IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received July 6, 2021, accepted September 10, 2021, date of publication September 20, 2021, date of current version September 29, 2021.

Digital Object Identifier 10.1109/ACCESS.2021.3114153

Research on Overvoltage Suppression by Blocking Diode and DC Circuit Breaker in LCC-VSC Hybrid HVDC System

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This work was supported in part by China Postdoctoral Science Foundation under Project 59, and in part by the Program for Science and Technology of the State Grid Corporation of China "Research on Overvoltage and Insulation Coordination of LCC-VSC Hybrid HVDC Transmission System."

ABSTRACT In this study, a LCC-VSC hybrid HVDC transmission system was taken as an example. The valve and neutral overvoltage of the hybrid HVDC system were simulated and then calculated at the VSC converter station by installing a blocking diode and a DC circuit breaker, as well as by grounding after neutral bus outage. The isolation effect of the blocking diode and the DC circuit breaker on the VSC converter station in the protection and the effect on the DC overvoltage were compared, and the difference was analyzed by complying with the mechanism of overvoltage. The effect of different locations of the blocking diode on the overvoltage suppression was compared, and it was concluded that different locations of blocking diode could raise different requirements for the insulation coordination of the converter valve. By analyzing energy sources of the neutral bus overvoltage at different stages, it was further concluded that the energy stored in the distributed inductance of the metal return line could be a vital source of neutral bus overvoltage energy. On that basis, an overvoltage suppression strategy for grounding neutral bus directly after the stop of the converter station was proposed.

INDEX TERMS Hybrid HVDC, blocking diode, DC breaker, switching overvoltage.

I. INTRODUCTION

Line-Commutated Converters (LCC-HVDC) technology has been employed to primarily achieve the large-capacity and long-distance transmission in China. It is employed for power transmission between two large power networks. Such a type of transmission system requires considerable reactive power compensation from two end converter stations, which applies to the large-capacity centralized power transmission. Voltage-Source Converters VSC-HVDC (Voltage-Source Converters VSC-HVDC) technology using MMC (Multi Model Converter) type converter valve as the core converter element exhibits several advantages, including its low reactive capacity requirement, no risk of commutation loss, and ability to connect to a passive AC power network, which is capable of meeting the needs of transmission to a small-capacity weak AC power network. As the manufacturing technology of converter valves has been progressively advanced and optimized, the mentioned transmission technology is developing towards large capacity transmission [1]–[3]. With the maturity of the MMC converter valve technology and the construction and commissioning of the relevant test projects over the past few years, combined with frequent outage accidents attributed to commutation failure in the inverted side of existing LCC DC transmission projects, a scheme has been proposed to replace the original LCC transmission project inverted station with VSC converter station, as an attempt to address the inverted side commutation failure [4]–[8]. LCC-VSC hybrid HVDC transmission technology, combining the advantages of the two types of transmission technology, has gradually become an important direction of HVDC transmission research [9].

The fault and control strategies pertaining to the LCC and VSC hybrid HVDC systems refer to the main direction of overvoltage studies. This study [10] presented a novel asymmetric DC voltage fault enhancement control method for the HVDC systems based on the hybrid modular multilevel converters (MMCs). For the hybrid MMC HVDC

The associate editor coordinating the review of this manuscript and approving it for publication was Sonia F. Pinto.

transmission system with a symmetrical unipolar configuration, the principle of the PTG fault treatment with enhanced control strategy was elucidated [11]. The matching characteristics of the LCC and the VSC in the hybrid HVDC system and the control strategies to eliminate DC line faults were analyzed. Literature [12] analyzed the equivalent models of the LCC and MMC stations, built a bus impedance matrix of the whole HVDC network, and then developed a calculation method of the fault traveling wave for the hybrid HVDC network. Literature [13], [14] studied the overvoltage mechanism under the blocking, the commutation failure, the restart and the short-circuit faults of line grounding. In addition, the static voltage characteristics were obtained, and the analytical expression of the transient overvoltage peak was proposed. Given the defects of the sub-module operation characteristics ex-hibited by the half-bridge MMC type VSC converter, the application of the full-bridge and half-bridge full-bridge hybrid VSC converter was studied as well. Literature [15], [16] studied the commutation failure of the LCC, and compared the transient overvoltage characteristics of the LCC-FBMMC system and the LCC-HBMMC system. Literature [17] analyzed the indirect faults in the station of the bipolar HVDC transmission system. A novel hybrid arm modular multilevel converter (MMC) was proposed to address the overvoltage problem in MMC with bipolar units in the arm close to the ground pole. Compared with the complex structure of the hybrid converters, the direct series of a blocking diode outside the converter has been selected more frequently. Literature [18] presented an overvoltage protection method for polar-to-ground faults in the half-bridge MMC symmetric unipolar DC trans-mission system. The MMC used the short mode protection as a rectifier, and the MCC as the inverting side installed a blocking diode at its DC end. Literature [19] suggested that the ability to recover from DC line faults could be achieved by delaying the trigger angle of the LCC and by installing high power diodes in overhead lines close to the inverter. With the emergence of the multi-terminal DC transmission technology, the design and application of DC circuit breakers have been significantly progressed [20]. Literature [21] presented the key technologies of the DC circuit breaker with the commutation drive circuit from four aspects (I.e., topology, fast mechanical switch, power electronics and com-mutation principle). Literature [22] used a capacitor to force the fault current to zero by using the reverse current injection method. A novel hybrid circuit breaker topology with a low conduction loss and a short interrupt time was presented. In literature [23], a hybrid HVDC circuit breaker based on anti-shunt thyristor and bidirectional interruption full bridge sub-module technology was presented, which was suggested to exhibit significant technical advantages in the current interruption capability and the semiconductor cost. Literature [24] presented a sequential switching strategy for hybrid HVDC circuit breakers to solve the transient problem during the DC fault interruption in the multi-terminal HVDC network. The switch strategy could reduce the peak fault current, the overvoltage and the clearance time by sequentially tripping the breaker modules within the breaker.

The mentioned studies analyzed the design, operation and fault handling control strategies of the hybrid system of the VSC DC and the LCC DC, and then proposed some control principles combining the LCC DC control. Specific to the hybrid HVDC transmission system, the protection of the DC current restriction control on one side of the VSC DC converter station has been primarily studied, and there are numerous corresponding schemes. This study took a hybrid HVDC transmission system as an example to compare and analyze the effects of the blocking diode and the DC circuit breaker on the overvoltage suppression and protection. Furthermore, the corresponding protection strategies for overvoltage control were discussed.

II. HVDC SYSTEM OVERVIEW

A hybrid HVDC transmission system was built with a rated DC voltage of 500 kV, a LCC converter station at the sending end, as well as a VSC converter station at the receiving end. The structure diagram of the system is presented in Fig. 1, and the main parameters of the system are listed in Tab. 1.

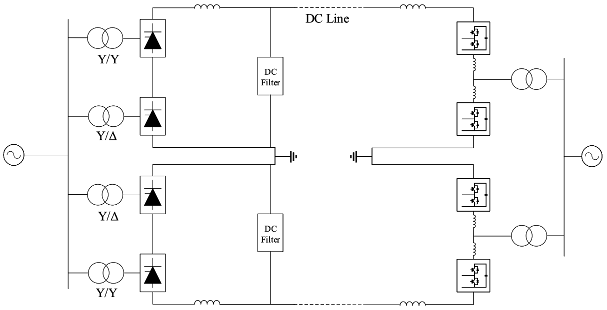

FIGURE 1. LCC-VSC hybrid HVDC system.

TABLE 1. Main parameters of the LCC-VSC hybrid HVDC system.

	Sending	Receiving
Converter Type	LCC	LCC+MMC
Converter Number	4	2
Converter Rate Capacity/ MVA	750	1500
AC Bus Rate Voltage/ kV	500	500
Converter DC Rate Voltage/ kV	250	500
DC Rate Current/A	3000	3000
Bridge arm reactor / mH	—	32
Smooth reactor/ mH	300	300
DC line length/km	600	
DC line resistance/Ω	4	

III. CHARACTERISTICS AND PROTECTION OF THE HYBRID HVDC SYSTEM

The operation principle of the MMC converter in the VSC converter station was completely inconsistent with that of the LCC converter, and the internal and external characteristics and control modes pertaining to the two converters were completely different as well. Different external characteristics could determine the operating mode, the switching overvoltage and the general DC system in the hybrid HVDC system.

Among them, there were two main differences in the external characteristics, i.e., voltage-current direction conversion and protection action mode.

A. CHARACTERISTICS OF HYBRID HVDC SYSTEM

1) VOLTAGE CURRENT DIRECTION CONVERSION

The core part of the converter of the LCC converter was the thyristor, the current in the thyristor could only flow in one direction. However, the output voltage of the converter could be altered by the trigger angle. When the trigger angle is less than 90 degrees, the output voltage of the LCC converter is the same as the current direction. When the trigger angle is over 90 degrees, the output voltage of the converter is opposite to the current direction and receive the energy from the DC line.(Shown in Fig 2)

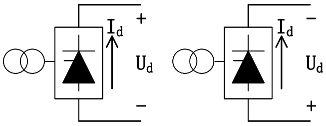

FIGURE 2. Rectifier and inverter state of the LCC converter.

The core component of the MMC converter was the MMC converter sub-module unit, which could fall to two types, i.e., half-bridge and full-bridge. As shown in Fig. 3, half-bridge sub-module has only half the number of IGBT switches compared with full-bridge sub-model MMC converter. Its structure and control system are more simple, economical and the type used in current projects. However, the output voltage direction of this type of converter cannot be reversed, and the output current direction can be set arbitrarily within the rated range according to the control signal, as shown in Fig. 4.

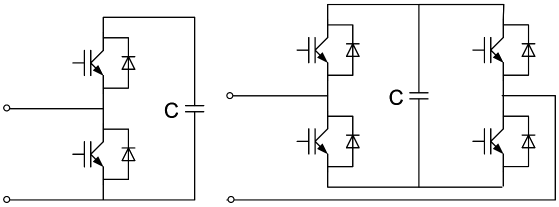

FIGURE 3. Half bridge sub-model and full bridge sub-model of the MMC converter.

2) PROTECTION ACTION MODE AND FEATURES

The starting process of the LCC converter is similar to that of the MMC converter, in which the voltage was first established, and then the current was established and raised to the set current value to complete the initiation. However, a significant difference was identified between the two converters in the operation of protection to stop.

For LCC converters, the operation of protection to stop could fall to rectification and inversion. The LCC rectifier state outage could reduce the output current from the surface by phase shifting to lower the output voltage, which could finally trigger the pulse blocking outage. The reverse side was to put the bypass pair of conduction pole and neutral bus first, and then wait for the rectifier side to drop the current close to zero before blocking triggered pulse stop converter. Outages of the LCC converters mainly aimed at reducing the output voltage and current of the converter.

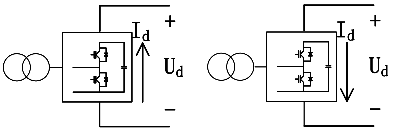

FIGURE 4. Rectifier and inverter state of the MMC converter.

Specific to MMC converters, the operation modes of the rectifier side and the inverter side were not essentially different because of the different distribution of the DQ component under their control. For half-bridge converters, the DC output voltage could not decrease to zero by pulse control alone. The DC output of converter would not be cut off until the AC breaker was broken. The interruption was to block trigger pulse first, and the converter was converted into a full bridge rectifier to output DC voltage to DC side (Fig. 5). After the AC switch cut off AC power, the converter would stop DC voltage output to DC side.

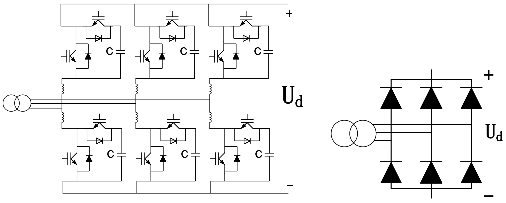

FIGURE 5. Equivalent diagram of the blocked MMC converter turning into the full bridge rectifier.

3) SUMMARY OF CHARACTERISTICS

As impacted by the voltage reversible current non-reversible characteristic of the LCC converter and the current reversible voltage non-reversible characteristic exhibited by half-bridge MMC converter, the power direction of the LCC-VSC hybrid HVDC transmission system could not be transmitted in two directions (e.g., the conventional LCC or VSC DC transmission system). Besides, only one end could be fixed as the transmission end, and the other end could be fixed as the receiving terminal. In the simulation system, the LCC was the sender, and the VSC acted as the receiver.

In this study, the VSC-LCC hybrid HVDC transmission system, the half-bridge MMC converter, before the AC switch was not cut off, would output DC voltage and current to the DC system, thereby affecting the DC operation overvoltage. The mentioned is also an important aspect in overvoltage research.

B. TWO OVERVOLTAGE PROTECTION MEASURES FOR HYBRID HVDC TRANSMISSION SYSTEM

This study primarily investigated the effect of adding blocking diode or DC circuit breaker at the entrance of the VSC converter station in the hybrid HVDC transmission system on the overvoltage of the hybrid HVDC System. The two types of devices were installed in the system (Fig. 6):

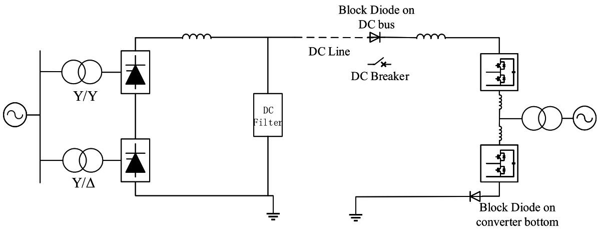

FIGURE 6. **Installation position of blocking diode and DC circuit breaker.**

1) BLOCKING DIODE

As mentioned in the literature [18], [19], [25], in the VSC-LCC hybrid HVDC transmission system, blocking diode was installed at the entry of the VSC converter as the inverter station, or the one-way thyristor could effectively limit DC fault current output by the inverter station using the half-bridge MMC converter. Thus, when the protection was initiated on the inverted side, the full bridge rectifier state on the inverted side would be prevented from outputting energy to the DC line side, affecting the other side of the converter station. The blocking diode installed at the polar inlet or at the bottom of the converter valve could be effective, and the effect of the mentioned two installation methods were compared in this study.

2) DC CIRCUIT BREAKER

After the faults on the line of the conventional LCC HVDC transmission system, both of the converter stations started the protection process, and the LCC converter performed the phase shift blocking operation, which could quickly reduce the voltage and current of the DC system to zero before the converter and the HVDC system stop operation. The operation of the DC part was controlled by the converter during the whole outage. There would be no abnormal increase of the DC current, and the AC power supply of the converter should be cut off to get rid of the malfunction. Accordingly, in the conventional two-terminal LCC HVDC transmission system, the necessity of DC circuit breaker was not prominent.

In the multi-terminal DC transmission system, when a converter station or a section of line failed, the whole DC system would lose considerable outage when its operation stopped. A DC breaker would be required to isolate the faulty DC converter station or line from other normal DC parts and reduce the effect of outage.

In the hybrid HVDC transmission system, since the half-bridge VSC converter presented the incompletely con-trolled DC power status during outage, it could continuously output energy to the DC line side until the AC power supply of the converter was disconnected. In the case of the system failure, the consequences of the failure would be more serious, and the DC equipment of the VSC converter station in the outage state should be quickly isolated and removed.

There would be no cycle zero-crossing point for the DC current relative to the AC, so the structure and principle of the DC circuit breaker could be completely inconsistent with the AC circuit breaker, and the cost could be significantly higher than that of the AC circuit breaker. There have been two main types of common DC circuit breakers, i.e., mechanical and hybrid [21]. A mechanical DC breaker could use an auxiliary zero-return circuit to generate a DC current cut off after the current passed zero, and then it could use the energy-consuming circuit to consume the voltage-current shock wave during the oscillation. Hybrid mainly used high voltage IGBT similar to MMC converter sub-module to work with lightning arrester to switch off DC current and consume energy during the transition, and ultimately to achieve DC interruption isolation.

The structure diagram of hybrid HVDC circuit breaker is shown in the Fig 7. The main circuit breaker is composed of an auxiliary breaker composed of IGBT group and a quick disconnect switch. In addition, there is a surge arrester branch in parallel with them to absorb the oscillation overvoltage generated in the breaking process, so as to protect the circuit breaker.

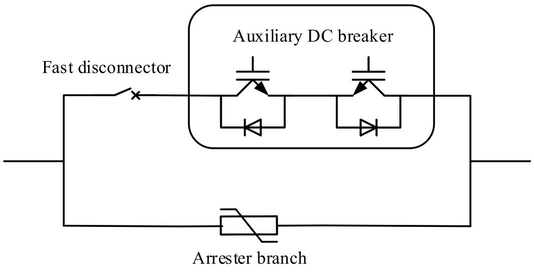

FIGURE 7. **Simple structure diagram of hybrid HVDC circuit breaker.**

IV. OVERVOLTAGE IN TYPICAL HYBRID HVDC TRANSMISSION SYSTEMS

In a conventional DC system, the switching overvoltage characteristics were related to the upper valve and neutral bus overvoltage of the main converter related to the other side of the station. [26] This study mainly investigated the hybrid HVDC overvoltage protection strategy by calculating and analyzing the mentioned two types of overvoltage.

The primary system structure and main surge arrester configurations of the LCC and the VSC converter stations in this project are illustrated in the figure. The main switching overvoltage involved in the study is listed in Table 2.

A. LCC CONVERTER VALVE OVERVOLTAGE

For Type I overvoltage in the table, when the LCC DC converter was running as a rectifier, the energy on the DC line and DC filter capacitance would be released via the

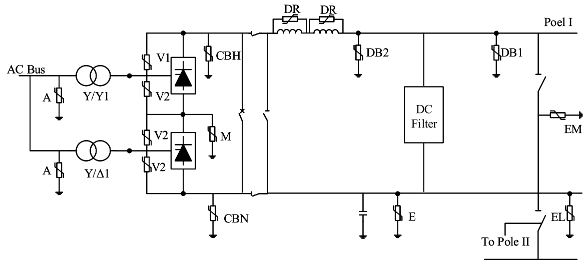

FIGURE 8. Arrester scheme in the LCC converter station.

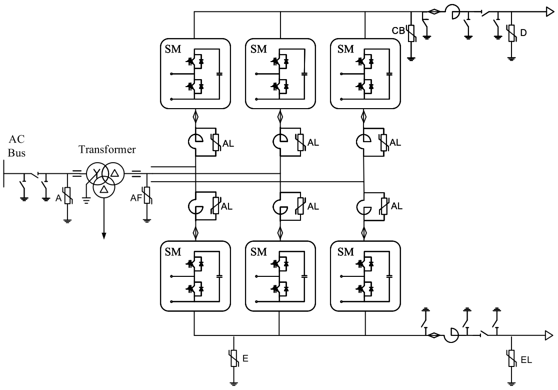

FIGURE 9. Arrester scheme in the VSC converter station.

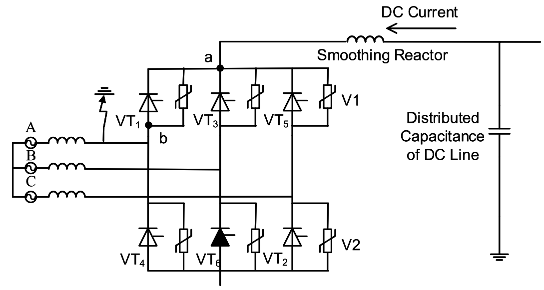

FIGURE 10. Mechanism of overvoltage on valve V1 in LCC converter station.

valve arrester V1 on the top of the 12-pulse converter when the grounding short circuit occurred to the ground at the side outlet of the Y-converter valve at the high voltage end. As a result, the valve arrester V1 would be subjected to the overvoltage of the voltage difference between the outgoing line of the converter valve side and the DC pole line, and a larger overvoltage energy would be absorbed [27] (Fig. 10).

In a hybrid HVDC transmission system, if the VSC converter station at the station could still output energy to the DC line during the protection and maintain the DC line voltage, the energy of the upper valve overvoltage at the LCC station would increase, and its severity would be aggravated.

B. NEUTRAL BUS OVERVOLTAGE IN LCC CONVERTER STATION

For the Type II overvoltage listed in the table, when the rectifier station of the LCC HVDC transmission system was running, the neutral bus of the converter station would generate overvoltage in the presence of the short circuit fault at the converter top and the DC pole line. On the whole, the overvoltage consisted of two connected processes. The first process was that when the ground fault just occurred, the rectifier was still in the rectifier operation state, which could be equivalent to a DC power source. The ground fault point caused one end of the DC power source to be directly grounded, and the ground voltage on the neutral bus at the other end of the rectifier would be raised to form an overvoltage. The second process was the phase-shifting blocking operation after the initiation of rectifier protection. When the output of the rectifier was turned off, the converter no longer had current flowing through it, whereas there was still current on the metal return line or ground pole leads connected by the neutral buss in the DC system that was not completely reduced to zero. Thus, the residual current could not be returned to the rectifier when the converter valve was closed. The neutral bus could only be released by a surge arrester, which formed the second stage of the neutral bus overvoltage. The overvoltage polarity of the two stages was opposite. At the first stage, the overvoltage could mainly depend on the operation status of the rectifier station. At the second stage, the energy originated from the DC current before the fault, and in the other part from the metal circuit or ground electrode lead current attributed to the fault. The mechanism of overvoltage and the waveform shown in Fig. 11 are illustrated below in Fig. 15:

C. NEUTRAL BUS OVERVOLTAGE IN VSC CONVERTER STATION

According to the type III overvoltage listed in the Tab. 2, for bipolar VSC DC converter stations with neutral bus, the neutral bus would be inverted to raise the voltage in the presence of a polar bus ground fault, due to the circuit composed of the DC power supply and the ground fault point. The overvoltage mechanism diagram is illustrated in Fig. 12. The overvoltage principle was consistent with that of the first

TABLE 2. Table of main switching overvoltage in HVDC system.

Type	HVDC System	Overvoltage on	Attributed to	Arresters involved
I	LCC	Valve	Ground fault between Y/y Transformer and converter	V1 in Fig. 8
II	LCC	Neutral bus	Monopolar Metallic Return, Ground at top of converter; Ground fault between Transformer and converter	CBN, EM, EL in Fig. 8
III	VSC	Neutral bus	Ground fault at DC bus, converter top	E and EL in Fig. 9

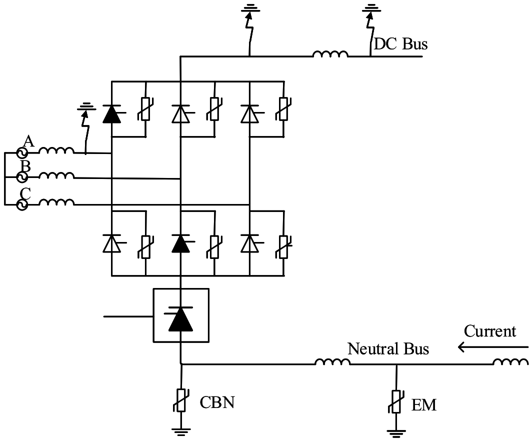

FIGURE 11. Schematic diagram of neutral bus overvoltage attributed to ground fault on top of converter.

stage of neutral bus overvoltage in LCC converter stations. However, the continuous current diode in the MMC module made the neutral bus overvoltage less than the second stage in the LCC converter station.

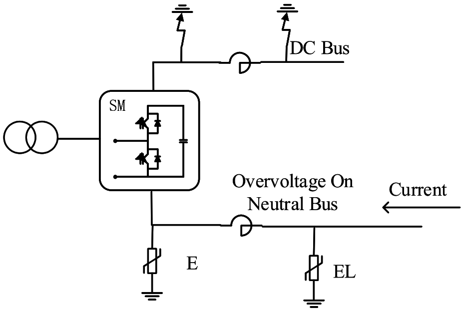

FIGURE 12. Schematic diagram of neutral bus overvoltage in VSC converter station.

V. CALCULATION AND ANALYSIS OF OVERVOLTAGES IN THE HYBRID HVDC TRANSMISSION SYSTEM

The mentioned overvoltages in the hybrid HVDC system were simulated and calculated, and the comparison of switching overvoltage characteristics under different measures of blocking diode and DC circuit breaker was considered. The calculation conditions for several measures are listed in the Tab. 3:

DC circuit breaker is an equipment controlled by protection system. The breaking operation time can be set according to different protection strategies. In this manuscript, two delay strategies are considered for DC breaker measures. One is DC breaker action immediately after the fault occurs, as Case 4, the other is to consider the breaking command message from the LCC converter station at the other end where the fault occurs. The VSC converter station receives the command and then operates as a DC circuit breaker, taking into account the maximum communication and information conversion delay of 20ms as Case 5. It can involve the overvoltage characteristics of DC circuit breaker in a more comprehensive way.

TABLE 3. List of cases for calculation and analysis.

	Measures
Case 1	No Block diode
Case 2	Block diode on pole bus
Case 3	Block diode on converter bottom
Case 4	DC circuit breaker
Case 5	DC circuit breaker operating with 20ms Delay

The system diagram corresponding to the corresponding measures is presented in Fig. 6. The results of overvoltage simulation under different measures are given below:

A. VALVE OVERVOLTAGE

Specific to the LCC-VSC hybrid HVDC transmission system in this study, the overvoltage of Type I valve was simulated and compared under five different conditions (Tab. 3). The valve overvoltage and the valve arrester energy waveforms are presented in the figures 13. Case 1 and Case 5 were suggested to have a long over-voltage duration, and the energy traveling through the valve arrester continued to increase, which exceeded that in the other three cases. In the mentioned cases, the overvoltage at both ends of the converter valve and the discharge current and energy flowing through the valve arrester are listed in Table 4.

TABLE 4. Results of overvoltage on valve under Case 1–5.

	Overvoltage/kV	Energy/MJ
Case 1	465	14.7
Case 2	461	1.58
Case 3	461	1.61
Case 4	461	2.19
Case 5	464	4.51

As suggested from the data in Tab. 4, when there was no blocking diode in Case 1, the energy passing through the valve arrester was significantly greater than that in the presence of a blocking diode. The VSC converter station on the opposite side of the hybrid DC system significantly impacted the valve overvoltage in the LCC converter station. The specific impact was reflected in the effect on DC bus voltage. Compared with DC bus voltage waveforms of the LCC converter station with or without blocking diodes (Fig. 14), in the presence of the blocking diodes, the DC bus voltage of the LCC decreased rapidly to a very low level; however, in the absence of the blocking diodes, the DC bus voltage was due to the role of the VSC converter station. There was always a higher voltage applied on it until the VSC side AC switch was disconnected from the MMC converter power supply. This persistent DC bus voltage led to a continuous increase in the overvoltage energy on the valve arrestors of the LCC converter station. Likewise, the delayed shutdown of DC circuit breakers in Case 5 could result in a greater valve overvoltage energy.

In case 4 and 5 with DC circuit breakers, the calculation results of the energy absorbed by the arrester branch in the circuit breaker at the time of switching are shown in Tab. 5:

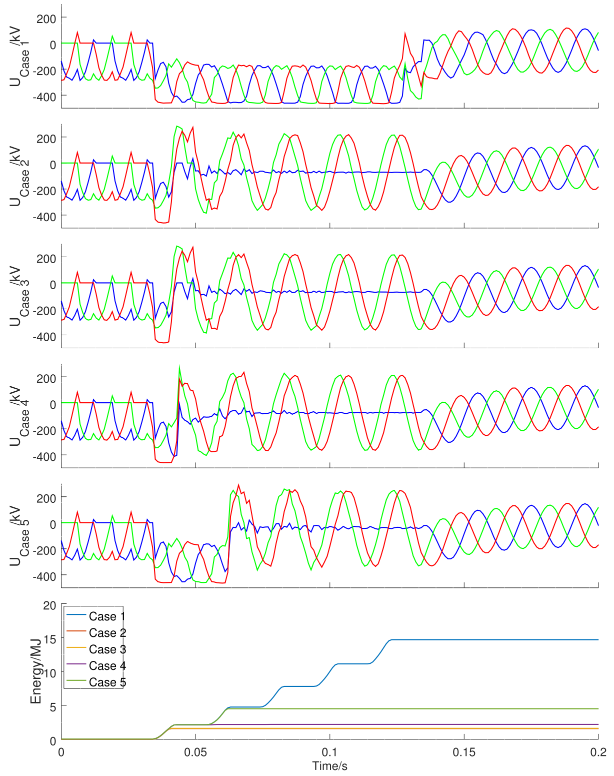

FIGURE 13. Waveform of overvoltage and energy on valve V1.

TABLE 5. Results of energy absorbed by arrester in DC breaker under Case 4 and 5.

	Interruption Current /kA	Energy/MJ
Case 4 no delay	0.74	0.05
Case 5 with 20ms delay	1.15	0.1

For Type I faults, the fault current output from the VSC converter to the LCC converter station is not large, so the energy absorbed by the surge arrester branch of the DC circuit breaker is not large when the DC current is interrupted.

B. NEUTRAL BUS OVERVOLTAGE IN LCC CONVERTER STATION

Specific to this LCC-VSC hybrid HVDC transmission system, the overvoltage of Type II neutral bus in LCC converter station under five different measures presented in the Tab. 3 was simulated and then compared. Fig. 15 presents the neutral bus overvoltage and the energy waveform of the neutral bus arrester in several cases. In Case 5, the overvoltage lasted long, and the energy traveling through the neutral bus arrester increased continuously, much more than that in the other four cases. In the mentioned five cases, the neutral overvoltage and the discharge current and energy flowing through the neutral arrester are listed in Tab. 6.

According to the simulation calculation data in the Fig. 15 and Tab. 6, the neutral bus overvoltage in Case 2-4 was the same as that in conventional LCC HVDC transmission systems, and the overvoltage fell to two stages with opposite polarity, independent of the state of the opposite VSC converter station. Besides the overvoltage in the mentioned two stages, three stages of overvoltage were identified in Case 1 and stage 3 and stage 4 in Case 5, thereby causing the neutral overvoltage energy in the mentioned two cases to exceed in several other cases [25]. These phenomenons mentioned are elucidated below:

In Case 1, there was no device on the DC circuit that could block the VSC converter from releasing energy to the DC line. Thus, after the triggering of the pulse blockage, the AC

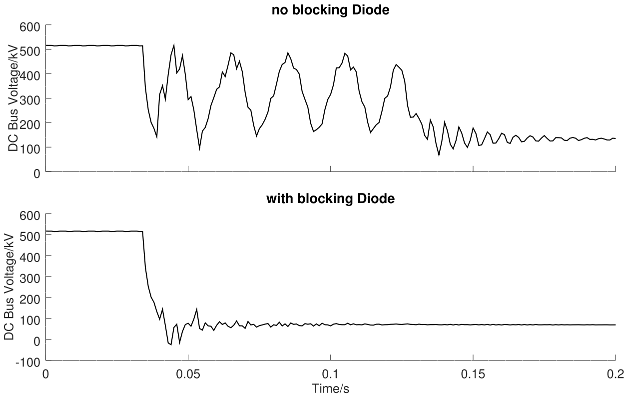

FIGURE 14. Waveform of voltage on DC bus with or without blocking diode.

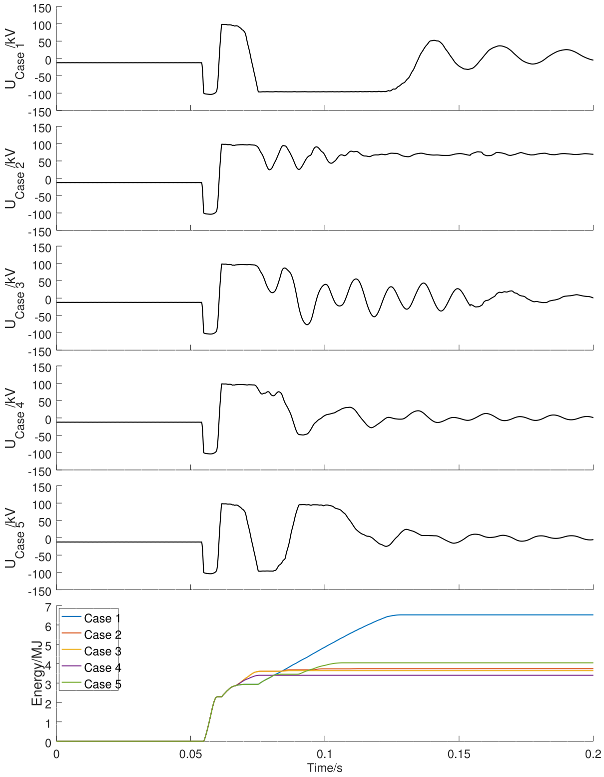

FIGURE 15. Waveform of overvoltage and energy on neutral bus arrester EM.

TABLE 6. Results of overvoltage on neutral bus under Case 1–5.

	Overvoltage/kV	Energy/MJ
Case 1	104	6.52
Case 2	104	3.74
Case 3	104	3.64
Case 4	104	3.40
Case 5	104	4.05

switch was switched off and connected to the DC system as an uncontrolled DC power source (Fig. 16), which caused the current to flow out of the LCC converter station along the metal return line, thereby resulting in the overvoltage on the neutral bus. The duration of such overvoltage was related to the disconnection time of the AC switch on the VSC side. When the AC switch was disconnected, the overvoltage disappears, the overvoltage at this stage caused the neutral bus arrester to absorb more overvoltage energy.

In Case 5, if a DC breaker with time delay was installed at the entry of the VSC converter station, the interruption would occur after the VSC converter was locked for a period (Fig. 17). Then, the grounding fault attributed to the VSC converter and the grounding point on the top of the valve of the LCC converter station was interrupted, which cut off the circuit of the short-circuit current flowing through the DC line to the grounding point, thereby eliminating the stage III overvoltage on the neutral bus of the LCC converter station. However, since the short-circuit current on the grounded line could not be immediately reduced to zero, it would flow to the neutral bus of the LCC converter station via the metal return line, thereby ultimately leading to the stage IV of the overvoltage of the LCC neutral bus. As a result, the overvoltage energy flowed through the neutral bus arrester.

In brief, there might be two other stages of neutral bus overvoltage in LCC converter station in the hybrid HVDC transmission system. The Stage III of overvoltage was due to short-circuit fault current injected into ground fault point by the VSC converter through the DC line and the ground pole line before the DC breaker was disconnected. The neutral overvoltage in Stage IV was attributed to the DC short-circuit current energy stored in the ground pole line of the VSC converter station during Stage III, and it was eventually released in the neutral bus arrester of the LCC converter station.

As revealed from the mentioned analysis of each stage of neutral bus overvoltage in LCC converter station above, part of the neutral bus overvoltage was attributed to the release of residual flow to the neutral bus on the DC line. This part of the residual current could not flow through the converter after the converter was shut down to form a circuit to return to the earth. Subsequently, it was formed by the surge arrestors on the neutral bus to return to the earth. Overvoltage was generated on the neutral bus during this process.

According to the above analysis, if the interruption delay of DC circuit breaker is further extended, the short-circuit current on the ground line of VSC converter station will rise to a higher level before the circuit breaker operating. During the Stage IV of the neutral bus overvoltage, more energy will be released to the neutral bus, which makes the surge arrester on the neutral bus absorb more overvoltage energy. Fig. 18 shows the comparison of current on ground line of VSC station, overvoltage on neutral bus of LCC station and energy absorbed arrester EM with breaking delay time of 0, 20 and 60ms. The calculation results of energy absorbed by arresters are listed in Tab. 7. This trend is clearly shown.

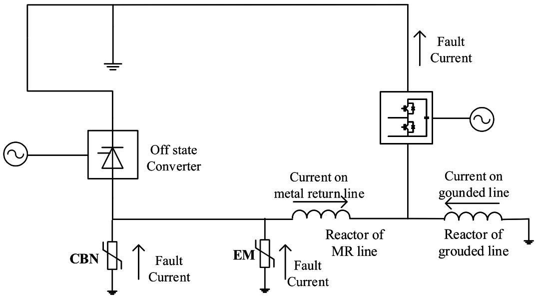

FIGURE 16. Stage III mechanism of overvoltage on neutral bus in LCC converter station.

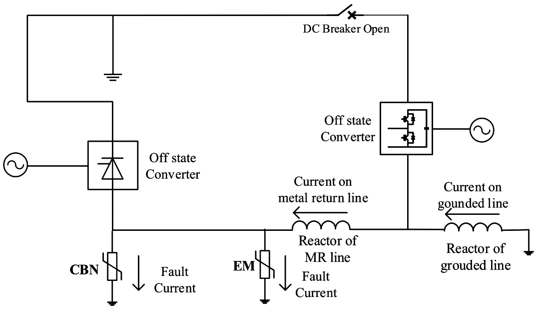

FIGURE 17. Stage IV mechanism of overvoltage on neutral bus in LCC converter station.

The magnitude of DC short-circuit current is different when DC circuit breaker breaks, and the energy absorbed by the arrester branch of the circuit breaker is also different. The calculation results of overvoltage energy absorbed by the arresters under the three different protection delay conditions (Case 4 and Case 5) are shown in the Tab 7. It can be seen that under type II overvoltage condition, the longer the DC circuit breaker's operation delay is, the greater the DC current to be broken is, and the greater the overvoltage energy absorbed by the arrester branch in the circuit breaker is. When the DC circuit breaker operates near the zero crossing point of fault current, the overvoltage oscillation caused by breaking will be smaller, which is similar to the effect of blocking diode.

Considering the influence of DC to ground current on power station equipment, and the steady-state operation voltage of neutral bus is not zero under metal return line operation mode. When the DC system is in normal operation, the neutral bus cannot be directly grounded. However, the neutral bus can be directly grounded after the DC converter is shut down. For the overvoltage feature, after the converter in the converter station was completely stopped, for LCC converter station, after the thyristor of the converter was switched off,

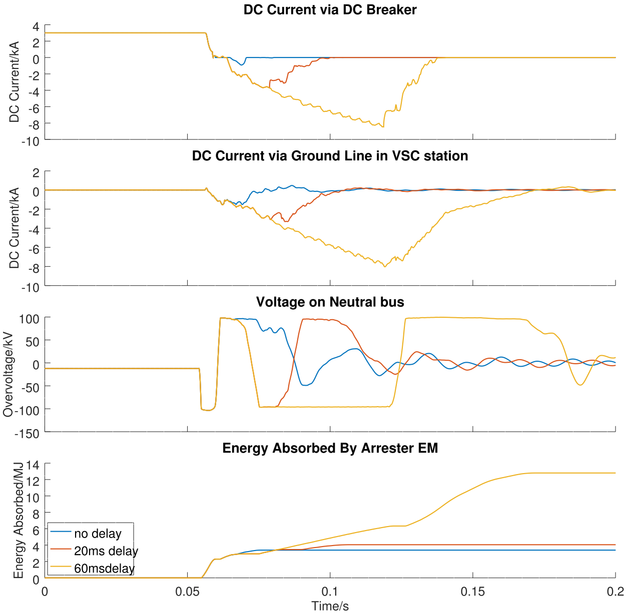

FIGURE 18. Waveform of current in DC breaker, ground line of VSC station, overvoltage and energy on neutral bus arrester EM.

TABLE 7. Results of energy absorbed by arresters under Case 4 and 5.

	Interruption Current /kA	EM Energy /MJ	Arrester branch Energy /MJ
Case 4 no delay	0.92	3.40	1.75
Case 5 with 20ms delay	3.71	4.05	18.2
Case 5 with 60ms delay	8.47	12.8	44.4

and for VSC converter station. After the AC switch was disconnected, an additional protection action was added to directly ground the neutral bus in the converter station, which could reduce the neutral bus overvoltage and the overvoltage energy absorbed by the neutral bus arrester. The relevant simulation results after the addition of this protection action are listed in Table 8:

As suggested from the calculation results, after the neutral bus grounding operation was added, the neutral bus of the converter station was grounded directly after the converter was stopped. Thus, the residual energy stored in the VSC grounded pole lead attributed to the blocked state of the VSC converter could flow directly through the neutral bus grounding point of the converter station. The latter two stages of neutral bus overvoltage energy would no longer affect the neutral bus, thereby effectively reducing the overvoltage energy absorbed by the neutral bus arrester in the LCC converter station. The mentioned strategy could supplement the neutral bus overvoltage protection strategy in the HVDC system to reduce the overvoltage energy pressure of the neutral bus arrester.

Under type II fault condition, the overvoltage energy absorbed by the branch of arrester of DC circuit breaker is caused by the continuous current effect of short-circuit current in DC line. This part of overvoltage energy is directly related to the size of short-circuit current when breaking.

TABLE 8. Results of overvoltage on neutral bus under Case 1 and 5 with ground switch.

	Overvoltage/kV	Energy/MJ
Case 1	104	3.20
Case 5 20ms Delay	104	3.20
Case 5 60ms Delay	104	3.20

When breaking short-circuit current is large, the energy is large, and when breaking short-circuit current is small, the energy is small. The overvoltage energy absorbed by the neutral bus arrester of LCC converter station is related to the protection action time of LCC converter station, the interruption time of blocking diode / DC circuit breaker at the entrance of VSC converter station, the duration of short-circuit current and the amplitude of short-circuit current. The overvoltage energy absorbed by the arrester branch of circuit breaker does not determine the overvoltage energy absorbed by neutral bus arrester. There is no direct correlation between them, but they are directly related to the short-circuit current amplitude.

C. NEUTRAL BUS OVERVOLTAGE IN VSC CONVERTER STATION

Consistent with the neutral bus overvoltage in the LCC converter station, the one in the VSC converter station would increase when a short-circuit failure occurred at the top of the converter valve (Fig. 12). For the hybrid HVDC project in this study, the five measures in Tab. 3 primarily isolated the VSC converter station from the DC system. The neutral bus of the VSC converter station as the inverter side was constantly grounded by the ground pole line, and the overvoltage amplitude was relatively low. Thus, the effect on neutral bus overvoltage in the VSC station was similar. For the converter bottom voltage, however, Case 3 differed from the other four cases in the Tab. 3.

Converter bottom overvoltage waveforms under case 3 and 1 are presented in the Fig. 19, and the amplitude calculation results are listed in the Tab. 9:

As indicated from the calculations in Fig. 19 and Tab. 9, the blocking diode in Case 3 installed on the bottom of converter would cause the bottom of the VSC converter station to withstand a higher level of overvoltage in case of failure. According to the overvoltage level and energy of the neutral bus in Case 1 and 3 shown in the Fig. 19, the overvoltage level of the neutral bus in the VSC converter station at this time was significantly higher than the scheme of the diode installation on the polar line. The mentioned result could be explained as the diode located at the bottom of the valve could not be reversed, and the pressure difference at both ends was 371kV, which was the output voltage of the VSC converter in the rectifier bridge state.

Under the condition of type III fault, although the protection delay of DC circuit breaker has little influence on the overvoltage of neutral bus in VSC converter station, it has great influence on the overvoltage energy absorbed by the arrester branch in the circuit breaker. As shown in

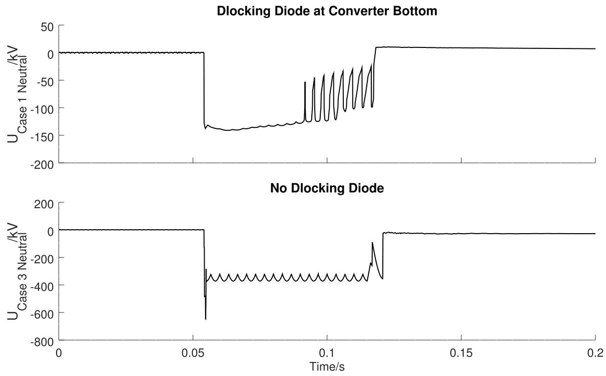

FIGURE 19. Comparison of bottom overvoltage waveforms between Case1 and Case 3 valves in the VSC converter station.

TABLE 9. Calculation results for converter bottom overvoltage amplitudes of Case1 and Case 3 in the VSC stations.

Overvoltage Case 1	Overvoltage Case 3
141kV	371kV

the calculation results Tab. 10, the shorter the protection delay of the circuit breaker, the greater the energy absorbed by the branch arrester. When the protection delay reaches 60ms, the overvoltage energy absorbed by the arrester is very small. The reason for this phenomenon is that under this fault condition, the short-circuit current cut off by the circuit breaker is provided by the LCC converter, and the low-voltage current limiting control equipped with the LCC converter will automatically reduce the short-circuit current rapidly. When the current drops to a lower level, the overvoltage energy caused by breaking the DC circuit breaker though the arrester branch will be low.

1) DISCUSSION ON THE INSTALLATION POSITION OF THE BLOCKING DIODE

The blocking diode in Case 3 mounted at the bottom of the VSC converter valve exhibited an advantage, i.e., it could effectively avoid excessive short-circuit current in the VSC converter due to the one-way pass characteristic of the diode, in the presence of the grounding failure on the valve top of the VSC converter. The diode was reversely subject to the DC output voltage of the VSC converter.

In this hybrid HVDC transmission project, if no blocking diode was installed at the bottom of the VSC converter valve, the short-circuit current could reach 8-10 kA before it was cut off by AC breaker in the presence of the grounding failure on the top of the VSC converter valve. This short-circuit current was not very large as compared with its rated current of 3,000 A. The reason for this was that the bridge arm reactor in the middle of the VSC converter and the Flat-wave reactor installed on the neutral bus could limit the increase speed of short-circuit current, so its DC short-circuit current could be relatively low.

TABLE 10. Energy absorbed by arresters branch under Case 4 and 5.

	Interruption Current /kA	Arrester branch Energy /MJ
Case 4 no delay	4.27	23.8
Case 5 with 20ms delay	1.59	2.55
Case 5 with 60ms delay	0.4	0.28

In brief, blocking diode installation on neutral bus could effectively suppress short-circuit current of the VSC converter, whereas it could also increase the insulation level of valve bottom and the requirement of energy absorption capacity of arrester at the matching position. As opposed to the mentioned, short-circuit current of the VSC converter effectively decreased the rising speed due to the existence of the bridge arm reactor and the smoothing reactor on neutral bus. As a result, the short-circuit current was insignificantly larger than the rated current, and the advantages of this scheme were not more prominent. Thus, if blocking diodes were used for the type of hybrid HVDC transmission system in this study, they could be recommended to be installed at the polar entrance in terms of the overall economy of the DC system and the safety and stability requirements of the equipment. However, for cases where the short-circuit current of the converter was significantly much greater than the rated current, it would be more appropriate to install the blocking diode at the converter bottom, in which the main role was to limit the short-circuit current of the converter.

2) DISCUSSION ON APPLICATION OF DC CIRCUIT BREAKER

DC circuit breaker is used to break the fault current in DC system and isolate the outage or fault converter station from the normal operation system. When DC circuit breaker interrupts a large DC short current, it bears oscillation overvoltage caused by interruption, and its internal arrester branch also absorbs large energy. Generally, the larger the DC current is, the more overvoltage energy the arrester absorbs. Normally, the shorter the action delay of the circuit breaker, the smaller the short-circuit current to be broken, and the smaller the overvoltage impact on the corresponding DC circuit breaker.

However, in the type III overvoltage study of hybrid HVDC system in this manuscript, the longer the action delay of DC circuit breaker is, the smaller the overvoltage impact is. The reason is that LCC converter can also reduce its output DC short-circuit fault current rapidly through protection action. This protection function of LCC makes it possible to reduce the fault current without using DC circuit breaker in 2-terminals LCC HVDC transmission system, and the DC converters at both ends need to be shut down.

To sum up, for this type III fault condition in the hybrid HVDC system in this manuscript, it is not necessary to use the DC circuit breaker to cut off the fault current directly, but use the protection action of LCC converter to cut off the fault, so as to avoid the breaking impulse on the DC circuit breaker. However, in multi terminal HVDC transmission system, DC circuit breaker can avoid all converter stations being shut down due to faults, and can achieve the purpose

TABLE 11. **Comparison table of overvoltage simulation results.**

	Type I overvoltage	TypeII overvoltage	Type III overvoltage
Case 1	Overvoltage with large energy	Overvoltage with large energy. With neutral overvoltage in VSC station	Same as normal VSC HVDC
Case 2	Same as normal LCC HVDC	Same as normal LCC HVDC	Same as normal VSC HVDC
Case 3	Same as normal LCC HVDC	Same as normal LCC HVDC	Large overvoltage on bottom of converter
Case 4	Same as normal LCC HVDC	Same as normal LCC HVDC	Same as normal VSC HVDC
Case 5	Overvoltage with large energy, and Energy is related to time delay	Overvoltage with large energy, and Energy is related to time delay.With neutral overvoltage in VSC station	Same as normal VSC HVDC
Case 5 with ground switch on neutral bus	Same as Case 5	Same as normal LCC HVDC	Neutral overvoltage within a short time

of isolating only the faulty converter stations. But it is not suitable to use LCC converter protection to remove faults in this case.

D. SUMMARY OF OVERVOLTAGE CALCULATION

Based on the mentioned simulation results, the following Table 11 compares the overvoltage situations.

As indicated from the comparison of the calculation results in Table 11, in a hybrid HVDC transmission system with half-bridge MMC sub-module, adding an one-way electric conduction device at its outbound port (e.g., a thyristor blocking diode) or an on-off circuit device (e.g., a DC breaker) could effectively reduce the severity of DC system overvoltage.

Single-pass blocking diodes could be installed at the polar inlet of the VSC converter station or at the converter bottom of the neutral bus. However, when diodes were installed at the converter bottom, the overvoltage at bottom in the VSC converter station would be severe.

With the scheme of installing DC circuit breaker at the entry of VSC station DC bus, when DC circuit breaker operated immediately after fault, the system overvoltage would be consistent with that of the blocking diode. The delayed action of DC circuit breaker would affect the overvoltage of Type I and Type II on the LCC side, which could be manifested by increasing the duration of the mentioned two types of overvoltages and their energy.

The protection measures of the grounding neutral bus directly after the outage of the converter station could effectively improve the neutral bus overvoltage in the DC system.

VI. CONCLUSION

The protection measures of the grounding neutral bus directly after the outage of the converter station could effectively improve the neutral bus overvoltage in the DC system.

1) The blocking diode with one-way on-current refers to a comparative and economical scheme, which is capable of cutting off the connection between VSC converter station and other converter station quickly after starting and stopping operation of the VSC converter station protection, thereby reducing the effect of VSC station on the external and incoming power. However, the one-way current conductivity above the blocking diode can only be applied to DC systems with the fixed power transmission direction. Besides blocking diodes from isolating VSC converter stations, DC circuit breakers are not limited by the direction of power transmission at the converter stations, and they can be employed in any type of the DC transmission system. However, protection delay parameters should be set, and the cost of circuit breaker equipment is high. Specific to LCC-VSC two-end hybrid HVDC transmission systems that can only transmit power in one direction, it is recommended to install blocking diodes at the polar entry of the VSC converter station. DC breakers more significantly apply to converter stations that require bidirectional transmission of power in multi-terminal DC systems.
2) Blocking diodes are more suitable at the DC line entry of the VSC converter station than at the bottom. The diode installed at the converter bottom aims to prevent excessive short-circuit current from occurring in the converter, whereas it would make the location withstand high amplitude overvoltage. Higher requirements are proposed for the insulation coordination of the equipment at this location. Accordingly, for hybrid HVDC systems with the not prominent short-circuit current of the converter, the installation at the DC line entry is prioritized.
3) To effectively limit the energy output of the VSC converter station, DC circuit breakers should be disconnected from the protection of the VSC converter station synchronously. In the presence of a certain delay, it will still aggravate the severity of switching overvoltages in the hybrid HVDC system.
4) If the DC circuit breaker can operate near the zero crossing point of breaking current, the impulse of breaking on the circuit breaker will be greatly reduced. For the DC transmission system with two ends, if there is LCC converter in it, the DC circuit breaker could not turn off the fault current which is provided by LCC converter immediately. It can wait for the protection of LCC converter to quickly reduce the fault current to a lower level, and then turn off the current to reduce the impulse on the DC circuit breaker.

5) In the presence of a short-circuit fault in a DC transmission system, the flow direction of the residual current formed by the energy stored in the distributed inductance of the circuit after the switching off of the two sides of the line (e.g., the metal circuit and the ground pole line) should be noticed. This residual energy will cause the neutral bus voltage of the converter station to rise and then release energy via the neutral bus arrester, and subsequently it will increase the severity of neutral bus overvoltage.
6) Since the AC/DC system is overall disconnected from the system after the converter is completely shut down, the neutral bus can be directly connected to the ground in the station to rapidly eliminate the residual energy in the distributed inductance of the metal loops and ground pole leads connected to the neutral bus, as well as to reduce the severity of the neutral bus overvoltage.

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