Study on the reactive power coordinated control in hybrid parallel HVDC system

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Abstract. Hybrid parallel HVDC system adopts line commutated converter high voltage direct current (LCC-HVDC) and voltage source converter high voltage direct current (MMC-HVDC) parallel structure, which combines the advantages of LCC-HVDC and MMC-HVDC. Based on the existing reactive power control of HVDC system, the reactive power coordination control strategy of hybrid parallel HVDC system is innovatively proposed in this paper. Firstly, the reactive power control of LCC-HVDC and MMC-HVDC are studied respectively. And then the voltage stability of LCC-HVDC fed weak AC system is analyzed. Furthermore, a reactive power coordination control strategy between reactive power compensation device of the converter station and MMC-HVDC is proposed. Finally, based on PSCAD/EMTDC simulation platform, a hybrid parallel HVDC simulation system is built. The reactive power coordination control strategy under steady and transient conditions is simulated and analyzed respectively. The analysis results show that the reactive power coordinated control strategy can suppress the voltage fluctuation of converter bus in steady state. At the same time, the reactive power coordinated control strategy can restrain the commutation failure of LCC-HVDC in the fault of receiving power grid and improve its fault recovery ability.

1. Introduction
The energy storage and load in China are inversely distributed. In order to promote the development of new energy sources and optimize the allocation of resources, high voltage direct current (HVDC) transmission technology has entered a booming stage. With the gradual formation of grid structure with AC and DC parallel and multi-infeed direct current system, the safe and stable operation of power grid is facing many problems and challenges [1]. Hybrid parallel DC (HPDC) system integrates the advantages of HVDC system based on line commutated converter (hereinafter referred to as "LCC-HVDC unit") and HVDC system based on voltage source converter (hereinafter referred to as "MMC-HVDC unit"). HPDC system can optimize grid structure and reduce the risk of large-scale power outage.

LCC-HVDC unit is often used to realize long-distance and large-capacity transmission. However, the voltage stability of LCC DC-fed weak AC systems seriously affects the safe and reliable operation of DC projects. MMC-HVDC unit has excellent control performance. It is without reactive power compensation and there is no commutation failure problem [2]. Reactive power control of MMC-HVDC unit can effectively improve the voltage stability level of LCC DC-fed weak AC system. This paper innovatively proposes a reactive power coordination control strategy between reactive power compensation equipment and MMC-HVDC unit by analyzing the slow reactive power control of LCC-HVDC unit and the fast reactive power control of MMC-HVDC unit. Finally, PSCAD/EMTDC
Simulation analysis is carried out with the HPDC system simulation model, which proves that the reactive power coordination control strategy can suppress the voltage fluctuation of converter buses in steady state. And the fault recovery characteristics of conventional DC system can be effectively improved.

2. Reactive power control of hybrid parallel HVDC system

2.1. Structure of hybrid parallel HVDC system
Hybrid parallel DC system integrates the advantages of LCC-HVDC unit and MMC-HVDC unit transmission system. LCC-HVDC unit 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 6 pulse converters on the inverter side. MMC-HVDC unit consists of 2 back-to-back modular multilevel converters (MMC). The schematic diagram of hybrid parallel DC system is shown in Figure 1.

![Figure 1. Schematic diagram of hybrid parallel HVDC system.](image)

2.2. Slow reactive power control of LCC-HVDC unit
LCC-HVDC unit needs to consume a lot of reactive power when it is running. According to the requirements of AC/DC system, the reactive power compensation device of converter station is designed to compensate the reactive power needed by converter. Slow reactive power control of LCC-HVDC unit is the switching control of reactive power compensation device. The substitution and filtering control are composed of each sub-function which realizes its specific control function in turn according to the preset priority and criterion. According to the order of the sub-functions of reactive power control from the highest priority 1 to the lowest priority 5, the slow reactive power control logic of converter station is formulated as shown in Figure 2.

![Figure 2. Logic diagram of reactive power control of LCC-HVDC in converter station.](image)

2.3. Fast reactive power control of MMC-HVDC unit
MMC-HVDC unit does not need reactive power compensation. Furthermore MMC-HVDC unit can play the role of Static Synchronous Compensator (STATCOM) when capacity permits to improve the voltage stability of AC system. MMC-HVDC unit control system includes inner-loop control and
The inner-loop control provides two independent controlled variables $I_d$ and $i_q$ for active and reactive control of MMC respectively. The control block diagram of MMC-HVDC unit is shown in Figure 3.

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

According to the voltage deviation of converter bus or the switching reactive power deviation of converter station, the outer-loop control of MMC-HVDC unit provides reference current $I_{qref}$ to the inner-loop control through proportional integral (PI) link. And the inner loop control real-time control $I_q$ to achieve no-difference tracking of the voltage of converter bus or the switching reactive power of converter station. The core of reactive power control of MMC-HVDC unit is to realize the dynamic reactive power compensation function of MMC by controlling $I_q$ in real-time.

### 3. Voltage stability of LCC-HVDC fed weak AC systems

#### 3.1. Reactive power packet configuration and voltage stability of converter bus

When the slow reactive power control of LCC-HVDC unit realizes reactive power grouping switching, the safe and stable operation of the conventional DC unit will be affected. According to GB/T31460-2015, the transient voltage change rate of converter bus caused by switching reactive power grouping should not exceed 2%, and the steady voltage change rate should not exceed 1%[5]. When the receiving power grid is weak, the voltage fluctuation caused by reactive power grouping switching becomes larger, which will limit the selection of reactive power grouping capacity. However, reducing reactive power grouping capacity will inevitably increase the number of reactive power grouping, increase the area of AC filter field and affect the flexibility and economy of converter station[6].

#### 3.2. Commutation failure and fault recovery characteristics of LCC-HVDC

When the receiving power grid fails, the voltage amplitude and phase of the converter bus will change, which will affect the commutation process of LCC-HVDC unit and lead to the commutation failure of the inverters[7]. The weaker the receiving power grid is, the more serious the voltage sag of the converter bus will be when the fault occurs and the more likely the commutation failure will be caused[8]. At the same time, the fault recovery of LCC-HVDC units is closely related to the dynamic reactive power compensation provided by the receiving power grid. Therefore, the receiving power grid is required to have sufficient voltage support capability[9].
Figure 4. Changes of electrical quantities in AC/DC system with DC current.

4. Reactive power coordinated control strategy in hybrid parallel HVDC system

Aiming at the problem of voltage stability in LCC DC-fed weak AC systems, this paper proposes a novel reactive power coordination control strategy between converter station reactive power compensation device and MMC-HVDC unit to improve the voltage stability of hybrid parallel DC system under steady and transient conditions respectively.

4.1. Steady state reactive power coordinated control strategy

When the converter bus voltage $U_{pcc}$ belongs to $[0.9, 1.1]$, the steady-state fluctuation of the converter bus voltage is determined. According to the coordinated control of the reactive power compensation equipment and the MMC-HVDC unit, the MMC-HVDC unit has priority to regulate the voltage. And the switching times of the reactive power compensation equipment are reduced as much as possible to restrain the voltage fluctuation of the converter bus. The specific control strategy is as follows:

(1) When $U_{pcc} < U_{pcc_{aim}}$, the steady-state voltage change rate caused by switching the reactive power compensation equipment in the converter station is not allowed to exceed 1%. Firstly the ability of the MMC-HVDC unit to raise the converter bus voltage by 1% is judged.

$$Q_{MMC_{max,s}} - Q_{MMC} > Q_m$$

(1)

In the formula (1), $Q_{MMC_{max,s}}$ is the reactive power output limit of the MMC-HVDC unit in steady state. $Q_{MMC}$ is the actual reactive power output of the MMC-HVDC unit and $Q_m$ is the reactive power limit of 1% increase of the converter bus voltage in steady state.

In order to calculate $Q_m$, reactive power required by unit voltage increment of converter bus is represented by introducing MMC-HVDC unit reactive power-voltage control coefficient $k$. In steady state, the reactive power provided by MMC-HVDC unit is changed in a small range. Reactive power increment $\Delta Q_{MMC_i}$ and voltage increment $\Delta U_{pcc_i}$ are collected. Assuming that $M$ sets of data are collected, the $k$ value can be expressed as follows:

$$k = \frac{1}{m} \left( \frac{\Delta Q_{MMC1}}{\Delta U_{pcc1}} + \frac{\Delta Q_{MMC2}}{\Delta U_{pcc2}} + ... + \frac{\Delta Q_{MMCm}}{\Delta U_{pccm}} \right)$$

(2)

$$Q_m = 0.01k$$

(3)

If the judgment of formula (1) is established, the control instruction of the reactive power compensation equipment and the MMC-HVDC unit is set to formula (4). The reactive power compensation equipment of the converter station does not operate and the MMC-HVDC unit increases the voltage of the converter bus by 1% or to the target value. After a predetermined time step (3) is entered.
In the formula (4) \( U_{\text{MMC_ref}} \) is the reference voltage value of the converter bus and \( f_{c,\text{swi}} \) is the action instruction of the reactive power compensation equipment in the converter station. If formula (1) is not valid, it is judged whether the voltage fluctuation of converter bus caused by putting in a maximum capacity reactive power group is satisfied.

\[
U_{\text{pcc}} < U_{\text{pcc,aim}} - \Delta U
\]

\[\Delta U = \frac{Q_{\text{max}}}{k} \]

If formula (5) is established, step (2) is entered. If it is not satisfied, step (3) is entered. (2)If the converter station still has a set of reactive power compensation equipment that has not been put into operation, it will be put into. It follows the principle that AC filter should be put in firstly. At the same time, the MMC-HVDC unit ensures that the voltage change rate of the converter bus does not exceed 1% after the reactive power compensation equipment of the converter station is put into operation. And the reactive power control instruction is set to formula (7). After a predetermined time step (4) is entered.

\[
\begin{align*}
U_{\text{MMC,ref}} &= U_{\text{pcc}} + 0.01 \\
f_{c,\text{swi}} &= 1
\end{align*}
\]

If there is no reactive power compensation equipment available in the converter station, the reactive power compensation equipment will not operate. The MMC-HVDC unit adjusts the voltage of the converter bus to a limited extent. The steady-state reactive power limit of MMC-HVDC unit is set to \( Q_{\text{MMC,max,s}} \). And the reactive power control instruction is set to formula (8). After a predetermined time step (5) is entered.

\[
\begin{align*}
Q_{\text{MMC,ref}} &= Q_{\text{MMC,max,s}} \\
f_{c,\text{swi}} &= 0
\end{align*}
\]

(3)Judging whether the flexible DC unit can raise the converter bus voltage to the target value \( U_{\text{pcc,aim}} \).

\[
Q_{\text{MMC,max,s}} - Q_{\text{MMC}} > (U_{\text{pcc,aim}} - U_{\text{pcc}}) / k
\]

If formula (9) is not valid, step(3) is turned into step(2). On the contrary, the voltage is regulated by a MMC-HVDC unit and the corresponding reactive power control instruction is set to formula (4). After a predetermined time step(4) is entered. (4)Determine whether \( U_{\text{pcc}} \) is equal to \( U_{\text{pcc,aim}} \). If \( U_{\text{pcc}} < U_{\text{pcc,aim}} \), step(4) is turned into step(1). If \( U_{\text{pcc}} = U_{\text{pcc,aim}} \), step(4) goes to step(5). (5)End.

When \( U_{\text{pcc}} < U_{\text{pcc,aim}} \), the flow chart of reactive power coordination control strategy between converter station reactive power compensation equipment and MMC-HVDC unit is shown in Figure 5.
4.2. Transient state reactive power coordinated control strategy

Transient reactive power coordination control strategy is adopted when the voltage of converter bus drops sharply due to the faults of AC system near the converter station. Voltage changes rapidly in the transient process. Voltage fluctuation of converter buses will be further caused by switching reactive power compensation equipment. Therefore, slow reactive power control of converter stations will be blocked in the transient. MMC-HVDC unit takes the rating voltage of converter bus as reference value. MMC-HVDC unit automatically adjusts the reactive power output according to the reactive power required for voltage regulation, restrains the commutation failure of conventional DC unit and provides dynamic reactive power compensation for LCC-HVDC fault recovery.

4.3. Simulation and verification

Based on the parameters of Luxi back-to-back DC project, the simulation system of HPDC system and weak receiving power grid is established in PSACD/EMTDC simulation software. The reactive power coordination control strategies in steady and transient conditions are simulated and analyzed respectively. In order to verify the effectiveness of the reactive power coordination control strategy, the operation characteristics of HPDC system in steady and transient state are compared and analyzed in two cases. Scheme 1: MMC-HVDC unit does not participate in reactive power control and scheme 2: reactive power coordination control strategy is adopted.

The simulation time is set to 3 seconds. The conveying power of the LCC-HVDC unit increases from 1.0 pu to 1.1 pu after 1 second. It lasts two seconds and recovers later. The waveform of the converter bus voltage is shown in Figure 6. Under both schemes the voltage of converter bus drops. The voltage of converter buses drops to 0.969pu and 0.980pu respectively under scheme 1 and scheme 2 when the conveying power of LCC-HVDC unit increases to 1.1pu. Moreover the voltage fluctuation of converter bus under scheme 2 is smaller than that under scheme 1 during the sudden power increasement of LCC-HVDC transmission. When the power is restored to 1.0 pu, the voltage of the converter bus under the two schemes will be restored to the rated value. The results show that the
reactive power coordination control strategy between MMC-HVDC unit and reactive power compensation equipment of converter station can provide reactive power support for weak AC system in steady state, reduce the voltage fluctuation of converter bus. What’s more, it will not cause commutation failure on the inverter side.

Due to the limitation of space, this paper only gives the simulation results of single-phase-to-ground fault in the receiving power grid. The single-phase grounding fault of converter bus lasts 0.1 second after 2 seconds. The simulation results are shown in Figure 7. The waveforms from (a) to (d) in Figure 7 are converter bus voltage, LCC-HVDC unit transmission power, DC voltage and turn-off angle. Because of the short fault time and the long response time of reactive power compensation equipment, no reactive power compensation equipment is put on/off during the fault period. The bus voltages of scheme 1 and scheme 2 at the instant of single-phase grounding of receiving end power grid decrease to 0.76pu and 0.8pu respectively at \( t=2s \). Because the receiving power grid is the weak AC system, the fault easily causes the voltage of the commutation bus dropping when there is no dynamic reactive power compensation device. It results in the commutation failure of the LCC-HVDC unit. In severe cases, the LCC-HVDC system will be blocked by oscillation because of the repeated commutation failures. In scheme 2, the MMC-HVDC unit rapidly generates full reactive power during the fault period. The LCC-HVDC unit is compensated by dynamic reactive power to restrain the voltage fluctuation of the converter bus, which improves the oscillation and sag of DC power and DC voltage to a certain extent. After eliminating the fault about 0.2s HPDC system will be restored to the rated value. During the commutation failure of LCC-HVDC unit the DC current \( I_d \) and turn-off angle \( \gamma \) increase sharply, which leads to reactive power consumption of LCC-HVDC unit increasing. It is necessary to absorb dynamic reactive power from AC system. Therefore, dynamic reactive power compensation has an important impact on the fault recovery characteristics of LCC-HVDC unit.
5. Conclusion
Aiming at the voltage stability of LCC-HVDC fed weak AC system, this paper proposes a reactive power coordination control strategy between reactive power compensation equipment in converter station and MMC-HVDC unit. The effectiveness of this strategy is verified by simulation analysis of Luxi back-to-back DC system. The main conclusions are as follows:

1) Hybrid parallel HVDC system adopts parallel structure of LCC-HVDC unit and MMC-HVDC unit. And reactive power control of MMC-HVDC unit can effectively solve the voltage stability problem of LCC-HVDC fed weak AC system.

2) When the voltage fluctuates under the steady state range, the MMC-HVDC unit is adopted to regulate the voltage through the coordinated control of the reactive power compensation equipment and the MMC-HVDC unit in the converter station. It is useful to reduce the number of reactive power grouping switching and improve the voltage stability of the converter bus.

3) The voltage fluctuation caused by AC system faults will be suppressed through the coordinated control strategy between reactive power compensation equipment of converter station and MMC-HVDC unit. It can reduce the probability of commutation failure of LCC-HVDC units and improve the fault recovery capability of AC/DC systems.

In summary, the proposed reactive power coordination control strategy for hybrid parallel HVDC system can not only restore the voltage of the converter bus to the target value when the voltage fluctuates steadily but also reduce the risk of commutation failure of LCC-HVDC unit when the AC system fails. Therefore it is beneficial to improve the stability of hybrid parallel HVDC system.

References
[1] ZHOU Baorong, HONG Chao, JIN Xiaoming, et al. Study on the transition from synchronized operation grid to asynchronous operation grid in China southern power grid. Proceedings of the CSEE, 2016, 36(8): 2084-2092.
[2] GUO Chunyi, ZHAO Chengyong, Allan, et al. Risk assessment framework design on flexibility power grid planning and its application prospect[J]. Electric Power Construction, 2012(10): 98-104.
[3] CHEN Huan, WANG Zhen, YANG Zhizhong, et al. Coordinated reactive power control approach for LCC-HVDC and VSC-HVDC in hybrid parallel HVDC system[J]. Power System Technology, 2017, 41(6): 1719-1725.
[4] ZHAO Chengyong, HU Dongliang, LI Guangkai. Analysis of Reactive Power Regulation Characteristics of a New Double-fed HVDC Transmission System[J]. Automation of Electric Power Systems, 2008, 32(21):51-55.
[5] ZHANG Wang, HAO Junfang, CAO Seng, et al. Design of reactive power control for HVDC converter station[J]. Power System Protection and Control, 2009, 37(14): 72-76.
[6] CHEN Peidong, GUAN Lin. Analysis and Modeling of Dynamic Reactive Power Demand and Power Recovery Characteristics of HVDC System[J]. Modern Electric Power, 2017, 34(4): 50-58.
[7] TU Jingzhe, ZHANG Jian, ZENG Bing, et al. HVDC transient reactive power characteristics and impact of control system parameters during commutation failure and recovery[J]. High Voltage Engineering, 2017, 43(7):2131-2139.
[8] MA Leipeng, WEI Gang, LI Qinyu, et al. Reactive power reserve optimization of power system considering HVDC transmission[J]. Power System Protection and Control, 2017(24): 146-151.
[9] YANG Huanhuan, CAI Zexiang, ZHU Lin, et al. Reactive Power Dynamic Characteristics of DC System and Its Impact on Transient Voltage Stability of Received Power Grid[J]. Electric Power Automation Equipment, 2017(10): 86-92.