Research on Control Strategy of MMC-MTDC System based on Improved Droop Control

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Abstract. Voltage droop control is a common control strategy for multi-terminal HVDC transmission systems, while the traditional voltage droop control strategy has problems, such as large DC voltage fluctuations and unbalanced power distribution. To maintain the voltage stability of MMC-MTDC system and the power balance between the converter stations, an improved droop control strategy is proposed in this paper. The droop coefficient is designed by comparing the measured value of the multi-terminal direct-current voltage with the reference value of voltage. The four-terminal MMC-MTDC simulation model is built in PSCAD/EMTDC, and the proposed control strategy is simulated and verified under both transient and steady state conditions. The results show that the proposed control strategy can reduce the DC voltage deviation of MMC-MTDC system and improve the reliability and stability of the system. The correctness and effectiveness of the proposed method are verified.

1. Introduction

Compared with the traditional HVDC transmission system, the flexible HVDC (MMC-HVDC) system has the advantages of large transmission capacity and flexible operation \cite{1-3}. Modular Multilevel Converter based Multi-Terminal High Voltage Direct-current (MMC-MTDC) system is a parallel or series connection between multiple rectifier stations and inverters \cite{4-5}. It can realize multi-source power supply and multi-landing point power supply, and is conducive to power coordination among various converter stations. Making the system more flexible and reliable \cite{6-7}. At present, the main control strategies of MMC-MTDC system are master slave control, voltage margin control, voltage sag control and their combination control \cite{8-9}. Voltage droop control can control DC voltage at multiple converter stations at the same time, and can distribute active power in proportion to droop coefficient according to voltage deviation value. It is widely used in MMC-MTDC system.

In recent years, domestic and foreign scholars have studied the voltage droop control strategy in many aspects. It is put forward the restriction condition of droop coefficient in multi-terminal HVDC transmission system to ensure that the main control station does not enter the current limiting mode in \cite{10}, but the unreasonable setting of droop coefficient will affect the control performance, etc. Ref. \cite{11} establishes the simulation model of VSC-MTDC system and derives the adjusting range of P-U characteristic curve of droop control. Ref. \cite{12} puts forward a strategy which combined adaptive slope
control strategy with power margin control can distribute unbalanced power, but the strategy cannot control the active power flow accurately and is not benefit to the stability of the system due to the simultaneous operation of multiple converter stations in the droop slope stage. Ref. [14] proposes a voltage droop following control strategy to achieve optimal distribution of power flow and stable control of voltage, however it exists the problem that this strategy does not consider the fault of the system.

The core of voltage sag control strategy is to design the coefficient of voltage droop, which may weaken control ability of direct-current voltage if it is unreasonable. Therefore, an improved droop control strategy is put forward to solve effectively the above problems in this paper. A simulation model of four-terminal MMC-MTDC system is built in PSCAD/EMTDC platform. Then the simulation experiments are carried out under steady and transient conditions respectively. The result shows the effectiveness and feasibility of the control strategy.

2. MMC-MTDC system structure

2.1. MMC topological structure

The structure of the inverter side of the MMC type HVDC transmission system is shown in Fig. 1.

Fig. 1. Reverse side structure diagram of MMC HVDC

2.2. MMC mathematical model

According to Kirchhoff’s voltage law (KVL), the mathematical model of MMC basic unit in abc coordinate system is:

\[
\begin{align*}
L \frac{d i_a}{dt} + R_i i_a &= v_a - u_d \\
L \frac{d i_b}{dt} + R_i i_b &= v_b - u_q \\
L \frac{d i_c}{dt} + R_i i_c &= v_c - u_q
\end{align*}
\]

where:

\[v_j = \frac{(u_{aj} - u_{pj})}{2}, \quad j = a, b, c\] (2)

Among them, \(I_0\), which is the AC side arm’s inductance, is given by \(L_0 = 2L\). \(R_0\), which is the arm’s resistance, is given by \(R_0 = 2R\). \(u_{aj}\) and \(u_{aj}\) are respectively bridge arm voltages composed of all sub modules of the upper arm and lower arm of the same bridge arm. \(i_a\), \(i_b\), \(i_c\) are respectively the phase current of the three phases a, b and c.

The formula (1) transformed into dq coordinate system is as follows:

\[
\begin{align*}
L \frac{di_d}{dt} &= -R_i i_d + \omega L i_q + v_d - u_d \\
L \frac{di_q}{dt} &= -R_i i_q - \omega L i_d + v_q - u_q \quad (3)
\end{align*}
\]
Where, $\omega$ is the angular frequency; $i_d$, $i_q$, $u_d$ and $u_q$ are respectively the d-axis and q-axis current and voltage components of AC equivalent inductance in the dq coordinates.

According to the theory of instantaneous reactive power, The DC components of active and reactive power fed into MMC of AC system at steady state can be expressed as:

$$
\begin{align*}
\bar{P} &= 1.5u_d i_d \\
\bar{Q} &= -1.5u_d i_q
\end{align*}
$$

(4)

2.3. MTDC topological structure

At present, MMC-MTDC is mainly connected in series and parallel. The parallel topology is beneficial to the regulating operation of the whole system and easy to extend, so this paper adopts parallel connection. The topological graph of the four-terminal MMC-MTDC system is shown in Fig. 2.

![Fig. 2. The four-terminal MMC-MTDC](image)

Where, MMC1 is the sender converter station, which inputs the power to the DC system; MMC2, MMC3 and MMC4 are the recipient converter stations, which outputs the power of the DC system to the AC system. The structure of the topology is simple and easy to expand. The four converter stations have two-way power transmission capability, which can realize coordinated power control.

3. MMC-MTDC control strategy

The outer loop control of MMC-MTDC controller mainly includes constant DC voltage control, constant DC power control and droop control. Droop control is realized through the relationship between direct-current power and direct-current voltage of each converter.

3.1. Traditional droop control strategy

The DC voltage control and the DC power control are mutually restricted so that DC voltage and DC power cannot simultaneously reach an optimum state when the droop control is put to use. The droop control characteristic and droop control block diagram is shown in Fig.3.

![Fig. 3. droop controller](image)

Where, $U_{ref}$ and $P_{ref}$ are respectively the reference values of direct-current voltage and direct-current power of the converter station. $U_{dc}$ and $P$ are respectively the measured values of direct-current
voltage and direct-current power of the converter station. As shown in Fig. a), the direct-current voltage and export power of the converter station are linearly related, and the slope of the control curve is $-1/K_p$. $K_p$ is the droop gain of the droop controller in Fig. b). As shown in Fig. 3, the error signal of the droop on the DC side can be expressed as:

$$e = P_{dc} - P + K_p(U_{dref} - U_{dc})$$

In the steady-state case, if the droop coefficient is small, the DC voltage quality is better, but the DC power will deviate from its reference value, resulting in low utilization rate of DC network transmission capacity. If the droop coefficient is large, the DC power distribution characteristic is better, but the DC voltage deviation value is larger, resulting in low DC voltage quality. Moreover, when the droop coefficient is constant, the system has the better control effect in a small interval, and weakens the control ability of DC voltage or DC power in most other intervals. Because of the above droop characteristics, the system cannot control the DC power and DC voltage of converter station better in traditional sag control. Therefore, an modified sag control strategy is put forward in paper.

### 3.2. Improved droop control strategy

The primary frequency modulation of the generator in the ac system is realized by the speed regulation system of the prime motor. The static frequency characteristic of the generator is approximately a straight line, namely:

$$K_o = -\Delta P_o / \Delta f$$

Where, $K_o$ is the unit adjustment power of the generator.

Due to the voltage drop loss of the long-distance transmission line, the DC voltage at each end of the converter station will be different in the MTDC systems. While in the AC system, if the frequency changes, the generator will adjust the $K_o$ according to the respective power. Referring to AC system, the voltage droop coefficient is designed by using the difference between the reference value of the terminal voltage and the average value of the actual measured value of each terminal voltage in the MMC-MTDC system. When the voltage drops, the output power of the receiving system will be reduced and the power injection of the sending system will be increased, so the power of the system can reach the equilibrium state again, and vice versa. The power of each converter station can be changed according to the DC voltage droop coefficient of each station, and the power of each station can be balanced without communication coordination. The improved voltage droop controller designed in this paper is shown in Fig. 4.

$U_{dref}$, $U_{dact}$ are respectively the actual measured voltage for each converter station. $K_{dact}$ is the droop coefficient of each converter station. The droop controller regards the average DC voltage of each converter station as the common direct-current reference voltage. When the voltage deviation occurs, the droop error signal of the DC side of each converter station can be adjusted in time, and responded in time when the power imbalance occurs in the system.

![Fig. 4. The structure of improved voltage droop controller](image-url)

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4. Simulation Study

4.1. simulation model
To validate the validities of the proposed control strategy, a simulation model of four-terminal MMC-MTDC system is built in PSCAD/EMTDC environment as shown in Fig. 1. The MMC modulation mode is the nearest level modulation. The input of the sub-module is selected by sequencing method, and the bridge arm circulation is restrained by using the circulation restraint strategy. The parameters of four-terminal MMC-MTDC system are designed as follows: converter station MMC1 is a constant DC voltage control mode, wherein \[ U_{dc} = 320kV \]; MMC2 and MMC3 are improved voltage droop control mode, and MMC4 works in a constant power mode. Bridge arm reactance and bridge arm resistance are given by \[ L = 2mH, R = 0.1\Omega \], respectively. DC side capacitance of converter station is given by \[ C = 10mF \]; maximum capacity of MMC1, MMC2, MMC3 and MMC4 are 400 MW, 200 MW, 200 MW and 300 MW, respectively. Where, MMC1 is the dominant station. In this paper, the steady-state power flow inversion and main converter station failure out of operation are simulated and validated respectively. The simulation waveforms of the system under traditional droop control and improved voltage droop control are compared.

4.2. Analysis of simulation results
Example 1: steady state
In MMC-MTDC system, the reference value of active power of MMC1, MMC2, MMC3 and MMC4 are 300 MW, 100 MW, -150 MW and -250 MW, respectively.

Fig. 5 shows the simulation waveforms under two control modes in steady state. Fig. a) and b) respectively show the active power waveforms under the conventional voltage sag control and the improved voltage sag control, while Fig. c) and Fig. d) respectively show the DC side voltage waveforms under the traditional voltage droop control and the improved voltage droop control. As can be seen from Fig. 5, the power deviation was assumed by MMC1 and the active power changes from 300MW to 200MW, while the power of MMC2 station remains unchanged when the active power of MMC3 changes from -150mw to -50mw at the time of 4s. At 6s, the power of MMC2 station turns over, and the active power changes from 100MW to -50mw, so the active power of MMC1 station increases from 200MW to 350MW. Compared with Fig. a), b), c) and d), the active power of MMC4 station increased, and the DC side voltage increased by 11 kV under the conventional voltage droop control, while the active power of MMC4 station remained unchanged, and the DC voltage increased by only 2 kV under the improved voltage sag control.

Therefore, compared with the conventional voltage droop control strategy, the power deviation is assumed by the primary station under the improved voltage droop control strategy, and the direct-current side voltage fluctuation of the system is smaller and the control precision is higher.
Example 2: main station exit operation in transient state
In the initial operation state of MMC-MTDC system, the active power reference values of MMC1, MMC2, MMC3 and MMC4 are 200MW, 100MW, -150mw and -150mw respectively. Fig. 6 shows the simulation waveforms under two control modes in the transient state. Fig. a) and b) respectively show the active power waveforms under the conventional voltage sag control and the improved voltage droop control, while Fig. c) and d) respectively show the DC side voltage waveforms under the traditional voltage droop control and the improved voltage droop control.

When the main station MMC1 exits operation at 4s, the power deviation is shared by MMC2 and MMC3. Compared with Fig. a) and b), the active power of MMC4 increases slightly, and the system enters stable operation after 0.5s under traditional voltage droop control. While the power of MMC4 remains unchanged, and the system has reached the state of balance after 0.3s. Also the DC side voltage of the system decreases by 12kV under traditional voltage sag control, however the direct-current side voltage of the system has decreased by 8kV under the improved voltage sag control.

In contrast to the conventional voltage droop control strategy, the system has a short time to stabilize and a small voltage fluctuation under the improved droop control strategy.

5. Conclusion
Aiming at the problems of large fluctuation of DC voltage and unbalanced power distribution in transient and steady state of MMC-MTDC system, an improved droop control strategy is proposed. A four-terminal MMC-MTDC system model is built in PSCAD/EMTDC for simulation and verification.
The results show that the control strategy can be used in steady-state power flow reversal. The system has a shorter time to stabilize, smaller voltage fluctuation and faster response speed. When the main station exits operation, the active power can be reasonably allocated to ensure the normal operation of the system.

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