Influence of coupling characteristics on commutation failure of new hybrid HVDC transmission system

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Abstract. Hybrid cascaded multi-terminal DC transmission provides a more flexible transmission method, improves the voltage stability of the inverter AC system, and reduces the probability of commutation failure. The hybrid LCC-VSC at the receiving end of the DC system is a new type of topology. In order to study the influence of coupling characteristics between VSC and LCC on commutation failure in AC power grid at receiving end, firstly, a hybrid LCC-VSC simulation model is built on PSCAD to analyze the operation characteristics of the system during the fault and verify the reactive power support ability of VSC to LCC, and the improvement effect of VSC on LCC-HVDC under different reactive power control modes is compared and analyzed. In order to study the influence of AC/DC coupling on commutation failure of LCC, commutation failure immune factor (CFII) was introduced to study the influence of AC system strength on commutation failure of LCC. Finally, considering that the influence of AC/DC coupling on commutation failure is closely related to the degree of coupling, the electrical distance between LCC and VSC is further studied. The results show that the conclusion can provide theoretical guidance for the design and analysis of related projects.

1. Introduction
With the extensive application of LCC-HVDC and the rapid development of VSC-HVDC, hybrid DC transmission system has become a hot spot for HVDC research. LCC-VSC hybrid DC transmission system combines the advantages of LCC-HVDC and VSC-HVDC, it can not only send high voltage grade, delivery big capacity, but also improve the end of the system stability and other issues brought by the commutation failure, and improve the operation characteristics of the AC system at the receiving end, which is helpful to solve the problem, which may cause major security risks of the power grid[1-5]. Domestic and foreign scholars have carried out a series of research on Hybrid DC transmission system, and achieved important results. In terms of improving system stability, [6-7] proposed to introduce VSC-HVDC into MIDC system to improve the stability of the whole system; [8] studied the fault recovery characteristics of VSC-HVDC and VSC-HVDC under short-circuit fault. In the aspect of evaluating the AC system voltage support strength of LCC-HVDC in hybrid multi infeed HVDC transmission system with VSC-HVDC, in the research on commutation failure of hybrid double infeed HVDC system, [9] designed to supply power to passive network through hybrid double infeed system. In [10-12], the transient operation characteristics of the hybrid double infeed HVDC system are studied, and the reactive power control method of VSC converter after AC system fault is designed, which improves the power and voltage recovery capability of the system;

Most of the above researches are based on hybrid double infeed system. However, the receiving end hybrid LCC-VSC of DC system is a new topology structure, which includes several different types of converter stations. It is a multi terminal DC system with multiple operation modes and complex
operation conditions, which increases the control complexity of the whole system. Because the AC voltage drop at the receiving end may lead to the commutation failure of LCC, in order to improve the safe and stable operation ability of the hybrid LCC-VSC system, it is necessary to study the influence mechanism of the coupling effect between VSC and LCC on the commutation failure of the receiving end AC power grid in the receiving end hybrid LCC-VSC system.

Therefore, in order to solve the above problems, based on the hybrid LCC-VSC simulation model at the receiving end, this paper firstly studies the improvement effect of VSC-HVDC on the commutation failure of LCC-HVDC, and analyzes the influence of different reactive power control modes of VSC. In this paper, a simulation model of the dual -infeed HVDC system is established in the PSCAD/EMTDC to verify the suppression effect of VSC on the commutation failure of LCC, and the influence mechanism of AC/DC coupling on commutation failure of LCC converter is revealed. The commutation failure immunity index (CFII) is used to study the commutation failure resistance and fault recovery characteristics of LCC-HVDC with different electrical distance and different AC system strength.

2. Hybrid LCC-VSC hvdc transmission system at receiving end

2.1. System Topology

Hybrid cascaded multi terminal DC transmission is a new type of DC transmission mode. It combines the advantages of LCC and VSC. The rectifier side (sending end) is located in a large energy base. Generally, it adopts LCC topology structure and is composed of double 12 pulse converters. It gives full play to the characteristics of large transmission capacity and low loss of LCC, and sends power to the load area through DC line L1. The high valve group at the inverter side (receiving end) is a conventional LCC structure, which is composed of 12 pulsating converters and connected to the local 220kV and above power grid. The low-end converter station on the inverter side is a parallel structure of multiple VSCS. The high-low valve groups are connected through DC lines L2, L3 and L4 to directly transmit power to each load center. The operation characteristics of the AC system at the receiving end can be improved by using the fast and flexible control characteristics of VSC, It is more suitable for connecting to multi infeed DC power grid, and has good engineering application prospect. The typical topology of ± 800kV hybrid cascade multi terminal HVDC transmission system is shown in Fig. 2.
2.2 Control Strategy

LCC-HVDC adopts control system similar to CIGRE standard test model [13]. Under normal operation, the rectifier side control is equipped with constant current control with minimum trigger angle limit, and the inverter side control is equipped with constant turn off angle control, constant current control, current error controller (CEC) [14] and low voltage current limiting link.

VSC-HVDC adopts direct current control strategy based on dq decoupling, which is divided into outer loop controller and inner loop current controller [15]. Outer loop controller: rectifier side adopts constant DC power and constant reactive power control; inverter side adopts constant DC voltage and constant reactive power control. The inner loop current controller adjusts the actual DQ axis current components $I_d$ and $I_q$ according to the current reference value output by the outer loop controller, so as to obtain the reference value of MMC HVDC output AC voltage. As shown in the figure [16].

![VSC control principle](image)

Figure 2. VSC control principle.

3. Mechanism of VSC improving LCC commutation failure

3.1 Commutation failure mechanism of LCC-VSC

Commutation failure refers to the phenomenon that under the action of reverse voltage, the valve out of conduction fails to recover the blocking ability in time or the commutation process fails to end, which makes the valve which should have been turned off turn on again under the action of forward voltage. It takes a certain time for the carrier in thyristor to recover the blocking ability during the reverse voltage, which is related to the parameters of thyristor elements. It is generally believed that as long as the turn
off angle of the converter is less than its inherent limit turn off angle \( \gamma_{\min} \), the inverter will fail in commutation. The change of \( \gamma \) is closely related to DC current and bus voltage. The formula for calculating the turn off angle of the converter can be expressed as follows\(^{[16]}\):

\[
\gamma = \arccos \left( \frac{\sqrt{2} k_d X_C}{U_L} + \cos \beta \right)
\]  

(1)

The former hierarchical access mode of LCC-HVDC can ensure that when commutation failure occurs at the high end (or the low end), the commutation failure will not occur at the low end (or high end), so as to minimize the impact of the fault on the system. In addition, VSC can reduce the probability of commutation failure. It can be seen from \([17]\) that VSC can improve the commutation failure of LCC-HVDC because VSC-HVDC has flexible voltage regulation ability. In this paper, based on PSCAD/EMTDC, the following two kinds of simulation examples are set up to compare the operation characteristics of two kinds of structures with only LCC at the receiving end and LCC + VSC at the receiving end in case of short circuit fault of AC bus at the receiving end.

When three-phase transient grounding fault occurs in the receiving end LCC AC system (the fault occurs at 0.8s and lasts for 0.1s), the operation characteristics of the system are shown in Fig3.

By comparing the waveforms of reactive power, AC bus voltage and turn off angle of the receiving end LCC side of the two structures, we can get the conclusion that when three-phase grounding fault occurs in AC bus at receiving end, VSC has stronger regulation ability for fault and fault recovery process, it can quickly provide reactive power, stabilize AC bus voltage, reduce LCC turn off time and improve LCC commutation failure.
3.2. Influence of VSC reactive power control mode on commutation failure

VSC reactive power control is divided into constant AC voltage control and constant reactive power control. In order to study the influence of two different reactive power control methods on commutation failure, based on PSCAD/EMTDC, three-phase grounding fault is set at the AC bus of LCC at 0.8s, and the fault duration is 100ms. The DC power of LCC-HVDC, the bus voltage of LCC-HVDC and the turn off angle of LCC-HVDC inverter are compared under two different reactive power control modes. The comparison waveform is shown in the Fig.4.

Case1 is constant reactive power control. Case2 is constant AC voltage control.

![Fig. 4. The comparison of the operation characteristic.](image)

It can be seen from the Fig.5 that under the AC voltage control strategy, the commutation voltage amplitude $u_{vt1}$ of LCC is larger, and the zero crossing point of commutation voltage is more delayed. In this case, the thyristor can obtain larger reverse commutation voltage time area, and then the commutation current $i_{vt}$ of LCC decreases faster, and the thyristor can obtain enough large reverse commutation voltage time area. The essence of VSC-HVDC to improve the commutation failure of...
LCC-HVDC lies in that VSC stabilizes the bus voltage of LCC by providing reactive power to the system, so that the thyristors in LCC converter can obtain larger reverse voltage time area during the turn off period, improve the commutation current reduction speed, and then enhance the ability to withstand the commutation failure of LCC-HVDC.

4. Simulation study on commutation failure characteristics of LCC-VSC coupling system

In the receiving end hybrid LCC-VSC access mode, from the DC side, the high-end and low-end converters are connected in series. From the AC side, LCC and VSC at the receiving end are connected to the AC system of 525kv voltage level respectively, and the AC buses are connected through tie lines. Therefore, the high-end and low-end converters of the receiving end hybrid HVDC transmission system have both DC side and AC side coupling relationship.

In order to quantitatively evaluate the commutation failure resistance of LCC-HVDC, CFII was used for comparative analysis. $U_{ac}$ is the rated line voltage (kV) of the inverter side converter bus, $L_{min}$ is the commutation failure critical inductance (H), and $P_{dc}$ is the rated DC power (MW) of the system. The larger the CFII, the stronger the inverter's ability to withstand commutation failure\cite{18-19}.

$$CFII = \frac{U_{ac}^2}{\omega L_{min} P_{dc}}$$ \tag{2}

In the simulation example, the multi run module of PSCAD/EMTDC software is used to set 20 fault points at equal intervals in a cycle of 0.02s. The critical fault inductance is the minimum inductance value without commutation failure at all fault points in a cycle.

4.1. Effect of converter coupling on commutation failure under different AC system strengths

In order to study the influence of different AC system strength on commutation failure, the ratio of short circuit capacity at converter bus to rated DC power is selected as the index to judge the strength of AC system at inverter side, namely short circuit ratio (SCR)\cite{20}.

$$SCR = \frac{U_{base}^2}{Z_g P_{dN}}$$ \tag{3}

$U_{base}$ is the rated value of AC voltage; $P_{dN}$ is the rated value of DC transmission power; $Z_g$ is the equivalent impedance value of AC system. In PSCAD simulation, three-phase grounding fault occurs at the receiving end AC bus at 0.8s, and the fault duration is 0.1s. Taking the electrical distance between two layers of AC bus as 50 km, the CFII value of LCC converter with differentSCR1 is obtained by changing SCR1 of receiving end LCC AC system, As shown in the Fig6.(a). By changing SCR2 of VSC side AC system, the curves of CFII value changing with SCR1 under different SCR2 are obtained, as shown in Fig6.(b).

Figure 6. Value of CFII.
The picture shows that when 525 kV LCC AC bus has three-phase short circuit fault, the voltage drop of 525 kV AC bus leads to commutation failure of converter. Increasing the strength of 500 kV AC system can effectively restrain voltage drop and DC current growth, thus improving commutation failure immunity of converter.

It can be seen from Fig. 6(b) that SCR2 of VSC AC system (non fault layer) has little influence on CFII value of LCC converter (fault layer), because the fault occurs at 525 kV AC bus, 525 kV AC system (fault layer) plays a dominant role in commutation voltage support of high-end converter. VSC AC system is separated from high-end converter by a certain electrical distance. Improving the strength of VSC AC system has no obvious effect on improving the commutation voltage support capacity of high-end converter.

In conclusion, the AC system strength of the non fault layer has little influence on the commutation failure resistance of the converter in the fault layer. For the non fault layer converter, when the non fault layer AC system is stronger than the fault layer AC system, adding the non fault layer AC system can improve the commutation failure resistance ability of the non fault layer converter, otherwise, the influence of the non fault layer AC system on the commutation failure resistance ability of the non fault layer converter is small.

4.2. Influence of coupling tightness on commutation failure

Due to the fact that two AC buses with different voltage levels at the receiving end are connected by the impedance of transformer and equivalent line, the coupling tightness directly affects the bus voltage fluctuation characteristics of AC system under fault conditions, thus affecting the commutation failure resistance ability of low-end converter. Changing the inductance of the tie line between LCC inverter and VSC inverter is used to simulate the different electrical distances between them. The critical inductance values of LCC-HVDC under three-phase inductive grounding fault and single-phase inductive grounding fault are measured when the electrical distance is 10km, 50km and 100km respectively. The following figure shows the critical inductance of three-phase grounding short circuit and single-phase(A-phase)grounding short-circuit simulation under different electrical distances.

![Graph of operation characteristics](image-url)

(a) Reactive power provided by VSC-HVDC.  (b) Voltage of AC bus at LCC side of receiving end.  (c) LCC turn off angle at receiving end.

Figure 7. The comparison of the operation characteristic.
By comparing the parameters above, it can be concluded that the commutation failure resistance of LCC-HVDC is related to the electrical distance between VSC and LCC. When the electrical distance of Hybrid DC transmission system is short (that is, VSC-HVDC has a strong voltage support effect on the AC bus voltage at the receiving end of LCC-HVDC), the LCC-HVDC system has higher CFII under single-phase short-circuit fault and three-phase short-circuit fault conditions, that is, it has higher CFII. With the increase of electrical distance, the voltage support function of VSC-HVDC is gradually weakened, and with the decrease of voltage support function of VSC-HVDC, its ability to withstand commutation failure decreases rapidly.

In summary, the tighter the AC and DC coupling, the stronger the commutation failure resistance of the faulty layer converter; the commutation failure resistance of the non-fault layer converter is not only affected by the tightness of the AC and DC coupling, but also the AC system strength of the fault layer is related. When the AC system strength of the fault layer is stronger, the tighter the AC and DC coupling is, the weaker the commutation failure resistance of the non-fault layer converter is. When the AC system strength of the fault layer is weak, then on the contrary.

5. Conclusions
In this paper, a hybrid LCC-VSC model is established to analyze the AC-DC coupling mechanism and commutation failure suppression mechanism of VSC-HVDC transmission system. Through PSCAD / EMTDC simulation, aiming at the coupling effect between VSC and LCC, the commutation failure mechanism of LCC-VSC system is analyzed and simulated. The conclusions are as follows

1) The mechanism of commutation failure of VSC-HVDC to LCC-HVDC in hybrid double infeed HVDC transmission system: VSC-HVDC provides reactive power compensation for the system during the grounding fault of LCC AC bus, stabilizes the AC bus voltage of VSC-HVDC, reduces the voltage sag of LCC-HVDC bus, and increases the commutation voltage time area of LCC converter valve.

2) The influence of AC system strength in non fault layer on commutation failure resistance of converter in fault layer is small, and its influence on commutation failure resistance ability of converter in non fault layer depends to a certain extent on the relative strength of AC system in non fault layer and AC system in fault layer.

3) In the hierarchical access mode, the closer the AC / DC coupling is, the stronger the commutation failure resistance of the fault layer converter is; while the commutation failure resistance ability of the non fault layer converter is not only affected by the compactness of the AC / DC coupling, but also related to the AC system strength of the fault layer.
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