 9 km

Table 2: Parameter of the tested system

5.1 HVAC operation mode to parallel operation mode

The performance of the proposed control is first verified during the transition from HVAC operation mode to parallel operation mode.

A. HVAC operation mode

Initially, WT 1, 2, and 3 generate 30 MW, 50 MW, and 50 MW respectively on HVAC operation mode while reactive power of each WT converter is controlled at 0, as shown in Fig. 4 (a) and (b). From 1.5 s to 2 s, WT 1 ramps its power from 30 MW to 200 MW, while WT 2 and WT 3 generated active power is decreased to 0 MW. The result in Fig. 4 (c) shows HVAC transmitted active power is increased from 130 MW to 200 MW.

At 3 s, the centralized control is enabled with V_{pccref} at 0.95 pu (with 80 ms delay). As HVAC link transmitted active power is larger than 0 MW, HVAC link power control is automatically saturated while offshore PCC voltage is regulated by the centralized control. Thus, the offshore PCC voltage is decreased from 1.067 pu at 3.08 s to 0.95 pu. Meanwhile WTs start to absorb 31 MVAr reactive power (positive Q_{wt} defined as WTs providing capacitive reactive power to the offshore ac network), as shown in Fig. 4 (d) and (b).

As seen in Fig. 4, the active power can be transmitted from offshore network to onshore grid on HVAC operation mode with the distributed control and offshore PCC voltage can be regulated with the centralized control.

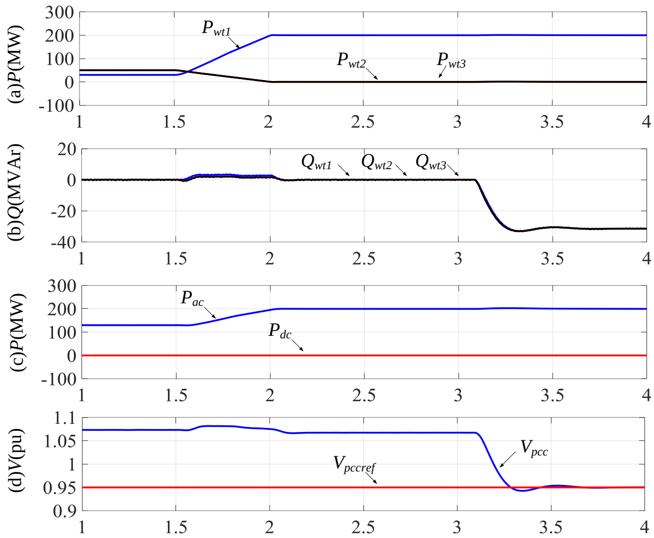

Fig. 4. Performance on HVAC operation mode

B. Parallel operation mode when $P_{wt} \leq 1000$ MW

At 4.5 s, DR-HVDC link is connected with offshore wind farm with DC voltage controlled at 1 pu by the onshore MMC, as shown in Fig. 5 (e). As the offshore PCC voltage at 0.95 pu is lower than the minimum AC voltage required for the diode rectifier to conduct, no disturbance is shown in HVAC link power transmission after the connection of DR-HVDC link, as shown in Fig. 5 (c).

During 5 s - 6 s, offshore PCC voltage reference is increased from 0.95 pu to 1.045 pu, as shown in Fig. 5 (d). With the increase of offshore PCC voltage reference, the voltage control saturates while HVAC link power control automatically de-saturates. As seen in Fig. 5 (c), HVAC link transmitted power is decreased to 0 while all wind power is transmitted to onshore grid through DR-HVDC link.

From 7 s to 8 s, WT 2 and WT 3 generated active power is increased from 0 MW to 200 MW, as shown in Fig. 5 (a). The increase of DR-HVDC transmitted active power leads to the increase of the diode rectifier reactive power consumption. At 10 s, 0.15 pu diode rectifier filter is added to compensate diode rectifier reactive power consumption. As a result, the reactive power output of WT decreases from 46 MVAr to -3 MVAr, as shown in Fig. 5 (b).

From 12 s to 13 s, WT 2 and WT 3 generated active power is increased from 200 MW to 400 MW. At 15 s, another 0.15 pu diode rectifier filter is added to reduce the WT reactive power output from 92 MVAr to 33 MVAr.

As can be seen in Fig. 5, smooth transition from HVAC operation mode to parallel operation mode is achieved with the proposed control. The wind power transmission from offshore wind farm to onshore grid is not interrupted during the operation mode transition. Moreover, when wind farm generated active power is less than 1000 MW, HVAC link power can be controlled at 0.

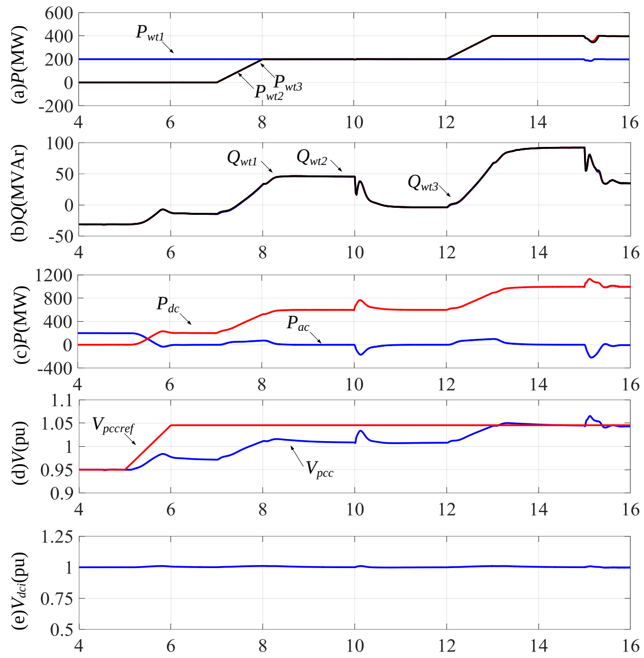

Fig. 5. Performance on parallel operation mode when Pwt ≤ 1000 MW

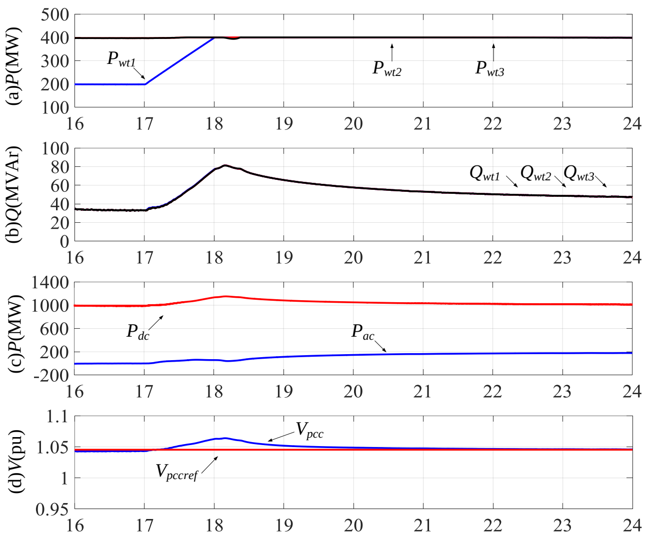

Fig. 6. Performance on parallel operation mode when P_{wt} > 1000 MW

C. Parallel operation when P_{wt} >1000MW

From 17 s to 18 s, WT 1 generated active power is increased from 200 MW to its rated power of 400 MW, as shown in Fig. 6 (a). The increase of active power leads to the increase of offshore PCC voltage to the maximum value of 1.045 pu, as shown in Fig. 6 (d). Thus the offshore PCC voltage control is no longer saturated. With the PCC voltage control, DR-HVDC link active power is controlled constant at its rated value of 1000 MW while the excessive wind power is transmitted to onshore grid through HVAC link, as shown in Fig. 6 (c). Fig. 6 (b) shows the reactive power is still well shared among the WTs.

As seen in Fig. 6, automatic and smooth transition from HVAC link power control to offshore PCC voltage control (DR-HVDC link power control at rated value) is achieved with the proposed centralized control, when WT generated active power starts to exceed DR-HVDC rated power.

5.2 Parallel operation mode to DR-HVDC operation mode

The performance of the system during the transition from parallel operation mode to DR-HVDC operation mode is illustrated in Fig. 7.

From 4 s to 5 s, WT 1 generated active power is decreased from 400 MW to 100 MW, as shown in Fig. 7 (a). The centralized control is switched from offshore PCC voltage control to HVAC link power control automatically. Thus, HVAC link transmitted active power is controlled at 0, as shown in Fig. 7 (c). At 6 s, HVAC link is disconnected from the offshore wind farm by opening the circuit breaker B1 (shown in Fig. 1). WT reactive power output decreases from 9 MVAr to -12 MVAr, as shown in Fig. 7 (b). After the disconnection of HVAC link, the offshore network frequency is determined by the WT reactive power droop control rather than the onshore gird. The offshore frequency decreases from 50 HZ to 49.7 HZ, as shown in Fig. 7 (e). As seen in Fig.7, smooth transition from parallel operation mode to DR-HVDC operation mode is achieved.

From 7 s to 8 s, WT 2 power is decreased from 400 MW to 200 MW on DR-HVDC operation mode, as shown in Fig. 7 (a). Thus, DR-HVDC link transmitted power is decreased from 900 MW to 700 MW, as shown in Fig. 7 (c). The decrease of the transmitted active power through DR-HVDC link results in the decrease of the offshore PCC voltage from 1.035 pu to 1.015 pu, as shown in Fig. 7 (d). Besides, the reactive power consumption of the diode rectifier is also decreased. As a result, the absorbed reactive power from each WT increases from 12 MVAr to 47 MVAr, as shown in Fig. 7 (b). The offshore frequency is decreased from 49.7 HZ to 49.3 HZ due to the reactive power frequency droop control, as shown in Fig. 7 (e). As can be seen, with the distributed control, the offshore wind power can be transmitted through DR-HVDC link to onshore grid successfully.

5.3 Parallel operation mode to HVAC operation mode

The performance of the system during the transition from parallel operation mode to HVAC operation mode is illustrated in Fig. 8.

During 3 s to 4 s, WT 1 generated active power decreases from 400 MW to 200 MW while WT 2 and 3 generated power is constant at 0 MW, as shown in Fig. 8 (a). All the power is initially transmitted through DR-HVDC link with HVAC link transmitted power controlled at 0, as shown in Fig. 8 (c).

From 5.5 s to 6 s, offshore PCC voltage reference decreases from 1.045 pu to 0.95 pu, as shown in Fig. 8 (d). The offshore

PCC voltage control is no longer saturated at 6.5 s, leading to the offshore PCC voltage decrease to 0.95 pu, as shown in Fig. 8 (d). As a result, all the power is transmitted through HVAC link rather than DR-HVDC link, as shown in Fig. 8 (c). At 9 s, DR-HVDC link is disconnected with the offshore wind farm by opening the circuit breaker B2 (shown in Fig. 1). As can be seen, smooth transition from parallel operation mode to HVAC operation mode is achieved with the proposed control.

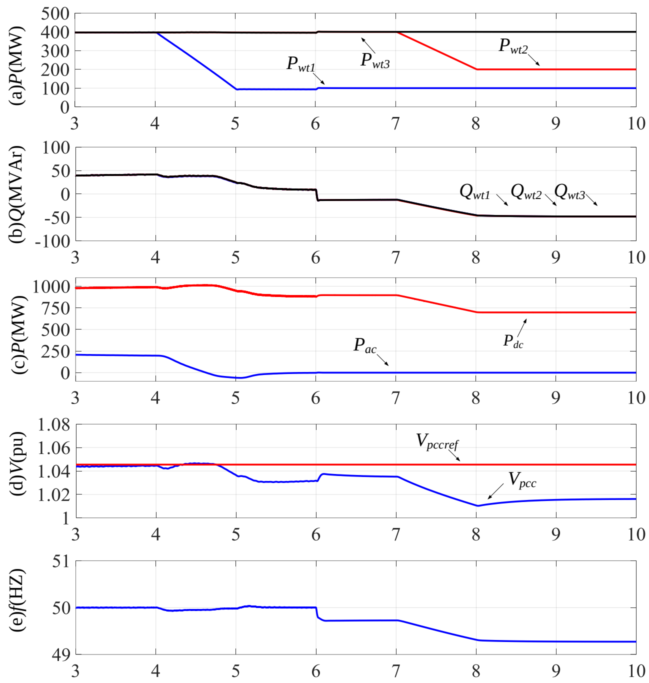

Fig. 7. Performance from parallel to DR-HVDC operation mode

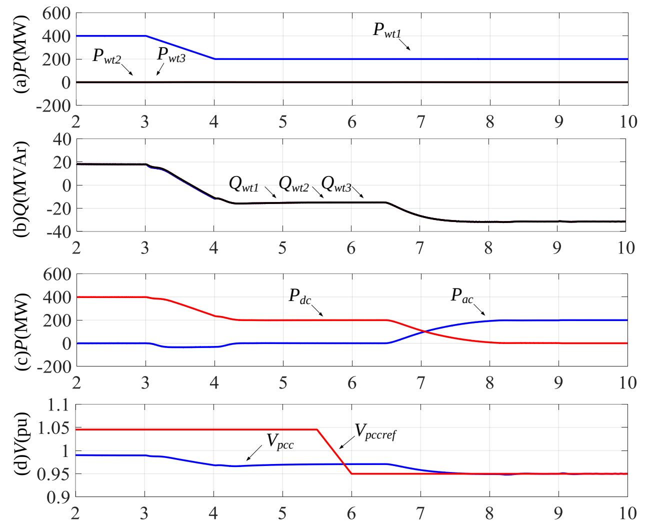

Fig. 8. Performance from parallel to HVAC operation mode

6 Conclusion

A WT control scheme including distributed control and centralized control is proposed in this paper to achieve stable operation of HVAC operation mode, DR-HVDC operation mode and parallel operation mode for integrating large offshore wind farms. The distributed control includes active power, reactive power control, frequency control, voltage control and current control. The centralized control includes offshore PCC voltage control and HVAC link power control. With the distributed control, there is no need to switch distributed control strategy during operation mode change. With the centralized control, smooth operation mode transition and power flow control under parallel operation mode can be achieved. Simulation results verify the proposed WT control during operation mode transition from HVAC operation mode to parallel operation mode, parallel operation mode to HVAC operation mode and parallel operation mode to DR-HVDC operation mode.

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