Research on Control Method of Multi-terminal Flexible DC Transmission System Based on Voltage Droop Control

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Abstract. Flexible DC transmission system has the advantages of small line loss, high reliability and strong controllability, and can reduce the frequency of system inactivity. In this paper, the voltage droop control method of flexible DC transmission system is studied in detail. Firstly, the principle and characteristics of the series structure, parallel structure and hybrid structure of multi-terminal flexible DC transmission system are introduced in detail. Based on this, the principle and characteristics of the control strategy of DC voltage droop control of the system are analyzed, and an improved voltage droop control strategy is proposed. Finally, a three-terminal flexible DC transmission system model is built on the Matlab/Simulink platform. The simulation results show that the control strategy plays a certain role in stabilizing DC, AC voltage, AC current and power balance control.

1. Introduction

HVDC transmission technology is generally applied in the remote transmission environment, isolated from other grid systems, but it has certain problems in the access of new energy power. On this basis, a new transmission technology based on fully-controlled devices and voltage source converters (VSC), namely DC transmission technology, emerged as the times require [1]. Multi-terminal flexible direct current (VSC-MTDC) is a technological extension of VSC-HVDC. It consists of at least three VSCs connected to other lines, which can effectively improve the economics and efficiency of the transmission system [2]-[4]. There are many research results on multi-terminal flexible DC transmission systems and DC voltage droop control. The two-terminal direct current transmission technology is summarized, and the basic concepts of multi-terminal direct current transmission and power grid are discussed in depth, and their respective technical characteristics are analyzed, which provides a basis for future generations to consider multi-terminal direct current transmission [5]. It is confirmed that the access of flexible DC transmission system can provide better dynamic reactive support, and it has also been widely used in large-scale offshore wind farms [6]-[8]. The latest research on the main wiring topology of flexible HVDC transmission system is emphasized, and its application scope, advantages and disadvantages are summarized and analyzed [9]-[11]. An improved droop control method is proposed to correct the droop coefficient of the converter by monitoring the local DC voltage. The improved inverter can reduce the DC voltage deviation. In the event of a serious fault, the improved control method can prevent the inverter overload operation [12]. Based on the current development status and research results, the flexible DC transmission system can provide a
feasible technical platform for the access of distributed power sources, improve the reliability and flexibility of power supply and good power quality, but when external disturbance occurs, the system appears faults, which still have significant problems in stabilizing DC voltage and power.

Based on these researches, this paper first introduces the topological structure of VSC-MTDC, and improves the traditional droop control strategy according to the control principle of voltage droop control, and proposes an improved control method for DC voltage feedback control droop coefficient. The control method is simple and reliable, and the actual operation is simple. Finally, a three-terminal flexible DC transmission system model is built, and its role in stabilizing DC, AC voltage, AC current and power balance control is verified.

2. VSC-MTDC Topology
VSC-MTDC system has the advantages of fast speed, simple operation and high reliability. It is a flexible and highly reliable control mode. At the same time, when a VSC exits from operation, the system will not be paralyzed to ensure the normal operation of the system. Due to the large number of converter stations, it is of great significance to select the appropriate topology of the flexible DC transmission system for the transmission efficiency and economic benefits of the transmission network. In general, the topological structure of VSC-MTDC mainly includes three types of series structure, parallel type structure and mixed type structure. The following is a detailed analysis of the main two structure.

2.1. Series structure
The series VSC-MTDC system is mainly used in applications where it is necessary to raise the low voltage to high voltage, as shown in Figure 1 is a typical series wiring diagram:

![Series wiring diagram](image)

**Figure 1.** Series wiring diagram

For the VSC-MTDC system, one of the multiple VSC must have a constant DC voltage control. Generally, the largest capacity is selected to achieve this function. Other VSCs select other adjustment methods according to specific needs. In the event of a voltage-controlled VSC failure, in order to prevent the entire circuit from being paralyzed, the system needs to change the other VSC control mode to the constant DC voltage control mode in time.

2.2. Parallel structure
There are various ways of parallel type structure, as shown below.
Compared with the series structure, the parallel topology has better flexibility and more types. Among the four parallel modes, the basic parallel type structure has the best economy, the structure is relatively simple and easy to implement, but its reliability is poor. Compared with the basic parallel structure, other wiring methods are used in different occasions. The ring network structure is mostly used in the DC microgrid, the network structure is mostly used in the internal networking of the power plant, and the star structure is mostly used in the DC distribution network [13]-[15].

3. VSC-MTDC Voltage droop control strategy
The control strategy of the VSC-MTDC system is mainly to stabilize the DC voltage within the specified range and the balance of active power. The control methods of VSC-MTDC system mainly include: master-slave control, voltage droop control and voltage droop control with margin. This section will mainly introduce the voltage droop control strategy and carry out research on improved droop control. The theoretical basis for the construction of a three-terminal flexible HVDC transmission system is provided.

3.1. Traditional voltage droop control and improvement
The droop control combines DC voltage control and power control. Its main function is to stabilize the output voltage and maintain power stability. The control principle is shown in Figure 3. Set the droop coefficient to $k_{\text{droop}}$, the actual value of the reference point DC voltage and the command value are $U_{\text{dc}}$ and $U_{\text{dref}}$, the current is $I_{\text{dref}}$, and the actual power of the converter station is actually $P_{\text{dc}}$ and $P_{\text{dref}}$, respectively. First, the relationship between DC voltage and DC current and the droop control output $\text{Out}$ are as follows:

$$I_{\text{dc}} - I_{\text{dref}} = k_{\text{droop}}(U_{\text{dc}} - U_{\text{dref}})$$

Figure 2. Parallel wiring diagram
Out = k_{droop} (P_{dref} - P_{dc}) + U_{dref} - U_{dc} \quad (2)

When the DC system is running stably, Out = 0, the inverter meets

\[ U_{dc} - U_{dref} = k_{droop} (P_{dref} - P_{dc}) \quad (3) \]

According to the above formula, the power distribution characteristic of the VSC-MTDC system depends on the droop coefficient k_{droop}.

In the traditional droop control, the drooping coefficients of all converter stations are set in advance, when the transmission voltage, power fluctuates or the topology of the DC network changes (for example, the converter station fails or stops, etc.) The traditional droop voltage control has the disadvantages of independent power distribution and low DC voltage quality. Due to the emergence of these problems, the study proposes an improved voltage droop control method that measures the local DC voltage and introduces it into the droop control coefficient (Figure 4). The correction value of the drooping coefficient of the converter station is:

\[ \Delta k_d = \mu |\Delta U_{dc}| \text{sgn}(|\Delta U_{dc}|) \quad (4) \]

In the formula, \( \Delta U_{dc} \) is the DC voltage deviation when the system is actually running. The improved control droop coefficient is:

\[ k'_d = k_d + \Delta k_d \quad (5) \]

Then the converter station is satisfied at this time as follows:

\[ U_{dc} - U_{dref} = (k_d + \Delta k_d)(P_{dref} - P_{dc}) \quad (6) \]

In the above formula: \( \mu \) is a constant, \( k \) is the rated droop coefficient when the converter station is running, its droop control coefficient is the same as the traditional design method, \( \text{sgn}(|\Delta U_{dc}|) \) is a symbol function, and its calculation expression is as follows:

\[ \text{sgn}(|\Delta U_{dc}|) = \begin{cases} 1, & |\Delta U_{dc}| > \Delta U_{dt} \\ -1, & |\Delta U_{dc}| < \Delta U_{dt} \end{cases} \quad (7) \]

\( \Delta U_{dt} \) is the DC voltage deviation threshold determined according to the requirements of real-time system operation, and can be automatically selected according to specific requirements. When \( \text{sgn}(|\Delta U_{dc}|) \) is negative, the droop coefficient is:

\[ k'_d = k_d - \mu |\Delta U_{dc}| \quad (8) \]

If the droop coefficient is set to be small, the DC voltage control of the system will be disordered. In this case, the minimum droop coefficient is set as follows:

\[ k_d - \mu |\Delta U_{dc}| > k_{dc} \quad (9) \]

Considering the need to leave a certain margin, the formula is
\[ \mu < \frac{k_d - k_{dl}}{\Delta U_{dc}} \]  

Meanwhile, when \( \text{sgn}(|\Delta U_{dc}|) \) is positive, the droop coefficient is:

\[ \mu < \frac{k_{dh} - k_d}{\Delta U_{dc}} \]  

\( k_{dl} \) and \( k_{dh} \) are respectively the lower limit value and the upper limit value of the control droop coefficient, and the system can set the value of \( \mu \) according to different conditions.

**Figure 3.** Voltage droop control

**Figure 4.** Improved droop control schematic

### 3.2. Control characteristic analysis

As shown in Figure 7, \( P_{dc_{\min}} \) and \( P_{dc_{\max}} \) are the lower and upper limits of the active power of the converter station, \( U_{dcH} \) and \( U_{dcL} \) are the upper and lower limits of the DC voltage set according to the system operation requirements, and \( U_{dcH} = U_{dcref} + \Delta U_{dc}, U_{dcL} = U_{dcref} - \Delta U_{dc} \). Assuming that the rated operating point of the system is point O, the improved droop control factor is the same as the conventional one. The following two cases are analyzed.

1. **Case 1**

Taking point A as an example, when the system has a small power loss and the correction coefficient is negative, the improved droop control can be used to reduce the droop coefficient and reduce the DC voltage deviation. The voltage deviation of the traditional droop control method is:

\[ \Delta U_{dc} = k_d (P_{dc_{ref}} - P_{dc}) = -k_d \Delta P_{dc} \]  

Then the improved DC voltage deviation is:

\[ \Delta U_{dc}' = \left( k_d - \mu |\Delta U_{dc}'| \right) (P_{dc_{ref}} - P_{dc}) \]  

\[ \Delta U_{dc}' = \begin{cases} 
-k_d \Delta P_{dc}, & U_{dc} < U_{dc_{ref}} \\ 
1 - \mu \Delta P_{dc}, & U_{dc} > U_{dc_{ref}} 
\end{cases} \]  

The difference between the DC voltage deviations is:
\[
\Delta U_{dc}^* - \Delta U_{dc} = \begin{cases} 
\frac{k_d \mu \Delta P_{dc}}{1 + \mu \Delta P_{dc}} & \Delta U_{dc} < 0 \\
\frac{-k_d \mu \Delta P_{dc}}{1 - \mu \Delta P_{dc}} & \Delta U_{dc} > 0 
\end{cases}
\] (15)

It can be seen from Figure 5 that in the case of the same power fluctuation, the DC voltage of the improved droop control point A is higher than the point B of the conventional droop control, which is consistent with the calculation result, so that the improved droop control can reduce the low stability. The DC voltage deviation during the operation of the state can avoid oscillation of the system, so that the voltage and frequency can be kept stable.

(2) Case 2

Taking C point as an example, after a serious fault occurs in the system, the unbalanced power is relatively large, the DC voltage deviation is greater than the preset threshold, the sign function is positive, and the droop coefficient is:

\[
k_d = k_d + \mu |\Delta U_{dc}| \quad (16)
\]

It can be seen that the improved droop coefficient is greater than the traditional droop coefficient, the controller biases the power control, and the improved DC voltage deviation is larger than the conventional control, but the improved control converter station absorbs less power, thus ensuring a larger margin.

![Figure 5. Improved control droop coefficient characteristic curve](image)

4. Simulation analysis

The simulation was carried out on the Matlab/Simulink platform, and a three-terminal flexible DC transmission system was built. The whole system mainly includes a three-terminal current source, a transformer, a reactor, etc., and then connected to the VSC connected to the local end. Each VSC has a large capacitor connected in parallel at both ends. After that, the three-terminal VSC is connected by a DC line to form a complete system. The parameters of each converter station are consistent. The parameters are as follows: The transformer has a transformer ratio of 210/160 (network side / valve side), DC capacitor is 1mF, bridge arm resistance is 0.2Ω, DC voltage is 700kV, VSC1 adopts improved droop control, VSC2, VSC3 adopt fixed power control, the main purpose is to verify the introduction of improved droop control. The three-terminal flexible DC transmission system stabilizes the output voltage and maintains power balance.
The first verification is that through the improved droop control, whether the three-terminal flexible DC transmission system can stabilize the DC voltage within the required range, measure the DC voltage on the DC line, and obtain the simulation results in the following figure:

**Figure 6. System overall structure**

**Figure 7. DC voltage waveform**

**Figure 8. AC voltage and AC current waveform**
It can be seen from Figure 7 that the voltage rises to a given power within 0.1s after the system is started, and then stabilizes at the set value thereafter, and the system can complete the stable control of the DC voltage. Then, in Figure 8, the blue line is the AC voltage, and the green line is the AC current. They are stable near the rated value after the system is stable, indicating that the stability of the system for AC voltage and AC current is also very significant.

![Figure 9. One-terminal power waveform](image)

![Figure 10. Other terminal power waveform](image)

It can be seen from the above figures that the final power basically maintains the algebra and the state of 0, which proves that the improved droop control can make the system run smoothly and the state of operation is highly reliable and the power quality is good.

5. Conclusion

This paper mainly studies the control strategy of multi-terminal flexible DC transmission system. The control strategy mainly introduces the droop control. Based on the voltage margin control and the traditional droop control, an improved droop control strategy is studied. The DC voltage feedback changes the droop control coefficient and designs the three-terminal flexible DC transmission system. The article generally shows:

1. The system uses improved droop control, which can effectively avoid the impact on the entire power grid due to small disturbances and improve the voltage quality of the DC system.

2. When a serious fault occurs, the improved droop control method can ensure that the DC voltage deviation within the allowable range is that the converter station has a certain adjustment capability and margin, thereby effectively preventing the converter station from overloading.
(3) The three-terminal flexible DC transmission system can stabilize the DC voltage within a certain range, and at the same time achieve power balance, so that the system runs more smoothly.

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