Combination strategy of DC power flow controller for multi-terminal HVDC system

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Abstract: The insertion of DC power-flow controller (DC-PFC) in the DC grid can increase the control dimension of the DC current and improve the active power distribution and coordination control of DC grid. In this study, the combined application of DC-PFC for multi-terminal HVDC system has been proposed. Based on the analysis of existing DC-PFC, it shows that the two combined application structures of DC-PFCs can achieve multi-objective power-flow control and increase the control dimension with greater flexibility. Also, a composite DC-PFC is proposed to obtain the completely decoupled power-flow control. A simulation mode is built to test the feasibility and effectiveness of the proposed composite DC-PFC.

1 Introduction

Voltage-source converter-based high-voltage direct current (VSC-HVDC) has increasingly played an important role in the large-capacity long-distance power transmission, large-scale renewable energy generation and other fields and become an important technical means to build a strong smart grid in China [1–3]. Multi-terminal flexible DC transmission network based on the voltage source converter can effectively solve the problems including the large-scale distributed renewable energy access and marine wind farm cluster and so on [4]. For complex multi-terminal DC transmission system, the lack of active power distribution and coordination control in any one line may be caused because the number of DC lines is often greater than the number of converter stations. Scholars have proposed that the insertion of DC power-flow controller (DC-PFC) in the DC grid can increase the control dimension of the DC power flow to achieve the power flow control of each line.

The line power flow in the DC grid is only decided by the line resistance and the line terminal voltage. Therefore, the power flow of the DC power network must be changed by changing the line resistance and the terminal voltage. The approaches of inserting variable resistance (VR) in a transmission line are proposed with simpler topology and control strategy in [5, 6]. VR is equivalent to increase the equivalent resistance of transmission lines, but with the shortcomings of a large loss and single direction power-flow adjustment.

On the other hand, the methods of adjusting the terminal voltage in DC grid involve the DC transformer, series adjustable voltage, and interline DC-PFC (IDC-PFC). The input and output sides of DC transformer are connected to both positive and negative polarity lines of different voltage levels of DC grid and that is equivalent to the condition that a series adjustable voltage source (SAVS) in transmission line changes the line power flow [7]. However, the equipment needs to withstand system-level voltage, which means design complexity and high cost. In [8–11], a SAVSs in the positive or negative polarity line are proposed to adjust the transmission line power flow. The device is only required to withstand lower voltage levels and power levels, but the external power source is necessary.

In [5], an IDC-PFC is proposed, which uses capacitance as the energy transfer hub to transfer one part of the power from one transmission line to the other transmission line. IDC-PFC can achieve power-flow control of two transmissions without external power source by the power exchange between two lines. In [12], IDC-PFC is simplified for topology, circuit modelling, and control strategy. However, the working principle of the circuit is equivalent to a voltage source frequency stringed and bypassed in the line, which will cause the problem of larger voltage ripple. In [13], an inductance as the energy transfer hub for a novel IDC-PFC is proposed, and the way of inserting capacitance into the line can reduce the voltage ripple greatly. In [14], the introduction of coupling inductance into the novel IDC-PFC makes it suitable for the situation of line power flow reversal occasions so as to meet the needs of different power flow direction occasions. However, IDC-PFC as a DC-PFC focusing on regulating two lines’ current, can only control one line’s current actively when the other line’s current is in passive control. Thus, IDC-PFC cannot take the initiative to control the current at the same time and the application is obviously limited.

In this paper, combination strategy of DC-PFC is proposed to increase the power-flow control dimension so as to achieve the system-level control for the multi-terminal HVDC grid. This paper takes the three-terminal DC transmission system as an example, analyses the degree of increasing power-flow control dimension and transmission loss through the combination of IDC-PFC. A completely decoupled novel DC-PFC which can control two lines’ current is thus proposed.

2 IDC-PFC function defect analysis

In order to illustrate the working principle of IDC-PFC, a typical ring-type three-terminal bipolar VSC-MTDC system is adopted as background to join IDC-PFC. The equivalent circuit is shown in Fig. 1. As shown in Fig. 1, VSC1 and VSC2 as power generation side transfer power to VSC3. IDC-PFC as power-flow controller device should be placed in the terminal VSC3 so as to be easy for installation and detection. This paper only analyses the IDC-PFC installed in the positive polarity circuit because of the
3 Combination strategy of DC-PFCs

In order to cope with various power flows with possible conditions, the aim of the power-flow controller is to adjust the DC power flow flexibly so as to achieve safe transmission and reduce the transmission power loss. To achieve fast, flexible and high-dimensional DC power-flow control, the combination of different DC-PFCs is required.

The three-terminal VSC-HVDC system in this paper has the same parameters as in [13] in order to be easy to compare the DC power-flow control performance. VSC1 and VSC2 are the constant power converters, and VSC3 is the constant voltage converter. Specific parameters are shown in Table 1.

From the analysis above, a single existing DC-PFC can only control the current of one transmission line. The solution to controlling the current of more lines is the combination of DC-PFCs. The power flow control dimensionality can increase when the number of DC-PFCs increases. That is, the multiple DC-PFC combinations can control the current of multiple lines. If IDC-PFC makes the current of one line increase more, VR in the corresponding line can be used to make the current lower or constant. If IDC-PFC makes the current of one line increase less, VR in the other line can be used to make the current lower or constant. Thus, the combination of DC-PFC can effectively compensate for the shortcomings of a single IDC-PFC since it can achieve the control of multiple lines and improve the flexibility and the security of the transmission power grid.

3.1 Combination of VR and IDC-PFC

The equivalent function of IDC-PFC is a series positive voltage source in one line and a series negative voltage source in the other line. That means a series positive resistance in one line and a series negative resistance in the other line. Inserting VR into transmission line is equivalent to a series positive resistance in a transmission line. IDC-PFC and VR are 1D DC-PFCs. The combination use of IDC-PFC and VR can actively change the equivalent resistance of two lines so as to control the current of two lines actively.

According to the topological characteristics of IDC-PFC, two adjustable VRs are inserted into the two lines of VSC. The structure of interline DC power-flow combination controller (IDC-PFCC) is shown in Fig. 3. Two VRs are in series with IDC-PFC. Its topology of combination application is shown in Fig. 4 based on [6, 13]. IDC-PFCC is still placed in the DC terminal of VSC3.

IDC-PFC can actively control the current of one line and IDC-PFCC can actively control the current of two lines. By adjusting the duty cycle of VR and IDC-PFC, the current of two lines is

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Table 1 Parameters of VSC-HVDC system

| Cable parameter   | Line1         | Line2         | Line3         |
|-------------------|---------------|---------------|---------------|
| length, km        | 200           | 300           | 100           |
| resistance, Ω     | 5              | 3             | 1             |
| inductance, mH     | 80             | 120           | 40            |
| VSC parameters    | P1 = 160 kW   | P2 = 80 kW    | V1 = 150 kW   |

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controlled. The power flow equation (1) of the three-terminal VSC-HVDC can be formed according to Fig. 2, where $P_3$, $P_2$, $P_1$ are the power rates of VSC1, VSC2, VSC3, respectively, $R_x$ and $R_y$ are the equivalent resistances of VRs in lines 2 and 3.

The IDC-PFC adopts port voltage control mode. When IDC-PFC transfers the power from lines 2 to 3, $V_{3y}$ is controlled. When IDC-PFC transfers the power from lines 3 to 2, $V_{3x}$ is controlled. The curves of $I_{1x}$, $I_{3x}$, $I_{2x}$ versus $V_{3x}$ and $V_{3y}$ can be calculated by

$$
\begin{align*}
V_1 - V_3 &= I_{13}(R_{13} + R_x) - V_{3y} \\
V_1 - V_2 &= I_{12}R_{12} \\
V_1 - V_3 &= I_{32}(R_{13} + R_x) + V_{3x} \\
V_{3y} = V_{3y} \\
I_x &= I_{12} + I_{3x} \\
I_y &= I_{23} - I_{12}
\end{align*}
$$

(1)

The characteristic curves of different power flow as $R_x$ or $R_y$ are 0, 0.5, 1, 1.5, 2 Ω shown in Fig. 5. In Fig. 5, the value range of $V_{3x}$ is $[0.6 \text{kV}]$, and $V_{3y}$ is in the range of $[-4 \text{kV}, 0]$. Firstly, the working principle is analysed when VRs are bypassed. It can be seen from Fig. 5 when the power is transferred from lines 2 to 3, $I_{12}$ and $I_{13}$ increase with the increase of $|V_{3y}|$. $I_{13}$ decreases with the increase of $|V_{3y}|$. When $|V_{3y}| = 3.6 \text{kV}, I_{13} = 0$, $I_{13}$ will be reversed if $|V_{3y}|$ continues to increase, i.e. the circulatory phenomenon will occur in the three-terminal VSC-HVDC system. So the working range of $V_{3y}$ is $[-3.6 \text{kV}, 0]$. Similarly, when $V_{3x}$ is $>4.5 \text{kV}$, $I_{12}$ and $I_{13}$ are reversed, and the circulatory phenomenon will happen. So the working range of $V_{3x}$ is $[0, 5.4 \text{kV}]$.

After the introduction of VR, the theoretical range of $V_{3x}$ and $V_{3y}$ will change. When $R_y$ works, the zero crossing of line 2 remains unchanged, and the absolute value of zero crossings in the lines 1 and 3 are larger; when $R_x$ is in operation, the zero crossing of line 3 remains unchanged, and the absolute value of zero crossings in lines 1 and 2 is larger. So when each line in series with VR for the different values, the zero crossings of the corresponding line remains unchanged. Then, the current is zero, and the voltage of the resistance is zero, which is equivalent to short-circuit. However, when the zero crossings of the non-corresponding lines changes, the absolute value of zero crossings all increases, thus leading to a larger work range of $V_{3x}$ and $V_{3y}$.

Compared with Figs. 5a and b, when the power is transmitted from lines 2 to 3 ($V_{3y}$ is negative), the current of three lines is more sensitive to the change of $R_x$; when the power is transmitted from lines 3 to 2 ($V_{3x}$ is positive), the current of three lines is more sensitive to the change of $R_y$. Inspired by this conclusion, this paper proposes a new control strategy of IDC-PFCC, i.e. the application of corresponding VR in different lines according to the need of power direction, which can adjust the current flexibly and improve the security of power-flow control.

3.2 Control strategy of IDC-PFCC

As shown in Fig. 6, the new characteristic curve can be generated by superimposing the curve of $R_x$ when $V_{3x}$ is positive and the curve of $R_y$ when $V_{3y}$ is positive. It can be seen from Fig. 6 that the combination of variable resistor and IDC-PFCC greatly improves the flexibility of DC grid power-flow control. As shown in Fig. 6, $I_{12}$, $I_{13}$, $I_{23}$ can be, respectively, $[-0.195 \text{kA}, 0]$, $[0, 1.240 \text{kA}]$, $[0, 0.326 \text{kA}]$ by adjusting the duty cycle of VR when $V_{3x}$ is 3 kV. The absolute value of the current curve slope of $I_{13}$ and $I_{23}$
can be decreased when increasing the \( R_y \) and \( R_x \), thus leading to the increase of the absolute value of zero crossings of \( I_{13} \) and \( I_{23} \). Therefore, the working range of IDC-PFCC is no longer limited. The circulation phenomenon can be avoided by increasing \( R_y \) and \( R_x \), which makes the transmission network more secure.

It can be assumed that the current of the transmission line cannot be >1.25 kA. In Fig. 6, when \( V_{S3} \) or \( V_{S3}^{\prime} \) increases to 3.06 kV or 1.36 kV, the value of \( I_{13} \) or \( I_{23} \) reaches 1.25 kA. VR is used and \( I_{13} \) or \( I_{23} \) is kept at 1.25 kA while continuing to increase \(|V_{S3}|\) or \(|V_{S3}^{\prime}|\), whose operating points are shown in Tables 2 and 3.

In terms of control strategy [6, 13], IDC-PFC adopts the mode of controlling the voltage, and VR adopts the mode of controlling the current. Integration of both parts of work promises the security of the system. IDC-PFCC can not only be used as a protection device for transmission lines, but also as a two-line DC-PFC. In Tables 2 and 3, the data indicates IDC-PFCC can actively control the current of two lines with the insertion of VRs. For example, when \( V_{S3} \) is controlled as 3.06 kV by IDC-PFCC, the current of line 2 is 1.25 kA, and the current of lines 1 and 3 is passively changed. After the insertion of VR, the current of line 3 is 0.302 kA when \( R_y = 1.5 \Omega \). VR will adjust the switching frequency according to the difference between the actual and the expected currents. Through the above analysis, IDC-PFC and VR as IDC-PFCC’s two parts, respectively, can actively control the current of two lines.

### 3.3 Combination of SAVS and IDC-PFC

The combination of VR and IDC-PFC can bring external transmission loss because of the existence of VR. As is shown in Fig. 6, another combination proposed in this paper is one series of SAVS and IDC-PFCC. Two SAVSs are in series with IDC-PFC, which is still placed in the DC terminal of VSC3. This combination strategy is also superimposing the resulting voltage of SAVS and IDC-PFCC, similar to the combination of IDC-PFC and VRs.

The combination can achieve three modes of adjusting the current of two lines. It is obvious that the combination of IDC-PFC and SAVSs is better than one of IDC-PFC and VRs because of the highly free range of the resulting voltage of SAVS. However, in Fig. 7, the combination needs two external voltage sources, whose cost is higher.

| Table 2 | Power flow when \( I_{12} = 1.25 \) kA |
| --- | --- |
| \( R_y, \Omega \) | 0 | 0.5 | 1 | 1.5 | 2 |
| \( I_{12}, \) kA | 0.728 | 0.7219 | 0.7233 | 0.7251 | 0.7268 |
| \( I_{11}, \) kA | 0.3306 | 0.3253 | 0.3202 | 0.3150 | 0.3098 |

| Table 3 | Power flow when \( I_{13} = 1.25 \) kA |
| --- | --- |
| \( R_y, \Omega \) | 0 | 0.5 | 1 | 1.5 | 2 |
| \( I_{13}, \) kA | 0.2137 | 0.2078 | 0.2114 | 0.2143 | 0.2176 |

| \( I_{11}, \) kA | 0.3179 | 0.3120 | 0.3065 | 0.3019 | 0.2970 |

### 4 Composite DC-PDC

Considering that the combination scheme in Section 3.3 needs to be connected in series with more voltage sources, the combination is simplified to propose a novel composite DC-PFC with only one external voltage source. Its topology of composite DC-PFC is shown in Fig. 8 based on [13], which is still placed in the DC terminal of VSC3. The novel topology not only maintains the function of IDC-PFC and SAVSs but also can actively control the current of two lines. It is supposed \( L_1 = L_2 = L \). The coupling inductance is the energy transfer hub of an external source and the capacitance is inserted into two lines.

The principle of circuit work is as follows:

(i) When \( Q_1 \) and \( Q_2 \) are turned on, inductor current \( I_{L1} \) increases linearly under the effect of capacitance voltage \( V_c \), the part of the energy in \( C_2 \) is transferred to \( L_1 \). The equivalent circuit is shown in Fig. 9a. We have
\[
I_{L1} \Delta I_{L1} = -\frac{V_c}{L} DT
\]
where \( D \) is the duty cycle of \( Q_1 \) and \( Q_2 \).

(ii) When \( Q_1 \) and \( Q_2 \) are turned off \( S_1 \) and \( S_4 \) are turned on simultaneously. The energy of \( L_1 \) is transferred to \( L_2 \) because of the coupling effect of the coupling inductor. The power exchange of \( L_2 \) and voltage source \( V_c \) happens. The equivalent circuit is shown in Fig. 9b. We have
\[
\Delta I_{L2} = -\frac{V_c}{L} KT
\]
where \( K \) is the duty cycle of \( S_3 \) and \( S_4 \).

(iii) When \( S_1 \) and \( S_4 \) are turned off and \( Q_1 \) and \( Q_4 \) are turned on simultaneously, the energy of \( L_2 \) is transferred to \( L_1 \). \( I_{L2} \) decreases linearly under the effect of capacitance voltage \( V_c \). The power exchange of \( L_1 \) and \( C_1 \) happens. The equivalent circuit is shown in Fig. 9c. We have
\[
\Delta I_{L1} = \frac{V_c}{L} (1 - D - K) T
\]
where \((1-D-K)\) is the duty cycle of \( Q_3 \) and \( Q_4 \)
\[
\begin{align*}
D &= \frac{1}{(V_s - V_y \cdot I_{L2}/I_{L1})/V_a + I_{L1}/I_{L2} + 1} \\
K &= 1 - D(1 + I_{L1}/I_{L2})
\end{align*}
\]
The power exchange among $L_1$, $L_2$, $C_1$, and $C_2$ makes composite DC-PFC control actively the current of two lines. The characteristic equation is seen in the equation [13]. We can conclude that $K$ and $D$ can be calculated by the expected $V_x$, $V_y$, $I_{c1}$, and $I_{c2}$.

5 Validation texts by simulation

In order to verify the validity of the composite DC-PFC in this paper, a three-terminal VSC-HVDC system mode with the composite DC-PFC is set up and the specific parameters can be seen in Table 1.

Suppose the reference voltage of $V_x$ is 0.5 kV, and the reference voltage of $V_y$ is 2 kV. The steady-state simulation is depicted in Fig. 10. Table 4 shows the comparisons of simulation and theoretical results. From Table 4, the simulation results agree well with the theoretical results, which prove that the proposed composite DC-PFC has good operating characteristics in steady state.

### Table 4 Comparison between theoretical values and simulation values

| Items | Theoretical value | Simulation value |
|-------|-------------------|------------------|
| $I_{13}$, $k$ | 1.3260 | 1.3261 |
| $I_{23}$, kA | 1.1450 | 1.1448 |
| $V_x$, kV | 2 | 2 |
| $V_y$, kV | 0.5 | 0.5 |

6 Conclusion

In this paper, both combinations of IDC-PFC and VRs and that of IDC-PFC and SAVSs are proposed to control the current of multiple lines in the multi-terminal VSC-HVDC system. Moreover, a composite DC-PFC is proposed to achieve the completely decoupled power-flow control, whose operation modes are analysed. A three-terminal VSC-HVDC system mode with the composite DC-PFC is set up to validate the effectiveness. The simulation results show the proposed DC-PFC has good operating characteristics in steady state. In addition, the proposed composite DC-PFC can be applied in more MTDC systems.

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