A Power De-coupling Control Strategy for MMC-HVDC System

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Abstract. Modular multilevel converter (MMC) has a wide range of applications in the field of HVDC. However, some of the electricity in MMC is coupled, which makes the design of control system more difficult and have a negative impact on the stable operation of the system. This paper puts forward a strategy to eliminate the coupling control, this method compensates the current cross-coupling terms of the d-axis and the q-axis in the dq coordinate system, SOGI(Second Order Generalized Integrator) and Q-PR(Quasi-PR) controller are used to accurately control the double frequency circulation in the internal unbalanced current, the coupling caused by the internal unbalance current and the sub-capacitor module voltage is compensated in the three-phase coordinate system. Finally, the simulation verification is carried out in PSCAD, which is compared with the traditional control method to verify that the proposed method can achieve complete power decoupling.

Keywords: Modular multilevel converter; Internal unbalance current; Submodule capacitance voltage; De-coupling control.

1. Introduction

With the rapid development of power electronics technology, MMC system is widely used in HVDC transmission technology\cite{1-5}. Compared with traditional converters, MMC adopts a large-scale cascade topology, which has attracted much attention in the DC transmission system due to its four-quadrant operation, strong scalability, high switching frequency and easy implementation of redundancy design\cite{6-8}. However, the variables of MMC are various and there is coupling between them, so that the control system can not meet the reliability \cite{8-9}. Especially when power changes, there is coupling relationship between active power and reactive power, which will influence the control effect to a great extent. Therefore, realizing complete power decoupling is the foundation for the system to operate safely.

The control system of MMC is the key to ensure the safety of MMC-HVDC. In \cite{10}, a simplified equivalent circuit theoretical model of MMC is proposed, the control of MMC can directly use the control strategy of traditional VSC, but the internal coupling of MMC is ignored. In \cite{11}, a control strategy of modular multilevel converter HVDC system based on internal loop current state feedback decoupling control is proposed, However, the state feedback control system has many parameters and complicated calculation formulas. In \cite{12}, capacitor voltage fluctuations of submodules within MMC are considered to realize current decoupling control and improve the dynamic performance of the system. In \cite{13}, the concept of internal potential corresponding to each current component is proposed, and internal potential is taken as the intermediate control quantity to realize direct decoupling control.

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of each current state quantity. The proposed method can realize the decoupling of DC internal potential control and sub-module capacitor voltage, realize the direct control of DC terminal voltage. This paper analyzes the coupling relationship between the AC side current of MMC and other variables, aiming at the problem that it is not easy to achieve power decoupling in traditional control systems, a control method is proposed to compensate the cross-coupling current of d-axis and q-axis in the dq coordinate system, and compensate the coupling caused by internal unbalanced current and sub-module capacitor voltage in the three-phase static coordinate system. Compared with the traditional power decoupling strategy, the proposed method can achieve completely power decoupling.

2. The Working Principle of MMC

2.1. MMC Topology

![Figure 1. MMC topology.](image)

The topology of the MMC is shown in Fig.1. $R_0$ and $L_0$ are equivalent losses and equivalent reactance of the bridge arm, $R$ is equivalent resistance of the AC side, $L$ is equivalent reactance of the AC side, $u_{px}$, $u_{nx}$ $(x=a,b,c)$ is the voltage of upper and lower bridge arms of any phase, $i_{px}$ and $i_{nx}$ is the current of upper and lower bridge arms of any phase, $u_x$ $(x = a,b,c)$ are AC side voltages, $U_{dc}$ and $I_{dc}$ are DC voltage and DC current.

2.2. MMC Mathematical Model

From Fig. 1, According to Kirchhoff’s law:

$$R_i \frac{di}{dt} + L_s \frac{dx}{dt} = e_x - u_x$$

$$u_{diff} = R_i \frac{di_{diff}}{dt} + L_q \frac{di_{diff}}{dt} = \frac{U_{dc}}{2} - \frac{u_{px} + u_{nx}}{2}$$

Where, $R_s = R + \frac{R_0}{2}$, $L_s = L + \frac{L_0}{2}$, $e_x = \frac{u_{px} - u_{nx}}{2}$ is the internal virtual electromotive force of MMC, $i_{diff} = \frac{i_{px} + i_{nx}}{2}$ is the unbalanced current in MMC, $i_x = i_{px} - i_{nx}$ is the current at the ac side, $u_{diff}$ is the
unbalanced voltage in MMC, it can be seen from equations (1) and (2) that the \( i_c \) can be controlled by controlling virtual electromotive \( e_x \), and \( i_{diff} \) can be controlled by controlling \( u_{diff} \).

Traditional control methods generally ignore the coupling relationship of MMC, the reference value of virtual electromotive \( e_{x_{ref}} \) in MMC can be obtained by AC side control strategy, through the DC loop control strategy, the command value of unbalanced voltage \( u_{diff_{ref}} \) in MMC can be obtained, thus the reference value of MMC upper and lower bridge arms can be obtained as:

\[
\begin{align*}
    u_{ps_{ref}} &= \frac{U_{dc}}{2} - e_{x_{ref}} - u_{diff_{ref}} \\
    u_{ns_{ref}} &= \frac{U_{dc}}{2} + e_{x_{ref}} - u_{diff_{ref}}
\end{align*}
\]

(3)

3. Traditional MMC Control Strategy

4. The Coupling of MMC

4.1. Submodule Model

The MMC sub-module model is shown in Fig.1. Where, \( u_{acjx} \), \( i_{p,j} \) (j=p,n) represents the x-phase submodule port voltage and bridge arm current, \( u_{dcjx} \) and \( i_{dcjx} \) respectively represent the capacitance voltage of the sub module and the current flowing through the capacitance. Given that each submodule runs stably, they can be considered the same and can be obtained as follows:

\[
\begin{align*}
    u_{dcjx1} &= u_{dcjx2} = \ldots = u_{dcjxn} \\
    i_{dcjx1} &= i_{dcjx2} = \ldots = i_{dcjxn}
\end{align*}
\]

(4)

The relationship between \( i_{dcjx} \) and \( u_{dcjx} \) is as follows:

\[
i_{dcjx} = C \frac{du_{dcjx}}{dt}
\]

(5)

The relationship between \( u_{acjx} \) and \( u_{dcjx} \) is as follows:

\[
u_{acjx} = S_{jx} u_{dcjx}
\]

(6)

Where, \( S_{jx} \) (j=p, n) represents the bridge arm switching function.
The relationship between bridge arm current and capacitor current flowing through submodule is as follows:

\[ i_{djc} = S_j i_{jc} \quad (7) \]

The relationship between bridge arm voltage and submodule port voltage can be expressed as:

\[ u_{jc} = N u_{acjc} \quad (8) \]

According to equations (6) and (8), it can be concluded that the relationship between bridge arm voltage and \( u_{djc} \) is as follows:

\[ u_{jc} = NS_j u_{djc} \quad (9) \]

### 4.2. AC-DC Average Model

The difference mode component of the average switching function \( S_{dmc} \) is generated by the modulation of the virtual electromotive force \( e_{x\_ref} \). The DC circuit voltage \( U_{dc}/2 - u_{diff_{x\_ref}} \) is modulated to produce a common mode component \( S_{cmm} \).

The average switching function of any phase bridge arm can be expressed as:

\[
\begin{align*}
S_{p\_x} &= S_{cmm} - S_{dmc} \\
S_{n\_x} &= S_{cmm} + S_{dmc}
\end{align*}
\quad (10)
\]

From equations (1), (2), (9) and (10), it can be concluded that the ac-dc loop equation is:

\[
\begin{bmatrix}
R_j i_s + L_s \frac{di_s}{dt} \\
R_j \frac{di_{diff}}{dt} + L_s \frac{di_{diff}}{dt}
\end{bmatrix}
= M \begin{bmatrix} S_{dmc} \\ S_{cmm} \end{bmatrix} - \begin{bmatrix} \frac{u_x}{2} \\ -\frac{u_{dc}}{2} \end{bmatrix}
\quad (11)
\]

Where, \( M = \begin{bmatrix} N u_{d\_c\_cmm} & N u_{d\_c\_dmc} \\ -N u_{d\_c\_dmc} & -N u_{d\_c\_cmm} \end{bmatrix} \)

\[ u_{d\_c\_dmc} = \frac{u_{d\_c\_cmm} - u_{d\_c\_dmc} \cdot \frac{2}{2}}, u_{d\_c\_cmm} = \frac{u_{d\_c\_cmm} + u_{d\_c\_dmc} \cdot \frac{2}{2}} \]

From what has been discussed above, the AC-DC average model can be obtained, as shown in Fig. 3.

**Figure 3.** AC-DC circuit average model.

### 4.3 The Internal Coupling

As can be seen from Fig. 4, \( i_x \) and \( i_{diff} \) in MMC are coupled with each other. According to equations (5), (7) and (10), the relationship between the capacitor voltage of the sub-module and \( i_x \) and \( i_{diff} \) can be obtained, as follows:
From equation (12), it can be concluded that the common mode and differential mode components of the submodule capacitor voltage are coupled with $i_x$ and $i_{diff}$. The coupling between variables makes the control of MMC more difficult.

Parker transform is performed on formula (11) to obtain the AC loop equation under dq coordinates[14]:

$$
\begin{align*}
\frac{di_d}{dt} &= \frac{1}{2L_s} \left[ u_{dc} - u_{eq} \right] + \frac{N}{2U_{dc}} u_{eq} \\
\frac{di_q}{dt} &= -R_s i_q + \omega L_s i_d - i_d
\end{align*}
$$

(13)

Where, $u_{dc}$ is the DC component of submodule capacitor voltage, $u_{dc1d}$, $u_{dc2d}$, $u_{dc1q}$, $u_{dc2q}$ is the fundamental frequency (double frequency) AC component of its dq axis, $U_{eq}$ and $U_{eq}$ are AC current signals of dq axis, $U_{cird}$ and $U_{cirq}$ are the control components of dq axis circulation.

It can be concluded from equation (13) that the coupling of AC and DC circuits and the coupling of submodule capacitor voltage with AC side current and internal unbalanced current will lead to mutual coupling of d-axis and q-axis current. The traditional control strategy will increase the control difficulty of MMC.

5. A Power De-coupling Control Strategy

To achieve complete power decoupling, the system should eliminate the coupling phenomenon of submodule capacitor voltage and internal unbalanced current. This paper proposes a power decoupling control strategy, as shown in Fig.4:

![Figure 4. MMC control strategy for decoupling.](image)

By eliminating the cross-coupling terms $\omega L_s i_d$ and $\omega L_s i_q$ through the traditional control method, the reference signals $u_{d\_ref}$ and $u_{q\_ref}$ under the dq axis are obtained, and then the control signal $e'_{s\_ref}$...
under the three-phase coordinates is obtained through the inverse Park transformation, $e'_{x_{\text{ref}}}$ is compensated according to the AC circuit in formula (11), and a new reference signal $e_{x_{\text{ref}}}$ is obtained.

In the method proposed in Fig. 4, the Second Order Generalized Integrator (SOGI) is combined with Quasi-PR controller to control the internal unbalance current, which is mainly aimed at the double frequency component in the circulation. The block diagram of SOGI and Quasi-PR controller is shown in Fig. 5:

![Figure 5. SOGI and Quasi-PR controller block diagram.]

6. The Simulation Verification

In order to prove the effectiveness of the decoupling control method, the simulation model as shown in Fig. 6 is built in PSCAD.

| project parameter | parameter |
|-------------------|-----------|
| Rated DC voltage $U_{dc}$/kV | 320 |
| The bridge arm reactance $L_0$/mH | 100 |
| The bridge arm resistance $\Omega$ | 0.1 |
| Number of submodules of single-phase bridge arm/N | 40 |
| Submodule capacitance /μF | 10000 |
| Quasi-pr controller parameters $k_p$ | 10 |
| Quasi-pr controller parameters $k_r$ | 100 |
| Quasi-pr controller parameters $\omega$ | $\pi$ |

![Figure 6. Simulation verification model.]

Fig. 7 and Fig. 8 respectively show the simulation waveforms under the traditional control strategy and the decoupling strategy. At 4s, the active power is flipped from 200MW to -200MW, in Fig. 7 (a), the active power tracking instruction value achieved power reversal at 4s, but the reactive power also changed when the active power changed, indicating that the complete decoupling could not be
achieved when the traditional control strategy was adopted. Fig. 8 (b) and (c) show the internal unbalance current and submodule capacitor voltage waveforms, which change correspondingly when the active power is flipped. Fig. 8 shows the simulation waveform under the decoupling strategy. Fig. 8 (a) shows the power waveform of active power flipped from 200MW to -200MW. It is not difficult to see that, when the active power changes, reactive power keeps stable, complete decoupling is achieved. Fig. 8 (b) and (c) show internal unbalance current and submodule capacitor voltage waveforms. The internal unbalance current and submodule capacitor voltage are also improved to some extent, and the fluctuation is reduced, making the system safer.

Figure 7. Simulation waveform under traditional control strategy.

Figure 8. The simulation waveform under the decoupling strategy in this paper.

Fig. 9 and Fig. 10 are the simulation waveform under the change of reactive power. The reactive power changes from 0 to 200MVar at 4s. It can be seen from Fig. 9 (a) that the active power also fluctuates briefly when the reactive power changes. This indicates that under the traditional control strategy, the active and reactive power cannot be completely decoupled due to the influence of internal unbalanced current and submodule capacitor voltage, and the internal unbalanced current and submodule capacitor voltage also fluctuate greatly.

It can be seen from Fig. 10 (a) that, when the reactive power increases, active power is still keeping its original value and complete decoupling can be achieved. The fluctuation of internal unbalance current and submodule capacitance voltage also becomes gentle, making the system more safe and stable.

Figure 9. Simulation waveform under traditional control strategy.

Figure 10. The simulation waveform under the decoupling strategy in this paper.

7. Conclusion

There are many variables in MMC, and there are coupling between variables, so the control system cannot completely guarantee the stability of the power grid. Aiming at the above problems, the
coupling relationship between AC current control and other variables in MMC is analyzed, proposed a
eliminate coupling control strategy, This method compensates the current cross-coupling terms of the
d-axis and the q-axis in the dq coordinate system, using SOGI and quasi-pr controller to accurately
control the double frequency circulation in the internal unbalanced current, the coupling between the
internal unbalance current and the submodule capacitance voltage is compensated in a three-phase
coordinate system. The proposed strategy is validated in PSCAD, it is found that the method can
realize the decoupling of active power and reactive power.

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