Research on Operation Status and Switching Strategy of AC/DC Control Device

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Abstract. The AC/DC hybrid distribution network is large in scale and high in voltage level, and contains more sources and loads, and the degree of control is more complicated. Therefore, the disconnection of the line in the AC/DC hybrid distribution network, the AC/DC fault of the system, and the change of the operating state of the flexible DC device may cause the operating mode of the system to change. In this paper, the corresponding system operation mode is proposed for the typical hand-hand AC/DC hybrid distribution network. The operating mode of the flexible DC device, the switching conditions of the flexible DC device, and the switching strategy are studied. The influence of the hot standby operation on the distribution network is analyzed, and the seamless switching of the flexible DC device is realized.

1. Introduction

The key equipment in the flexible DC distribution network is related to whether the flexible DC distribution network can operate safely and reliably. Compared with the traditional AC distribution network, the system architecture and working mode of the flexible DC distribution network are different. Therefore, the key equipment in the traditional AC distribution network cannot be fully applied to the flexible DC distribution network. The operation switching of the flexible DC device is affected by the operation mode of the system, including the switching between the operation modes and the control mode. The change of the system operation mode may be the switching between the operation modes, or may be the switching between different control modes in the normal operation mode. This paper focuses on the operation mode and control characteristics of AC/DC hybrid distribution network, and studies the switching conditions and switching strategies of its operation mode.

2. The operation mode of the flexible DC control device

The operating modes of the straightening device include a normal operating mode, a blocking mode, a hot standby mode, and an existing open exiting operation mode.

2.1. Normal operating mode

The flexible DC control device can operate stably in the normal operation mode, and mainly relates to the mode switching of the flexible device, and realizes the control target in different control modes. According to different control methods, the total control modes include the following:
At present, the control methods for voltage source converters can be mainly divided into two categories: indirect control and direct control.

1) Direct control

Direct control is also known as indirect current control, which is achieved by controlling the amplitude and phase of the fundamental voltage of the AC side output voltage of the compliance device. The structure is simple, but there are disadvantages such as slow current dynamic response on the AC side and difficulty in achieving overcurrent control.

2) Indirect control

Indirect control, i.e., direct current control, is also referred to as vector control. It is usually composed of two loops, the outer loop voltage control and the inner loop current control, and has a fast current response characteristic.

a) Conventional control

Conventional controllers include constant DC voltage control, constant active power control, constant reactive power control, constant AC voltage control, and constant frequency control. The phase signal output from the phase-locked link is used to provide the reference phase required for voltage vector orientation control and trigger pulse generation. The trigger pulse generation step is based on the PWM principle, and the trigger voltage of each bridge arm of the inverter is generated by using the reference voltage and the synchronous phase signal output by the current loop.

b) Droop control

Voltage droop control is a method of learning frequency modulation in an AC system. One frequency modulation is to approximate the static frequency characteristic of the prime mover of the generator set to a straight line, satisfying $K_g = \Delta P_g / \Delta f$. When the system frequency changes, the generator will adjust the power according to the respective units to increase or decrease the output power, thereby achieving the purpose of power balance. As shown in picture 2.
The outer ring control diagram of the droop controller is shown in Figure 3, where $k$ is the slope of the droop control.

2.2. Blocking mode
The flexible DC control device requires fast operation of the start and stop of the entire distribution network, and how to ensure the safe operation of the flexible DC device is a core part of the DC protection system. On the one hand, it is possible to selectively and quickly remove short circuits or abnormal operating equipment in the system under equipment failure or abnormal conditions to prevent larger areas of failures and accidents. On the other hand, flexible DC devices use high-power power electronic devices such as IGBTs. The cost is high, and the faults are judged and blocked by means of processing, which can effectively protect the flexible DC device and avoid greater economic losses.

2.3. Hot standby mode
After the device exits the operation or the device has not been put into operation, it must first go through the hot standby state, that is, the state in which the primary device is powered but not powered. In the hot standby mode, the transmission power of the flexible substation can be quickly adjusted. Once the grid loses some power due to a fault, the flexible DC unit can immediately increase the load quickly, compensate for the lost power output, keep the system frequency stable and the stable operation of the distribution network.

The thermal standby of the flexible DC device should meet the following conditions:
- $g)$ Valve is locked;
- $h)$ No abnormalities in the control system and valve-based electronics;
- $i)$ No abnormalities in the protection system;
- $j)$ Protection does not detect failure;
- $k)$ Did not receive a stop start command;
- $l)$ No abnormality in valve cold control;
- $m)$ No protective l
n)atching or trip signal within 15s before operation.

2.4. Exit run mode
Exiting the running state means that the flexible DC device is isolated from the power supply and is not powered. When the flexible DC device fails or is repaired, the device is out of operation at this time.

3. Flexible DC control device operation mode switching strategy
   1) Switching between normal operation state and blocking and exiting operation status
      The straightening device is switched from normal operation to blocking operation, driven by the blocking signal, and then switched to the exit mode by the blocking operation, i.e., the device is not powered.
   2) Normal operation and hot standby
      After the device exits the operation or the device is not put into operation, it must first go through the hot standby state, that is, the main device is powered and not powered. When the device hot standby state is switched to the normal operation mode, the pre-synchronization is first performed when connecting to the AC large power grid, thereby achieving seamless handover.

![Figure 4. AC/DC distribution network and flexible substation diagram](image)

3.1. Operational state switching analysis
As shown in Figure 4, when VSC2 is in normal operation mode, the segment isolation switch at the single bus segment affects the operating state of VSC2. When the isolating switch is not disconnected, it is connected to the AC line at this time to jointly supply power to the display hall, which is an active
running state. When the isolating switch is disconnected, the VSC2 is separately powered to the load, which is a passive operating state.

1) Active operating state switches to passive operating state

Assume that the display hall load is a constant impedance load, the required active power of the load is $P_L$, and the required reactive power is $Q_L$; The active power delivered by VSC2 to the load is $P_{MMC2}$, and the required reactive power is $Q_{MMC2}$; The active power transmitted by the busbar to the load at the segment isolation switch is $P_{AC}$, and the required reactive power is $Q_{AC}$.

If the initial state is: the segment isolation switch is not disconnected, VSC2 is in active operation. In an unplanned state, the switch is suddenly turned off, so the control mode is not switched. At this time, when the active and reactive power required by the load is greater than the active and reactive power that the receiving converter can provide, it is satisfied:

$$\begin{cases} P_{MMC2} < P_L \\ Q_{MMC2} < Q_L \end{cases}$$  \hspace{1cm} (1)

Since the load is a constant impedance characteristic, and the active and reactive power provided by the VSC2 is less than the power required by the load, a part of the deficiency occurs, so the output voltage amplitude drops suddenly. Since the power supplied by VSC2 remains unchanged, the amplitude of the output voltage decreases, causing the amplitude of the output current to rise.

If the output AC voltage is:

$$\begin{cases} U_a = U \cos \theta \\ U_b = U \cos \left( \theta - \frac{2\pi}{3} \right) \\ U_c = U \cos \left( \theta + \frac{2\pi}{3} \right) \end{cases}$$  \hspace{1cm} (2)

Then the corresponding abc/dq transformation matrix is:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} U \cos (\theta - \theta_{PLL}) \\ U \sin (\theta - \theta_{PLL}) \end{bmatrix}$$  \hspace{1cm} (3)

It can be known from equation (3.3) that hysteresis changes occur, so that $u_q$ is less than 0. The PI controller through the phase-locked loop further increases the error, the slope of the phase-locked loop output phase PLL decreases, and the output AC voltage frequency $f$ also changes. Small. At the same time, the frequency is reduced, so that the phase of the AC voltage output is further delayed, so that $u_q$ is still less than 0. The entire system cannot form an orderly negative feedback adjustment process, the system frequency $f$ is continuously reduced, and the system collapses.

2) Passive running state switches to active operating state

Under the vector control of the unplanned situation, the relevant switching strategy needs to be designed before the active operation can be successfully switched to the passive running state. In the case of planning, you only need to change the VSC2 control mode to achieve successful switching. For the passive operating state to switch to the active operating state, it is the planned situation. Therefore, the switching of the operating state needs to satisfy two conditions, namely, the change of the control mode and the satisfaction of the ideal closing condition.
Since VSC2 is originally operated in a passive network state, its voltage amplitude, frequency, and phase are quite different from those on the grid side. If it is directly closed, it will cause a huge inrush current in the grid connection and damage the inverter. The VSC2 operates in a passive state and requires grid synchronization before switching to the active operating state.

3.2. Seamless switching conditions

Before the grid-connected operation, the control system detects the amplitude difference, frequency difference and phase angle difference of the voltage across the grid switch, and provides the voltage and frequency synchronization command to the control system through the closed-loop adjustment unit. When the error is within the allowable range, the grid-connected signal is synchronized to the detection unit. This control process is called a pre-synchronization operation.

Assume that the vector relationship between the AC bus voltage and the large grid voltage is shown in Figure 5 before the off-grid to grid connection. \(U_{\text{grid}}\) and \(U_{\text{pcc}}\) are the d-axis components of the large grid and AC bus voltage in the same dq rotating coordinate system. Assume that the operating angular frequency of the large \(\omega_{\text{grid}}\) leads the operating angular frequency \(\omega_{\text{pcc}}\) of the microgrid. In the short time before the grid connection, the voltage phase angle of the large grid leads the AC bus voltage phase \(\theta_{\text{grid}}\) in the case of phase a. The AC voltage \(u_a\) and the grid voltage \(u_{ga}\) that are not yet connected to the grid are:

\[
\begin{align*}
    u_a &= U_{pcc}^d \sin(\omega_{pcc} t + \theta_{pcc}) \\
    u_{ga} &= U_{grid}^d \sin(\omega_{grid} t + \theta_{grid})
\end{align*}
\]

Let \(t=0\) at the moment when the static switch is closed, that is, ignore the influence of the frequency, and the instantaneous difference between the two voltages is:

\[
    u_c = u_{ga} - u_a = U_{grid}^d \sin \theta_{grid} - U_{pcc}^d \sin \theta_{pcc}
\]

1) When the voltage phases of \(u_{ga}\) and \(u_a\) are equal and the amplitude difference is 1/100 of the rated voltage, the instantaneous difference \(u_e=0.01U_n\);

2) When the voltage amplitudes of \(u_{ga}\) and \(u_a\) are equal and the phase difference is 1/100 of \(2\pi\), the instantaneous difference \(u_e=0.0628U_n\); When the voltage amplitudes of \(u_{ga}\) and \(u_a\) are equal and the phase difference is 1/2 of the full cycle \(2\pi\), the instantaneous difference \(u_e=U_n\), in which case the instantaneous voltage deviation reaches the maximum value.

![Figure 5. AC bus voltage and grid voltage vector](image-url)
Therefore, to achieve seamless switching, before the grid-connected operation, the amplitude difference and phase difference between the AC bus voltage and the large power grid must be strictly controlled within a certain small range, especially the phase difference is small enough.

3.3. VSG-based seamless switching technology

Under vector control, the conversion of the two operating states must be changed to change the control mode. One of the advantages of VSG control is that there is no need to switch control modes. The receiving converter based on VSG control can automatically adapt to two operating states, but pre-synchronization operation is required before the closing, so that the output voltage of the converter meets the ideal closing condition.

The drooping link of the virtual excitation system causes the inverter output voltage to deviate from the receiving end of the large power grid in the passive operating state, so the voltage pre-synchronization link is added here. Simulate the role of the secondary frequency modulation link, adding the reactive power integral link, ie:

\[
\Delta Q_{\text{pre}} = \left( k_p + \frac{k_i}{s} \right) (Q_{\text{ref}} - Q)
\]  

(7)

The control block diagram of the virtual excitation system adapted to pre-synchronization is shown in Figure 6.

If the voltage amplitude deviation is ignored, the frequency is consistent and \( \omega \), the voltage difference generated by forced networking is:

\[
U_{\text{grida}} - U_a = 2U \cos \left( \theta_{\text{grida}} + \frac{\theta_a}{2} \right) \sin \left( \frac{\theta_{\text{grida}} - \theta_a}{2} \right)
\]

(8)

![Figure 6. Control block diagram of virtual excitation system adapted to pre-synchronization](image)

As shown in Figure 7 below, assume that the switch at the common coupling point PCC is closed and there is a virtual impedance. Then, when the VSC2 output voltage \( u_{abc} \) deviates from the grid voltage \( u_{\text{grid}} \), there is a virtual current on the line at the virtual impedance.
Fig. 7. Schematic diagram of line virtual impedance

Assuming that the grid voltage phase is 0 and the VSC2 output voltage $u_{abc}$ phase is $\omega$, the virtual current $I$ can be expressed as:

$$I = \frac{U_{\text{grid}} - U_{abc}}{R + jX}$$

$$= \frac{U_{\text{grid}} R - U_{abc} R \cos \theta - U_{\text{pcc}} X \sin \theta}{Z} - j \frac{U_{\text{grid}} X - U_{\text{pcc}} X \cos \theta - U_{\text{pcc}} R \sin \theta_{\text{pcc}}}{Z} \theta$$

$$= U_{\text{grid}} \cos \theta_{\text{c}} - U_{\text{pcc}} \cos (\theta_{\text{c}} - \theta) - j U_{\text{grid}} \sin \theta_{\text{c}} + U_{\text{pcc}} \sin (\theta_{\text{c}} - \theta)$$

$U_{\text{grid}}$ and $U_{abc}$ are respectively the effective value of grid voltage and the effective value of VSC2 output voltage; $R$ and $X$ are virtual inductance and virtual reactance respectively; $Z$ is the virtual impedance, and $\theta$ is the virtual impedance angle satisfying formula (3.10):

$$\begin{align*}
Z &= \sqrt{R^2 + X^2} \\
\theta_{\text{c}} &= \arctan \frac{X}{R}
\end{align*}$$

It can be known from equation (4.11) that when the virtual current $\dot{I}$ is zero, it needs to be satisfied:

$$\begin{align*}
U_{\text{grid}} &= U_{\text{pcc}} \\
\theta &= 0
\end{align*}$$

The switch at the PCC can be closed and connected to the grid. Therefore, the virtual current can be controlled to achieve phase pre-synchronization before grid connection.
As shown in Fig 8, the virtual current $i_v$ is obtained from the deviation voltage of the VSC2 output voltage $u_{abc}$ and the grid voltage $u_{grid}$. The virtual power $P_v$ can be obtained from the grid voltage $u_{grid}$ and the virtual current $i_v$. After $P_v$ passes through the proportional-integral regulator, $\Delta \omega_v$ is obtained, which is added to the angular frequency $\omega$ obtained by the VSG control, So get the reference angular frequency $\omega_f$ required for the pre-synchronization link. After the integration step, the reference phase $\theta_i$ can be obtained.

VSC2 is switched from a passive operating state to an active operating state. First, it is necessary to ensure that the secondary frequency modulation link S1 is cut into operation, so that the frequency of the passive island operating state tracks the large grid frequency; Secondly, the reactive power integral link S2 is closed, so that the output voltage amplitude of the VSC2 is consistent with the grid; Finally, the virtual current phase modulation link S3 is switched, and the output voltage phase of the VSC2 is controlled to follow the grid voltage phase to realize the pre-synchronization operation before the grid-connected operation.

4. Conclusion

In this paper, the operation mode and control characteristics of flexible AC/DC hybrid distribution network are studied, and the switching conditions and switching strategies of its operation mode are studied. For the flexible substation of AC/DC distribution network, the switching relationship between each operation mode is studied, and the discussion on the normal operation and the hot standby is discussed. Aiming at the seamless switching technology during hot standby operation, the key factors and control methods of hot standby operation are studied, which provides a reference for the seamless switching technology of hot standby operation.

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