Reactive Power Compensation Device Performance Analysis in Fault Recovery of Weak AC System

Jie Lei, Xiaobo Tang*, Kai Dengb, Zhoupeng Shen, Zhiyuan Wang, Zongtao You
School of Nanjing Normal University, Nanjing 210042, China

*Corresponding author e-mail: xiaobotang@126.com, *940650668@qq.com, b1475914079@qq.com

Abstract. With the large-scale and large-capacity operation of HVDC transmission, the operating characteristics of the receiving-side power grid have changed significantly. In order to improve the dynamic recovery performance of HVDC transmission system, it is urgent to configure dynamic VAR compensation device in the system inverter Station. In this paper, the PSCAD/EMTDC electromagnetic transient simulation software is used to study the dynamic recovery performance of HVDC system for several different var compensating devices in HVDC inverter. In the case of HVDC inverter station commutation bus short-circuit fault, the effect of static var compensator (SVC), fixed capacitor (FC) and synchronous compensator (SC) on system power recovery is studied. The research results show that fixed capacitors have a certain effect on system fault recovery; SVC can effectively improve the voltage level after the fault but its effect and response speed are not as good as SC, At the same time, a large number of TSC will weaken the strength of the AC system; Synchronous compensator can quickly provide emergency reactive support for the system, accelerate system recovery, and enhance system strength, with obvious advantages.

1. Introduction
As of November 2017, China has built a total of 18 UHV transmission lines. With the large-capacity and long-distance UHV AC-DC transmission put into operation. The DC installation location is more and more concentrated, and the characteristics of the receiving-side power grid change significantly. At present, a lot of effective research has been carried out on the mutual influence of AC and DC systems. Inverter commutation failure has become the most common fault in HVDC systems, and is the main factor affecting the safe and stable operation of AC/DC hybrid systems. The fault of the inverter station often leads to the commutation failure of the system. During the commutation failure process, the reactive power of the receiving-side system will change greatly, which is manifested as a "reactive shock load" that is unfavorable to the system, which will directly lead to the instability of the voltage, transmission power interruption [1]. The converters at both ends of the DC system consume a large amount of reactive power during operation. Under normal circumstances, the reactive power consumed by the rectifier and the inverter is about 30%~50% and 40%~60% respectively of the delivered active power [2-4]. When the system fails to normal commutation, the inverter will absorb more reactive power, which may cause problems such as transient overvoltage, unstable harmonics,
and unstable voltage. The power grid's "strong dc and weak ac" characteristics are more obvious. In order to alleviate the security and stability problems caused by this, it is objectively required that large-scale HVDC must match dynamic reactive power compensation.

2. AC system strength and short circuit ratio

In practical engineering and theoretical research, the short-circuit ratio is usually used to measure the relative strength between AC and DC. The strength of the AC system can usually be expressed as the ratio of the short circuit capacity of the AC system to the rated transmission power of the DC system. If the reference voltage of the HVDC system is the rated voltage of the commutating bus and the reference power is the rated transmission power of the DC system, the short circuit ratio of the system can be expressed by the following formula (1):

\[
SCR = \frac{S_{\infty}}{P_{dN}} = \frac{1}{Z_{pu}}
\]

In the formula (1): \(S_{\infty}\) is the short circuit capacity of the AC system; \(P_{dN}\) is the rated transmission power of the DC transmission system; \(Z_{pu}\) is the equivalent impedance value of the AC system. Consider the effects of the station's AC filter and other reactive power compensation devices, introducing an effective short circuit ratio ESCR:

\[
ESCR = \frac{S_{\infty}Q_c}{P_{dN}} = \frac{1}{Z_{pu}} - B_{cpu}
\]

In the formula (2): \(Q_c\) is the reactive power generated by the AC filter and the compensation capacitor under rated conditions; \(B_{cpu}\) is the equivalent impedance value of the AC filter and the compensation capacitor.

The engineering practice proves that the greater the MSCR, the greater the strength of the AC system, the more powerful reactive power support can be provided when the system is disturbed, the voltage drop of the commutating bus is suppressed, and the risk of commutation failure is reduced, thereby improving the stability of the whole system. According to the traditional single-feed AC/DC system strength division standard [5], the criteria for judging the strength of multi-feed AC/DC system by using MSCR are: 1 Very weak system, MSCR<1.5; 2 Weak system, 1.5<MSCR<2.5; 3 Strong system, MSCR>2.5.

When a short-circuit fault occurs in a weak AC system, a severe voltage drop usually occurs, and the system cannot provide the reactive power required for rapid recovery, which may result in a slower power recovery. At the same time, under the action of harmonics and voltage oscillation, the continuous commutation failure of the inverter is prone to occur, which further delays the recovery speed of the system. The reactive power of the strong AC system is sufficient, and the voltage drop during the fault is relatively small. In order to increase the system's reactive margin, stabilize the voltage and ensure the safe and stable operation of the system, In order to increase the system's reactive margin, stabilize the voltage and ensure the safe and stable operation of the system, it is necessary to install a reactive power compensation device such as a static var compensator (SVC) or fixed capacitor or synchronous compensator (SC) [6].
3. Principle of reactive power compensation device

In the steady state process of HVDC transmission, the reactive power of HVDC is basically independent of the DC line parameters of the system, and closely related to the reactive power consumed by the converter station. Especially in the transient process of the system, the reactive power imbalance of the inverter station will directly lead to system voltage instability, which will aggravate the impact of the fault and bring more profound adverse effects to the receiving-side power grid. Generally, during normal operation of the system, the reactive power consumed by the converter station is provided by the filter and capacitor on the AC side. However, in the case of faults, the reactive power provided by the AC filter and capacitor is very limited. In order to effectively improve the voltage stability of the system under fault conditions and speed up the power recovery of the system, dynamic reactive power compensation devices is generally installed in the HVDC system.

3.1. Principle and characteristics of static var compensator

As a typical representative of power electronic compensation, SVC changes its own impedance characteristics through the control of thyristors, and regulates its own reactive power output. The technology is relatively mature. Therefore, static compensators are widely used in HVDC transmission systems. The SVC is generally composed of a Thyristor Controlled Reactor (TCR) and a Thyristor Switched Capacitor (TSC). The equivalent impedance of the TCR and the TSC is changed by controlling the conduction angle $\alpha$ of the thyristor. When a short-circuit fault occurs in the system, the SVC can quickly follow system changes, maintain system voltage and suppress oscillation by injecting or absorbing reactive current into the system. The structure of the SVC is shown in Figure 1.

\[
Q = Q_{TSC} - Q_{TCR} = U_N^2 \left( \alpha_c - \frac{\alpha - \sin \alpha}{\pi X_L} \right)
\]  

(3)

It can be known from equation (3) that the reactive power output of SVC is proportional to the square of its output voltage. When the system voltage drops significantly, the reactive power output of SVC decreases squarely, causing insufficient reactive power, resulting in further voltage drop.

It can be seen from equation (2) that the larger the compensation capacitance of the system, the smaller the effective short circuit ratio (ESCR) of the system. It will adversely affect the recovery of the HVDC system. When the AC bus on the inverter side fails, the voltage of the converter busbar drops greatly. After the SVC feels the low voltage, the TCR will be disconnected and put into the TSC.
If the capacitor bank is put too much, the effective short circuit ratio of the system will decrease. Even causes continuous commutation failure.

3.2. Synchronous compensator

As a synchronous rotating device, it can provide short-circuit capacity for the system as well as dynamic voltage support through strong excitation. When the synchronous compensator is connected to the grid, it is actually a synchronous motor running at no load. It is mainly used to provide or absorb reactive power to the system and improve the system power factor. Synchronous compensator regulates the reactive power of the output by changing the Excitation current. When the SC is operating in the over-excitation state, the SC supplies reactive power to the system, increases the system voltage, and maintains the voltage stability of the system. In the Under-excitation operating state, the SC absorbs excess reactive power from the system and reduces the voltage of the system.

The equivalent circuit of SC is shown in Figure 2.

Figure 2. Synchronous compensator equivalent circuit diagram.

According to the equivalent circuit diagram of the synchronous compensator shown in Figure 2, the equation of the induced electromotive force of SC is:

\[ \dot{E}_q = j I_a + U \]

(4)

The SC controls the nature and magnitude of the reactive power provided by adjusting the magnitude and direction of the field current. When the SC normal excitation, the induced electromotive force is in phase with the terminal voltage; when overexcitation, the excitation current lags the induced electromotive force by 90°, the SC provides reactive power to the system; when under-excitation, the excitation current leads the induced electromotive force by 90°. The SC absorbs reactive power from the system.

Therefore, according to the equation (4), when the voltage of the SC terminal is suddenly changed, the reactive power generated by the SC can be expressed by the following formula:

\[ Q = \frac{E U_N - U_N^2}{X_s} \]

(5)

It can be seen from equation (5) that when the system voltage drops, SC will increase the reactive output, support the system voltage, and increase the system strength [7].

4. Simulation mode

The simulation system of this paper adopts the CIGRE Benchmark Mode [8] in PSCAD/EMTDC electromagnetic transient software [9], simulating dynamic response characteristics of different types
of system faults based on the system. The system model is a single-pole HVDC system with 500kv DC and 1000MW capacity. The inverter side AC rated voltage is 230kv.

Under the rated operating conditions of the system, the AC filter provides 500 MVA of reactive power, and the set of fixed capacitors of the inverter provides 125 MVA. In order to compare the performance of different reactive power compensation devices for system failure recovery. Replace the fixed capacitor with the same capacity synchronous compensator (SC) and static var compensator (SVC) at the inverter bus of the system inverter station. Since the recovery characteristics during system failure are affected by the reactive power compensation device control system, both SC and static var compensators use the standard control system within PSCAD/EMTDC.

5. Electromagnetic transient simulation analysis

5.1. Inverter station commutation bus three-phase direct earth fault

The system short circuit ratio SCR=2.5 in the CIGRE HVDC model is a typical weak AC system. On this basis, the effect of dynamic reactive power compensation on system fault recovery is simulated. When the system is running for 5s, single-phase and three-phase faults occur on the inverter side AC bus. The fault is cut after 0.1s and the grounding resistance is changed to simulate different fault positions. Figure 3 shows the recovery of the transmitted power of the system when the three-phase direct earth fault of the AC side of the inverter side is faulty. According to the simulation results, Figure 3 shows that the power recovery speed of the system is different when different compensation devices are used for reactive power compensation. With the power restored to 0.9 pu as the reference, when the fixed capacitor FC is used for compensation, the system DC transmission power is restored to 0.90 pu at t=5.54 s; When SVC is used for compensation, the dc power recovery time will be restored to 0.90pu at time t=5.50s; When SC is used for compensation, the DC power recovery time of the system is significantly shortened, and it returns to 0.90 pu at t=5.31 s. SC is better than SVC and FC for the recovery characteristics of the system.

![Figure 3. Inverter side three-phase direct ground short circuit fault.](image-url)

5.2. Inverter station commutation bus remote three-phase short-circuit fault

Simulate short-circuit faults at different distances by changing the short-circuit grounding resistance of the system. In order to simulate the long-distance three-phase short-circuit fault on the inverter side, increase the short-circuit grounding resistance R (R=220Ω) of the system. Under such conditions, although the system has a drop in power, no commutation failure has occurred. Figure 4 shows the effect of each reactive power compensation device on the transmission power of the system. The simulation results show that when the three-phase short-circuit fault occurs at the far end of the inverter side, the fault severity is light. At this time, the fixed capacitor has less impact on the system power recovery than the SVC. The SC has a very obvious advantage due to the strong reactive power support capability.
By reducing the short-circuit resistance $R$ ($R = 20 \, \Omega$), the system is subjected to a relatively serious fault on the inverter side, and the system undergoes continuous commutation failure. Figure 5 shows the performance of each reactive power compensation device against the continuous commutation failure of the system. Due to the serious fault, the reactive output of the fixed capacitor is greatly affected by the voltage of the AC bus on the inverter side, and the power recovery of the system is limited under severe faults; During the system short-circuit fault and the fault re-cutting, the SVC repeatedly switches the TSC, causing the AC bus voltage of the inverter station to oscillate, resulting in power oscillation. In addition, due to the input of TSC, the system short circuit ratio is reduced, the strength of the AC system is reduced, the system power recovery becomes difficult, and the number of system commutation failures is increased.

5.3. Inverter station commutation bus single-phase direct earth fault
Change the fault type of the inverter side commutation bus and set a single-phase asymmetrical fault at the commutation bus. When a single-phase asymmetrical fault occurs in the system, the reduction of the AC voltage will cause the system to fail to commutate, and the single-phase AC voltage will decrease, causing the natural commutation point to shift, which will also increase the severity of the system. When a single-phase direct earth fault occurs on the inverter side, the recovery effect of different reactive power compensation methods on the system power is shown in Fig. 6. It can be seen from the simulation results that in the case of single-phase direct-ground short-circuit fault of the inverter station, the effect of different reactive power compensation methods on system power recovery is similar to that of three-phase direct ground short-circuit fault, and SC has obvious advantages for system power recovery.
5.4. Inverter station commutation bus remote single-phase short-circuit fault

Change the size of the fault grounding resistance and simulate the influence of different compensation modes on the system power recovery under the condition of single-phase short-circuit fault at the remote end of the inverter. The power recovery of the system under grounding resistance $R=152\Omega$ and $R=75\Omega$ is analyzed separately. When the grounding resistance is $R=152\Omega$, under the compensation of the fixed capacitor, the system is at the critical point of commutation failure. Figure 7(a) shows the recovery effect of the system under different compensation modes when the single-phase remote ground fault $R=152\Omega$; Figure 7(b) shows the recovery effect of the system under different compensation modes when the single-phase remote ground fault $R=75\Omega$.

![Figure 7](image)

**Figure 7.** Remote single-phase short-circuit fault on the inverter side.

It can be seen from Fig. 7 that when the grounding resistance $R$ is $152\Omega$, the fixed capacitor compensation makes the system at the critical point of commutation failure. However, when compensating with the same capacity SVC, the system has a commutation failure, indicating that the fault occurs and the repeated switching of the TSC after the fault is removed reduces the strength of the AC system and aggravates the system fault. In addition, reducing the grounding resistance increases the degree of system failure. It can be found that when the grounding resistance is $R=75\Omega$, the input of SVC causes two commutation failures in the system, which seriously affects the power recovery of the system. The SC's own characteristics, the strong excitation state can provide a large number of emergency reactive support, maintain the AC bus voltage level, improve the strength of the AC system, and enhance the stability of the system.

6. Conclusion

Large-scale DC feed into the receiving-side grid reduces the dynamic reactive reserve of the system. The large-scale DC feed only provides active power, does not provide reactive power, the system dynamic reactive power reserve is significantly reduced, and the short-circuit capacity of the receiving system is reduced, resulting in a weakened ability of the system to resist commutation failure. Failure
to commutate will cause power transmission to be interrupted, and the voltage of the receiving grid will be unstable, which will greatly affect the receiving grid. In order to cope with the adverse impact of commutation failure on the receiving power grid, the reactive power compensation device is used to balance the system, provide strong reactive power support during the system transient process, maintain the bus voltage and speed up power recovery. Based on the PSCAD/EMTDC electromagnetic simulation platform, the reactive power compensation is used to study the fault recovery characteristics of the weak receiving AC system. The simulation results show that:

1. The installation of reactive power compensation device can provide reactive power support to the system, maintain the transient voltage level, and accelerate the power recovery of the system.

2. The system fails to commutate, and SVC can effectively improve the system, reduce the reactive power absorbed by the DC from the AC system, and speed up the recovery of the system. However, when the strength of the receiving AC system is weak and the fault is serious, the input of SVC causes the strength of the AC system to further weaken.

3. Synchronous compensator has a distinct advantage over fixed capacitors and static var compensators. In the case of a serious short-circuit fault in the system, it will enter a strong excitation state, and a large amount of reactive power can be issued in a short time, providing emergency reactive voltage support for the system, which can effectively accelerate DC power recovery and enhance the strength of the AC system.

7. References
[1] Tu Jingzhe ,Zhang Jian ,Zeng Bing ,Liu Mingsong ,Yi Jun ,Bu Guangquan .The transient reactive power characteristics and control parameters of DC commutation failure and recovery process[J].High Voltage Engineering,2017,43(07):2131-2139 .
[2] Zhejiang University Research Group. DC Transmission [M]. Beijing: Water Power Press, 1985: 90-163.
[3] Xu Zheng .Analysis of Dynamic Behavior of AC/DC Power System [M].Beijing: Mechanical Industry Press, 2004:61-66.
[4] KUNDUR P. Power system stability and control [M].New York:Mc Graw-Hill, 1994:463-580.
[5] Krishayya P C S, Adapa R, Holm M, et al. IEEE Std 1204-1997: IEEE guide for planning DC links terminating at AC locations having low short-circuit capacities. Part I: AC/DC system interaction phenomena[R]. France: CIGRE, 1997.
[6] Zhou Changchun, Xu Zheng. Simulation analysis of HVDC fault recovery characteristics of weak ac system [J]. Power System Technology, 2003(11):18-21.
[7] WANG Yating , ZHANG Yichi , ZHOU Qinyong , et al. Study on application of new generation large capacity synchronous condenser in power grid[J]. Power System Technology, 2017, 41(01):22-28.
[8] Szechtman M, Wess T, Thio C V. First benchmark model for HVDC control studies [J]. Electra, 1991, 135(4): 54-67.
[9] Manitoba HVDC Center. PSCAD/EMTDC user’s manual [R].Winipeg,Canada:Manitoba HVDC Center,1998.