Influence of VSC Converter Station on Switching Overvoltage of LCC Converter Station in LCC-VSC Hybrid DC System

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Abstract. LCC-VSC hybrid DC system combines the advantages of LCC in transmitting large-capacity electric energy and VSC in power transmitting to weak AC power system without commutation failure, which makes the transmission form more flexible. A HVDC overvoltage calculation model of VSC converter station with LCC converter at the sending end and MMC converter at the receiving end is established in this paper. The principle of influence which is exerted by VSC converter station on LCC converter station is researched. The differences of Overvoltage of LCC converter station in hybrid DC System with blocking diode and not are compared and analyzed. The reason for larger overvoltage energy of LCC converter station is obtained. The necessity of blocking VSC station reverse DC voltage output is presented. The results show that the blocking diode plays an important role in limiting the overvoltage energy of LCC converter station in Hybrid DC system, which needs to be equipped in Hybrid DC system. After the blocking diode is installed, the insulation coordination of the LCC converter station at the transmission end can be the same as that of the conventional LCC HVDC transmission system.

1. Introduction

High Voltage Direct Current technology based on Line Commutated Converters (LCC-HVDC) is the main method of large-capacity and long-distance transmission in China, which is used to connect the power transmission between two large power grids. This type of transmission system that is suitable for large-capacity centralized power transmission requires not only that the AC grids on both sides of the sending end and receiving end are strong enough, but also that the converter stations at both ends provide a large amount of reactive power compensation. High Voltage Direct Current technology based on Voltage Source Converters (VSC-HVDC) with Modular Multilevel Converter (MMC) as the core has the advantages of small reactive power requirements, no risk of commutation failure, and the ability to connect passive AC grids. It can meet the needs of power transmission to small-capacity weak AC grids. In addition to being used for large-capacity long-distance transmission projects, it is also the main solution for transmitting power to weak island grids such as island grids. As a HVDC transmission technology, VSC-HVDC also has the advantages of flexible power control and rapid response. With the continuous maturity of MMC converter valve technology in recent years and the completion of pilot projects, as well as the frequent occurrence of outage accidents caused by the failure of commutation on the inverter side of the LCC-HVDC transmission project that was built earlier, it is proposed to replace the original LCC transmission project inverter station with VSC
converter station to solve the problem of inverter-side commutation failure. LCC-VSC Hybrid DC transmission technology has gradually become a hotspot in the research of DC transmission.

At present, the research on LCC-VSC Hybrid DC System mainly focuses on DC loop topology design, MMC converter fault ride-through control, LCC, coordinated control strategy for hybrid system composed of full bridge and half bridge MMC converter module, and coordinated control strategy for hybrid system composed of VSC and LCC converter station. The overvoltage research of the hybrid system mainly focuses on the overvoltage during the shutdown, restart, and fault ride-through of the DC converter station caused by the AC system faults on both sides, while the research on the switching overvoltage in LCC-VSC Hybrid DC System is less. Literature [1] studies the topology of LCC-VSC Hybrid DC System, and comparatively analyzes the advantages and disadvantages of several hybrid DC topologies in economy and technology. In reference [2], the hybrid DC topology of MMC at the sending end and LCC at the receiving end is studied, and the corresponding control methods are proposed. In reference [3], the fault traversing control strategy of MMC converter with half bridge module and full bridge module accounting for 50% respectively in VSC converter station at the receiving end under rectifier side fault is studied. An improved circulation control strategy and a temporary current suppression strategy based on virtual resistance and current index limit are proposed. In reference [4-8], the coordinated control mode of LCC and VSC converter is studied and further extended to multi terminal system. The principle of multi terminal system control strategy is analyzed and the additional control strategy under fault is simulated. Literature [4] studies the fast and stable control strategy of VSC converter station under AC side fault in HVDC system. In reference [9], the overvoltage of several typical DC side faults in MMC DC transmission system is analyzed and calculated, and the corresponding suppression measures are proposed. In reference [10], in order to make up for the defect that half bridge MMC converter cannot directly remove DC fault, a method of blocking DC fault current by installing high-power diode valve group at DC outlet of inverter side is proposed, which provides a direction for fault removal and overvoltage suppression of MMC converter station.

These studies discussed and analyzed the design, operation and fault handling control strategy of VSC flexible DC and LCC traditional DC hybrid system, and put forward some control principles combined with LCC DC control. However, there is no in-depth study on the characteristics of the LCC DC overvoltage in the hybrid system and its similarities and differences with the LCC DC transmission system. This article will take LCC-VSC Hybrid DC System as an example, and combine the valve overvoltage and neutral bus overvoltage mechanisms in the LCC DC system to simulate and analyze the neutral bus overvoltage characteristics of the hybrid system. The principle of VSC converter station's influence on the overvoltage of LCC converter station and the corresponding solutions are studied. Finally, the conditions that the design of LCC system overvoltage and insulation coordination in the hybrid DC system refers to the traditional LCC DC system is proposed.

2. System Overview
A hybrid DC transmission system with a rated DC voltage of 500 kV, an LCC converter station at the sending end, and a VSC converter station at the receiving end is established. The system structure is shown in Figure 1, and the main system parameters are shown in Table 1.
3. Difference between LCC converter station and VSC converter station

The operating principles of the MMC converter and the LCC converter in the VSC converter station are completely different, and the characteristics and control methods of the two converters are also completely different. As far as the overall external characteristics of the two types of converter stations are concerned, there are two major differences in voltage and current direction conversion and start-stop methods.

3.1. voltage and current direction conversion

The core component of the LCC converter is the thyristor. The current in the thyristor can only flow from the anode to the cathode, and cannot flow in the reverse direction. However, the output voltage of the LCC converter can change direction according to different quadrants of the trigger angle.

The core device of the MMC converter is the MMC converter submodule unit, and the MMC module unit can be divided into two categories: half-bridge type and full-bridge type. As shown in figure 2, compared with the full-bridge submodule MMC converter, the half-bridge submodule MMC converter that is used in current project has only half the number of IGBT switches, and its structure and control system are simple. The output current direction can be arbitrarily set within the rated range according to the modulation of the control signal, but the output voltage direction of this type of converter cannot be reversed.

3.2. Start-stop methods and characteristics

The start-up process of the LCC converter is similar to that of the MMC converter, in that the voltage is first established, then the current is established and the current is raised to the set current value to complete the startup. But these two converters have a big difference in the way to stop. For LCC converter, the stop of it is to reduce the output current of converter by reducing the output voltage. In the process, the converter will not output energy to DC line.

For the half-bridge MMC converter, the trigger pulse is locked first in the stop process, which make the converter change into a full bridge rectifier to output DC voltage to DC side, and then the converter stops the output to DC side after the AC switch cuts off the AC power supply.
3.3. Summary
The voltage of LCC converter can be reversed, but the current cannot be reversed. The current of half-bridge MMC converter can be reversed, but the voltage cannot be reversed. The sending end and receiving end of LCC-VSC Hybrid DC System can only be fixed. In the research of this paper, LCC is used as the sending end for rectification and VSC as the receiving end for inversion.

4. Types of switching overvoltage in LCC converter station studied
Based on the analysis of the previous section, the output voltage and current to the DC side during the stop of MMC converter have an impact on the DC transmission system fault transient process of LCC converter station, which thus affects the switching overvoltage characteristics of LCC converter station. This paper mainly studies two types of overvoltage in LCC converter station that are easily affected by it: valve overvoltage and neutral bus overvoltage. The mechanism and process of these two types of overvoltage will be introduced below.

4.1. Valve overvoltage in LCC DC transmission system

4.1.1. Mechanism of overvoltage. Mechanism of overvoltage on valve in LCC converter station is shown in Figure 3. When there is a short circuit to ground at the outlet of valve side of Y converter transformer at the high voltage end of LCC DC converter station that is operating as a rectifier station, the energy on the DC line and the DC filter capacitor will be released through the uppermost valve arrester V11 of the twelve-pulse converter. As a result, the arrester V11 is subjected to overvoltage caused by the voltage difference between the DC line and the outlet of converter transformer valve side and absorbs large overvoltage energy [11].

![Figure 3. Mechanism of overvoltage on valve in LCC converter station](image)

4.2. Neutral bus overvoltage in LCC DC transmission system

4.2.1. Mechanism of overvoltage. Taking the ground fault of the DC positive valve top as an example, the specific process of this type of overvoltage is as follows [12]. When the system is in the metallic return operation mode, and a short circuit to ground occurs at the valve top of the rectifier station, the equivalent circuit schematic diagram of converter fault is shown in figure 4(a) and (b). Due to the ground fault at the valve top, the voltage at the valve bottom becomes negative rated voltage, resulting in severe overvoltage on the neutral bus.

Then the DC protection system starts to operate and the trigger phase angle of the rectifier is shifted back, causing that the converter no longer outputs the fault current in the reverse direction to the fault point, which means the end of the first stage of neutral bus overvoltage.
When the grounding fault at the valve top occurs, there is normal DC current on the metallic return. Due to the rapid shutdown of the converter after the operation of protection system, the current on the metallic return has not completely dropped to zero. However, current can no longer flow into the converter from the valve bottom due to the shutdown of the converter. As shown in figure 4 (b), the DC freewheeling current on the metallic return is charging the neutral bus of the rectifier station, which gradually raises the neutral bus voltage until the neutral bus arrester operates again. The current flows into the earth through the neutral bus arrester until the freewheeling current on the metallic return is exhausted and the neutral bus voltage drops to normal again. This process is the second stage of neutral bus overvoltage.

During the occurrence and development of this overvoltage, the LCC inverter station has no obvious influence on it, so this overvoltage is only related to the condition of the rectifier in the LCC DC system.

5. Overvoltage characteristics of the LCC-VSC Hybrid System

During the development and treatment of the above two switching overvoltage faults, the LCC inverter station was shut down synchronously and no high DC voltage or current is output to the DC line. Therefore, LCC inverter station has no obvious influence on the overvoltage process. However, the half-bridge VSC converter station will output DC voltage and energy to the DC side during shutdown, which will affect the overvoltage of the LCC converter station on the rectifier side. The following is a simulation analysis of the influence.

5.1. Blocking diode

When the above-mentioned valve overvoltage and neutral bus overvoltage occur in LCC-VSC Hybrid DC System, their characteristics may be affected by the VSC converter station at the receiving end. Literature [1, 10] all mentions that in LCC-VSC Hybrid DC System, installing blocking diode at the entrance of VSC inverter station as shown in the system diagram of figure 1 can effectively limit DC fault current output from inverter station using half-bridge MMC converter.

5.2. Situation with blocking diodes

5.2.1. Valve overvoltage. In the case of blocking diodes, waveforms of the valve voltage and the current and energy through valve arrester are shown in figure 5. It can be seen from figure 5 that the overvoltage across the valve is relatively large within 20ms of the fault, i.e. one power frequency cycle. The overvoltage is concentrated on one phase valve, and the overvoltage energy is concentrated on one valve arrester. Under this condition, the overvoltage across the valve and the discharge current and energy through the valve arrester are listed in table 2.
Figure 5. Waveform of overvoltage and energy on valve with blocking diode

Table 2. Result of overvoltage on valve with blocking diode

|                          | Maximum voltage(kV) | Maximum current(kA) | Overvoltage energy(MJ) |
|--------------------------|----------------------|----------------------|-------------------------|
| With current limiting thyristor | 461                  | 0.784                | 1.58                    |
| Tian-Guang HVDC results    | 474                  | 0.65                 | 1.63                    |

From the data in table 2 and the valve overvoltage data in literature [13], it can be seen that the valve arrester overvoltage energy of the system is similar to that of LCC converter stations with the same voltage level, and its overvoltage waveform and development process are also the same. It can be considered that under the condition that the LCC-VSC Hybrid DC System has blocking diodes, the valve overvoltage of LCC converter station is not affected by VSC converter station, which is similar to the valve overvoltage process of traditional LCC DC converter station.

5.2.2. Neutral bus overvoltage. In the case of LCC converter station valve top ground fault with blocking diodes, waveforms of the neutral bus voltage and the current and energy flowing through the neutral bus arrester are shown in figure 6. From the data in table 3 and the neutral overvoltage data and overvoltage waveform in literature [12], it can be seen that the neutral bus overvoltage of LCC converter station is not affected by VSC converter station when LCC-VSC Hybrid DC System has blocking diodes, which is similar to the valve overvoltage of traditional LCC DC converter station.

Figure 6. Waveform of overvoltage and energy on neutral bus with blocking diode

Table 3. Result of overvoltage on neutral bus with blocking diode

|                          | Maximum voltage(kV) | Maximum current(kA) | Overvoltage energy(MJ) |
|--------------------------|----------------------|----------------------|-------------------------|
| With blocking diodes     | 104                  | 5.96                 | 3.74                    |

5.3. Situation without blocking diodes

When no blocking diode is installed in LCC-VSC Hybrid DC System, the simulation calculation of VSC converter station's influence on valve overvoltage and neutral bus overvoltage is as follows:
5.3.1. Valve overvoltage. Without blocking diodes, waveforms of the valve voltage and the current and energy flowing through the valve arrester are shown in figure 7. Compared with the overvoltage waveform in case of blocking diodes in figure 5, the overvoltage duration in the waveform is longer. Moreover, the overvoltage energy through the three-phase valve arrester rises in turn, and the energy value is much larger than that with blocking diodes. Valve overvoltage and discharge current and energy flowing through valve arrester under this working condition are shown in table 4.

![Figure 7. Waveform of overvoltage and energy on valve without blocking diode](image)

**Table 4. Result of overvoltage on valve without blocking diode**

|                  | Max voltage(kV) | Max current(kA) | Energy(MJ) |
|------------------|-----------------|-----------------|------------|
| Without thyristor| 465             | 1.17            | 14.7       |

The data in table 4 show that the energy through the valve arrester without blocking diodes is much higher than that with blocking diodes, and the VSC converter station in the hybrid system has a great impact on the valve overvoltage in LCC converter station. The specific effect is reflected in the effect on the DC-bus voltage. As shown in figure 8 and figure 9, comparing the DC-bus voltage waveforms of LCC converter station with and without blocking diodes, it can be seen that when blocking diodes are present, the voltage on the LCC DC-bus rapidly drops to a very low level. However, the DC-bus voltage is always higher when no blocking diodes are present due to the action of VSC converter station until the AC switch on the VSC side turns off and cuts off the MMC converter power supply. This persistent DC-bus voltage causes the overvoltage energy on the valve arrester of LCC converter station to continuously increase.

![Figure 8. Waveform of voltage on DC-bus with blocking diode](image)  
![Figure 9. Waveform of voltage on DC-bus without blocking diode](image)

5.3.2. Neutral bus overvoltage. Without blocking diodes, waveforms of the neutral bus voltage and the current and energy flowing through the neutral bus arrester are shown in figure 10. Compared with the overvoltage waveform in case of blocking diodes, the overvoltage of this waveform has obviously two more phases. The overvoltage difference between the two cases is mainly after the second stage. Under the condition of no blocking diode, neutral bus overvoltage continues to exist, overvoltage
energy continues to rise, and the energy value is much larger than that under the condition of blocking diodes. The discharge current and energy flowing through the neutral bus arrester are shown in table 5.

The data in table 5 show that the energy through the neutral bus arrester under the condition of no blocking diode is much higher than that under the condition of blocking diodes, and the VSC converter station on the opposite side of the hybrid system has a great impact on the neutral bus overvoltage of LCC converter station.

This effect is embodied after the second phase of overvoltage. Under the condition of current limiting diodes, the overvoltage process will end after the overvoltage generated by the freewheeling current on the metallic return attenuates. However, in the absence of a current limiting diode, the overvoltage generated by the freewheeling current on the metallic return reverses phase after attenuation and continuously injects energy into the neutral bus arrester, and after 80ms, the neutral bus overvoltage reverses phase again and injects large overvoltage energy into the neutral bus arrester, which finally makes the energy in the whole overvoltage process far exceed that with the current limiting diodes.

Figure 10. Waveform of overvoltage and energy on neutral bus without blocking diode

Table 5. Result of overvoltage on valve without blocking diode

| Without thyristor | Max voltage(kV) | Max current(kA) | Energy(MJ) |
|-------------------|-----------------|----------------|------------|
|                   | 104             | 5.96           | 19.7       |

The reason for this difference is that the half-bridge MMC converter on inverter side is equivalent to a six-pulse full-bridge rectified voltage source when the trigger pulse is stopped. At this time, the grounding point of rectifier station valve top, DC positive bus, MMC converter and earth electrode line of VSC converter station constitute a complete short circuit fault circuit, as shown in figure 11. When it reaches 0.103s in figure 10, due to the successful disconnection of the AC switch in the MMC converter, the MMC converter loses power supply and is no longer a DC current source. Then the ground fault current loop that outputs to the valve top on rectifier side is cut off, as shown in figure 12. However, at this time, there is still a large short-circuit current on the earth electrode line of VSC converter station, which cannot be immediately reduced to zero. A part of this current is released to the neutral bus on the rectifier side through the metallic return, causing the neutral bus to rise again in reverse phase. An overvoltage phenomenon occurs and a large amount of overvoltage energy passes through the neutral bus arrester.

In summary, under the condition of no blocking diode, due to the DC-to-ground short-circuit process caused by the DC voltage source characteristics during the shutdown of VSC converter station on the inverter, the overvoltage of neutral bus on rectifier side increases by two stages and the overvoltage energy increases greatly.
5.4. Summary
Based on the above simulation results, it can be seen that the VSC converter station on the inverter side will have a great impact on the overvoltage of the LCC converter station on the rectifier side without blocking diodes. The main mechanism of its influence lies in the DC full-bridge rectification state during the shutdown process. The condition that the state can affect the overvoltage is that the DC bus voltage participates in the generation and development process of the switching overvoltage. Specifically, the faults occurring in the DC system can form a loop through the earth, MMC converter and the fault point. MMC converter will become a DC fault current source at this time. The DC fault current will continue to exist until the AC side power supply is cut off and the DC source is completely removed. This process has a great influence on the development of overvoltage caused by LCC converter station faults. The main function of blocking diodes is to cut off the loop formed by the fault point, earth and MMC converter, thus eliminating the effect of VSC converter station on overvoltage.

6. Conclusion
To sum up, according to the above analysis of overvoltage characteristic, the following conclusions are drawn.

The DC overvoltage of LCC converter station in LCC-VSC Hybrid DC System is similar to that of traditional LCC DC system, but its development process is affected by VSC converter station at the receiving end and is different.

When LCC converter station operates as inverter side, it will not output energy to DC side during shutdown, while VSC converter station will output DC voltage and energy to DC side during shutdown transient process. This is the biggest difference between LCC and VSC converter station transient characteristics, which results in the different overvoltage of LCC converter station on rectifier side in the two DC systems.

Due to the stage characteristics of full-bridge rectifier during the shutdown of half-bridge MMC converter in VSC converter station, it will have a great impact on partial overvoltage of LCC converter station on rectifier side, such as valve overvoltage and neutral bus overvoltage, which will greatly increase the overvoltage energy to be absorbed by arrester.

Installing blocking diodes at the outlet of VSC converter station on inverter side can effectively avoid the adverse effects of VSC converter station on LCC converter station overvoltage.

Overvoltage unrelated to DC bus voltage in LCC converter station, such as neutral bus overvoltage caused by short circuit to ground at the outlet of converter transformer valve side are not affected by VSC converter station regardless of whether blocking diodes are installed in the hybrid system.

When the inverter side of LCC DC transmission system is replaced by VSC converter station, VSC converter station will not normally operate as a rectifier station. In this case, blocking diodes are used
to effectively block the output voltage to DC side during the shutdown process, which can keep the overvoltage transient condition of LCC converter station on rectifier side similar to that before the renovation, so that the insulation matching design of converter station does not need to be changed.

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