Research on the Coordinated control Strategy of fault crossing capability of offshore wind power multi-terminal flexible DC system

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Abstract. To improve the ride-through capability (RTC) of the multi-terminal offshore wind power flexible DC system in response to faults, this paper is based on the basic structure and control strategy of the voltage source converter (VSC) station of the multi-terminal offshore wind power flexible DC transmission system (MTDC), and aims at the AC grid connected to the system with three-phase short circuits and wind turbine output changes. According to the situation, the mechanism of voltage drop caused by the fault is analyzed, and the DC chopper energy bleeder circuit is connected to the DC side to cooperate with the comprehensive control scheme for fault ride-through of multi-terminal offshore wind power flexible DC collection system. Through theoretical analysis and building a simulation model, the design of the control strategy of the flexible collection system and the simulation study of fault ride-through is carried out on the Shandong Peninsula Beihai Wind Farm. The results show that: the VSC station controller of the offshore wind power multi-terminal system can make the multi-terminal system wind power distribution and consumption reasonable, and realize the stable operation of the system.

1. Introduction

There are multiple transmission methods for offshore wind power. For large-scale offshore wind farms, it is more suitable for multi-terminal grid connection, which is more stable and flexible. However, severe three-phase faults will inevitably occur in the AC grid, which induces an increase in the DC bus voltage. If the system does not have the capability of fault ride-through, the wind power system will be disconnected from the grid [1], and restart after shutdown. It will cause a lot of economic losses, and the disconnection of large-scale wind turbines will seriously lead to unbalanced power distribution and large frequency fluctuations in related areas [2]. How to improve the characteristics of the wind power flexible direct output system when the AC grid fails to ensure system stability and achieve fault ride-through has important practical significance.

At present, the LVRT control strategy of wind power VSC-MTDC system is mainly aimed at the 3-phase short-circuit fault on one side of the wind farm, that is, the outlet of the offshore converter station. Literature [3, 4] proposes a system fault safety zone for the wind power MMC-HVDC system. And according to the design principle of the bleeder resistance, the switching control strategy suitable for different wind power operating conditions is given, but the control scheme of the MTDC system is not considered. Literature [5, 8] mainly analyzes the regulation ability of the wind farm, and then
completes the LVRT of the system through the improvement of its own control strategy. The focus of the above two documents focuses on the control strategy when the fault occurs at the outlet of the wind farm, and does not consider how to control the fault at the outlet of the grid-side converter station in the multi-terminal system. Literature [6, 7, 9] proposed the use of a controllable energy dissipation resistor (DC Chopper) on the DC side. First, the access method was analyzed, and then the system fault ride-through scheme was summarized. Analysis shows that the solution can maintain the energy balance in the wind power flexible system, but the solution analysis of the multi-terminal wind power system has not been made.

Based on the mathematical model of HVDC and the control strategy of the VSC station of the offshore wind power multi-terminal flexible DC system, this paper analyzes, studies and designs a comprehensive fault ride through control scheme based on dynamic chopper circuit and VSC controller, to ensure that the whole system can operate stably when the AC side has faults. The simulation results show that the control scheme is effective enough to realize the FRT (fault ride-through) of the MTDC offshore wind power system.

2. Mathematical model of offshore wind power multi-terminal flexible DC system

The multi terminal model studied in this paper is a four terminal offshore wind power collection flexible DC system. The sending side is the wind farm (corresponding to the converter stations are vsc1 and vsc4), and the receiving side is the AC power grid (corresponding to the converter stations are vsc2 and vsc3). The rectifier side and the inverter side are both connected with active power systems, as shown in Figure 1.

![Schematic diagram of VSC-MTDC system on peninsula north.](image)

For multi-terminal systems, a single VSC-HVDC model is a basic unit. The VSC can be expressed as a mathematical model(1), $i_{sd}$ and $i_{sq}$ are AC grid current on the dq axis, respectively; $u_{sd}$, $u_{sq}$ are AC grid voltage on the dq axis, respectively; $u_{cd}$, $u_{cq}$ are AC side voltage fundamental wave of converter station on the dq axis, respectively.

$$
\begin{align*}
\frac{du_{cd}}{dt} &= -R_{i_d} + \omega L_{i_q} + u_{cd} - u_{sd} \\
\frac{du_{cq}}{dt} &= -\omega L_{i_d} - R_{i_q} + u_{cq} - u_{sq}
\end{align*}
$$

(1)

In order to independently control the current, active power $P$ and reactive power $Q$, the coordinate transformation is decoupled to obtain the direct current. It can be seen that the dq axis current is affected by the controlled variables $u_{cd}$, $u_{cq}$ from formula (1), the current cross-coupling terms $L_{i_q}$, $L_{i_d}$, and the AC grid voltage $u_{sd}$, $u_{sq}$. In order to obtain the decoupled instantaneous $P$ and $Q$, under the balance condition of 3-phase grid voltage, generally let $U_s$ on d-axis, then $U_{sq} = 0$, $U_{sd} = U_s$. After decoupling:

$$
\begin{align*}
I_d &= \frac{P}{u_{sd}} \\
I_q &= \frac{Q}{u_{sq}}
\end{align*}
$$

(2)

From formula (2), it can be seen that $P$ and $Q$ are decoupled and controlled respectively. This scheme will adopt PI control to stabilize the power and voltage balance of the VSC.
3. Control scheme of VSC-MTDC system

In the wind power flexible MTDC collection system, unlike the traditional two-terminal system, the control programme of the MTDC system should be more flexible. The solution needs to have basic stable control of voltage, power, frequency and other related variables. For multi-terminal systems, a balance node must also be selected to achieve the stability of the system.

\[
\begin{align*}
\dot{u}_d &= u_d - (R_i + L \frac{di_d}{dt}) + \omega L_i q - u_d - \omega L_i d \\
\dot{u}_q &= u_q - (R_i + L \frac{di_q}{dt}) - \omega L_i d - u_q - \omega L_i q
\end{align*}
\]

(3)

\[
\begin{align*}
\delta q &= K_1(i_{qref} - i_q) + K_2 \int (i_{qref} - i_q) dt \\
\delta d &= K_1(i_{dref} - i_d) + K_2 \int (i_{dref} - i_d) dt
\end{align*}
\]

(4)

Where: \(v_d, v_q\) are the outputs of the current loop PI controllers; According to formula (1), \(i_{dref}, i_{qref}\) are the inner loop current reference command values directly converted from the output values of \(P\) controller and \(Q\) controller respectively; \(\omega L_i d\) and \(\omega L_i q\) are the coupling compensation terms of \(dq\) axis voltage, which makes the nonlinear equation decoupled. The control diagram of the constant DC voltage, constant \(P\) and constant \(Q\) control is shown in Figure 2.

4. Scheme design for improving FRTC

The above control strategy cannot achieve fault ride-through when the VSC-MTDC system has a serious fault, which will cause system over-voltage and affect system stability. In order to solve this problem, this paper uses the DC Chopper circuit and the converter station control strategy to cooperate with each other to realize the system fault ride-through.

4.1. Working principle of dynamic DC Chopper circuit

The DC Chopper circuit is added to the DC side of the converter station entrance of the offshore flexible multi-terminal wind power system. The specific working state is divided into two states: input and cut-out. As shown in Figure 3,

Figure 2. Block diagram of decoupling control of constant \(P\), constant \(Q\) and constant DC voltage.

Figure 3. DC Chopper circuit in net side converter station.
When the fault is cut out by the protection circuit, the system DC bus voltage will be restored to the normal rated value under the action of the VSC constant DC voltage control. In actual situations, the bleeder resistance in the DC chopper circuit needs to be set to an appropriate value. The setting value of the bleeder resistance $R_{load}$ in the DC Chopper circuit is related to the maximum withstand power $P_{\text{max}}$ of the system and the protection threshold $U_{dc\_\text{max}}$ set by the DC side bus voltage. As in formula (5):

$$R_{load} = \frac{U_{dc\_\text{max}}^2}{P_{\text{max}}}$$  \hspace{1cm} (5)

When the system is unstable, it is easy to cause the DC Chopper circuit to switch too frequently, so this article adopts PI controller to alleviate this situation.

### 4.2. Coordinated control strategy of offshore wind power VSC-MTDC system

When failure occurs in the multi-terminal system, the voltage will drop, and the receiving converter station will first control the reactive power to improve the VRTC. When the AC power grid voltage drop to 0.2pu-0.9pu, the wind farm also needs to supply reactive current for supporting the system to maintain the rated voltage. And the wind farm also needs to supply reactive current $i_{Q\_\text{ref}}$ is equation (6), the reference value of $Q\_\text{ref}$ is equation (7), and the reference value of active current $i_{P\_\text{ref}}$ is equation (8). Among them, $i_{cs\_\text{max}}$ is the maximum allowable current of the converter station (generally set to 1.2 times the unit value).

$$\begin{cases}
U_s \in [0.2, 0.9]\text{pu} ; & i_{Q\_\text{ref}} \geq 1.5 \times (0.9 - U_s)I_s \\
U_s \in (0.9,) \text{pu} ; & i_{Q\_\text{ref}} = 0
\end{cases}$$ \hspace{1cm} (6)

$$Q_{\text{ref}} = -1.5 \times (0.9 - U_s)I_s \times 1.5U_s$$ \hspace{1cm} (7)

$$i_{P\_\text{ref}} = \sqrt{i_{cs\_\text{max}}^2 - i_{Q\_\text{ref}}^2} - i_{Q\_\text{ref}}$$ \hspace{1cm} (8)

When the AC grid fails, the shore converter station will first control the reactive power to improve the VRTC. When a complex fault occurs, the fault is detected as a serious fault, and the redundant power causes the DC bus voltage $U_{dc}$ to exceed its upper operating threshold $U_{dc\_\text{max}}$, the controller is switched to Complex FRT control strategy. When the fault is removed and the DC bus voltage is lower than the lower limit value of the threshold, controller switches back. The specific complex traversing coordinated control scheme is shown in Table 1.

| Fault location          | Fault degree | Converter station of wind farm | Main converter station at grid side | Secondary converter station at grid side |
|------------------------|--------------|--------------------------------|-----------------------------------|------------------------------------------|
|                         |              |                                | Control switching                  | DC Chopper circuit                       |
|                         |              |                                | Voltage ride through control       | on                                      |
|                         |              |                                | Constant DC voltage control        | off                                     |
| Outlet of main converter station at grid side | Minor fault | Constant power and AC voltage control | Voltage ride through control | on |
|                         | Serious failure |                                | Constant DC voltage control        | off                                     |
| Outlet of Secondary converter station at grid side | Minor fault |                                | Constant DC voltage control        | on                                     |
|                         | Serious failure |                                | Voltage ride through control       | off                                     |
5. System simulation verification and analysis

Based on the Shandong Peninsula North Wind Power Base on MATLAB/Simulink, a four-terminal model of flexible grid-connected ring topology of offshore wind power is built. The stable operation DC voltage is set as 0.95pu. The following will analyze the waveforms at VSC2 when the power grid side of the simulated converter station (master station VSC2) fails.

When a 3-phase short-circuit fault occurs on the VSC2 grid side (3.3s-3.8s), the AC voltage on the VSC2 grid side severely drops as shown in Figure 5(a). Since the system did not take any control measures at the beginning of the fault, as shown in Figure 4(a), the three-phase short circuit caused the rise of DC bus voltage ($U_{dc}$). Due to grid fault, the $U_{dc}$ reaches the threshold of the control strategy, then the master control is switched to the VRT control strategy, VSC3 switched to constant DC voltage control strategy, and the bleeder circuit put into system. Within 0.1s, the bleeder circuit will coordinate with the VRT control strategy to control the DC voltage back to 0.95pu. It can be seen from Figure 5 that when a 3-phase short-circuit fault occurs on the VSC2 grid side, the AC side voltage drops more severely, and both $P_{ac}$ and $Q_{ac}$ become zero.

![Figure 4. DC voltage and power waveform of VSC2 DC side.](image)

![Figure 5. AC voltage, active and reactive power waveform of VSC2 AC side.](image)

6. Conclusion

Based on the problem of FRT capability of offshore wind power multi terminal flexible direct current system, this paper proposes a coordinated control strategy of FRT by combining dynamic DC chopper circuit with VSC control strategy of multi terminal system:

(1)When VSC-MTDC system is operating in a stable state, the proposed VSC converter station control strategy can make the system operate stably and safely, and absorb wind power reasonably.

(2)When VSC-MTDC system is in the serious fault state, the voltage sag amplitude is large, and the redundant power can be released by switching the master-slave control and starting the DC chopper circuit, to achieve the purpose of stabilizing and balancing the DC bus voltage. The results show that the control strategy can realize the system fault ride through, which proposed in this paper.

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