Research on Factors Affecting Power Flow of Direct Current Grid Considering Different Control Modes

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Abstract. Direct Current grid technology based on flexible Direct Current transmission is one of the key means to solve large-scale grid integration and consumption of new energy. The flexible Direct Current transmission technology developed in recent years has superior control performance, strong flexibility, and independent control of active power. And reactive power, can be connected to the weak Alternating Current system. This article derives the power flow equation of the Direct Current transmission network by establishing a mathematical model of the Direct Current transmission network and combining different system-level control strategies in the Direct Current transmission network. The Newton-Raphson method is used to solve the power flow distribution of the Direct Current network when the master-slave control and droop control are adopted. The influence of the two control methods on the power flow distribution of the Direct Current network is compared through a calculation example.

1. Introduction
The flexible interconnected power grid based on power electronic devices has become one of the hot issues in modern power system research due to its flexible and adaptable characteristics. The flexible interconnected power grid includes an Alternating Current system, a Direct Current system, and a voltage sourced converter (VSC) system. With the emergence of distributed power, the Direct Current system has become a research hotspot due to its high controllability and good absorbing ability. Many scholars have carried out a lot of research on this. Literature [1] introduced the Gauss Seidel method based on the grounding impedance matrix in the steady-state power flow calculation of the Direct Current grid by the alternating iteration method. Literature [2] proposed a unified Direct Current mathematical model including the entire Direct Current part, and used it in the alternating iterative algorithm to improve the calculation efficiency. Literature [3] proposed a Direct Current grid power flow calculation method considering multiple control methods, and deduced the calculation methods of power flow variables, Jacobi Matrix and network parameters under different control methods. Literature [4] proposed an Alternating Current-Direct Current network power flow algorithm considering multi-point Direct Current voltage control, but did not thoroughly analyze the specific impact of different control methods on the power flow equation. Literature [5] proposed a Direct Current power flow algorithm with a power flow controller, and mainly analyzed the influence of the introduction of a power flow controller on the parameters of the Direct Current network. Literature [6]...
proposed the Gauss Seidel method based on the nodal impedance matrix to calculate the steady-state power flow of the Direct Current grid.

Master-slave control and droop control are commonly used system-level control strategies in Direct Current transmission networks. Literature [7] designed an improved droop control. This method can correct the droop coefficient by detecting the local voltage, which can reduce the Direct Current voltage deviation when a small disturbance occurs, and can prevent the inverter from overloading when a serious fault occurs. Literature [8] proposed a hybrid control strategy and designed a 4-order hybrid controller to optimize the control effect of the Direct Current voltage. Literature [9] modified the droop coefficient by improving the optimal power flow algorithm to realize the economic operation of the Direct Current system. Literature [10] studies the operation mode of the Direct Current distribution network and the mode switching of converter stations, and proposes a method of constant voltage control of the master station and PUI control of the slave station based on the master-slave control, which can effectively solve the complicated mode switching problem. The literature [11] proposes a control strategy containing distributed energy storage participation to control energy storage to compensate voltage fluctuations and grid frequency fluctuations by deriving the voltage frequency coupling relationship between the Alternating Current and Direct Current interfaces and the cascade sag characteristics of the bidirectional Direct Current interface. Literature [12] proposed a control strategy involving distributed energy storage. By deriving the voltage-frequency coupling relationship between the Alternating Current and Direct Current interfaces and the cascading droop characteristics of the two-way Direct Current interface, the energy storage was controlled to compensate for voltage fluctuations and grid frequency fluctuations. Literature [13] proposed a self-organizing droop control considering voltage deviation and power margin. Based on the traditional droop control, considering the power margin of the converter station, constant voltage control is added, and a self-organizing update based on cellular automata is designed, which effectively improves the stability of the system. The above-mentioned documents improve the Direct Current system voltage control strategy from multiple angles, mainly focusing on droop control and master-slave control.

By establishing the mathematical model of the Direct Current network, based on the unified mathematical expressions of master-slave control and droop control, this paper derives the power flow solving equations of the Direct Current transmission network, and uses the Newton-Raphson method to solve the power flow distribution of the Direct Current network under different control modes. To study the influence of different control modes on the power flow distribution of the Direct Current network.

2. Direct Current transmission system model

2.1. Direct Current transmission system

Multiple nodes in the Direct Current transmission system are connected in parallel to a common Direct Current line to achieve power exchange. The nodes in the Direct Current transmission system can use different connection modes such as star and ring to form different topologies. A typical four-terminal ring Direct Current transmission system is shown in Figure 1. In a parallel Direct Current system composed of N converters, two commonly used system-level control modes are master-slave control and droop control.

![Fig. 1. Four-terminal ring Direct Current transmission system](image)
2.2. Master-slave control
The master-slave control method distributes the current sharing control function to each module. The parallel system includes a bidirectional Direct Current/Direct Current converter and multiple slave bidirectional Direct Current/Direct Current converters. The main bidirectional Direct Current/Direct Current converter adopts constant voltage control to stabilize the Direct Current bus voltage. The constant current control (constant power control) is adopted from the bidirectional Direct Current/Direct Current converter.

Fig. 2. Parallel control block diagram of converters adopting master-slave control strategy

Figure 2 is a block diagram of the parallel control of converters using a master-slave control strategy. In the picture, DG1 is the master bidirectional Direct Current/Direct Current converter, DG2 and DG3 are the slave converters, and LOAD is the system load.

1) Constant pressure control
Constant voltage control is generally the control strategy of the master network unit in the master-slave control structure. Stabilize the bus voltage when the Direct Current microgrid is operating in islands to ensure the stable operation of the system. Its output power is adjusted according to the load demand of the Direct Current microgrid. The micro power supply that adopts constant voltage control must be a micro power supply with dispatchable power, and has sufficient power adjustment margin when the load of the system changes. Generally, the battery energy storage system adopts constant voltage control.

Fig. 3. Block diagram of constant voltage control

Figure 3 is a block diagram of constant voltage control. The controller selects dual-loop control, electrochemical outer loop, and current inner loop. Select the side of the output voltage to the Direct Current bus as the control value. The voltage feedback value is compared with the given voltage value. The error is passed through the PI regulator, the output signal is used as the current loop reference value, the inductor current is selected as the feedback value, and the difference is passed through the PI regulator. Its output is sent to the PWM generator, and two PWM signals with opposite phases are generated to control the switch tubes respectively.

2) Constant current control
The constant current control strategy is mainly suitable for schedulable distributed sources. The bidirectional Direct Current/Direct Current converter with constant current control outputs active power according to dispatch power command, or outputs constant current according to current command. When the bidirectional Direct Current/Direct Current converter adopts constant current control, no matter how the bus voltage changes, the active power or current output by the bidirectional Direct Current/Direct Current converter will run according to the given command.
2.3. Droop control

In droop control, the relationship between the output power of each converter and the Direct Current voltage presents droop characteristics. The nodes in the system do not have a master-slave distinction. All nodes have equal status and will participate in the process of Direct Current voltage regulation and power distribution.

For the four-terminal Direct Current transmission system shown in Figure 4, the droop control is shown in Figure 5. When the power injected by a node into the Direct Current network decreases, causing the Direct Current bus voltage to decrease, other nodes will increase the output power or reduce the absorbed power according to the droop characteristics to prevent the Direct Current bus voltage from falling. Droop control is essentially a negative feedback system, which has higher reliability and flexibility compared with master-slave control.

\[
U = U_0 - KP
\]

In the formula, \( U \) and \( P \) respectively represent the Direct Current side voltage and output power of the converter; \( U_0 \) is the voltage on the Direct Current side of the converter when the output power of the converter is zero; \( K \) is the absolute value of the slope of the droop curve.

Master-slave control can be regarded as a special droop control. In order to unify the master-slave control and droop control in form, formula (1) can be rewritten as:

\[
0 = K'_c (U - U^*) + K'_p (P - P^*)
\]

In the formula, \( U^* \) and \( P^* \) respectively represent the reference voltage and reference power of the converter; \( U_0 \), \( K'_c \), \( K'_p \), satisfy relation \( U_0 = U^* + KP \) and \( K = K'_c / K'_p \).

In order to achieve system stability, the values of \( k_c \) and \( k_p \) must not be less than zero. When \( k_c = 0 \), the node is a constant power control, which is a slave node in the system; When both \( k_c \) and \( k_p \) are not 0, the node is drooping control. In a Direct Current network, there can only be at most one node as the master node to control the Direct Current voltage of the system, that is, at most there is only one converter \( k_c = 0 \).

3. Power flow calculation of multi-terminal Direct Current transmission system

Assuming that there are \( n \) nodes in the Direct Current network, after sorting, the \( n \)th node is a slack node, which controls the Direct Current voltage of the multi-terminal Direct Current system.
According to the node current relationship of the Direct Current system, the formulas can be obtained:

\[ I_{dc,i} = \sum_{j=1}^{n} Y_{dc,ij} (U_{dc,j} - U_{dc,i}) = \sum_{j=1}^{n} Y_{dc,ij} U_{dc,j} \]

\[ I_{dc,i} = \frac{P_{dc,i}}{U_{dc,i}} \]

In the formula, \( P_{dc,i} \), \( U_{dc,i} \) are the power, voltage and current at node \( i \) of the Direct Current network, \( y_{dc,i} = 1/U_{dc,i} \) is the double-circuit line resistance of the Direct Current line \( i-j \).

\[ \begin{cases} Y_{dc,ij} = -Y_{dc,ji} \\ y_{dc,i} = \sum_{j=1}^{n} y_{dc,ij}, i = 1, 2, \ldots, n \end{cases} \]

Simultaneous equations (3)(4), the power flow calculation equations based on the node current relationship are obtained as:

\[ \sum_{j=1}^{n} Y_{dc,ij} U_{dc,j} - \frac{P_{dc,j}}{U_{dc,j}} = 0 \]

First consider the case of single-point Direct Current voltage control. Since the slack node voltage is known, it does not participate in the iteration. There are \( n-1 \) equations in total. \( U_{a}, U_{a+1}, \ldots, U_{a+n-1} \) is the quantity to be demanded, \( P_{a}, P_{a+1}, \ldots, P_{a+n-1} \) is a known quantity, The Newton Raphson Method is used to solve the equations (3), and the Jacobian matrix is shown in equation (7).

\[ \begin{cases} J_{dc}(i,j) = Y_{dc,ji} + P_{dc,i} / U_{dc,i}^2 \\ J_{dc}(i,i) = Y_{dc,ij}, i \neq j \end{cases} \]

Next, consider the power flow calculation under the Direct Current voltage droop control mode. Taking the U-P curve relationship as an example, as shown in equation (6), the corresponding system power flow calculation model based on the node current relationship is shown in equation (8):

\[ P_{dc,i} = K^*_{dc,i} (U^*_{dc,i} - U_{dc,i}) + P'_{dc,i} \]

\[ \sum_{j=1}^{n} Y_{dc,ij} U_{dc,j} - K^*_{dc,i} (U^*_{dc,j} - U_{dc,j}) + P'_{dc,j} = 0 \]

In the formula, \( K \) is the droop control gain, which represents the sensitivity of the Direct Current power at node \( i \) to its Direct Current voltage. When \( K \) is 0, the node is under constant active power control, when \( K \) is large enough, the node is controlled by constant Direct Current voltage. In equation (6), the node voltage reference value \( U_{a,i}^* \) for droop control, the node power reference \( P_{a,i}^* \) can be solved by equation (4). The quantity to be sought is \( U_{a}, U_{a+1}, \ldots, U_{a+n-1} \). Using Newton Raphson's method to solve equations (8), the corresponding Jacobian matrix is shown in equation (8). After solving \( U_{a,i} \), the node power \( P_{a,i} \) can be solved according to equation (6).

\[ \begin{cases} J_{dc}(i,j) = Y_{dc,ij} + (K^*_{dc,i} U_{dc,j}^* + P'_{dc,j}) / U_{dc,j}^2 \\ J_{dc}(i,i) = Y_{dc,ij}, i \neq j \end{cases} \]

4. Example analysis
The Direct Current network in the calculation example is an eight-terminal Direct Current transmission system with a rated voltage of 400kW, and the system topology is shown in Figure 6. The impedance parameter of the overhead line is 0.0114Ω/km, and the impedance parameter of the cable is 0.0095Ω/km. The convergence accuracy \( \varepsilon \) of the power flow calculation is set to 10-12.
4.1. Power flow calculation when master-slave control is adopted

Suppose that in the master-slave control, converter 1 is the master node to control the Direct Current voltage of the system, and the other converters are slave nodes to control the output power of the Direct Current side. The initial conditions of power flow calculation are shown in Table 1, and the results of power flow calculation are shown in Table 2. The initial value of the Direct Current side voltage of each node in the system is 404kV. After 5 iterations, the power flow calculation results have converged.

Table 1. Initial conditions of power flow calculation under master-slave control

| Node | Node voltage $U^* / kV$ | Output Power $P^* / MW$ |
|------|--------------------------|-------------------------|
| 1    | 404                      | Unknown                 |
| 2    | Unknown                  | 600                     |
| 3    | Unknown                  | 1000                    |
| 4    | Unknown                  | -300                    |
| 5    | Unknown                  | 200                     |
| 6    | Unknown                  | -1500                   |
| 7    | Unknown                  | 0                       |
| 8    | Unknown                  | -1700                   |

Table 2. Power flow calculation results under master-slave control

| Node | Node voltage $U^* / kV$ | Output Power $P^* / MW$ |
|------|--------------------------|-------------------------|
| 1    | 404                      | 1769.3619               |
| 2    | 405.7876                 | 600                     |
| 3    | 406.3620                 | 1000                    |
| 4    | 404.4072                 | -300                    |
| 5    | 403.1572                 | 200                     |
| 6    | 399.5424                 | -1500                   |
| 7    | 397.2992                 | 0                       |
| 8    | 393.6064                 | -1700                   |

4.2. Power flow calculation when droop control is adopted

When using droop control, assuming that the droop coefficients of all nodes are the same, take $K_v = 1$, $K_p = 10$, the remaining parameters are the same as when the master-slave control is adopted.
The operating reference points of each node converter with droop control are shown in Table 3, and the power flow calculation results are shown in Table 4. The power flow calculation converges after 4 iterations.

### Table 3. Reference points under droop control

| Node | Node voltage $U^c / kV$ | Output Power $P^c / MW$ |
|------|--------------------------|--------------------------|
| 1    | 404                      | 1700                     |
| 2    | 404                      | 600                      |
| 3    | 404                      | 1000                     |
| 4    | 404                      | -300                     |
| 5    | 404                      | 200                      |
| 6    | 404                      | -1500                    |
| 7    | 404                      | 0                        |
| 8    | 404                      | -1700                    |

### Table 4. Power flow calculation results under droop control

| Node | Node voltage $U^c / kV$ | Output Power $P^c / MW$ |
|------|--------------------------|--------------------------|
| 1    | 405.9108                 | 1585.3584                |
| 2    | 407.0264                 | 418.4112                 |
| 3    | 407.2352                 | 805.8816                 |
| 4    | 405.4944                 | -389.6736                |
| 5    | 404.6668                 | 159.9960                 |
| 6    | 402.1396                 | -1388.3712               |
| 7    | 400.8600                 | 188.3976                 |
| 8    | 397.9836                 | -1339.0056               |

Through comparison, it can be found that in a Direct Current network formed by multiple converters in parallel, when the master-slave control is adopted, the voltage of the master node and the output power of the slave node are both given values; while the droop control is adopted, the voltages of all nodes and the output power deviates from the reference value. This is determined by the proportional relationship between the output power of the node and the voltage of the node in the droop control. Because of the impedance of the transmission line, the power flow on the transmission line makes the voltage of each node in the Direct Current system different. Although droop control has high reliability, there is a deviation in the node voltage, so the output power of the node will also deviate from the reference value. In practical applications, these two control methods can be combined to set the node that requires high output power accuracy as a slave node, using power control, and using droop control for nodes with larger spare capacity to meet applications in different scenarios demand.

### 5. Conclusion

Direct Current transmission technology plays an important role in ensuring power supply, promoting the development and utilization of renewable energy, protecting the environment, solving the unbalanced energy distribution, and improving the safety level of the power grid, etc. It has significant development potential and application prospects, and will form a hybrid Alternating Current-Direct Current power grid in the future. In this paper, the steady-state mathematical model of Direct Current network is built, and the tidal current calculation method of Direct Current network is studied by combining different control methods of converters, and the accuracy of the tidal current calculation method is verified with examples.
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