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Research on influencing factors of emergency power support for voltage source converter-based multi-terminal high-voltage direct current transmission system

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Abstract: Voltage source converter-based multi-terminal high-voltage direct current (VSC-MTDC) transmission system can realize a multi-point power supply, multi-drop power receiving, and mutual coordination between the converter stations to ensure the reliability of the transmission. Based on the PSCAD/EMTDC platform, a five-terminal DC transmission system model is established. According to the fast power regulation capability and overload capacity of the VSC-MTDC power transmission system, an analysis of additional emergency power support for a transmission system under large disturbance conditions was carried out. A new control strategy for emergency power support that introduces its basic principle is proposed in this paper. It uses the short-term overload capability of the DC system. By changing the power reserve of the converter station and the electrical distance between the converter stations, the influence of the power reserve and the electrical distance on the emergency power supply guarantee is analyzed the stability of the system is improved, thereby improving the sudden change of power caused by voltage fluctuations, and the feasibility of the control module is verified by PSCAD simulation. The simulation results show that when the system power supply suddenly changes, the converter stations at a short distance and large power reserve has a better effect on emergency power supply protection. A comparative study of the active power support of a single converter station and multiple converter stations is carried out. The research results show that the use of emergency power support in the DC transmission system has a good effect on maintaining the stability of the inter-connection system and the reliability of the power supply.

Key words: coordinated control, emergency DC power support, influencing factor, VSC-MTDC transmission

1. Introduction

With the introduction of the energy internet concept and the steady advancement of new energy grids, great progress has been made in high-voltage direct-current (HVDC) transmission technology based on voltage source converters. Comparing with the line-commutated converter-based high voltage direct-current (LCC-HVDC) transmission, the control method of VSC-HVDC independent of the AC grid is relatively simple and reliable, and solves many technical bottlenecks inherent in traditional DC transmission technology. It has no commutation failure problems, and can control active power and reactive power independently. As a static synchronous compensator (STATCOM), it can dynamically compensate the reactive power of the AC bus, stabilize the AC side voltage of the system, and can also supply power to the passive network, form a multi-terminal network, etc. Compared to the LCC-HVDC gird, the VSC-HVDC grid is more likely to form a multi-machine and multi-area interconnected power grid, which is used for wind farm grid connection, AC system asynchronous grid connection, island power supply, and distributed power grid connection. With the continuous improvement of power demands, the Chinese power grid gradually develops in the direction of long-distance, large-capacity, multi-energy complementarity coordination, while voltage source converter based multi-terminal high-voltage direct current (VSC-MTDC) transmission provides a realistic basis for this demand. In Reference [1], a four-terminal MTDC system is taken as an example to illustrate the vector control mode of the VSC-HVDC system, that is, the current d-q decoupling control mode. Due to the decoupling effect, the current loop can control the active power and the reactive power separately. In Research [2], the author conducts experiments according to the size of the disturbance power, considers the factors that affect the support effect of the converter station, and formulates an emergency DC power supply (EDCPS) scheme under different power disturbances to achieve power compensation in the disturbance area.

The converters of VSC-MTDC are composed of power electronic switching devices, which can withstand large overload. Its constant power control can quickly adjust the power to the preset value through the power adjustment device. By utilizing the fast power regulation and the overload capability of VSC-HVDC, the part of the missing power of AC system can be supported by the DC system through an EDCPS, which can maintain the transient stability of the AC-DC interconnect system when the AC system is subjected to large disturbance or malfunction. However, with the development of HVDC transmission systems to large-capacity, long-distance, multi-terminal flexible systems, it is particularly essential to consider the property of the EDCPS at the disturbance situation. In Reference [3] the mechanism of the EDCPS is described and verified by the simulation showing that the emergency DC power support effect of the Central China Power Grid in the event of a bipolar blocking fault is better than the usual cutting machine load shedding influence. It indicates the significance of the EDCPS under the large capacity and complex power grid to solve the problem of preferential support after DC blocking faults.

In Reference [4], the authors proposed a method based on the selection of trajectory sensitivity that determined the optimal power-boosting strategy by improving the sensitivity of fault-free DC-line power to improving stability. In Reference [5], a strategy of dynamic regional deviation and VSC-HVDC emergency power support coordinated control for asynchronous interconnection of the VSC-HVDC system is proposed to determine the fault area power demand and supportable capacity, and optimize the emergency power support effect. There are also literatures that directly explore the influencing factors of EDCPS. In Reference [6], a dynamic DC power support strategy is put forward, and the DC support sequence table is promptly updated by the changing dominant generators. In Reference [7], the DC quasi-steady-state model is utilized to analyze the curves of DC voltage and DC current in various modes. The simulation results show that the AC voltage fluctuations of the converter station have an impact on the EDCPS. In Reference [8], the further analyzed the impact of ECDPS on transient stability in terms of improving system frequency.

From the current research reports, there are few studies on the influencing factors of the EDCPS in the VSC-MTDC transmission system. This paper studies the influencing factors of VSC-MTDC emergency power coordinated optimal control, aiming at providing a reference for that. For the above problems, this paper establishes a five-terminal MTDC transmission model. Two factors that may affect the support effect of the converter station are proposed: the power reserve and electrical distance of the converter station. Considering the recovery effect of emergency power support on active power fluctuation and DC voltage under these influencing factors, it shows that the system needs emergency power support. When the converter station has a larger active power reserve, is prevented from being fully loaded, and if such a converter station is situated within a short distance, it is selected for priority support to avoid large-scale transfer of power flow. The main contributions of this paper are changing the standby power and transmission distance of the converter station, the comparison of single emergency support and coordinated emergency support. The influence of these influencing factors on the EDCPS is observed. Finally, the simulation results are verified by off-line digital simulation technology through the PSCAD/EMTDC simulation platform.

The structure of this paper is as follows. In Section 2, the control method of the five-terminal DC system and the inner loop current control are introduced. In Section 3, the adjustment mechanism of emergency power supply influencing factors of emergency power support and additional emergency support are introduced in detail. In order to prove the dynamic influence of emergency power support on the active power of the power system, the simulation verification is carried out in Section 4. Finally, some conclusions are drawn in Section 5.

2. VSC-MTDC transmission system

The VSC-MTDC transmission system refers to a transmission system with three or more converter stations. According to the different operating conditions and design requirements, the VSC-MTDC transmission system has mainly three connection modes: series connection, parallel connection and hybrid connection. The parallel VSC-MTDC system has the characteristics of strong expansibility, high operation flexibility, and low line loss, which has been widely accepted in most projects, which can realize multi-power supply and multi-drop power reception. With the research and the expand of modern power electronics technology in recent years, VSC-HVDC technology has made great progress, mainly reflected in the structure and control mode of the converter station. Converter stations mostly used two-level or three-level topologies at early stages. To avoid defects of these two topologies, R. Marquart and A. Lesnicar of Germany proposed a modular multilevel converter topology.

This paper focuses on the analysis of the influence factors of the EDCPS on VSC-MTDC without considering the influence of different topologies of converter stations. Due to the simple topology of the two-level converter, the small footprint and the small number of capacitors, the converter valve has the same capacity, which is convenient for modular design, manufacture and maintenance, and has a wide voltage range and is easy to control. Therefore, a simple two-level topology composed of a VSC-MTDC system will be illustrated in this paper [9].

Firstly, we establish a five-terminal MTDC transmission model, as shown in Fig. 1, where icons S1, S2, S3, S4 and S5 represent the generators, and converter stations from VSC1 to VSC5 are located at five different locations. $L_1 \sim L_5$ are the DC transmission line, the distance between VSC1~VSC5 and the DC bus is 25 km, and the line impedance is 0.25 ohm. VSC1 and VSC2 are the transmitting converter stations, and VSC3, VSC4 and VSC5 are the three receiving power stations. In a steady state, the main station VSC1 of the system adopts the DC voltage active power drop control strategy, and the VSC-MTDC system can transmit power bidirectionally through the DC transmission line. Normally, active power is sent from the transmitter to the receiver.

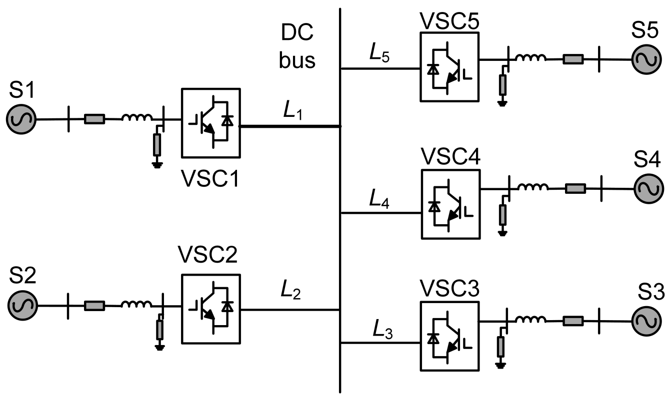


Fig. 1. Five-terminal VSC-HVDC transmission

2.1. VSC-HVDC structure and control principle

A schematic diagram of a single-ended VSC is shown in Fig. 2. There, R is the equivalent resistance of the converter and the commutating reactance, L_s is the inductance of the commutating reactor, U_c is the voltage phasor of the inverter output, U_s is the AC bus voltage, U_{dc} is the DC voltage, R_v stands for the equivalent load, P_s and Q_s represent the active power and reactive power of the common contact on the AC side, P_c and Q_c represent the active and reactive power absorbed by the inverter from the AC system and I_{dc} is the DC line current. The converter station, transformer's losses and harmonics are usually ignored is research, and the d-q decoupling control method is adopted [10].

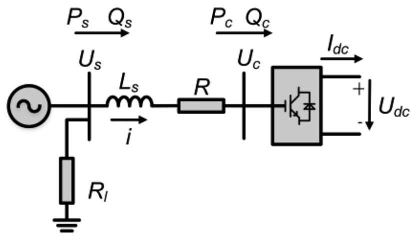


Fig. 2. Single-terminal VSC schematic

Let's convert the *abc* three-phase stationary coordinate system into the d-q rotating coordinate system. Its mathematical model can be expressed as:

$$\begin{cases} L\dfrac{\mathrm{d}i_d}{\mathrm{d}t} + Ri_d = u_{sd} - u_{cd} - \omega Li_q \\ L\dfrac{\mathrm{d}i_q}{\mathrm{d}t} + Ri_q = u_{sq} - u_{cq} - \omega Li_d \end{cases}, \tag{1}$$

where u_{sd} and u_{sq} represent the components of the AC voltage u_s of the d-axis and the q-axis. Here orienting u_s to the d-axis (that is, the d-axis coincides with the a-axis), it was inferred that $u_{sd} = u_s$, $u_{sq} = 0$. P_S and Q_S are, respectively, regarded as active power and reactive power injected into the converter station by the AC grid, and ω is considered to be the synchronously rotational angular velocity of the voltage vector. When the d-axis is positioned on the bus voltage vector of the AC system, ignoring the converter losses, the active power P_S and reactive power Q_S in the d-q synchronous rotating coordinate system can be expressed as:

$$\begin{cases} P_s = \dfrac{3}{2}(u_{sd}i_d + u_{sq}i_q) = \dfrac{3}{2}u_{sd}i_d \\ Q_s = \dfrac{3}{2}(u_{sd}i_q + u_{sq}i_d) = \dfrac{3}{2}u_{sd}i_q \end{cases}, \tag{2}$$

$$\begin{cases} u_d = u_{sd} - u_{cd} - \omega Li_q \\ u_q = u_{sq} - u_{cq} - \omega Li_d \end{cases}. \tag{3}$$

According to Formula (2), when the DC voltage of the system is constant, the magnitude of active power and reactive power is related to the d-axis current i_d and the q-axis current i_q, that is, the system current is controlled by performing power control. As can be seen from Eq. (3), i_d and i_q are coupled to each other. That is, the voltage coupling compensation and feedforward compensation are introduced to compensate the coupling terms ωLi_d and ωLi_q in Eq. (3). Let's introduce the variables u_d and u_q. That is, two independent current control loops are obtained. According to the above formula, the closed-loop decoupling controller is designed, and the proportional integral link is added.

This paper adopts a combination of the trial-and-error method and dichotomy method to determine PI parameters by comparing input and output waveforms through a large number of simulations. In Fig. 3, the outer loop controls power or DC voltage and the inner loop controls current.

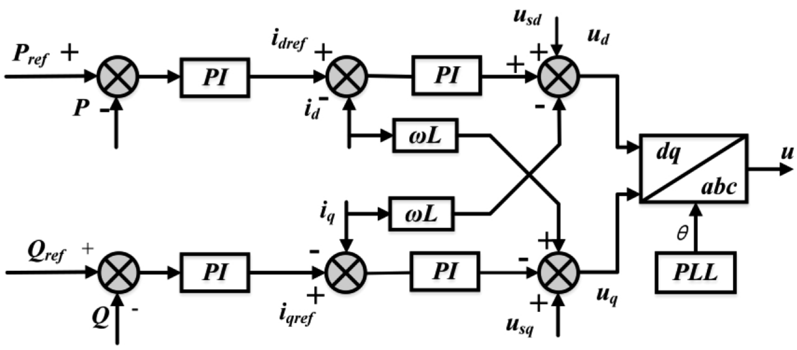


Fig. 3. d-q decoupling controller

In Fig. 3, P_{ref} and Q_{ref} are the reference values of active power and reactive power in the steady state of the system, respectively. $i_{d\,ref}$ and $i_{q\,ref}$ indicate the reference values of the d-axis current and q-axis current, u is the output three-phase voltage.

3. Emergency DC power support control

When a large disturbance occurs in the transmission line, if the method of cutting off the generator or cutting off the line is adopted, the circuits participating in the power transmission in the parallel system will be reduced, which may cause the secondary fluctuation of the grid voltage and reduce the transmission capacity of the system. At such a situation, the output power of the generator will increase, and the rotor will accelerate, resulting in unstable frequency. In this case, it is necessary to perform an EDCPS on the system, increasing the corresponding power in case of interference. [11].

3.1. Emergency DC power support impact mechanism

The DC transmission line has a strong overload capacity, and the additional emergency power control can quickly adjust the transmission power value of the DC transmission line, maintain the rationality of the system parameters, and ensure the smooth operation of the system. Additional emergency power support in the case of large disturbances can be analyzed by the extended equal area criterion (EEAC) [12].

The multi-machine power system for large disturbance is divided into two categories according to the degree of disturbance. The two feeders of the VSC1 and VSC2 five-terminal systems are divided into two groups, one is called the sending group, and the other the receiver group. Therefore, a five-terminal system is equivalent to a two-machine infinite system. Assuming that the receiving end system is disturbed, insufficient power will cause the rotor speed of the receiving end motor to decrease and the frequency to decrease. Disturbances alter the generator output, resulting in excess power and increased frequency in the system. The power angle deviation and frequency deviation are generated between the transmitter and the receiver, and they increase with the increase of the instability time. The rotor motion equation of the equivalent generator can be shown as

$$H\frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} = P_T - P_e\,, \tag{4}$$

where H and D represent the inertia coefficient and damping coefficient of the equivalent generator. When there is a large disturbance, the influence of the damping coefficient D is ignored. We can get the following formula:

$$H\frac{d^2\delta}{dt^2} + \frac{EU_r}{x}\sin\delta = P_T - P_d\,, \tag{5}$$

where $P_T - P_d$ is regarded as the "electromagnetic power" of the transmitting, and by changing the DC power P_d to adjust the output power of the generator, the power support problem can be analyzed by the equal area method. When the DC line is disturbed, the power required by the system should be urgently increased to maintain the DC voltage stability of the system [13].

3.2. Emergency DC power support principle

In the VSC-HVDC control system, the outer-loop is usually controlled by power, the inner-loop is controlled by current, and the final current is applied to the inner-loop for modulation. The current-loop adopts the emergency power signal, and the inner-loop controls the inverter. The power compensation signal can also be directly added to the power outer-loop to make up for the lack of power. The emergency power control principle is shown in Fig. 4.

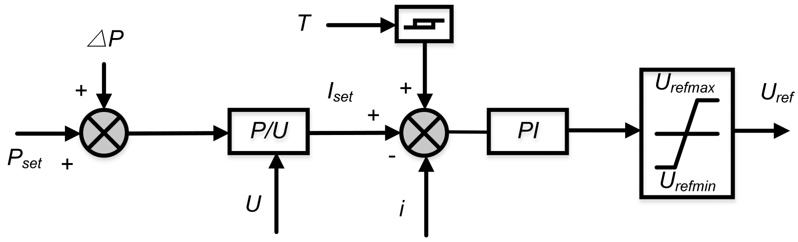


Fig. 4. Emergency power control principle

In Fig. 4, P_{set} is the setting value of the steady-state active power of the system, and ΔP is the power adjustment value. The input signal T represents the logical trigger signal. The ΔP and P_{set} are added together by the voltage to obtain the current reference value I_{set}. In addition, in order to suppress the active fluctuation of the DC transmission line, a current modulation signal is added to the current. The controller is prevented from malfunctioning when active fluctuations are present, and a limiter is introduced to filter out unnecessary harmonic data. In this PI controller, P takes 0.2, I takes 0.5.

3.3. Emergency DC power support impact factors

The power reserve of the converter station and the electrical distance between stations are used to measure the system's EDCPS [14].

a) Power reserves impact

Additional EDCPS control is introduced at the converter station outer-loop, with the converter station power reserve. Its control structure is shown in the Fig. 5.

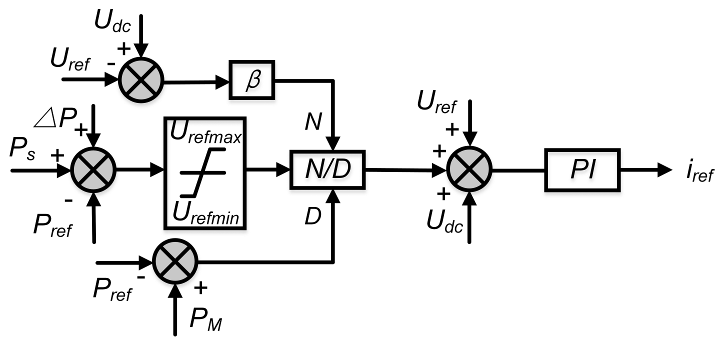


Fig. 5. Consider emergency power control under commutation station power reserve

In Fig. 5, P_M is the rated capacity of the converter station, P_{ref} is the active power command value, and ΔP is the power support value when a large disturbance occurs. The power reserve of the converter station is changed by changing the value P_M [15].

b) Electrical distance

In the power system network calculation, the power plant and the substation are treated as one node, and the impedance of the line and reactor connecting nodes is called the contact impedance. In theory, the electrical distance between two nodes can be represented by the corresponding elements of the node impedance matrix. However, the node impedance matrix of the actual power system is very complicated, and the solution is difficult and cumbersome [16]. Since the line contact impedances of the five converter stations used in this paper are equal, so the distance from the output node of the DC line to the tie line is regarded as the electrical distance discussed in this research. At the same time, considering the fast regulation characteristics of the VSC-HVDC system, DC power disturbance is considered as the power step of the converter station.

4. Simulation analysis

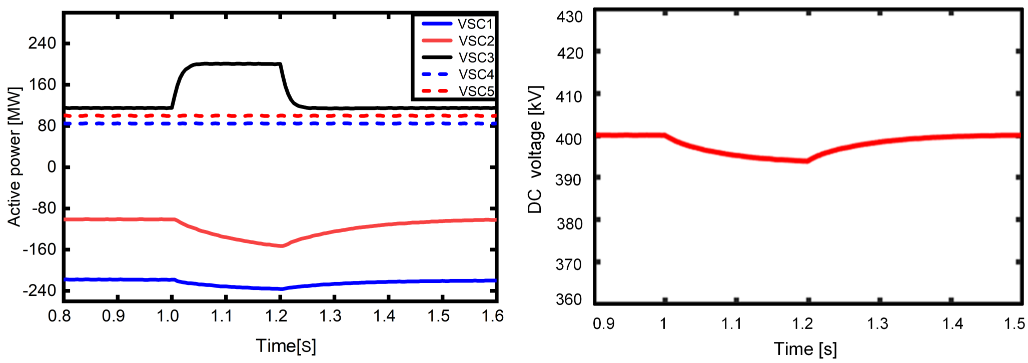
The five-terminal MTDC transmission system model is established in the PSCAD/EMTDC simulation platform [17–19]. The structure is shown in Fig. 1. The installed capacity of five of the converter stations is shown in Table 1.

Table 1. Converter station capacity and initial power

VSC number	VSC1	VSC2	VSC3	VSC4	VSC5
Rated capacity (MW)	250	200	200	150	150
Rated power (MW)	–220	–100	115	85	100

The rated positive and negative voltage $U_{dc\text{-}ref} = 400$ kV, the capacitance value is 1 000 μF, the AC voltage is 220 kV, β is 0.5, that is, $U_{dc\text{-}h} = 420$ kV, $U_{dc\text{-}l} = 380$ kV. In addition, the voltage used in this paper is the DC bus voltage. The power command values of the converter stations 1–5 are shown in Table 1.

Power disturbance setting: at 1 s, the power disturbance of VSC3 is setting, and power 3 increase from 115 MW to 200 MW in 0.2 s. During the disturbance, power changes and DC voltage changes of each converter station during the disturbance period are shown in Fig. 6. When the power of VSC3 drops, the system generates an unbalanced power of 85 MW, which is shared by VSC1 and VSC2 to compensate for the power fluctuation of the system. The specific power is determined by the droop coefficient of droop control. According to the power flow direction and control mode of the converter station, it can be seen that the change of VSC3 directly leads to the change of power of VSC1 and VSC2. At this time, the power change reduces the DC voltage of the common bus from 399.8 kV to 392.6 kV.

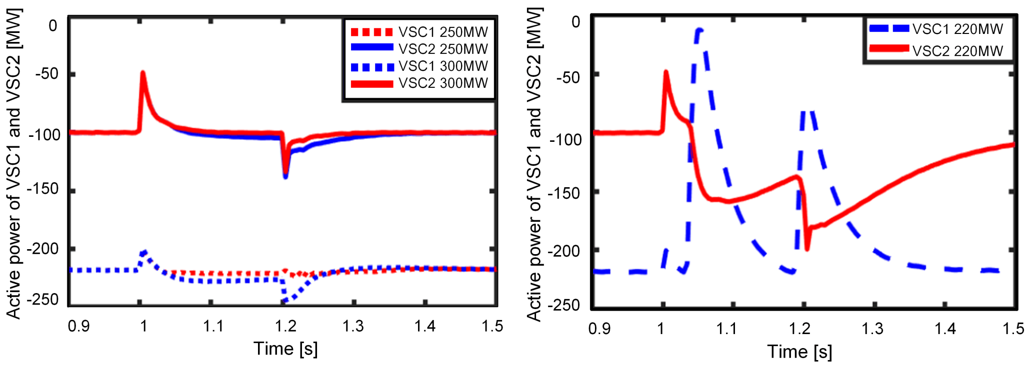


(a) (b)

Fig. 6. Simulation results of system active power command change power: (a) active power; (b) DC voltage

The VSC-MTDC system is an interconnected system. When one converter station is disturbed, it will cause active changes of other converter stations. According to the power flow of the VSC-MTDC system, VSC1 and VSC2 are the transmitting systems, VSC3, VSC4 and VSC5 are the receiving ends. As can be seen from Fig. 6, when VSC3 is disturbed, VSC1 and VSC2 occur with different degrees of power variation. Therefore, VSC1 and VSC2 can be compensated for the power at the time of the disturbance by the power active supports.

Case 1: When power 3 drops, power 1 drops by 20 MW, and power 2 drops by 60 MW. VSC1 and VSC2 respectively, add the emergency power support signal at 1 s for 0.2 s. Since VSC1 is the dominant station, the power reserve of VSC1 is used as the influencing factor, to change the capacity of the converter station. Figure 7(a) shows the power changes of VSC1 and VSC2 when the capacity of VSC1 is 250 MW and 300 MW. Figure 7(b) shows the converter station power variation when VSC1 capacity is 220 MW. As can be seen from Fig. 7, the change in the power reserve of the converter station has little effect on the power variation during emergency power support, but when the converter station has no power reserve, the emergency power support effect is not ideal.



(a) (b)

Fig. 7. Simulation results under different converter station capacity support:
(a) 250 MW and 300 MW; (b) 220 MW

Figure 8 shows the variation of DC voltage corresponding to different converter station margins. It can be seen that when the capacity of the converter station is 220 MW, the dc voltage of the system decreases from 399.7 kV to 391.8 kV in 1.2 s. At this time, the converter station has sufficient margin and the system DC voltage tends to be stable.

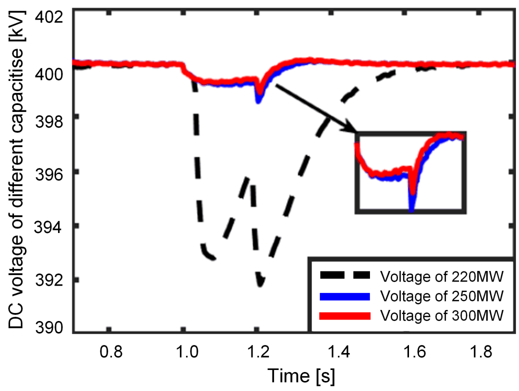
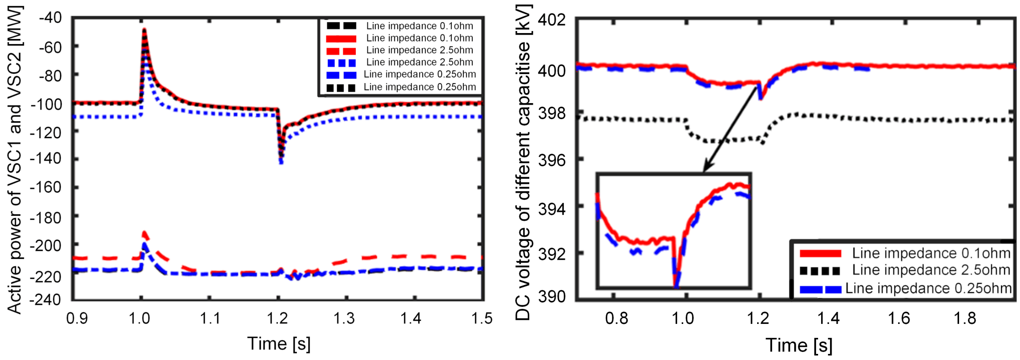


Fig. 8. DC voltage under different capacities

Case 2: An analysis of the impact of power reserve on emergency power support at the converter station when disturbance occurs. Based on Case 1, the transmission distances of the VSC1 and VSC2 converter stations are used as the influencing factors to study the influence on emergency power support. The line impedance supporting the converter station was respectively, 0.1 ohm, 0.25 ohm and 2.5 ohm to simulate the influence of emergency power support at various distances. The power change of each converter station is shown in Fig. 9(a). The DC line voltage change is shown in Fig. 9(b).



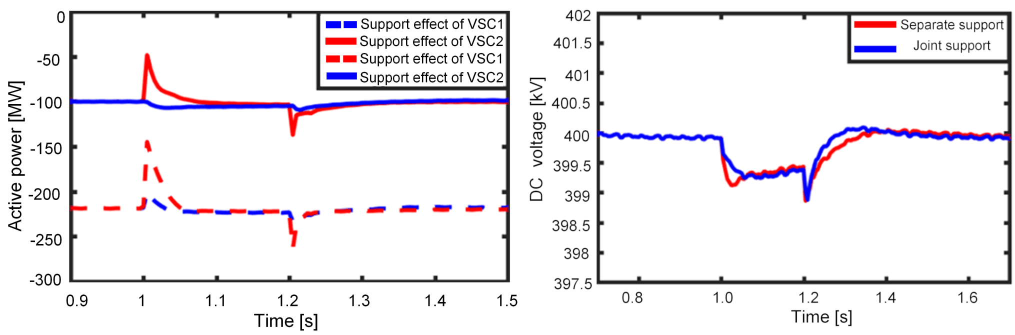
(a) (b)

Fig. 9. Simulation results under different line impedance support: (a) active power; (b) DC voltage

As can be seen from above Fig. 9(a), the closer the converter station providing emergency power support is, the better the support effect, and as the distance between stations increases, the voltage of the DC line drops. As shown in Fig. 9(b), the DC voltage drops from 399.7 kV to 397 kV.

Case 3: Comparative analysis of individual emergency power support and common emergency power support. The support strategy in the sending group is divided into two cases. When the system suffers from large disturbances: primary station VSC1 alone bears the system power shortage; VSC1 and VSC2 share the power support. The simulation results are shown as follows:

As can be seen from Fig. 10(a), when VSC1 is used alone, the power fluctuation of VSC2 is small. In addition, the DC voltages of the two support modes in Fig. 10(b) are not significantly different, those voltages are 399.34 kV and 399.40 kV. However, when VSC1 is separately supported, the DC current impact is large, as shown in Fig. 11. The figure presents a case where the inrush current of one converter station changes to a limit, and the other converter station still has



(a) (b)

Fig. 10. Simulated results under different distance support modes: (a) active power; (b) DC voltage

a margin. Since both VSC1 and VSC2 have sufficient power reserve at this time, the two stations should share the power support.

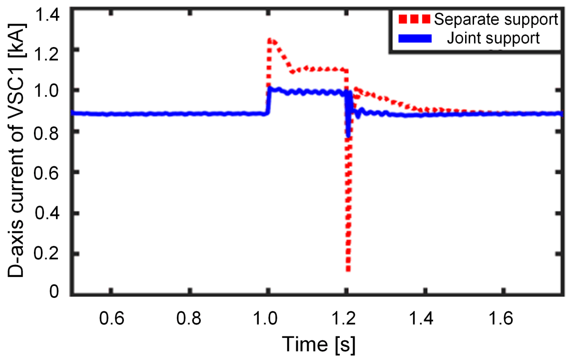


Fig. 11. *d*-axis current variation in two modes of support

5. Conclusion

This paper studies the power support factors of the VSC-MTDC transmission system under large disturbance conditions. Taking the five-terminal MTDC power transmission system as an example, the power of the converter station is converted by using the overload capability and fast power regulation capability of the VSC-HVDC power transmission system. Factors such as margin and inter-station distance are used as objects. The PSCAD/EMTDC simulation platform compares the changes of power, voltage and current during large disturbances. The following conclusions can be drawn:

a) The system is under great disturbance, and the DC voltage of the receiving converter station decrease. The support effect of the converter station with power reserve is better than that of the converter station without power reserve. In addition, as the power reserve of the converter station increases, the support effect is better.
b) The system is under great disturbance, the power reserve of the converter station is fixed, and the converter station with a closer distance from the disturbance point has a better support effect. The support distance of the converter station will affect the change of the DC voltage. When the distance reaches a certain level, the DC voltage drops. This situation is unfavorable for the stable operation of the system.
c) A converter station is disturbed, the support distance is fixed, and there is an implicit difference in DC voltage between the multi-machine support effect and the single-machine support effect, but the converter station does not have enough power reserve. When participating in the support, the DC current during stand-alone support is greatly changed compared to multi-machine support, which can badly effect the system, and the inrush current may trigger other protection devices to malfunction. A multi-machine common support strategy should be adopted, and a converter station with a large power reserve should undertake more support power.

Acknowledgments

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