Research on Voltage Control of Multi Terminal Flexible Medium Voltage DC Distribution Network

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Abstract. In order to solve the problem that the original control strategy cannot meet the voltage quality requirements of the system under various operation modes due to the expansion of DC distribution network scale, this paper studies the voltage control strategy of a ring type medium voltage DC distribution network. Firstly, the traditional control method is improved, the droop control is added to the margin control as the slave station control method. At the same time, the DC transformer connected with the energy storage is used as the backup voltage regulating station in case of power shortage to meet the voltage quality requirements of the system in normal operation and fault. Then, a DC voltage control strategy based on depth first search is proposed to solve the problem of voltage deviation caused by system fault, so that the distribution network can automatically adjust the control according to the real-time structure in case of fault and improve the voltage quality. Finally, the proposed control strategy is simulated in PSCAD / EMTDC to verify the effectiveness of the control strategy.

1. Introduction

Flexible DC distribution network has become a research hotspot at home and abroad because of its high power quality, flexible power supply mode and convenient access to distributed generation or DC loads [1-2]. Different from the AC system, the DC system only needs to control DC voltage to meet the stability of DC voltage. At the same time, due to the weak inertia and low damping characteristics of the DC system, the control difficulty of DC voltage is more difficult than that of the AC system [3-4].

At present, the research on voltage control of flexible DC system is rich [5]. In literature [6], a feedforward compensation method based on band-pass filter is added to the master-slave control, which increases the stability of the system in operation, but the operation in case of failure is not considered. In literature [7], an adaptive virtual inertia control of DC distribution network based on variable droop coefficient is proposed, which can increase the inertia of the system and restrain the fluctuation of DC voltage through the swing of droop curve of voltage regulator when the power of the system fluctuates. In literature [8], DC distribution network is introduced into the idea of hierarchical and partitioned control. But essentially, it belongs to droop control, so it also leads to the voltage deviation in the steady-state operation. In paper [9], a fast voltage margin control method is proposed. By setting a trade-off coefficient, the response speed and control speed of the controller can be improved when the DC voltage deviation is large, but when the converter station is increased, there is still a problem of margin design. The control strategy of DC distribution network should not only meet
the voltage stability under normal conditions, but also eliminate or reduce the DC voltage deviation caused by faults as much as possible through control when the system fails.

In this paper, the voltage control strategy of a multi terminal DC distribution network is studied. Firstly, the topology of medium voltage DC distribution network based on ring structure is proposed. Then, to make sure the voltage quality during the operation of distribution network, adopted the combination of DC voltage margin control and droop control as the control mode of voltage source converter(VSC), the DC solid state transformer(DCSST) connected with energy storage is added as the backup station as the means of emergency voltage regulation. Finally, a method combining depth first search (DFS) and voltage control is proposed, which can eliminate or even reduce the voltage deviation caused by fault when the structure of distribution network changes due to fault. Finally, in order to verify the effectiveness of the control strategy, a simulation model is built in PSCAD/EMTDC to simulate the control strategy.

2. Structure of flexible DC distribution network
The topology of the flexible DC distribution network studied in this paper is shown in Figure 1. The structure can accommodate multiple distributed power sources and loads, and also have high power supply reliability. In this structure, VSC is connected with the AC system to realize the AC/DC conversion, the DCSST is used to realize the medium voltage and low voltage DC conversion, providing the grid connection interface for the photovoltaic system, energy storage system and low-voltage DC distribution network.

3. Voltage coordination control strategy between converter stations
In view of the limitation of the traditional single control method, the droop control and margin control are combined as the coordinated control strategy among the multi converter stations in the DC distribution network.

In Figure 1, the converter station VSC1 that can be used as the power balance node is selected as the master station, which adopts constant voltage control, and its control block diagram is shown in Figure 2. The regulation margin of the master station is $[P_{g_{min}}, P_{g_{max}}]$. When the power reaches its
limits, the station will automatically operate according to the limiting power when it loses the voltage regulation capacity.

Choose VSC2 and VSC3 as slave stations. The slave station works in droop control mode with margin. When the voltage deviation does not exceed \([U_{dc1min}, U_{dc1max}]\), the slave station operates under constant power control, which means that the master station does not reach the upper limit of regulation. When the master station is unable to maintain the DC voltage or master station out of operation, it will lead to DC voltage out of limit. Unlike the traditional margin control mode, the slave station will automatically switch to the droop control mode. The voltage droop control characteristic of the VSC can be expressed as formula (1). The characteristics of droop control make it possible for the system to have multiple slave stations working with different droop coefficients.

\[
U_{dc} = U_{dcref} + k(P_{ref} - P)
\]  

Where: \(U_{dcref}\) represents the reference value of droop control DC voltage. \(P_{ref}\) represents the reference value of droop control active power. \(k\) represents the droop coefficient.

The control switch block diagram of slave station is shown in Figure 3(a). In normal operation, the Ctrl is at position 0. When \(U_{dc} > U_{dc1max}\) or \(U_{dc} < U_{dc1min}\), Ctrl switches to position 1 in droop control mode. When the output power of the slave station reaches the upper limit, it will automatically work according to the limit power, and lose the voltage regulation capacity. The voltage regulation margin of slave station are \([U_{dc2min}, U_{dc1min}]\) and \([U_{dc1max}, U_{dc2max}]\).

If the master station and the slave station lose the capacity of voltage regulation, the distribution network is in an emergency situation. If no measures are taken, the voltage will have a large deviation. Here, the DCSST with bidirectional power transmission capacity connected to the energy storage is used as the backup converter station. Its control switch block diagram is shown in Figure 3(b). When the master converter station and the slave converter station reach the regulation capacity limit or system failure cause the DC voltage exceeds the limit, they can work in the power support mode, and the energy storage equipment discharges to maintain the DC voltage level at the medium voltage side, that is when the DC voltage is less than \(U_{dc2min}\), Ctrl switches to 3. If the load of the system continues to increase, the distribution network will not be able to meet the demand of the load, and the DC voltage will drop. Therefore, it is necessary to cut off some unimportant loads to maintain the stability of DC voltage.

4. DC voltage control based on depth first search
When the DC distribution network fails and the system structure changes, especially when the master station is out of operation, the slave station should be worked at droop control to ensure the system voltage stability. Even if the load of DC distribution network is small, the DC voltage will still have deviation. For converter stations, it is impossible to distinguish whether the voltage deviation is caused by load increase or fault, so the voltage deviation cannot be eliminated or reduced only by the coordinated control between converter stations. At this time, the quality of DC voltage quality should be improved by energy management system adjust power flow or control strategy.
When the master station is out of operation, change the control mode of the slave station with large regulating capacity to the constant voltage control, the voltage quality of distribution network will be improved. If the system can quickly identify the real-time topology of DC distribution network and adjust the control strategy based on the change of topology, it will be beneficial to improve the quality of DC voltage. In this paper, a method of topology identification, depth first search (DFS), is combined with control strategy, which can quickly reflect to the control system when the distribution network structure changes and change the control mode of the controller, so as to effectively reduce the voltage deviation of the DC bus.

The principle of depth first search algorithm is:
(1) Start from a vertex in the graph and access this vertex.
(2) If the adjacent vertex of the currently accessed vertex has not been accessed, select one to access; otherwise, return to the most recently visited vertex. Search in this way until all the vertices connected with the starting vertex have been accessed.
(3) If there are still vertices in the graph that are not accessed, select one of them as the starting vertex and visit it, turn step (2); otherwise, the traversal ends.

When there are no undiscovered or searched nodes in the whole system, it means that the topology map has been searched. Combining the depth first search with the control of DC distribution network, the specific implementation process is as follows:

1) Firstly, establish the graph according to the topology of DC distribution network, and mark the converter station with the ability to control medium voltage DC voltage as the special node (or source node). The priority of each special node is set from small to large Arabic numerals. Smaller numbers mean higher priorities. If there have more than one slave station, the converter station with larger regulation capacity is usually set as a higher priority.

2) Select a source node as the initial node to identify the distribution network topology and output the search results according to DFS algorithm, and take each source node search result as a subarea. At this time, ensure that all nodes have been searched. Sort the special nodes in each sub area according to the priority, output the node number represented by the highest priority converter station, and adjust the control strategy in each area according to the priority order of converter station.

3) If the highest priority in the area is the master station, all converter station control strategies remain unchanged. If the highest priority is slave station, adjust the slave station controller as shown in Figure 4(a). The Ctrl will be switched to position 4. And station will operate at the constant 20kV voltage control. Similarly, if the highest priority is backup station, the controller as shown in Figure 4(b) will be switched to position 5, and the DCSST will operate at a constant 20kV medium voltage control.

![Diagram](image)

(a) (b)

Figure4. Control switch block diagram of converter station based on DFS.

This control strategy does not need complex power flow calculation. The basis of the change of the control mode is the real-time topology of the distribution network, so its time response speed is faster, which is equivalent to a fast secondary voltage regulation on the coordination control layer of the distribution network.
5. Simulation Analysis

In order to verify the effectiveness of the control strategy proposed in this paper, the DC distribution network as shown in Figure 1 is built in PSCAD/EMTDC, simulated the normal operation and fault operation of the distribution network. The initial voltage value of droop control in slave station is 20.2kV/19.8kV, and the droop coefficients of VSC2 and VSC3 are both 0.3. The maximum output power of the VSC1 is 3.5MW. The power reference values for VSC2 and VSC3 constant power control are 0.5MW and 1MW, the maximum output power is 1.5MW and 2MW. For DCSST1, the initial value of voltage control at medium voltage side is 20.55kV/19.45kV. Distributed generation keeps constant power output during operation.

5.1. Simulation analysis during normal operation

Set the light load start of the distribution network, and the total power deficiency is 0.5MW (Here, the load power deficiency is the total load of the system minus the power of distributed generation). The load was increased by 3MW after 1s, 3MW after 2s, and 1.2MW after 3s. The dynamic process voltage and power curves are shown in Figure 5(a) (b).

![Figure 5. Dynamic response waveform of each converter station during operation.](image)

At the beginning of the simulation, total power deficiency of distribution network is 0.5MW, the VSC2 and VSC3 operate at fixed power of 1MW and 0.5MW respectively. The voltage is controlled by the master station VSC1, and VSC1 absorbs the 1MW power of the distribution network. At 1s, the load is increased by 3MW, and the increased load does not exceed the power output upper limit of the master station, so it is all borne by the master station. VSC1 power flow reverses from absorbing 1MW power to outputting 2MW power. The voltage and current fluctuate in the process of power flow reversal. After 0.2s dynamic process, the voltage is stabilized at 20kV again. The voltage fluctuation does not exceed ±5% of the rated value. At 2s, the system load continues to increase by 3MW. At this time, the master station VSC1 reaches the regulation set margin value of 3.5MW, and turns to constant power operation, and the DC voltage decreases to produce deviation. VSC2 and VSC3 automatically switch to droop control mode to maintain DC voltage after sensing voltage deviation. After about 0.2s dynamic process, the voltage is stable at 19.6kV, with a voltage deviation of about 0.4kV.

![Figure 6. Dynamic response of DCSST in 3s.](image)
When the load is increased by 1.2MW at 3s, slave station VSC2 and VSC3 also reach the regulation margin values of 1.5MW and 2MW respectively. Backup station DCSST1 will change the control to DC voltage control at the constant medium voltage side. The dynamic response of DCSST1 at 3s is shown in Figure 5. When the DC voltage at the medium voltage side is lower than 19.45kv, the DCSST1 starts to control the voltage at the constant medium voltage side, the power flow of DCSST1 turns over, which changes from absorbing 0.25MW to outputting 0.25MW power. The output power of VSC2 and VSC3 reaches the limit value and operates according to the power of 2MW and 1.5MW respectively. The DC bus voltage is controlled by DCSST1. The voltage at the medium side of each converter station is stable at about 19.5kv after about 0.15s dynamic process.

5.2. Simulation analysis of isolated operation based on DFS control strategy

Simulate the isolated operation of the distribution network as shown in Figure 1. At the beginning, the system operates normally. After 1.5s, lines T2 and T5 are disconnected. The DC distribution network is divided into two parts. At 2s, dispatching instructions based on DFS control are received. The dynamic response of DC voltage of each converter station is shown in Figure 7(a).

The fault in 1.5s causes the DC distribution network to be in isolated operation state. Part A includes master station VSC1, slave station VSC3, PV module and load, part B includes slave station VSC2, backup station and load. When the fault occurs, the operation mode of part A is the same as that of the slave station. At this time, the master station controls the system voltage. Because of the occurrence of the fault, the DC voltage is stable after generating a transient fluctuation of about 0.15s, and the maximum voltage fluctuation is not more than 1% of the rated voltage. VSC1 is the highest priority station of distribution network topology search and identification, and the control mode can be stable at the rated level without changing.

For part B, it is the same as the master station exiting operation. The DC voltage after 1.5s is maintained by the droop control mode below VSC2, and the voltage is stable at about 19.6kv. If no measures are taken, the system will operate at a constant voltage of 19.6kv. After the fault occurs, the DFS identifies that the highest priority station of part B of the distribution network is VSC2, and sends out control adjustment instructions. At 2s, VSC2 receives the instructions to change the control mode to constant 20kV Voltage Control. The transient fluctuation of voltage about 0.2S is stable at 20kV,
and the maximum overshoot of DC voltage is 1.5%. Before adding the DFS based control strategy, the DC voltage can still be stable in a certain deviation range according to the original control strategy. After adding the control strategy based DFS, the voltage quality is improved.

The dynamic response of converter station output current and power under isolated operation is shown in Figure 7(b), (c). The fault occurs in 1.5s, resulting in power redistribution and current fluctuation. In part A, the DC voltage deviation of VSC3 side is not more than 0.2kV, so VSC3 operates at a constant power of 0.5MW. At this time, the load power of part A is small. In order to maintain the system voltage, VSC1 reverses the power flow and absorbs the redundant 0.3MW power in the DC distribution network. In order to maintain DC voltage, the output power of part B is increased to 1.73MW. At 2s, the control of part B converter station changes, but the output power and current of the converter station are stable only after a small fluctuation due to the change of the controller.

6. Conclusion
In this paper, the voltage control strategy of flexible multi terminal DC distribution network is studied. Aiming at the problem that the traditional control strategy cannot satisfy the fast and efficient control of voltage due to the increase of port number and complexity of DC distribution network, the control method which combines droop control with margin control is adopted, and on this basis, the DCSST connected with energy storage is introduced as the control method of back-up voltage regulation station. At the same time, aiming at the problem of voltage deviation caused by the system fault, a secondary voltage regulation method based on depth first search is proposed, which can quickly identify the distribution network structure in case of system fault and switch the control strategy based on it. Finally, the simulation results show that this method can effectively eliminate or reduce the voltage deviation caused by the fault.

References
[1] Peng, K., Chen, J.J., Xu, B.Y., et al., 2019, "Stability and control of flexible DC distribution system"[J].Automation of Electric Power Systems, 43 (23):90-100+115.
[2] Y. Li, L. He, F. Liu, C. Li, Y. Cao and M. Shahidehpour, 2019, "Flexible Voltage Control Strategy Considering Distributed Energy Storages for DC Distribution Network," in IEEE Transactions on Smart Grid, vol. 10, no. 1, pp. 163-172, Jan. doi: 10.1109/TSG.2017.2734166.
[3] Xiong, R., Ji, Y., Li, R., et al., 2018,"Summary of key technology and application demonstration of DC distribution system"[J]. Proceedings of the CSEE, 38(23):6802-6813+7115.
[4] Y. Ji et al., 2018, "Overall control scheme for VSC-based medium-voltage DC power distribution networks," in IET Generation, Transmission & Distribution, vol. 12, no. 6, pp. 1438-1445, 27 3 doi: 10.1049/iet-gtd.2017.0912.
[5] P. Simiyu, A. Xin, G. T. Bitew, M. Shahzad, W. Kunyu and L. K. Tuan, 2019, "Review of the DC voltage coordinated control strategies for multi-terminal VSC-MVDC distribution network," in The Journal of Engineering, vol. no. 16, pp. 1462-1468, 3 2019, doi: 10.1049/joe.2018.8841.
[6] Zhao, X.S., Peng, K., Zhang, X.H., et al. 2019, "Stability and optimal control of multi terminal flexible DC distribution system under master-slave control mode"[J]. Electric Power Automation Equipment, 39(02): 14-20.
[7] Mi, G.S, Zhan, J., Gao, L., et al. "Droop control optimization strategy of VSC-MTDC system"[J].Proceedings of the CSU-EPSA, 2020,32(01): 101-107.
[8] Wu H., Wu, J.H., Liu, Q.J., et al. 2018, "Research on coordinated stability control for multi terminal DC distribution network"[J]. Distribution & Utilization, 35(08):45-51+60.
[9] Li, M.H., Liu, X.M., Chen, P., 2016, "Fast voltage margin control strategy for multi terminal flexible HVDC system"[J]. Power System Technology, 40(10): 3045-3051