Research on MMC-IDCPFC Control Strategy for Multi-terminal Flexible HVDC Transmission System

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Keywords: MMC-MTDC, Multi-terminal AC/DC hybrid network, Power flow control, Improved droop-control strategy.

Abstract. To solve the problem of grid connected and large-scale green and clean energy accommodation, flexible AC/DC transmission technology has become a research hotspot in recent years, and power flow control in DC network is a major problem. In this paper, A novel adaptive DC voltage droop control strategy based on MMC-IDCPFC for multi-terminal flexible HVDC transmission system is proposed. The integral loop is introduced into the droop control to realize the effective control of the power flow of the DC system by MMC-IDCPFC. Finally, a three-terminal MMC-HVDC system based on MMC-IDCPFC is built on PSCAD/EMTDC simulation platform, and the simulation results show that the proposed control strategy is correct and effective.

Introduction

In recent years, with the vigorous development and efficient utilization of green and clean energy, multi-terminal HVDC transmission technology with the characteristics of long transmission distance, large transmission capacity and flexible operation mode becomes one of the effective technical to solve the problem of large-scale clean energy grid-connected and absorption \cite{1}. DC power grid technology is at the initial stage of development, there are still many problems to be solved by experts and scholars at home and abroad. And, with the increase of the number of nodes in the DC power grid and the complexity of the network structure, the power flow control in the DC network becomes a major problem. Researchers use DC power flow controller to achieve the power flow control in the DC system by MMC-IDCPFC. Finally, a three-terminal MMC-HVDC system based on MMC-IDCPFC is built on PSCAD/EMTDC simulation platform, and the simulation results show that the proposed control strategy is correct and effective.
IDCPFC circuit topology are proposed, and a single ring control strategy is adopted. In [10-11], a three-terminal DC power flow controller based on MMC is shown, and the topology is given out, but the detailed control strategy is not shown.

The IDCPFC achieves DC line voltage stability and reasonable power distribution. At present, there are three main DC voltage control strategies in flexible HVDC transmission system: master-slave control, voltage margin control and droop control. The master-slave control strategy requires communication between converter stations. The voltage margin control strategy is easy to cause power oscillation due to improper margin setting. The droop control strategy achieves DC line voltage stability according to the slope relationship between the power, current, frequency and voltage given by the converter station \([12-16]\). Wu Jie and Wang Zhixin put forward a smooth switching control mode for the system after transient fault by using backstepping method to design a nonlinear controller in \([16]\). Liu Yuchao, Wu Jian, Liu Huaiyuan, et al. show an adaptive droop control strategy for power sharing, which adaptively adjusts the droop coefficient according to its own power in \([17]\).

In \([18-19]\), an optimal droop control strategy considering line loss and power margin of converter stations is proposed. Li Peng, Li Xinning, Chen Anwei et al. put forward an adaptive control strategy for adjusting droop coefficient according to different power margins of converters, which aims at minimizing the operation loss of HVDC transmission system \([20]\). In \([21]\), an improved droop control strategy by introducing a power influence factor and adaptively changing the droop coefficient is proposed.

In the traditional droop control strategy, the difference, which is the output of the PI regulator, between the electrical measured value and the reference value is one of the input values of the inner loop controller. Also, it is difficult to achieve the DC voltage or power without static adjustment \([14]\). Moreover, in the complex conditions of the large-scale MTDC system, because the droop coefficient of the traditional droop control is constant, it reduce the flexibility and economy of the system. In the adaptive droop control strategy, the selection of the drooping coefficient of the converter station is generally inverse proportion to the capacity of the converter station \([13]\).

The aim of this paper is to propose a novel DC voltage adaptive droop control strategy to realize the effective control of power flow in DC system by MMC-IDCPFC. Firstly, the topological structure and working principle of MMC-IDCPFC are given. On this basis, the integral loop is introduced into the droop controller to adjust the droop coefficient adaptively. Finally, a three-terminal DC power grid is built in the PSCAD/EMTDC simulation software, and IDCPFC is installed in the DC network, and verify the proposed control strategy by simulation.

**MMC-IDCPFC Topology and Its Working Principle**

According to the structural characteristics of flexible DC power grid, among the three proposed DC power flow controllers (including series variable resistors, DC-DC converters, series variable voltage sources and new type of DC power flow controllers based on MMC), the interline DC power flow controller based on MMC realize the DC power flow control as well as the internal power balance of IDCPFC. It does not need to take energy from the external large AC system and save the cost of energy acquisition and insulation.

**MMC Topological Structure**

MMC is one of the popular topologies in HVDC transmission systems in recent years. Figure.1 shows the topology of converter MMC. Each bridge arm consists of \(N\) sub-modules (SM), equivalent resistance \(R_0\) and equivalent reactor \(L_0\). The upper and lower two symmetrical arms constitute a phase unit, each SM consists of two IGBT \((T_1, T_2)\), two single-phase parallel diodes \((D_1, D_2)\) and a capacitor \(C_0\).

In the figure, \(u_s\) is the capacitance voltage of the sub-module, \(u_{sm}\) and \(i_{sm}\) are the output voltage and current of the single sub-module, respectively. \(u_{cj}\) and \(i_{cj}\) \((j=a, b, c)\) are the voltage and current
on the AC side of MMC, respectively. $i_{pj}$ and $i_{nj}$ are the flowing current of the upper and lower arms of each phase (subscript p indicates the upper arm and subscript n indicates the lower arm), $U_{dc}$ and $I_{dc}$ are the voltage and current on the DC side of MMC.

$$i_{pj} = \frac{I_{dc}}{3} + \frac{i_{cj}}{2}$$
$$i_{nj} = \frac{I_{dc}}{3} - \frac{i_{cj}}{2}$$

the voltage on the DC side is:

$$U_{dc} = u_{pj} + u_{nj}$$

The KVL equation is applied to the upper and lower arm respectively.

$$u_{cj} - \left( \frac{U_{dc}}{2} - u_{pj} \right) = L_0 \frac{di_{pj}}{dt} + R_0 i_{pj}$$
$$u_{cj} - (u_{nj} - \frac{U_{dc}}{2}) = L_0 \frac{di_{nj}}{dt} + R_0 i_{nj}$$

**MMC-IDCPFC Topological Structure**

The topology of MMC-IDCPFC is shown in Figure 2. The MMC-IDCPFC is installed at MMC1 of three-terminal HVDC transmission system, including two converter stations (A, B) and an AC transformer. The DC side of the MMCA and MMCB are connected to $l_{13}$ and $l_{12}$, and the AC side is connected by a transformer. In the three-terminal HVDC transmission system, the ring network is connected by bipolar wiring, MMC1 is a constant DC voltage control mode, and both MMC2 and MMC3 adopt a constant power control mode. Modular multilevel converters are cascaded by half-bridge sub-modules. The DC line of the three-terminal flexible DC transmission system uses the same DC cable, the AC side voltage is 230kv, and the DC side voltage is 340kv.
Figure 2. Topology structure of MMC-IDCPFC.

**MMC-IDCPFC Working Principle**

According to the system structure in Figure 2, the power flow distribution of the HVDC system is as follows:

\[
\begin{align*}
I_{12} &= \frac{U_2 - U_1 - U_B}{R_{12}} \\
I_{13} &= \frac{U_3 - U_1 - U_A}{R_{13}} \\
I_{23} &= \frac{U_3 - U_2}{R_{23}}
\end{align*}
\]  
(4)

\[
\begin{align*}
P_{12} &= U_2 I_{12} = U_2 \frac{U_2 - U_1 - U_B}{R_{12}} \\
P_{13} &= U_3 I_{13} = U_3 \frac{U_3 - U_1 - U_A}{R_{13}} \\
P_{23} &= U_3 I_{23} = U_3 \frac{U_3 - U_2}{R_{23}}
\end{align*}
\]  
(5)

\[
\begin{align*}
P_1 &= U_1 (I_{12} + I_{13}) = U_1 \left( \frac{U_2 - U_1 - U_B}{R_{12}} + \frac{U_3 - U_1 - U_A}{R_{13}} \right) \\
P_2 &= U_2 (I_{23} - I_{12}) = U_2 \left( \frac{U_3 - U_2}{R_{23}} - \frac{U_2 - U_1 - U_B}{R_{12}} \right) \\
P_3 &= U_3 (I_{13} + I_{23}) = U_3 \left( \frac{U_3 - U_1 - U_A}{R_{13}} + \frac{U_3 - U_2}{R_{23}} \right)
\end{align*}
\]  
(6)

Where, \(I_{12}, I_{13}\) and \(I_{23}\) are current of \(I_{12}, I_{13}\) and \(I_{23}\); \(U_1, U_2\) and \(U_3\) are the node voltage for converter stations of DC system; \(U_A, U_B\) are the voltage for MMC-IDCPFC on line \(I_{13}\) and \(I_{12}\).
$R_{12}, R_{13}$ and $R_{23}$ are the resistance for DC lines; $P_{12}, P_{13}$ and $P_{23}$ are the power for DC lines; $P_1, P_2$ and $P_3$ are the output or input power for converter stations.

Formula (5) shows that the voltage values of the 2th and 3th converter stations can be adjusted by controlling the $U_A$ and $U_B$ of the MMC-IDCPFC, and the magnitude and direction of $I_{12}, I_{13}$ and $I_{23}$ on the DC line be changed, then the power flow of the system be controlled.

**Control Strategy of MMC-IDCPFC**

Control strategy is the key problem of MMC-IDCPFC, which is essential for the stable operation of MMC-IDCPFC and the effective control of power flow.

The MMC converter control active and reactive power independently, the two stations in MMC-IDCPFC can be rectified or inverted. In this paper, MMC-IDCPFC adopts an improved adaptive droop control strategy. In the traditional droop control strategy, the droop coefficient $k_{droops}$ is given in advance, such as

$$k_{droops} = \frac{\Delta P_s}{\Delta U_{dcs}}$$  \hspace{1cm} (7)

Where, $\Delta P_s$ and $\Delta U_{dcs}$ are the power deviation and DC voltage deviation of MMC, they are given in advance according to the requirements of the system. The fluctuation range of the DC voltage is generally 5% of the rated voltage $U_{dcref}$ of the HVDC transmission system.

$$\Delta U_{dc} = U_{dcref} \times 5\%$$  \hspace{1cm} (8)

The droop coefficient of traditional droop control is pre-determined, and it is not flexible. To solve this problem, an improved adaptive droop control strategy is proposed. The droop controller adjusts the droop coefficient $k_{droop}$ in real time according to the active power and the instantaneous value of the DC side voltage, and the relationship can be expressed as shown in equation (9):

$$P_m - P_{ref} = k_{droop} \left( U_{dcm} - U_{dcref} \right)$$  \hspace{1cm} (9)

Where, $U_{dcm}$, $U_{ref}$ are the actual measured value and reference value of DC voltage for converter stations; $P_m$, $P_{ref}$ are the actual measured value and reference value of power for converter stations.

A structural diagram of the improved adaptive droop control strategy of the MMC-IDCPFC is shown in Figure 3. For droop coefficient, the slow-changing characteristic of the integrator is used to obtain the smooth curve of the droop coefficient $k_{droop}$, thereby the adaptive non-error adjustment of droop control is realized.

![Figure 3. Improved adaptive droop control strategy.](image-url)
Where, $\Delta U_1$ and $\Delta U_2$ represent the difference between the instantaneous value and the given value of DC side voltage before and after correction, respectively. $k_{\text{droop}1}$ is the real-time droop coefficient obtained from the instantaneous and given values of active power and DC side voltage. $I$ is the integrator proposed in this paper. The integrator integrates time-varying droop coefficients, and the droop coefficients $k_{\text{droop}}$ is revised.

As shown in Figure.3, when the improved adaptive droop control strategy is introduced, the deviation value $\Delta$ of the input PI controller becomes:

$$\Delta = U_{\text{dcm}} - U_{\text{dcref}} + k_i \int \left( \frac{P_m - P_{\text{ref}}}{k_{\text{droop}}} \right) dt$$

(10)

Where, $k_i$ is the integral parameters introduced, then

$$I_{d_{\text{-ref}}} = k_{p_c} \Delta + k_{i_c} \int \Delta dt$$

(11)

Where, $I_{d_{\text{-ref}}}$ is the current component of the d axis; $k_{p_c}$ and $k_{i_c}$ are the proportional and integral parameters of the PI controller, respectively.

Simulation Experiment

To verify the effectiveness of the control strategy proposed in this paper, a three-terminal HVDC transmission system with MMC-IDCPFC, which shown in Fig.2, is built on the PSCAD/EMTDC simulation platform. The length of each line are $l_{13} = 100km$, $l_{12} = 100km$ and $l_{23} = 50km$. In the model, MMC1 is the main station, which adopts constant DC voltage control; MMC2 and MMC3 use constant power control; MMCA and MMCB are the A and B stations of the DC power flow controller between the lines, which adopt the traditional droop control strategy and the improved adaptive droop control strategy proposed, respectively. Two converter stations of MMC-IDCPFC adopt the same parameters, part of parameters are shown in Table 1.

The system operates for a total of 10 seconds. At 2.5th seconds, the MMC-IDCPFC is put to the three-terminal HVDC transmission system. At 5th seconds, the converter MMC2 DC line side adds 500MW load.

### Table 1. Parameters of MMC.

| Name                         | Value  |
|------------------------------|--------|
| Sampling period $T_S/\mu s$  | 50     |
| AC side voltage $U_S/Kv$     | 230    |
| DC side voltage $U_{dc}/Kv$  | 340    |
| Sub module capacitance $C_0/mF$ | 13  |
| Sub module capacitor voltage $U_c/kV$ | 16 |
| Bridge arm inductor $L_0/mF$ | 12    |
| The number of sub modules in a single bridge arm $N$ | 20 |

The simulation waveforms of the traditional droop control strategy and the improved adaptive droop control strategy of MMC-IDCPFC are compared.

Figure 4 shows the DC voltage simulation waveforms of MMC-IDCPFC with traditional droop control strategy and improved adaptive droop control strategy proposed. Comparing the two waveforms, it is obvious that the improved adaptive droop control strategy proposed has smaller DC voltage fluctuation and faster stabilization than the traditional droop control strategy.
Figure 4. DC voltage.

Figure 5 shows the DC power simulation waveform of the installed MMC-IDCPFC using the traditional droop control strategy and the improved droop control strategy proposed in the paper. Figure 5(a) shows the DC side active power using the traditional droop control strategy, and after loading, it is slightly upturned and not stable. Figure (b) is the DC side active power using the improved droop control strategy proposed in this paper. The power waveform remains stable after the load is applied.

Comparing the results of two simulation verifications, the improved droop control strategy proposed in the paper is compared with the traditional droop control strategy, the system stability is better, and the system trend can be more smoothly and quickly controlled.

Conclusion

In this paper, a three-terminal MMC-HVDC system based on MMC-IDCPFC is built on the PSCAD/EMTDC simulation platform. The traditional droop control strategy and the improved adaptive droop control strategy are simulated and compared in MMC-IDCPFC system. The results of two simulation calculations show that the smoothness of the droop coefficient changes after the introduction of the integrating link, and the power flow is controlled more smoothly and quickly. The correctness and effectiveness of the proposed control strategy are verified. The research results of this paper provide reference for the study of power flow control between AC and DC networks in MMC-MTDC transmission system.

Acknowledgement

This research was financially supported by the National Natural Science Fund Project (51567016).

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