Study on the Reactive Power Control in Hybrid DC Asynchronous Interconnection System

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Abstract. Reactive power control of hybrid DC asynchronous interconnection system has a vital impact on the safety, reliability and high quality of AC/DC power transmission system. The LCC-HVDC unit and MMC-HVDC unit share the same station control system in the hybrid DC asynchronous interconnected system. Firstly, this paper studies the reactive power switching control of LCC-HVDC system, including five subfunctions and control strategies of the reactive power switching control. Secondly, the reactive power auxiliary control of LCC-HVDC system including low load reactive power regulation function and Gamma-Kick function is studied. And the shortcomings of using reactive power auxiliary control are pointed out. Finally, the reactive power control of MMC-HVDC system is deeply studied. The mathematical model of MMC-HVDC control system is established. Reactive power control of MMC-HVDC can be used to replace reactive power auxiliary control of LCC-HVDC to improve the converter utilization and service life.

1. Introduction
The imbalance of energy storage and load distribution determines that long-distance and large-capacity transmission becomes the inevitable choice for developing the power grid and meeting the demand of electricity in China. High Voltage Direct Current (HVDC) transmission technology has obvious advantages in long-distance and large-scale transmission. In recent years, with the vigorous development of HVDC transmission projects, the grid structures with parallel AC-DC and multi-infeed direct current have gradually formed. The safe and stable operation of power grid is facing many problems and challenges. In 2016, China southern power grid realized the asynchronous interconnection between Yunnan power grid and southern China power grid by Guanyin Yan DC and Luxi Back-to-Back DC projects. It optimized network structure and eliminated the risk of large-scale blackouts. After comprehensively comparing the economy, land occupation, technology and engineering demonstration significance the parallel connection structure of LCC-HVDC and MMC-HVDC are used to form the hybrid DC asynchronous interconnected system in the Luxi back-to-back HVDC project. The superior control performance of the flexible transmission technology is utilized to
further improve the operation of the hybrid DC transmission system. The voltage stability of LCC-HVDC transmission system is improved. Hybrid DC asynchronous interconnection system integrates the advantages of LCC-HVDC and MMC-HVDC transmission system. LCC-HVDC is connected by two 12 pulse converters through a smoothing reactor ($L_d$). Each 12-pulse converter is composed of two 6-pulse converters. The DC grounding electrode is located between the two 6-pulse converters on the inverter side. MMC-HVDC consists of two back-to-back modular multilevel converters (MMC). Because the probability of DC faults in back-to-back DC system is very low, the cascaded MMC composed of half-bridge sub-modules without DC side fault self-cleaning ability will not seriously reduce the power supply reliability and availability of MMC-HVDC. The schematic diagram of hybrid DC asynchronous interconnection system is shown in Figure 1.

![Figure 1. schematic diagram of hybrid DC asynchronous interconnection system](image)

LCC-HVDC and MMC-HVDC share the same station level control system in the hybrid DC asynchronous interconnection system. Reactive power control belongs to the DC station control system. In this paper, reactive power control of LCC-HVDC and MMC-HVDC are studied respectively. Firstly, the reactive power switching control strategy and function of LCC-HVDC are analyzed. And then the reactive power auxiliary control of LCC-HVDC: low load reactive power regulation function and Gamma-Kick function are studied. Finally, the mathematic model of MMC-HVDC control system is established and the principle of reactive power control is deeply studied. It is analyzed that reactive power control of MMC-HVDC replaces reactive power auxiliary control of LCC-HVDC to improve the utilization rate and service life of converter.

2. Reactive power switching control of LCC-HVDC

LCC-HVDC system needs absorbing a lot of reactive power. At the same time the required reactive power changes with circumstance. Besides, LCC-HVDC system is a huge harmonic source for the AC system. If it is not controlled, it will seriously damage the reactive power balance and power quality of the grid. Therefore, the reactive power compensation configuration of LCC-HVDC system has a crucial impact on the designing and planning of HVDC project. The reactive power switching control of LCC-HVDC can effectively control the switching of various reactive power compensation devices in the converter station in real time so that the reactive power exchange between the AC system and DC system or voltage of converter bus is within the prescribed range. The reactive power compensation equipments in the converter station include AC filter, shunt capacitor and shunt reactor. All kinds of reactive power compensation equipment have the characteristics of "step-type" compensation.

2.1. Function of reactive power switching control

Reactive power switching control of LCC-HVDC system includes reactive power control, AC voltage control and filter control. According to the preset priority and criteria, the reactive power control subfunction realizes its specific control function without conflict. The coordination among the subfunctions is realized through the scheduled reactive power control strategy. And the optimal control
effect is achieved. According to the order of the highest priority 1 to the lowest priority 5, the subfunctions of reactive power control are shown in Table 1.

| Priority | Subfunction of reactive power control | Content of subfunction |
|----------|--------------------------------------|------------------------|
| 1        | Abs Min Filter Control               | Ensure that the filter is not overloaded. Ensure that the AC system voltage connected to the converter station during the operation of the DC system does not exceed its maximum and minimum values. |
| 2        | $U_{\text{max/min}}$ Control         | Ensure that the maximum capacitive reactive power delivered to the AC system at the converter station does not exceed the maximum value. |
| 3        | $Q_{\text{max}}$ Control            | In order to satisfy the filtering performance of the system, the filter banks are put into the filter group according to the required filter type and number. $Q_{\text{con}}$ takes reactive power switching as the criterion to control the reactive power exchange within the allowable deviation $\pm Q$ by switching filters. $U_{\text{con}}$ takes reactive power switching as the criterion to control the converter station bus voltage variation within the allowable deviation $\pm Q$ by switching filters. |
| 4        | Min Filter Control                   | $Q_{\text{con}}$ takes reactive power switching as the criterion to control the reactive power exchange within the allowable deviation $\pm Q$ by switching filters. $U_{\text{con}}$ takes reactive power switching as the criterion to control the converter station bus voltage variation within the allowable deviation $\pm Q$ by switching filters. |
| 5        | $Q_{\text{con}}/U_{\text{con}}$ Control | $Q_{\text{con}}$ takes reactive power switching as the criterion to control the reactive power exchange within the allowable deviation $\pm Q$ by switching filters. $U_{\text{con}}$ takes reactive power switching as the criterion to control the converter station bus voltage variation within the allowable deviation $\pm Q$ by switching filters. |

2.2. Strategy of reactive power switching control

According to the logic of reactive power control priority, the corresponding reactive power control strategy is formulated to achieve the coordination of each sub-function and meet the requirements of reactive power control. The specific control strategy is as follows:

Step 1: Abs Min Filter control has the highest priority. According to different working conditions and different power levels, the number and type of filter banks are determined by the filter capacity limitation. Then the absolute minimum filter banks are put into operation, and the control conditions of Abs Min Filter control are monitored in the full power range of DC operation. When other sub-functions request the removal of reactive power units, it determines whether the removal meets the Abs Min Filter control conditions. If it is not satisfied, the Abs Min Filter control will prohibit the removal operation.

Step 2: If the Umax/min control detects that the AC bus voltage is higher than the maximum $U_{\text{MAX,LIMIT}}$ and lasts for a period of time after the Abs Min Filter control condition is satisfied, the reactive units are removed sequentially until the AC bus voltage returns to normal; and vice versa.

Step 3: After the Umax/min control condition is satisfied, the $Q_{\text{max}}$ control starts to monitor the reactive power of the converter station feeding into the AC system. When the detection result exceeds its predetermined maximum $Q_{\text{acmax}}$, the instruction to remove the reactive power unit is executed. $Q_{\text{max}}$ control can not two-way control reactive power unit to input or cut but can only control the removal of reactive power unit.

Step 4: After the $Q_{\text{max}}$ control condition is satisfied, the Min Filter control first calculates the type of filter banks and the minimum capacity required to satisfy the filtering requirements of the converter station according to the operating state of the converter station and the DC transmission power. When the filter condition is not satisfied, the filter bank is input according to the result of precomputation.

Step 5: $Q_{\text{con}}/U_{\text{con}}$ controls the reactive power exchange $Q_{\text{exc}}$ and the commutation bus voltage $U_{\text{pcc}}$ in the AC/DC system to be within the prescribed range by the reactive power unit switching on or off. $Q_{\text{con}}/U_{\text{con}}$ controls are respectively used to suppress reactive power balance and AC bus voltage fluctuation in AC/DC system. When the DC system is fed into the weak grid, reactive power will
significantly affect the stability of AC voltage. Therefore, $U_{con}$ control is usually used when the AC system is weak to suppress the voltage fluctuation of the converter bus more effectively.

3. Reactive power auxiliary control of LCC-HVDC

3.1. Low load reactive power regulation function

Low-load reactive power regulation function is to increase the trigger angle or turn-off angle of the converter to absorb excess reactive power when HVDC project is running at low power, which plays a good role in back-to-back HVDC project. When the DC system operates at low load and can not continue to remove reactive power units, the converter absorbs less reactive power than reactive power compensation. The converter will inject a large number of excess reactive power into the AC system. It is easy to cause the voltage of the converter station and nearby stations to rise. Even the voltage may overrun. It poses a threat to the stable operation of the grid. Increasing the trigger angle to increase the reactive power absorbed by the converter is a natural characteristic of the converter, but the operation performance of the HVDC transmission project will deteriorate after increasing the trigger angle, which also has a very adverse impact on the life of the equipment. Therefore, the HVDC transmission project is not suitable for long-term operation in the transmission project.

3.2. Low load reactive power regulation function

LCC-HVDC reactive power switching control can cause voltage fluctuation of converter bus. The Gamma-kick function can reduce AC voltage fluctuation by controlling turn-off angle quickly and reversely. When the reactive power control of converter station detects the requirement of switching in the reactive power unit, the turn-off angle is suddenly increased within a relatively short period of time after the switching signal of switching in the filter is sent out, which makes the converter absorb reactive power increasing suddenly to counteract the voltage of the converter bus increasing suddenly. Then the turn-off angle will gradually decrease to normal value at a relatively long time. Similarly, when the reactive power control of converter station detects the requirement of removing reactive power unit, the turn-off angle increases gradually in a relatively long time. And the turn-off angle decreases abruptly to the normal value within a relatively short time after the signal of removing reactive power unit is sent out, which makes the reactive power absorbed by converter reducing suddenly to counteract the sudden drop of the voltage of converter bus bar.

As is shown in Figure 2, when the reactive power unit is switched on the output of the Gamma-Kick function increases to $\gamma_{max}$ in T-short time and then decreases from $\gamma_{max}$ to normal in T-long time. Besides, when the reactive power unit is removed the output of Gamma-Kick function increases to $\gamma_{max}$ in T-long time and then decreases from $\gamma_{max}$ to normal in T-short time. The value of $\gamma_{max}$, T-long, T-short on the rectifier and inverter should be determined according to the actual system. T-long and T-short should match the response time of the voltage control system. The exact time constants can be tested in the factory system test and the final commissioning process. In engineering applications, the increment of turn-off angle is usually between 2 and 7 degrees. T-short is more than ten milliseconds. T-long can be between hundreds of milliseconds and several seconds. Similar to the low-load reactive power regulation function, the Gamma-Kick function suppresses AC voltage fluctuations by increasing the turn-off angle at the expense of converter utilization, which has greater drawbacks.
4. Reactive power control of MMC-HVDC

Comparing with LCC-HVDC, MMC-HVDC not only does not need to provide reactive power compensation, but also can play the role of static synchronous compensator (STATCOM) when the capacity permits. MMC-HVDC provides dynamic reactive power to the AC system and improves the voltage stability of the connected system. MMC-HVDC control system includes internal loop control and external loop control. Reactive power control is implemented in external loop control. The block diagram of MMC-HVDC control system is shown in Figure 3.

![Control block diagram of MMC-HVDC](image)

**Figure 3.** Control block diagram of MMC-HVDC

4.1. Internal loop control of MMC-HVDC

According to Figure 4, the KVL law can be used for the upper and lower arm of k(a,b,c) phase units.
$u_k = \frac{U_{dc}}{2} - e_{kp} - R_0i_{kp} - L_0 \frac{di_{kp}}{dt}$
$u_k = \frac{U_{dc}}{2} + e_{kn} + R_0i_{kn} + L_0 \frac{di_{kn}}{dt}$

\[R_0\] represents the equivalent resistance of the bridge arm. \(e_{kp}\) and \(e_{kn}\) respectively represent the equivalent electromotive force of the upper and lower bridge arms. The voltage \(u_{kp}\) and \(u_{kn}\) are formed under the action of the bridge arm current. Due to the symmetry of the phase units, the DC current \(I_{dc}\) is evenly distributed among the three phase units, and the DC current in each phase unit is \(I_{dc}/3\). Because the reactance \(L_0\) of the upper and lower arm are equal, the alternating current \(i_k\) is equally distributed between the upper and lower arm. The current of the upper and lower arm are respectively equal.

$$u_p = \frac{I_{dc}}{3} + \frac{i_{kp}}{2}$$
$$i_{in} = \frac{I_{dc}}{3} - \frac{i_{kn}}{2}$$

Join the formula(1) and formula(2) and make \(e_k = \frac{e_{kp} - e_{kn}}{2}\)
$$e_k = u_k + \frac{1}{2} R_0 i_k + \frac{1}{2} L_0 \frac{di_k}{dt}$$

\(e_k\) is the AC electromotive force of \(k(a, b, c)\) phase. formula(3) describes the relationship between the controllable electromotive force \(e_k\) of the phase unit and the voltage and current of the AC side. For the formula(3), the park transform and the Laplasse transform are used.

$$e_d = u_d + \frac{1}{2} (R_0 + sL_0) i_d + \frac{1}{2} \omega L_0 i_d$$
$$e_q = u_q + \frac{1}{2} (R_0 + sL_0) i_q - \frac{1}{2} \omega L_0 i_q$$

\(i_d\) and \(i_q\) are controlle\(d\) variables. \(e_d\) and \(e_q\) are controlling variables. \(u_d\) and \(u_q\) are disturbance variables.

4.2. External loop control of MMC-HVDC

The reference values of active and reactive control variables provide current reference values for the internal loop current control in the external loop control receiving system. Commonly external loop control methods include active power control(constant active power control, constant DC voltage control, constant frequency control) and reactive power control (constant reactive power control and constant AC voltage control). In order to ensure the stability of DC voltage and the balance of active power, one of converter station must adopt constant DC voltage control, the other must adopt constant active power control or constant frequency control. In order to obtain the relationship between active and reactive power and AC current \(i_k\), the following deduction is carried out. Decompose the formula(4) into two subsystems: positive sequence and negative sequence component.

$$e_d^+ = u_d^+ + \frac{1}{2} (R_0 + sL_0) i_d^+ + \frac{1}{2} \omega L_0 i_d^+$$
$$e_q^+ = u_q^+ + \frac{1}{2} (R_0 + sL_0) i_q^+ - \frac{1}{2} \omega L_0 i_d^+$$
The asymmetrical three-phase voltage $u_k$ without zero sequence components can be represented by two orthogonal positive sequence and negative sequence components.

\[
\begin{align*}
\mathbf{u}_k &= e^{j\omega t} u_{\alpha\beta}^+ + e^{-j\omega t} u_{\alpha\beta}^- \\
u_{\alpha\beta}^+ &= u_d^+ + j u_q^+ \\
u_{\alpha\beta}^- &= u_d^- + j u_q^-
\end{align*}
\]

Similarly,

\[
\begin{align*}
\mathbf{i}_{abc} &= e^{j\omega t} i_{abc}^+ + e^{-j\omega t} i_{abc}^- \\
i_{abc}^+ &= i_d^+ + j i_q^+ \\
i_{abc}^- &= i_d^- + j i_q^-
\end{align*}
\]

\[
S = P + jQ = (e^{j\omega t} u_{\alpha\beta}^+ + e^{-j\omega t} u_{\alpha\beta}^-) (e^{j\omega t} i_{\alpha\beta}^+ + e^{-j\omega t} i_{\alpha\beta}^-)^*
\]

It can be seen from formula (12) that the double frequency fluctuation component will appear in the active power and reactive power due to the unbalanced voltage. When the steady state ($u_q=0$) and the negative sequence current component is suppressed, the DC component of the active and reactive power sent into the MMC by the AC system can be expressed as

\[
\begin{align*}
P(t) &= P_0 + P_{c2} \cos 2\omega t + P_{s2} \sin 2\omega t \\
Q(t) &= Q_0 + Q_{c2} \cos 2\omega t + Q_{s2} \sin 2\omega t
\end{align*}
\]
Figure 5. Coordination between reactive power control of LCC-HVDC and MMC-HVDC

5. Conclusion
Based on the existing research results of reactive power control in HVDC transmission project, this paper introduces the reactive power control functions of hybrid DC asynchronous interconnection system in detail. The coordination between the subfunctions of reactive power switching control of LCC-HVDC and the main work of reactive power auxiliary control functions of MMC-HVDC are analyzed. The reactive power control of MMC-HVDC is analyzed in detail, and the mathematical model of reactive power control of MMC-HVDC is established. The reactive power coordination control between LCC-HVDC and MMC-HVDC is studied.

(1) The reactive power switching control of LCC-HVDC needs to complete the principle of reactive power grouping according to the actual project requirements. The reactive power switching control subfunctions include Abs Min Filter control, Umax/min control, Qmax control, Min Filter control and Qcon/Ucon control. The reactive power switching control is formulated according to the corresponding priority logic. The reactive power control strategy realizes the coordination of all subfunctions to achieve reactive power control requirements.

(2) The reactive power auxiliary control of LCC-HVDC includes low load reactive power regulation function and Gamma-Kick function. By adjusting the trigger angle or turn-off angle of the converter, the reactive power absorbed or emitted by the converter can be changed to achieve reactive power control. However, this kind of control has a negative impact on the operational characteristics of HVDC transmission at the expense of converter utilization. Although the control of reactive power balance and commutation bus voltage is realized, there are great defects.

(3) The reactive power control of MMC-HVDC can track the AC bus voltage of the converter station or the reactive power exchanged between the converter station and the system through fast and accurate reactive power regulation. In view of the shortcomings of LCC-HVDC reactive power auxiliary control and the superiority of MMC-HVDC reactive power control, MMC-HVDC can be used to coordinate with LCC-HVDC reactive power control to improve system operation economy and equipment utilization.

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