Dynamic Reactive Power Coordination Control Method for UHVDC Converter Station

Hui Li¹*, Zhen Wang², Pengfei Liu³, Wen Wang³, Ting Zhou³, Wenqi Mao³, Haifeng Liu¹, and Xiaofei Wang¹

¹State Grid Hunan Electric Power Company Limited Research Institute, Changsha, Hunan, 410007, China
²School of Electrical and Information Engineering, Changsha University of Science & Technology, Changsha, Hunan, 410076, China
³State Grid Hunan Electric Power Company Limited, Changsha, Hunan, 410007, China
*e-mail: lihui4219@sina.com

Abstract. In recent years, UHVDC transmission has developed rapidly. However, large-capacity DC converters generally use semi-controlled devices. The receiving converter station consumes a large amount of reactive power, which is easy to change when the AC bus voltage drops. The commutation failure happened, and more reactive power is absorbed from the AC system, which threatens the stability of the bus voltage. In order to study the dynamic reactive power coordination control strategy of UHVDC converter station, this paper compares the commonly used reactive power compensation equipment, and points out that synchronous condenser (SC) has significant advantages in reactive power regulation. This paper proposes a DC control system and SC coordination control scheme, and simulates the strategy through the electromagnetic transient simulation software PSCAD. The simulation shows that the synchronous condenser can provide continuously adjustable dynamic reactive power support during the change of the system switching filter, avoiding the risk of grid voltage drop exceeding the limit and improving the stability of the AC bus voltage.

1. Introduction
With the rapid development of UHVDC transmission, modern power grids gradually form a new type of AC-DC hybrid large-scale power grid with UHV grid as the main grid and coordinated development of multiple voltage levels. The change of power grid structure makes the operation of power system present many new characteristics, which brings new challenges to operation control. At present, the DC system is mainly connected to the load center where the grid voltage is weak. When the DC high power is transmitted and the load center is insufficient, the DC commutation failure may result in insufficient dynamic voltage support capability of the AC grid, and the risk of voltage instability of the AC grid at the receiving end increases.

During a weak AC system failure, a more severe voltage drop usually occurs, and the system cannot provide the reactive power required for rapid recovery, resulting in a slow recovery rate, and under the fluctuation of commutation bus voltage, the subsequent commutation failures of the inverters are easy to occur, which will further reduce the recovery speed of the system. Therefore, the large-scale operation of the UHVDC project puts forward higher requirements on the dynamic reactive
power support capability of the receiving end system. How to improve the dynamic reactive power support capability and voltage stability of the receiving end AC system has become a key factor to ensure the safe and stable operation of UHVDC system and the receiving end weak power grid.

The reactive power control strategies and research results of existing reactive power compensation devices in converter stations are mainly based on the requirements for stable operation or the control of DC system itself, and the reactive power compensation device is not considered or coordinated control with DC systems to achieve optimal or maximum dynamic reactive compensation. For example, Gamma kick is a strategy which suppresses the voltage fluctuation of the bus by controlling the gamma angle in reverse, when the AC filter/reactive power compensation device is to be cut off, the gamma angle was increased relatively slowly in advance, once the device is cut off, immediately reduce the gamma angle to the normal command value. This makes the absorption of reactive power more and more during the cutting, resulting in an increase in the bus voltage drop, which is easy to cause voltage instability. This method has a limited suppression effect on the grid voltage fluctuation when switching filters. Considering the different working conditions, there is a certain difference in the demand for reactive power at converter station. Therefore, by studying the reactive characteristics and requirements in converter station under various working conditions, a coordinated control mechanism is introduced between the DC control system and the SC, which are coordinated under different reactive demands of the system. The action can maximize the reactive power support of the existing SC in various working conditions, and ensure the safe and stable operation of DC system.

This paper proposes a scheme for coordinating and controlling reactive power between the UHVDC control and protection system, the SC and AC filter groups. Before the switching of the AC filter group is controlled, the pre-switching command is issued to the SC. After the SC receives the pre-switching command, the reactive power is reduced/increased by a certain ratio. After the AC filter is switched, SC is running at constant voltage. The model is built and simulated by PSCAD; the simulation results show that the SC can provide continuous and adjustable dynamic reactive support during the change of the system switching filter, avoiding the risk of the grid voltage falling over limit, thus improves the stability of the AC bus voltage.

2. Selection of reactive power compensation device
The dynamic reactive power compensation devices currently used in power system mainly include static var compensator (SVC), static synchronous compensator (STATCOM) and synchronous condenser (SC). SVC realizes fast switching and parallel capacitor operation through thyristor, which can effectively track the reactive fluctuation of power grid or load and perform real-time compensation. However, it also reduces the short-circuit ratio on the AC side. In the event of a fault, it is easy to occur secondary commutation failure. Therefore, the SVC is usually configured to the strong AC system, which has certain limitations. STATCOM is a new reactive power compensation device developed in recent years. It realizes reactive power exchange with AC system by adjusting the amplitude and phase of output voltage, and it can provide fast response time and symmetrical lead or lag reactive current, which effectively adjusts the reactive power of the transmission line; The SC can be regarded as a synchronous motor without any active load or mechanical load. Its main purpose is to provide or absorb reactive power to the system and improve the power factor. The SC is generally equipped with an automatic adjustment excitation device, which can automatically increase the output reactive power to maintain the voltage when the grid voltage is lowered.

As a rotating equipment, compared with SVC and STATCOM, the SC has better stability and no harmonics. It has unique advantages in improving the short-circuit ratio of the AC receiving grid, improving the limit power of DC transmission, and enhancing the strength and flexibility of the grid. Its operating characteristics are related to the value of the no-load electromotive force $E_0$, and the value of $E_0$ is a function of the excitation current $I_f$. Changing the $I_f$ can affect the operating characteristics of the SC in the system. The excitation system of the condenser is generally composed of two parts, excitation power unit and excitation regulator, as shown in Figure.1. The excitation power unit supplies excitation current to the rotor, and the excitation regulator controls the output of
the excitation power unit based on the input signal and the given adjustment criterion. The entire excitation automatic control system is a feedback control system composed of excitation regulator, excitation power unit and generator.

![Figure 1](image-url)

**Figure 1** SC excitation automatic control system block diagram

When the fault occurs at the near end of the AC grid or the commutation valve fails to commutate and the voltage drops, the large-capacity SC can perform strong excitation support voltage and system stability, and gain time for fault removal; In the case that the DC system is blocked by a fault or cuts off the active load, it can enter the leading phase operation mode, absorb a large amount of excess reactive power, thereby suppressing the system voltage rise; When the system is running normally, it can be late or leading phase operation provides continuously adjustable dynamic reactive support for the AC grid. In addition, the SC can also raise the minimum voltage of the system during the fault, which can reduce the probability of commutation failure in the DC system. Therefore, the SC can comprehensively improve the dynamic reactive power reserve of the system, solve various types of voltage stability problems.

However, the excellent reactive power support capability of the SC requires an excellent control strategy, and it needs to have a good cooperation relationship with AC filter and the DC control system under various working conditions of the power grid. Study the characteristics of system voltage and reactive power fluctuation after UHVDC transmission channel failure, considering the coordination and optimization of the reactive control function of the DC control system and SC control system, maximizing the ability of the existing SC to support the AC and DC system, is still a key technical problem to be solved.

### 3. Analysis of reactive power characteristics of SC

The SC will almost never exchange active power with the system. After the fault occurs, the increment of the SC’s reactive power at the busbar can be expressed as:

$$
\Delta Q = U_i \Delta i_d + \Delta U i_{d0}
$$

(1)

In the formula, $\Delta Q$ is the instantaneous reactive power increment of SC; $\Delta U$ is the bus voltage increment; $\Delta i_d$ is the d-axis reactive current increment of the condenser; $i_{d0}$ is the d-axis reactive current value before the fault, and the instantaneous reactive power generated by the condenser is approximately:

$$
\Delta Q = -\frac{U_i \Delta U}{X'_d + X_s} + \Delta U i_{d0}
$$

(2)

In the formula, $x_s$ is the equivalent reactance between the SC and the bus, $x''_d$ is the d-axis transient reactance, and when the $i_{d0}$ at steady state is ignored, the instantaneous reactive output variation of SC during the sub-transient process is similar with $-\Delta U$. When the AC bus voltage drops ($\Delta U < 0$), the SC emits reactive power. When the transient process of the stator and the damper winding are neglected, the reactive current increment during the transient process can be expressed as:
\[
\Delta i_d = \frac{[K_{3E}(K_A + 1) - 1] \Delta U}{(K_{3E} T_d s + 1)(X_d' + X_s')} - \frac{\Delta U}{X_d' + X_s'}
\]  

In this formula,

\[
K_{3E} = \frac{X_d' + X_s'}{X_d' + X_s' + K_A X_s'}
\]  

Among them, \(x_d\) is the synchronous reactance of the SC’s d-axis, \(x_d'\) is the d-axis transient reactance, \(k_A\) is the excitation magnification, \(T_{d0}\) is the d-axis open-circuit transient time constant. Substituting equation (4) into equation (1), increment of the SC’s transient reactive output is:

\[
\Delta Q = -\frac{[K_{3E}(K_A + 1) - 1] U_L}{(K_{3E} T_{d0} + 1)(X_d + X_s)} \Delta U - \frac{U_L}{X_d' + X_s'} \Delta U + \Delta U i_{d0}
\]  

It can be known from equation (5) that when the \(i_{d0}\) at steady state is ignored, the bus voltage drops during the transient process, and the SC emits reactive power, and the higher the \(-\Delta U\), the more reactive power is emitted by the SC. From the perspective of the system AC side, the reactive exchange of the line is reduced, thereby effectively suppressing the bus voltage drop, which is equivalent to avoiding the commutation failure of the LCC-HVDC. However, considering the coordination and optimization of reactive control function of the SC and DC control system, maximizing the existing ability of SC to support the AC/DC system, is still a key technical problem to be solved.

4. Reactive power coordination control strategy

4.1. Overview of cooperative control strategy

In order to comprehensively consider the coordination action between the DC control and protection system, the SC and filter group, a dynamic reactive power coordination control method and system for the SC of UHVDC converter station are proposed. The DC control and protection system sends a pre-input command to the SC at the first specified time length \(\Delta T_1\) before AC filter group is switched, and the SC receives the pre-input or pre-cut command to reduce or increase the reactive power by a certain ratio. After the AC filter is switched, the SC mode is switched to the constant voltage mode to restore the grid voltage to the rated value. In this way, the inverter station can avoid the risk of a grid voltage drop or exceeding the upper limit, reducing the probability of a commutation failure at the receiving end, increasing the stability of the AC bus voltage and providing more reliable reactive support. Figure.2 is a schematic diagram of a topology structure of a dynamic reactive power coordinated control system.

![Figure.2 Schematic diagram of the topology](image)

4.2. Input Filter

According to the technical guidelines for reactive power compensation and configuration of QGDW146-2006 high-voltage DC converter station, the transient voltage change rate of the switching group is generally not more than 1.5%~2%, and the steady-state voltage change rate of the switching group is generally not more than the 75% of the converter transformer tap length, that is to say, the
change of steady-state AC bus voltage should not cause the on-load tap-changer action of converter transformer.

Firstly, it is judged whether there is a DC blocking or the bus voltage is too high. If there is such a situation, the subsequent coordinated control steps are not directly executed, otherwise the following steps are performed:

- The UHVDC control and protection system issues a pre-injection command to the SC at the first specified time length $\Delta T_1$ before the control of AC filter group inputs;
- After receiving the pre-injection command, the SC reduces the bus voltage reference value $V_{ref}$ to make itself leading phase operation and absorb the reactive power. At this moment, the bus voltage will drop slightly but will not fall below the minimum voltage limit allowed for normal operation, it is not less than $0.98U_{nom}$. $U_{nom}$ is the rated voltage value of the power grid;
- After the AC filter group puts in, specifically after the delay of the second specified duration $\Delta T_2$ ($\Delta T_2 > \Delta T_1$), the reference voltage $V_{ref}$ of the SC is adjusted back to $U_{nom}$, and the SC is switched to a constant voltage mode operation, absorbing residual reactive power, bus voltage quickly recovers to $U_{nom}$;
- End and exit the coordinated control system.

Figure 3 is a Control block diagram of the input/cut-off AC filter.

4.3. Cut Filter

Firstly, it is judged whether there is a DC blocking or the bus voltage is too high. If there is such a situation, the subsequent coordinated control steps are not directly executed, otherwise the following steps are performed:

- The UHVDC control and protection system issues a pre-cut command to the SC at a first specified time length $\Delta T_1$ before the AC filter group is cut off;
- After receiving the pre-cut command, the SC increases $V_{ref}$ to make itself late phase operation and emit reactive power. At this moment, the bus voltage will rise slightly but not exceed the maximum voltage limit allowed for normal operation, it is not higher than $1.02U_{nom}$;
- After the AC filter group is cut off, it is specifically after the delay of the third specified time period $\Delta T_3$ ($\Delta T_3 > \Delta T_1$), the $V_{ref}$ of SC is adjusted back to $U_{nom}$, and the SC operation mode is set to constant voltage mode, compensation for reactive power shortage, the bus voltage is quickly restored to $U_{nom}$;
- End and exit the coordinated control system.

The AC filter group mentioned above is input/cut off, specifically, it refers to the way that the SC and the UHVDC control and protection system communicate that the status of the AC filter group is in the input/cut off state. By obtaining the status by communication, it is possible to more accurately ensure that the bus voltage reference value $V_{ref}$ of the SC is adjusted back to $U_{nom}$ after the AC
filter group is input. This improves the fault tolerance of the AC filter group switching fault. Figure 4 is a flow chart of dynamic reactive power coordination control method.

5. Simulation analysis

5.1. Establishment of Simulation model

In order to verify the effectiveness of the reactive power coordination control method proposed in this paper, two conditions are applied to the filter input and cut, and each condition is built with two models to compare the bus voltage response with the coordinated control strategy in PSCAD. Among them, the SC module is composed of a synchronous motor model and an excitation model in PSCAD's self-contained example. The basic parameters of the simulation system are: the rated voltage of the grid is 500 kV, the SC's late phase running capability is 300 Mvar, $x_d=1.2\text{pu}$, $x_d'=0.22\text{pu}$, $x_d''=0.21\text{pu}$, $T_d'=0.9s$, $T_d''=0.06s$, and the transformer is $Y/\Delta$ wiring, 500/13.7kV, capacity is 360MVA.

The input model is 260 Mvar for each phase, and the type is HP12/24 filter. In the simulation, the reclosing phase by phase strategy is adopted to reduce the transient voltage shock when the three phases are simultaneously input, and the bus voltage can be guaranteed not to fall below 490kV instantaneously. The input timing of each phase is selected at the voltage zero crossing of each phase, phase A is 2.4s, phase C is 2.4033s, and phase B is 2.4067s. The cut-off model is 260 Mvar for each phase, the type is HP12/24 filter too, and the three phases are simultaneously removed at 2.4s. The respective comparison experiments are the HP12/24 filter switching without the coordinated control strategy, and Figure 5 is a schematic diagram of the switching filter group.
5.2. Simulation result analysis

Figure 6 is a plot of the bus voltage reference value $V_{\text{ref}}$ when the AC filter group is placed. Before 2s, $V_{\text{ref}}$ corresponds to the grid rated voltage 500kV. When at 2.4s, putting into the filter group. When 2s, the value of $V_{\text{ref}}$ is decreased in advance, and $\Delta T_1$ is 0.4s. After the input is completed, that is, the $V_{\text{ref}}$ is adjusted to the rated voltage $U_{\text{nom}}$ at 3s, and $\Delta T_2$ is 0.6s.

Figure 7 shows the bus voltage curve for comparison with the control strategy when the filter group is put into operation. Curve 1 uses the strategy, which is put into the filter at 2.4s. At 2s, the bus voltage reference value $V_{\text{ref}}$ is decreased in advance. At this time, the SC is switching to leading phase and absorbs reactive power, so that the bus voltage drops slightly and does not fall 490kV. When put into the filter, the bus voltage rises rapidly. Because the control system pre-sets the command from the condenser to decrease the bus voltage, the transient voltage generated by the input process will not higher than 510kV, at 3s, $V_{\text{ref}}$ is adjusted to $U_{\text{nom}}$, the bus voltage rises slightly, and can quickly recover to about 500kV. In contrast, curve 2 directly input the filter in 2.4s without strategy, and the transient voltage is obviously over-limit, which does not meet the requirements.

Figure 5 Switching filter group diagram

Figure 6 $V_{\text{ref}}$ curve when put into the AC filter group

Figure 7 Bus voltage change diagram when input AC filter group
Figure 8 is a graph showing the change in $V_{\text{ref}}$ when the AC filter group is cut-off. Before 2s, $V_{\text{ref}}$ is the rated voltage, the filter group is cut off at 2.4s, and $V_{\text{ref}}$ is increased in advance at 2s, corresponding to $\Delta T_1$ is 0.4s. When the resection is completed, $V_{\text{ref}}$ is modified to $U_{\text{nom}}$ at 3s, and $\Delta T_3$ is 0.6s.

![Figure 8](image_url)

Figure 8 $V_{\text{ref}}$ curve when the AC filter group is cut off

Figure 9 shows the bus voltage curve for comparison with the control strategy when the filter group is cut off. Curve 3 uses the strategy, which is cut off the filter at 2.4 s. At 2s, the bus voltage reference value $V_{\text{ref}}$ is increased in advance. At this time, the SC is switching to late phase and emits reactive power, so that the bus voltage increases slightly and does not higher than 510kV. When cut off the filter, the bus voltage drops rapidly. Because the control system pre-sets the command from the condenser to increase the bus voltage, the transient voltage generated by the input process will not lower than 490kV, at 3s, $V_{\text{ref}}$ is adjusted to $U_{\text{nom}}$, the bus voltage drops slightly, and can quickly recover to about 500kV. In contrast, curve 4 directly cut off the filter in 2.4s without strategy, and the transient voltage significantly below the minimum, which does not meet the requirements.

![Figure 9](image_url)

Figure 9 Bus voltage change diagram when the AC filter group is cut

The system operation status before and after the coordination strategy optimization is shown in Table 1. It can be seen that after optimization, the terminal voltage characteristics have been significantly improved.

|                      | Input Before optimization | Input after optimization | resection Before optimization | resection after optimization |
|----------------------|---------------------------|--------------------------|-------------------------------|------------------------------|
| Maximum transient voltage change rate (%) | 2.82 | 2 | 2.96 | 2 |
| Bus voltage recovery time (s) | 0.9 | 0.95 | 0.9 | 0.9 |
| Whether to cause DC power to fall back | No | No | No | No |
| Whether it causes DC blocking | No | No | No | No |

6. Conclusion

In this paper, PSCAD is used to simulate and analyze the dynamic reactive power coordination control method of UHVDC converter station. The simulation results under the two working conditions of filter group is input and cut off, which shows the proposed coordination. The effectiveness of the control strategy is summarized as follows:
By controlling the SC, the reactive power can be absorbed/emitted before the switching time of the AC filter arrives, which is more conducive to bus voltage stability.

SC can provide continuously adjustable dynamic reactive support during the change of the system switching filter, avoiding the risk of grid voltage drop exceeding the limit and improving the stability of the AC bus voltage.

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References
[1] REN Zhen, OU Kajian, JING Yong. Digital simulation of HVDC transmission system based on PSCAD/EMTDC, Electric Power Automation Equipment, 2002, 22(9) :11-12.
[2] ZHANG Kaiyu, CUI Yong, ZHUANG Kanqin, MIAO Yuancheng, YANG Zenghui, FENG Yuyao, ZHANG Qiqi, YU Yinghui. Analysis of the influence of synchronous condensers on receiving-end grid with multi-infeed HVDC. Power System Protection and Control, 2017,45(22):139-143.
[3] S. I. Rychkov. Reactive power control services based on a generator operating as a synchronous condenser[J]. Power Technology and Engineering,2013,46(5).
[4] Chan-Ki Kim, Gilsoo Jang, Byung-Mo Yang. Dynamic performance of HVDC system according to exciter characteristics of synchronous compensator in a weak AC system[J]. Electric Power Systems Research,2002,63(3).
[5] Nayak O B, Gole A M, Chapman D G, et al. Dynamic performance of static and synchronous compensators at an HVDC inverter bus in a very weak AC system[J]. IEEE Trans on Power Delivery,1994,9(3): 1350-1358.
[6] Waruna Chandrasena, Bruno Bisewski, Jeff Carrara. Effects of phase-shifting transformers and synchronous condensers on breaker transient recovery voltages[J]. Electric Power Systems Research,2008,79(3).
[7] CUI Ting, SHEN Yangwu, ZHANG Bin, ZHANG Keren, ZUO Jian, GUO Hu. Influences of 300 Mvar synchronous condensers on the stabilities of Hunan power grid. HUNAN ELECTRIC POWER, 2016,36(03):1-4+8.
[8] WANG Yating, ZHANG Yichi, ZHOU Qinyong, LI Zhiqiang, JIANG Yilang, WU Junling, GAO Chao, TU Jingzhe, SHEN Chen. Study on Application of New Generation Large Capacity Synchronous Condenser in Power Grid. Power System Technology, 2017,41(01):22-28.
[9] Sun Yuanzhang, Wang Zhifang, Lu Qiang. The Effect of SVC on the Voltage stability. Proceedings of the CSEE,1997,17(6):373-376.
[10] Yan Wei, Tian Tian, Zhang Haibing, Fu Jin, Mao Guozhi, Liu Zhihong. Heuristic Strategy for Dynamic Reactive Power Optimiztion Incorporating Action Time Constraints Between Adjacent Time Intervals. Automation of Electric Power Systems,2008,32(10):71-75.
[11] LI Hui, XU Hao, GUO Siyuan, WU Jinbo, LIU Haiying, OUYANG Fan. Switching Strategy and Optimization of AC Filter for ±800kV Xiangtan Converter Station. Power Capacitor & Reactive Power Compensation, 2017,38(03):36-42.
[12] LI Hui, LIU Weiliang, XU Hao, GUO Siyuan, LIU Haiying, ZHAO Yongsheng, AO Fei, LI Gang, YU Bin. On-Site Parameter Setting and Testing Method for Phase-Selection Switching-on Control Device of UHVDC Converter Station. Power System Technology, 2018,42(01):133-139.