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Research on regional emergency DC power support strategy of VSC-MTDC transmission system

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Abstract: In the asynchronous interconnected power grid that is composed of the multi-terminal voltage-source converter high voltage direct current (VSC-MTDC) system, the control methods of each converter station and the frequency of the connected AC system are not the same. When a fault occurs in any place of the asynchronous interconnected system, it will cause the system to have power shortage or surplus, affecting the safe and stable operation of the interconnected power grid. In order to solve the problem of insufficient regional active power reserve, based on the VSC-MTDC asynchronous regional interconnection system and the principle of regional sharing, the dynamic power controller under disturbance conditions is established, and the controller parameters are set to achieve the accuracy of unbalanced power in the disturbance area measuring. Then, according to the degree of the disturbance power, considering the factors that affect the support effect of the converter station, an emergency DC power support (EDCPS) scheme under different power disturbances is formulated to achieve power compensation for the disturbance area. Based on PSCAD/EMTDC software, the proposed control strategy is simulated. The result shows that the converter station closer to the disturbance area has a better support effect, and the dynamic active power controller can timely and accurately deliver to the disturbance area when the active power reserve is insufficient.

Key words: coordinated control, dynamic active power support, emergency DC power support, VSC-MTDC

1. Introduction

With the completion of a large number of high-voltage DC transmission (HVDC) projects, China's power grid has gradually formed a large-capacity, long-distance, AC-DC hybrid situation. Faults such as AC system failures and converter commutation failures (CF) limit the capability of power transmission between converter stations [1, 2]. Because the controller of the voltage-source converter high voltage direct current (VSC-HVDC) can control the active power and the reactive power separately, and there is no commutation failure, etc., it can form a multi-terminal voltage-source converter high voltage direct current (VSC-MTDC) network, connect multiple power plants and loads in different geographical locations, so as to realize the purpose of multiple power supply and multiple load receiving. For example, in 2014, the Nan'ao three-terminal VSC-HVDC transmission project in Guangdong Province was the first VSC-MTDC system to be used for wind power grid connection [3]. In 2020, the State Grid Corporation of China (SGCC) has built the Zhangbei five-terminal VSC-MTDC transmission project with the highest voltage level and the largest transmission capacity in China, which will provide green power guarantee for the 2022 Olympic Games [4, 5].

In the existing asynchronous interconnected power grid of the VSC-MTDC, the VSC-HVDC has played a role in isolating the mutual influence of the AC systems on both sides. But this also limits the capability of power support of the interconnected power grid under the fault [6,7]. When the transmission line has unbalanced power, it will cause the voltage of the transmission line and the bus frequency of the converter station instable. The problem of emergency power support from the DC grid to the AC system in the China Southern Power Grid (CSPG) is studied in [8]. The limiting factors of the emergency power support of the DC system is analyzed in detail [9]. According to the problem of the AC system fault of the modular multilevel converter high-voltage direct current (MMC-HVDC), Li G. proposes the method of PI control for decoupling active power and reactive power [10]. This method plays a role in power support when the unbalanced power appears in the MMC-HVDC. However, Li G. only considers the support problem of one converter station, and ignores the mutual support between converter stations. Based on the extended equal area (EEAC) theory, Li C. presents the strategy of support coordination between the VSC-HVDC and line-commutated converter high voltage direct current (LCC-HVDC) [11]. He presents the priority of power support under blocking faults, and proposes the calculation method of the unbalanced power. Aiming at the problem of frequency stability when power disturbance occurs in the interconnected grid, a frequency modulation signal is used in the VSC-MTDC controller so that the converter station can use the feedback of the frequency signal in the AC system to provide power support. But this method does not take into account the problem of power support when the converter station capacity reaches the maximum [12]. Based on the transmission power capacity of the non-faulted area grid and the power shortage of the faulted grid, Zhang W. presents a calculation method of the maximum supportable power of the VSC-HVDC. The method can ensure that the fault side obtains as much power as possible [13]. According to the stability margin of the important sections of the DC grid, Xu T. presents the method of priority of DC support, which optimizes the support scheme [14].

Based on the existing studies, it is found that the existing emergency DC power support (EDCPS) control strategy rarely considers the function of dynamic regional control of the AC system power controller. For the power shortage of the certain regional power grid, the dynamic regional control can accurately and timely realize the potential of other regional power grids for backup sharing. Based on the aforementioned research, a dynamic active power controller is presented in this paper in order to solve the problem of power support between regions in an asynchronous interconnected power grid. According to the electrical distance and power margin between converter stations, a power support strategy is proposed to provide a reference for the stability of an asynchronous interconnected power grid when the unbalanced power appears.

2. VSC-MTDC regional interconnection system

2.1. Physical model of VSC-MTDC

The VSC-HVDC system uses a decoupling control method in the d–q synchronous reference frame. The basic principle is to convert the three-phase current in the *abc* three-phase stationary reference frame to the current in the two-phase synchronous rotating reference frame. The inner loop controller controls the current, and the outer loop controller controls the power. In the two-terminal VSC-HVDC system, one end is usually used to control the DC voltage, and the other is to control the active power or the AC voltage [15, 16].

The VSC-MTDC is consisting of three or more VSC stations. According to the different operating conditions, the VSC-MTDC transmission system mainly has three connection structures: tandem structure, parallel structure and hybrid structure. Among them, the parallel structure has the characteristics of strong scalability, high operating flexibility, and small power loss. In the conventional VSC-MTDC system, at least one converter station is required to have the ability to control the DC voltage. The purpose is to keep the stability of the DC voltage of the VSC-MTDC [17, 18]. Other converter stations use constant power control or constant AC voltage control as required. The research object of this paper is the parallel radial five-terminal VSC-HVDC interconnection system which is shown in Fig. 1.

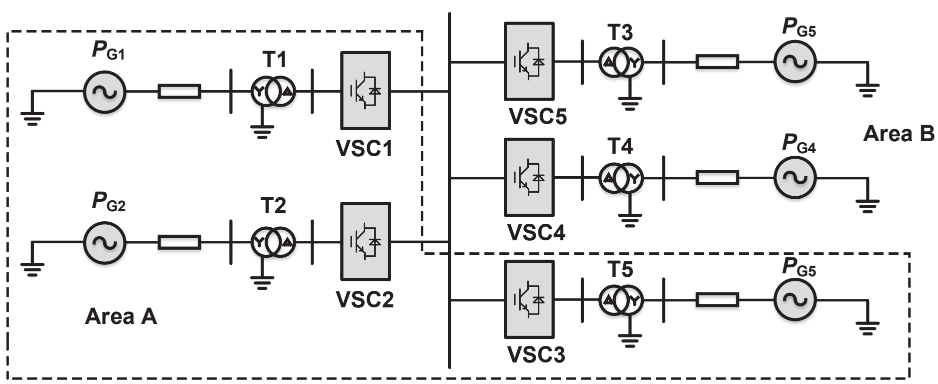


Fig. 1. Parallel radial five-terminal VSC-MTDC system

In Fig. 1, P_{G1}, P_{G2}, P_{G3}, P_{G4}, P_{G5} are AC systems, and the generator assembly capacity are P_{G1}: 480 MW, P_{G2}: 360 MW, P_{G3}: 360 MW, P_{G4}: 360 MW and P_{G5}: 360 MW. VSC1 and VSC2 are the sending-end rectifier stations. VSC3, VSC4 and VSC5 are the receiving-end inverter stations. The operating parameters of the inverter station and converter station are shown in Table 1. VSC1, VSC2 and VSC3 are the main area defined as A. VSC4 and VSC5 are defined as area B. The rated transmission voltage of the VSC-MTDC system is 400 kV. The power flow direction is the positive direction of the AC system flowing to the DC grid.

Table 1. Converter station operating parameters

VSC station number	**VSC1**	**VSC2**	**VSC3**	**VSC4**	**VSC5**
Rated capacity	250 MW	200 MW	200 MW	200 MW	200 MW
Initial power	200 MW	160 MW	85 MW	120 MW	135 MW
Rated frequency	50 Hz	50 Hz	50 Hz	60 Hz	60 Hz

2.2. Mathematical model of VSC in *d–q* reference frame

Based on the d–q decoupling control method that is used in the VSC-HVDC system, the outer loop controller generates d-axis and q-axis reference values, and the inner loop controller implements tracking control of the current reference value. The mathematical model under the synchronous rotating reference frame is:

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

where: u_{sd} is the component of the AC voltage (u_s) of the d-axis, u_{sq} is the component of the AC voltage (u_s) of the q-axis, i_q is the q-axis component of the grid current, i_d is the d-axis component. ω is considered as the synchronously rotational angular velocity of the voltage vector.

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

It can be seen from Equation (2) that P_s is controlled only by the d-axis current i_d, and Q_s is controlled only by the q-axis current i_q. By controlling the two components of the alternating current, i_d and i_q, the active power and reactive power of the system can be controlled separately.

3. EDCPS of VSC-MTDC system

3.1. VSC-MTDC emergency DC power control applications

The EDCPS of the VSC-MTDC system can be divided into active power emergency coordinated control and reactive power emergency coordinated control. The VSC-HVDC controller can control active power and reactive power separately. The emergency coordinated control of the active power is an emergency DC power support strategy that is taken in the event of a serious fault or a large disturbance in the power grid. The main application occasions: when a certain DC transmission line suffers from unbalanced power. The power command of other DC transmission lines can be increased, and determining the value of the compensation power according to the power shortage.

The DC grid has a certain overload capacity, which is divided into continuous overload and short-term overload. The continuous overload capacity of China's HVDC transmission system occurs 1.05 times to 1.1 times during normal operation, and it can be maintained for about 2 hours. The short-term overload capacity of 5 seconds occurs 1.5 times during normal operation. Overload limits can make reactors, converter transformers and other devices fully utilize the overload capacity under different working conditions. The purpose is to improve the stability of the HVDC under transient conditions. The overload capacity of the DC grid is shown in Fig. 2.

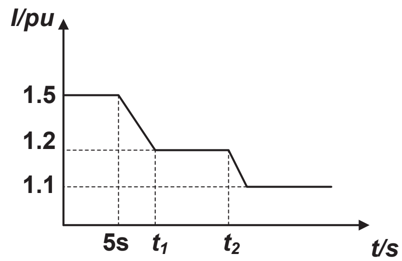


Fig. 2. VSC-HVDC overload capacity

3.2. The principle of the EDCPS controller of VSC-MTDC

The modulation method of the VSC-HVDC system is a large-scale modulation. Based on the characteristics of the fast and controllable power of the VSC-HVDC system, an open-loop active additional controller is designed. According to Equation (2), the EDCPS of active power can be transformed into the control of the inner loop current. As shown in Fig. 3, the power control and emergency power modulation signal both act on the current control.

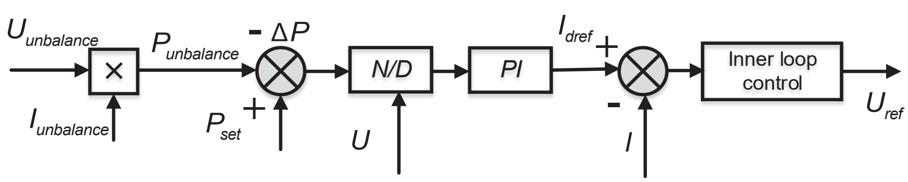


Fig. 3. VSC-MTDC emergency power control diagram

where: $U_{\text{unbalance}}$ is the unbalanced voltage, $I_{\text{unbalance}}$ is the unbalanced current, $P_{\text{unbalance}}$ is the unbalanced power, P_{set} is the power reference value, ΔP is the power support signal, U is the AC bus voltage, U_{ref} is the setting value of DC voltage.

$U_{\text{unbalance}}$ and $I_{\text{unbalance}}$ are multiplied to get $P_{\text{unbalance}}$. When the power loss is very small, the power of the AC system is approximately equal to the power of the DC grid. The difference between P_{set} and $P_{\text{unbalance}}$ is ΔP. The power support signal is divided by U to get the current signal. The current signal is adjusted by PI to become $I_{d\,\text{ref}}$. The result of the subtraction of the current setting signal and the current instantaneous value I acts on the inner loop control and then participates in the regulation. When the emergency power support is actually executed, the power support amount may not be equal to the command value due to the power support limitation.

AC system faults often cause fluctuation of the DC voltage. If the current signal is selected as the input point of auxiliary control following the HVDC modulation method, the actual transmission power will be affected by the DC voltage and cannot be constant. Therefore, the modulation signal is applied directly at the closed-loop power control.

4. Dynamic area support control

4.1. Limitations of single area emergency power support

The two areas in Fig. 1 are connected asynchronously, both frequency and control method of the two areas are different. When the unbalanced power appears in a certain area and there is a shortage of transmission power, the reserve capacity and the overload capacity of the DC grid in the area cannot meet the support needs of the area. In addition, the overload capacity of the DC grid is a continuous function of the ambient temperature and overload operating time. It can be seen from Fig. 2 that the short-term overload capacity duration of the VSC-MTDC system is only 3 s∼10 s, which may have a certain effect on the transient stability of the power angle after the fault. But for frequency recovery, the time is short. Therefore, for the emergency support of DC power, using only the 2 h overload capacity of the DC grid seems insufficient.

4.2. DC voltage-power droop control method

The DC system in area A adopts the DC voltage-power droop control method. When the VSC-MTDC suffers from unbalanced power, this method can make the line with larger power margin automatically allocate the power support tasks of each converter station in the area according to the power shortage, and keep the DC voltage at a stable level. The controller in Fig. 4 is an example, and the slope is recorded as K.

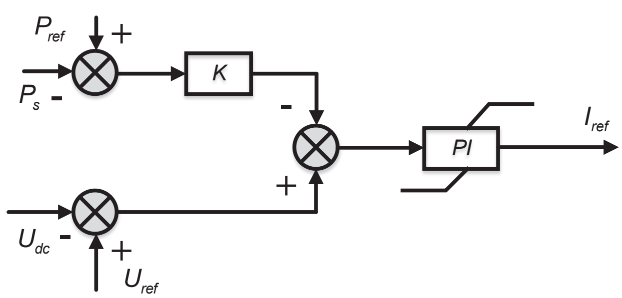


Fig. 4. Voltage-power controller

It can be seen from Fig. 4 that the calculation relationship between voltage and power is:

$$U_{\text{ref}} - U_{dc} = (P_{\text{ref}} - P_s) \times K. \tag{3}$$

Suppose there are a total of m converter stations in the area that use voltage-power droop control methods. At time t, the unbalanced power appears in the DC grid, which is recorded as

ΔP. There are n converter stations that can provide power support. For the converter station i, its stable operating point changes from (U_{dc}, P_i) to (U_{dc}^1, P_i^1). Let the power change of the converter station i is $\Delta P_i = P_i^1 - P_i$. The change of the DC voltage is:

$$\Delta U_{dc} = U_{dc}^1 - U_{dc} = \left(P_i^1 - P_i\right) \times K_i = \Delta P_i K_i\,. \tag{4}$$

Supportable power in the area can be expressed as:

$$\Delta P = \sum_{i=1}^{n} \Delta P_j = \Delta U_{dc} \times \sum_{i=1}^{n} \frac{1}{K_j} = \Delta P_i K_i \times \sum_{j=1}^{n} \frac{1}{K_j}\,. \tag{5}$$

It can be concluded that the power that the converter station should increase is:

$$\Delta P_i = \frac{\Delta U_{dc}}{K_i} = \Delta P \Big/ \left(K_i \times \sum_{i=1}^{n} 1/K_j\right). \tag{6}$$

It can be seen from Equation (6) that when the converter station adopts the DC voltage-power control method, the power bearing capacity of the DC grid is related to the slope K. The smaller the K, the larger the power value that can be undertaken.

4.3. Design of dynamic active power controller

When the converter station in the area A loses control of the power due to full load, the power support outside the area should be activated. In order to ensure that the converter station outside area A can react in real time according to the power shortage of area A, the dynamic active power controller should have the following conditions:

1) real-time monitoring of the operation of the lines in area A,
2) when the unbalanced power appears, the amount of power support is determined according to the power transmission of the DC grid and until the unbalanced power disappears.

Based on the above two points, the controller is added to the closed loop input link of the DC constant power station. The controller is shown in Fig. 5 and the internal logic signal principle is shown in Fig. 6.

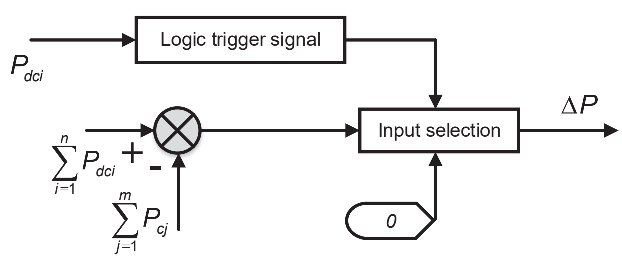


Fig. 5. Dynamic active power support controller

where: P_{dci} is the DC power transmitted by the i-th line in the area A, P_{cj} is the rated capacity of the j-th line in area A.

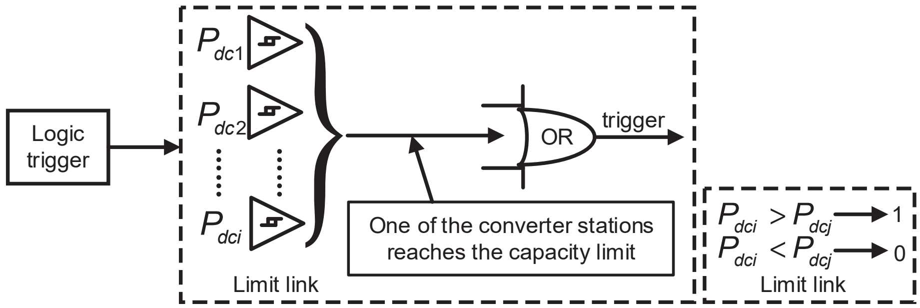


Fig. 6. Trigger signal diagram

The real-time transmission power of the DC grid is used by the controller in area A as the index of the logic trigger signal, and the transmission power of the DC line is collected by the controller in real time, and a limit link is set. When the P_{dci} reaches the power transmission limit, the converter station switches to constant power control, and the power signal triggers the controller to perform power support. The out-of-area power support amount is P_{out}, and its relationship with the inner-area transmission power is:

$$\sum_{i=1}^{m} P_{dci} - \sum_{j=1}^{m} P_{cj} = \Delta P_{\text{out}} . \tag{7}$$

When the DC power P_{dci} transmitted by the converter station in area A reaches the rated capacity of the converter station, the dynamic active power support controller on the line outside the area can respond in time and send a power boost signal to the VSC-MTDC. When the unbalanced power is over, the controller receives the power recovery command and stops supporting.

5. VSC-MTDC system emergency power support strategy

There are two key points of the EDCPS for the VSC-MTDC transmission system: One is whether the normal converter station can provide enough power,the other is how to distribute the power of the normal converter station to make the support effect more optimized. The above conditions can ensure the stability of the system after the EDCPS. Based on the above analysis, the main research ideas of this article are given below.

A five-terminal VSC-HVDC transmission system model is built in the PSCAD simulation platform and the structure is shown in Fig. 1. Area A includes VSC1, VSC2 and VSC3. All three use the control method of voltage-power droop. The rated frequency of area A is 50 Hz. Unbalanced power of the DC grid will directly affect the power transmission of the remaining DC lines. Area B and area A are interconnected asynchronously. Constant power control is used in area B. The bus frequency of area B is 60 Hz. Under the steady state condition, each end maintains power balance. When the unbalanced power of the DC line is small and it does not exceed the total support capacity of the converter station in area A, the converter stations in area A provide power support by themselves. This process should follow the priority support of the converter station which has a closer distance and larger power margin. When the unbalanced power is large, there is no more active standby capacity in area A. If the power of the DC grid in the area A is increased, the DC voltage will fluctuate greatly, which will adversely affect the stability of the VSC-MTDC system. At this time, it is necessary to call the dynamic active power capacity of the other regional converter stations to start cross-regional DC power support, and the close electrical distance and large margin system also should be chosen by out-of-area support [19, 20].

The ability of normal lines to provide DC power depends on the capacity of the converter station. The power for support cannot exceed the transmission capacity of converter stations or even be lower than the transmission capacity.

There are n areas and m lines, and the transmission capacity of the power grid in the non-fault area is defined as:

$$P_{\text{support}} \le \sum_{k=1}^{n} P_{sk}\,, \tag{8}$$

where P_{support} is the active power which can be injected in the VSC-MTDC when the unbalanced power appears. P_{sk} is the maximum support power that areas of the VSC-MTDC system provide.

$$P_{sk} = \sum_{\lambda=1}^{m} P_{\lambda} - P_{dc\_t}\,, \tag{9}$$

where P_{λ} is the rated capacity of the λ-th VSC. P_{dc_t} is the regional steady-state current before the EDCPS.

Restrictions:

The amount of received power support in the area with fault is equal to the power shortage:

$$P_{\text{unbalance}} = P_{re}\,. \tag{10}$$

The active power and reactive power of all AC systems and DC grids of the asynchronous interconnected power grid are balanced:

$$\begin{cases} \Delta P_{ki} = 0 \\ \Delta P_{dk\lambda} = 0 \\ \Delta Q_{k\lambda} = 0 \end{cases}, \tag{11}$$

where: ΔP_{ki} is the active unbalance of the i-th AC node in the k-th area, $\Delta P_{dk\lambda}$ is the unbalanced active power of the DC grid connected to the k-th area, $\Delta Q_{k\lambda}$ is the reactive unbalance of the i-th AC system in the k-th area.

It integrates the emergency power controller and dynamic active power support controller of the DC transmission line, and combines the power margin of the converter station and the electrical distance. The support strategy is based on the following principles:

1. If the unbalanced power is less than the total power margin in area A, the converter station in area A is preferentially selected for the EDCPS.
2. Preferentially selecting the DC line with a close distance between the sending end and the receiving end disturbance converter station to support, so that the large-scale transfer of power flow can be avoided.

3. If the power support exceeds the maximum overload capacity of the system in area A, calling the line outside area B for the EDCPS.
4. During the support process, adding dynamic active power support controllers to area A to track the power operation in real time and providing the EDCPS.

The strategy implementation flowchart is shown in Fig. 7.

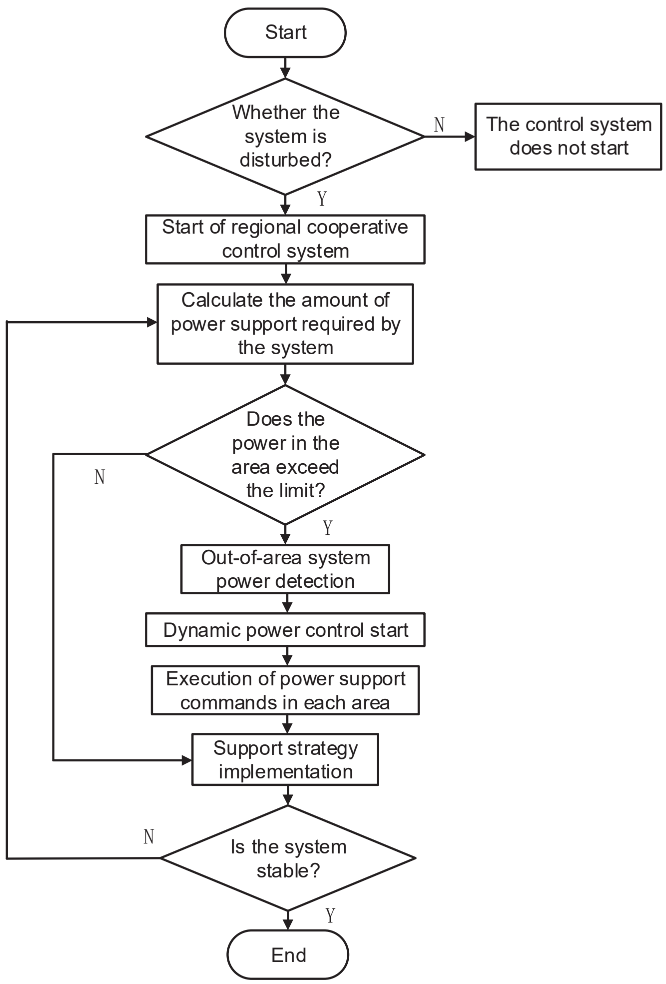


Fig. 7. Strategy implementation flow chart

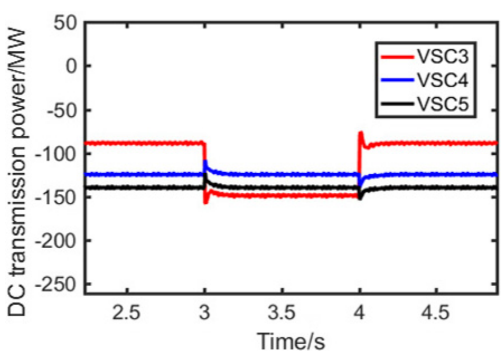
6. Simulation

Based on the PSCAD/EMTDC platform, there is an electromagnetic transient model of a five-terminal VSC-HVDC transmission system model built to verify the feasibility of the above strategy. VSC1, VSC2, and VSC3 are regional main networks (area A), and the voltage-power droop control method is used in each converter station. VSC4 and VSC5 are out-of-area power grids (area B), which are connected to the main network through the DC grid, and the constant active power control method is adopted by each converter station. The rated positive and negative voltage of the system is 400 kV, and ±1.25% of the voltage fluctuation is taken as the limit value. In the initial operating state, VSC1 and VSC2 supply power to the VSC3 in area A and VSC4 and VSC5 in B area, respectively.

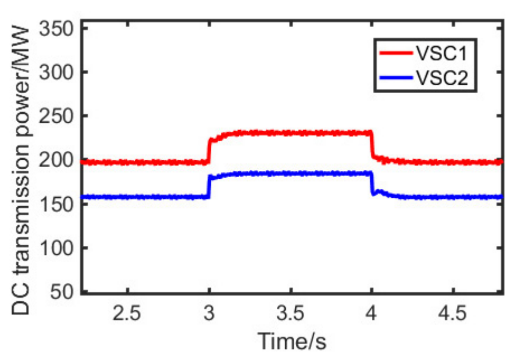
Case 1: When the value of the unbalanced power does not reach the total support amount of area A.

Under normal operation, the initial power command value of VSC1 in area A is –200 MW, and the initial power of VSC2 is –160 MW. The received power of VSC3 is 80 MW. The received power of VSC4 is 120 MW, and the received power of VSC5 is 140 MW. The power is basically balanced.

At 3 s, the amount of DC power delivered by VSC3 is $\Delta P = -60$ MW, and the time lasts 1 s, as shown in Fig. 8(a). At this time, there is a margin of 90 MW in area A, and the power shortage has not reached the power support limit. According to the control characteristics of the converter station, power support is provided by VSC1 and VSC2 through their respective operating slopes. As can be seen from Fig. 8(b), the active power of VSC1 increased by 32 MW and the active power of VSC2 increased by 25 MW and the power balance is basically maintained.



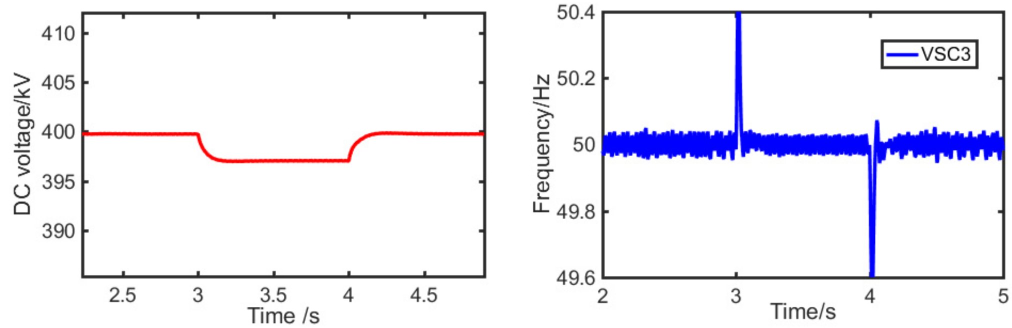
(a) DC power at the receiving end of converter station



(b) DC power at the sending end of converter station

Fig. 8. System power shortage does not exceed the support capability of the area A converter station

As shown in Fig. 9(a), the amount of power change of VSC3 does not exceed the sum of the amount of power support in area A, and the DC voltage does not exceed the limit. At this time, the converter station outside area A does not provide power support. In this case, converter stations in area A follow the voltage-power droop control method and provide power support to the VSC-MTDC system in time, and the bus frequency of the converter station with unbalanced power is still stable. Due to the supporting effect, the bus frequency fluctuation of the converter station with fault decreases, which is smaller than the power fluctuation during the normal operation. As shown in Fig. 9(b), the support in this case improves the bus frequency fluctuation of the converter station.



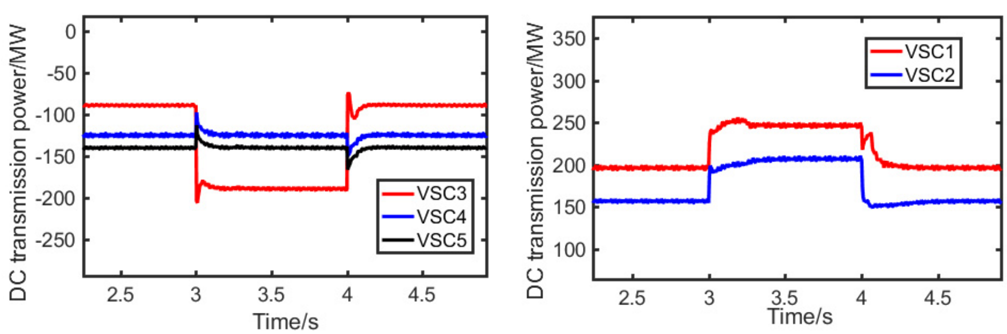
(a) DC voltage

(b) Bus frequency of VSC3

Fig. 9. Simulation results of emergency DC power support in area A converter station

Case 2: The value of the unbalanced power exceeds the total amount of support in area A, and it is necessary to call the support in area B.

The initial power of this example is the same as that of *Case* 1. At 3 s, the change of DC power of VSC3 is $\Delta P = -100$ MW, as shown in Fig. 10(a). Due to the control characteristics of VSC1 and VSC2, these two converter stations each undertake corresponding power support tasks without the dynamic power controller. At this time, the transmission power of VSC1 and VSC2 both reach the capacity limit (250 MW, 200 MW), and there is no extra power in area A. The power curves of VSC1 and VSC2 from 3 s to 4 s are shown in Fig. 10.



(a) Power change at the receiving end converter station

(b) Transmitting station at the sending end exceeds the limit

Fig. 10. Power deficit exceeds the support capacity of the regional A converter station

As shown in Fig. 11, due to the full load of VSC1 and VSC2 at this time, there is a power shortage in the VSC-MTDC system and the fluctuation of DC voltage increases. In order to solve the above problems, the dynamic active power controller is introduced in the support converter station to calculate the power shortage of the DC grid and provide power support. It can be seen from Fig. 12 that the transmission power of VSC4 is increased. As shown in Fig. 13(a), the DC voltage of the VSC-MTDC system has increased. It can be seen from Fig. 13(b) after the action of the dynamic active power controller in the converter stations of area B, the bus frequency of VSC3 is stable, and the frequency fluctuation during the fault is improved compared to the case without additional control.

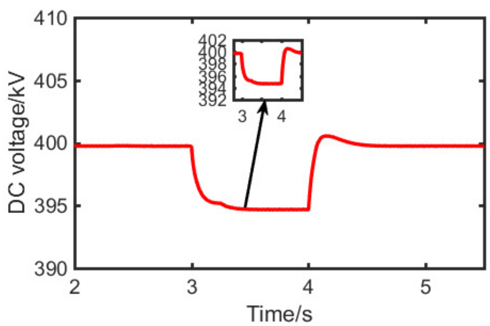


Fig. 11. DC voltage exceeds the limit

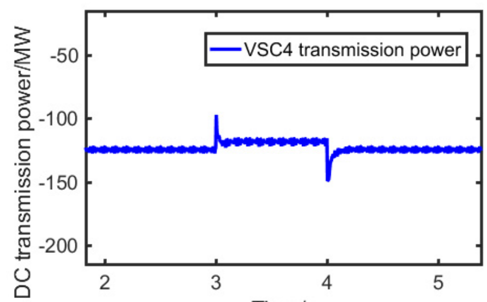
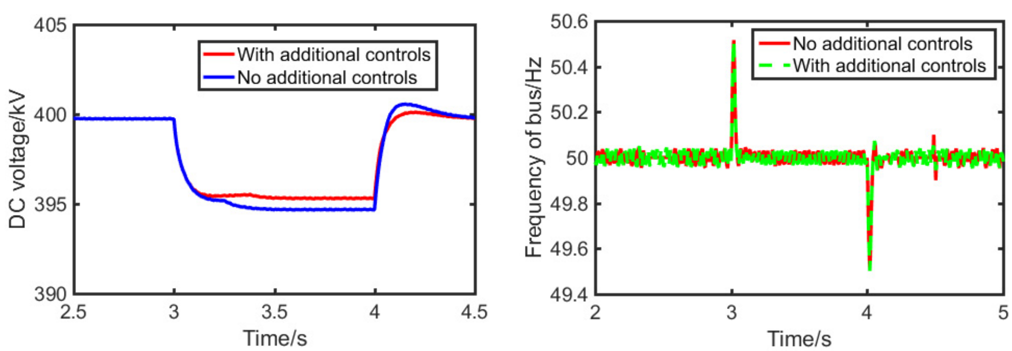


Fig. 12. VSC4 power changes after installing a controller



(a) Comparison of DC voltage with and without controller

(b) Comparison of VSC3 bus frequency after power support outside the area

Fig. 13. Simulation results of dynamic active power controller in the area B

When the converter stations in area B provide power support, the electrical distance factor among converter stations should be considered. In Fig. 14, the red curve is the waveform of DC voltage when the electrical distance is 2 ohm and the blue curve is the waveform of DC voltage when the electrical distance is 0.01 ohm. According to the two curves, the blue curve is higher than the red curve when the electrical distance is closer. The boosting amount of the DC voltage is better than that of the converter station farther away. Therefore, it is necessary to select the nearest converter station for power support.

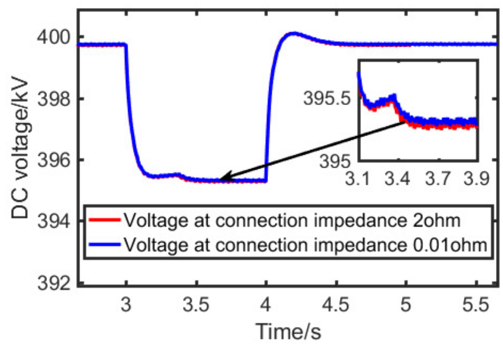


Fig. 14. VSC4 support effect at different distances

7. Conclusions

A five-terminal VSC-HVDC transmission system is built in this research. A dynamic active power controller is designed by using the VSC-HVDC transmission overload capacity and fast power control capability,and it is used in an asynchronous interconnected power grid with different areas. Based on the principle of regional backup, the power support strategy is proposed, and the feasibility of the method is verified by PSCAD/EMTDC. The conclusion is as follows:

1. The DC voltage-active control method can quickly and reasonably distribute the power to the line with a sufficient margin when the unbalanced power appears in the DC grid.
2. The dynamic active power controller can obtain the power operation status and data from the area in real time. The controller can make the power support outside the area timely when the support amount of the converter station in the area reaches the limit, and it can make the control results more accurate and raise the DC voltage of the system and improve the bus frequency of the disturbed converter station.
3. The dynamic active power controller proposed in this paper is coordinated with the emergency support of VSC-HVDC lines in the area to effectively solve the problem of insufficient active power reserve in a certain area of the power grid. The DC voltage can be kept in a safe operating range through outside support. In addition, when performing power support in a multi-DC system, the power value of the converter station with a large power margin and a short electrical distance is given priority.

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References

[1] Li X., Zeng Q., Wang Y., Zhang Y., *Control strategies of voltage source converter based direct current transmission system*, Gaodianya Jishu/High Voltage Engineering, vol. 42, no. 10, pp. 3025–3037 (2016).

[2] Kontos E., Tsolaridis G., Teodorescu R., Bauer P., *Full-bridge MMC DC fault ride-through and STATCOM operation in multi-terminal HVDC grids*, Bulletin of the Polish Academy of Sciences: Technical Sciences, vol. 65, no. 5, pp. 653–662 (2017).

[3] Huang R., Zhu Z., Chen J., Chen M., Zou C., Xu S., *Research and Experimental Validation of Control and Protection Strategy of HVDC Circuit Breaker in Fault Condition Application in Nan'ao Multi-Terminal VSC-HVDC System*, Dianwang Jishu/Power System Technology, vol. 42, no. 7, pp. 2339–2345 (2018).

[4] Guo X., Zhou Y., Mei N., Zhao B., *Construction and Characteristic Analysis of Zhangbei Flexible DC Grid*, Dianwang Jishu/Power System Technology, vol. 42, no. 11, pp. 3698–3707 (2018).

[5] Xu T. *et al.*, *Design and Application of Emergency Coordination Control System for Multi-infeed HVDC Receiving-end System Coping with Frequency Stability Problem*, Dianli Xitong Zidonghua/Automation of Electric Power Systems, vol. 41, no. 8, pp. 98–104 (2017).

[6] Lin Q., Li X., Hu N., Wang X., Li K., *A multi-agent based emergency DC power support strategy*, Dianwang Jishu/Power System Technology, vol. 38, no. 5, pp. 1150–1155 (2014).

[7] Yu T., Shen D., Ren Z., *Research on emergency power shifting control of multi-circuit HVDC systems from Central China Power Grid to East China Power Grid*, Power System Technology, vol. 28, no. 12, pp. 1–4+19 (2004).

[8] Yang W., Xue Y., Jing Y., Chao J., Huang W., Hong C., Yang B., *Emergency DC power support to AC power system in the south china power grid*, Dianli Xitong Zidonghua/Automation of Electric Power Systems, vol. 27, no. 17, pp. 68–72 (2003).

[9] Weng H., Xu Z., Xu F., Tu Q., Dong H., *Research on constraint factor of emergency power support of HVDC systems*, Zhongguo Dianji Gongcheng Xuebao/Proceedings of the Chinese Society of Electrical Engineering, vol. 34, no. 10, pp. 1519–1527 (2014).

[10] Li G., Fu G., Wang S., Li J., *Emergency power support control for MMC flexible HVDC transmission system during AC fault*, Power System Protection and Control, vol. 46, no. 13, pp. 107–112 (2018).

[11] Li Cong, Li Y., Guo J., He P., *Research on emergency DC power support coordinated control for hybrid multi-infeed HVDC system*, Archives of Electrical Engineering, vol. 69, no. 1, pp. 5–12 (2020).

[12] Zhu R., Li X., Ying D., *A frequency stability control strategy for interconnected VSC-MTDC transmission system*, Dianwang Jishu/Power System Technology, vol. 38, no. 10, pp. 2729–2734 (2014).

[13] Zhang W., Fang X., *The Support for Regional Grid Catastrophe Recovery from Multi-terminal DC Asynchronous Interconnection*, Power System and Automation, vol. 39, no. 1, pp. 66–69 (2017).

[14] Xu T. *et al.*, *Coordinated Control Strategy of Multi-DC Emergency Power Support to Improve Frequency Stability of Power Systems*, Dianli Xitong Zidonghua/Automation of Electric Power Systems, vol. 42, no. 22, pp. 69–77+143 (2018).

[15] Rakibuzzaman S., Robin P., Mike B., *The Impact of Voltage Regulation of Multiinfeed VSC-HVDC on Power System Stability*, IEEE Transactions on Energy Conversion, vol. 33, no. 4, pp. 1614-1627 (2018).

[16] Nadew A.B., Cornelis A.P., *Analysis of Faults in Multiterminal HVDC Grid for Definition of Test Requirements of HVDC Circuit Breakers*, IEEE Transactions on Power Delivery, vol. 33, no. 1, pp. 403–411 (2018).

[17] Fuchs A., Imhof M., Demiray T., Morari M., *Stabilization of large power systems using vsc-hvdc and model predictive control*, IEEE Transactions on Power Delivery, vol. 29, no. 1, pp. 480–488 (2014).

[18] Harnefors L., Johansson N., Zhang L., Berggren B., *Interarea oscillation damping using active-power modulation of multiterminal HVDC transmissions*, IEEE Transactions on Power Systems, vol. 29, no. 5, pp. 2529–2538 (2014).

[19] Tang G., He Z., Pang H., *Research, application and development of VSC-HVDC engineering technology*, Dianli Xitong Zidonghua/Automation of Electric Power Systems, vol. 37, no. 15, pp. 3–14 (2013).

[20] Naushath M., Athula D., Aniruddha M., Ioni T., *Investigation of Fault Ride-Through Capability of Hybrid VSC-LCC Multi-Terminal HVDC Transmission Systems*, IEEE Transactions on Power Delivery, vol. 34, no. 1, pp. 241–250 (2019).