Multi-hierarchy control strategy in abc coordinate for modular multilevel matrix converter in fractional frequency transmission system

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Abstract: This paper proposes a multi-hierarchy control strategy in abc coordinate for modular multilevel matrix converter (M³C) in fractional frequency transmission system (FFTS). The proposed control strategy avoids complicated coordinate transformations when the traditional control strategies based on coordinate transformation are adopted. Four hierarchies are designed to balance the capacitor voltages. In different hierarchies, the capacitor voltage ripples have different frequencies. According to this characteristic, different bandwidths of voltage filters are adopted in different hierarchies, resulting in different control speeds among the four hierarchies. This will not only speed up the control but also assure the control accuracy. Simulation results verify the feasibility and effectiveness of the proposed strategy.

1 Introduction

Nowadays, fractional frequency transmission system (FFTS) has attracted more and more attentions [1–7], and one typical application is the submarine cable power transmission between offshore wind farm and on-land power grid [3–7]. Compared with HVAC, FFTS has a larger maximum transmissible capacity and a longer transmission distance as the AC frequency decreases [1–5]. Compared with HVDC, the cost of converter stations in FFTS is lower especially when only one converter station is required in FFTS [5–7]. Furthermore, the FFTS can elegantly solve some inherent problems of HVDC, such as space charge accumulation in power cable [8, 9] and the necessity of DC circuit breaker [9, 10].

The modular multilevel matrix converter (M³C) was first presented in 2001 [11]. This converter owns the advantages of easy scalability, high-power quality, and controllable power factor on both sides. Therefore, it is considered as a promising topology for adjustable speed drive applications [11–13]. Recently, M³C has been proposed to take the place of the line commutated AC/AC cycloconverter in FFTS and the control strategies have been investigated in literatures [14–16].

The control of M³C is pretty complex since there are nine arms and the circulating current relationships are complicated. The SVPWM method and the model predictive control method were proposed for M³C [17, 18]. However, both methods are not suitable for high voltage situation as the number of bridge cells increase. The most widely researched and applied control methods are based on the double αβ0 transformation proposed by F. Kammerer [19]. The application of double αβ0 transformation can simplify the mathematical model of M³C and realise the fully decoupled control all control freedom degree. Further researches based on double αβ0 transformation have been done in [13, 20]. In fact, the control variables for each hierarchy are independent from each other in abc coordinate, and the control of M³C can be achieved in abc coordinate without any coordinate transform, which can simplify the control.

Here, a multi-hierarchy control strategy in abc coordinate is proposed for M³C in FFTS. The proposed strategy can avoid complicated coordinate transformations and complex variable relations in αβ0 or dq coordinates. Four hierarchies are designed to well balance the capacitor voltages. What is more, in different hierarchies, the capacitor voltage fluctuations have different frequencies. According to this characteristic, different bandwidths of voltage filters are adopted in different hierarchies, resulting in different control speeds among four hierarchies. This will not only speed up the control but also assure the control accuracy. Simulation results verify the feasibility and effectiveness of the proposed strategy.

2 Basic structure of M³C

Basic structure of M³C is shown in Fig. 1. There are three subconverters (SC a, b, c) from FFS and three subconverters (SC u, v, w) from PFS. Each subconverter contains three arms. For example, subconverter a, contains arm au, av, aw; subconverter u, contains arm au, bu, cu. Each arm is constituted by N full-bridge submodules (SMs) connected with an inductor L. u and i(x = a, b, c) are, respectively, the FFS-voltage and current. u and i are, respectively, the PFS-voltage and current. ux and uy are, respectively, arm voltage and current. The frequencies of FFS and PFS are fₛ = 50/3, f₁ = 50 Hz, respectively.

3 Multi-hierarchy control method

3.1 Active power analysis

In order to elicit the control strategy and choose appropriate control variables for capacitor voltages, active power analysis is done first. In steady state, ignoring the influences of arm inductance, the arm voltages can be obtained as

\[ u_{xy} = u_x - u_y \]  

(1)

The relationship among arm current and currents of FFS and PFS satisfies

\[ i_{xy} = i_x/3 + i_y/3 + \Delta i_{uc,xy} \]  

(2)

where \( \Delta i_{uc,xy} \) is the circulating current of arm xy. \( \Delta i_{uc,xy} \) only flows among three arms within a subconverter, and does not affect the current of a subconverter, that is,
The active powers of the whole M$^3$C can be obtained as

$$P_{all} = \sum_{x=a,b,c} P_x = \sum_{y = u,v,w} P_y = \frac{1}{T_f} \int_0^{T_f} 3u_y i_y \, dt$$  \hspace{1cm} (7)$$

From (7), the current $3i_x$ or $3i_y$ can be adopted to control the average voltage of whole M$^3$C; From (5), the current $i_x$ can be adopted to control the average voltage of subconverter $x$; From (6), the current $i_y$ can be adopted to control the average voltage of subconverter $y$; From (4), circulating current $\Delta i_{cir,xy}$ can be adopted to control the average voltage of arm $xy$.

### 3.2 Control method

Multi-hierarchy control method in abc coordinate is adopted to balance the capacitor voltage of M$^3$C. There are four hierarchies: average voltage control of whole M$^3$C, average voltage control of a subconverter, average voltage control of an arm; capacitor voltage control within an arm.

#### 3.2.1 Average voltage control of whole M$^3$C

The whole current of PFS ($I_{all} = 3I_x$) is chosen to control the average voltage of whole M$^3$C as shown in Fig. 2. In Fig. 2, $u_{AV}$ is the reference voltage of capacitor; $u_{AV}$ is the average voltage of subconverter $y$; $u_{AV}$ is the average voltage of the whole M$^3$C; $W_{AV}(s)$ is the filter of this hierarchy; $P_{AV}$ is the output of PI controller; $I_{all}$ is the reference current of PFS.

#### 3.2.2 Average voltage control of a subconverter

Average voltage of a subconverter is controlled by adjusting current distribution of PFS as shown in Fig. 3. In Fig. 3, $u_{AV}$ is the average voltage of arm $xy$; $W_{AV}(s)$ is the filter of this hierarchy; $P_{AV}$ is the output of PI controller; $\Delta i_{cir,xy}$ is the fine-tuning current to adjust current distribution among three subconverters; $\Delta i_y$ is the magnitude of reference current of subconverter $y$.

#### 3.2.3 Average voltage control of an arm

Average voltage of an arm is controlled by circulating current as shown in Fig. 4. In Fig. 4, $W_{arm}(s)$ is the filter of this hierarchy; $P_{AV}$ is the output of PI controller; $\Delta i_y$ is the circulating current of arm $xy$; $\Delta i_y$ is the reference current of FFS; $i_y$ is the reference current of arm $xy$.

#### 3.2.4 Capacitor voltage control within an arm

The nearest level modulation (NLM) method is adopted to balance the
capacitor voltage within an arm. The arm current direct control method [21] and NLM are shown in Fig. 5.

4 Filters for each hierarchies

In Section 3.2, each control hierarchy contains a filter, which removes capacitor ripple voltage and obtains DC component. Traditionally, the filters of all hierarchies are the same with a low cut frequency, which debases the dynamic performance of M\textsuperscript{3}C. Here, by analysing the characteristic of ripple voltage of each hierarchy, hierarchical filters are designed to improve the dynamic performance of M\textsuperscript{3}C as well as keep the steady-state performance.

Suppose that the voltages and currents of, respectively, PFS and FFS are sinusoidal waveforms in positive sequence as

\[
\begin{align*}
U_u &= U_{imm}\cos(\omega t + \sigma_u), \\
i_i &= I_{imm}\cos(\omega t + \sigma_i - \Theta), \\
i_a &= U_{imm}\cos(\omega t + \sigma_a + \alpha), \\
i_b &= I_{imm}\cos(\omega t + \sigma_b + \alpha - \Phi)
\end{align*}
\]  

(8)

(9)

where \(U_{imm}\) and \(I_{imm}\) are the magnitudes of phase voltages of, respectively, FFS and PFS; \(I_{im}\) and \(I_{im}\) are the magnitudes of phase currents of, respectively, FFS and PFS; \(\omega\) and \(\omega\) are angular frequency of, respectively, FFS and PFS; \(\sigma_u, \sigma_i, \sigma_a, \sigma_b\) are initial phases of, respectively, FFS and PFS; \(\Theta\) and \(\Phi\) are power factor angles of, respectively, FFS and PFS. In steady state, the active powers of, respectively, FFS and PFS satisfy

\[
U_{imm}\cos\Theta = U_{imm}\cos\Phi
\]  

(10)

From (3), since \(\Delta_{c,xy}\) only flows among three arms within a subconverter, it will not affect the subconverter current. Therefore, \(\Delta_{c,xy}\) only affects arm ripple voltage, and it will not affect the subconverter ripple voltage. To simplify the analysis of ripple voltage, assume \(\Delta_{c,xy} = 0\). In fact, this assumption does not affect the following analysis. The relationship among arm current and currents of FFS and PFS satisfies

\[
i_{xy} = i_s/3 + i_y/3
\]  

(11)

4.1 Instantaneous powers of each hierarchy

Instantaneous powers of nine arms can be obtained from (1),(8)–(11), where those of arm au, av, aw are shown in (12)–(14).

\[
\begin{align*}
p_{au} &= u_{au}\cos = \{U_{imm}\\cos[(\omega t - \omega)(t - \alpha + \varphi) - U_{imm}\cos[(\omega t - \omega)(t - \alpha + \varphi) + 2\sigma
\]

(12)

\[
-p_{au} &= u_{aw}\cos = \{U_{imm}\cos[(\omega t - \omega)(t - \alpha + \varphi + 2\pi/3) + U_{imm}\cos[(\omega t - \omega)(t - \alpha + \varphi - 2\pi/3) - U_{imm}\cos[(\omega t - \alpha + \varphi - 2\pi/3)]/6
\]

(13)

\[
-p_{av} &= u_{av}\cos = \{U_{imm}\cos[(\omega t - \omega)(t - \alpha + \varphi - 2\pi/3) + U_{imm}\cos[(\omega t - \omega)(t - \alpha + \varphi + 2\pi/3) - U_{imm}\cos[(\omega t - \alpha + \varphi + 2\pi/3)]/6
\]

(14)

The instantaneous power of subconverter a can be obtained from (12)–(14) as

\[
p_a = \sum_{y = a, b, c} p_{ay} = \frac{U_{imm}}{2}\cos(2\omega t + 2\sigma - \theta)
\]  

(15)

The instantaneous powers of subconverter b, c and u, v, w can be obtained in a similar way as

\[
p_b = \sum_{y = b, c} p_{by} = \frac{U_{imm}}{2}\cos(2\omega t + 2\sigma - \theta + 2\pi/3)
\]  

(16)

\[
p_c = \sum_{y = b, c} p_{cy} = \frac{U_{imm}}{2}\cos(2\omega t + 2\sigma - \theta - 2\pi/3)
\]  

(17)

\[
p_u = \sum_{x = a, b, c} p_{ux} = \frac{U_{imm}}{2}\cos(2\omega t + 2\sigma + 2\alpha - \phi)
\]  

(18)

\[
p_v = \sum_{x = a, b, c} p_{vx} = \frac{U_{imm}}{2}\cos(2\omega t + 2\sigma + 2\alpha - \phi + 2\pi/3)
\]  

(19)

\[
p_w = \sum_{x = a, b, c} p_{wx} = \frac{U_{imm}}{2}\cos(2\omega t + 2\sigma + 2\alpha - \phi - 2\pi/3)
\]  

(20)

The instantaneous power of M\textsuperscript{3}C can be obtained from (15) to (17) or from (18) to (20) as

\[
p_{all} = \sum_{y = a, b, c} p_{ay} = \sum_{y = a, b, c} p_{by} = 0
\]  

(21)

4.2 Ripple voltages of each hierarchy

In steady state, the current flowing through the capacitor of SM can be obtained according to the theorem of conservation of power as

\[
\dot{u}_y = p_{sy}/NU_d = u_{sy}/NU_d
\]  

(22)

where \(u_{sy}\) is the rated voltage of a capacitor. Then, the ripple voltage of SM can be obtained according to (22) as

\[
\dot{u}_y^2 = \frac{1}{C}\int u_y^2 \, dt = \frac{1}{NU_d C}\int u_{sy} u_y \, dt
\]  

(23)

The capacitor voltages of nine arms contain four kinds of ripple voltages. For example, the ripple voltage of arm au can be obtained by putting (12) into (23) as (24). From (24), there are four kinds of ripple voltages in arm au, the corresponding frequencies are \(f_i - f_j\), \(f_i + f_j\), 2\(f_i\), 2\(f_j\). Since in FFTS, \(f_i = 50/3\) Hz, \(f_j = 50\) Hz, then the value of four kinds of frequencies are shown in (25). (see (24))

\[
\begin{align*}
f_i - f_j &= 2f_j = 100/3\text{Hz} \\
f_i + f_j &= 200/3\text{Hz} \\
2f_i &= 300/3\text{Hz}
\end{align*}
\]  

(25)

From (25), the frequencies \(f_i - f_j\) and \(2f_j\) are identical. Therefore, there are only three kinds of frequencies in arm ripple voltages.

The voltage ripple of each SM within an arm is the same with that of an arm. The voltage ripples of subconverters a, b, c and subconverters u, v, w can be obtained by putting (15)–(20) into (23) as

\[
\begin{align*}
v_y &= \frac{U_{imm}}{12NU_d C}\sin(2\omega t + 2\sigma - \theta + k\pi/3)
\end{align*}
\]  

(26)

\[
\begin{align*}
v_y &= -\frac{U_{imm}}{12NU_d C}\sin(2\omega t + 2\sigma - \theta + m\pi/3)
\end{align*}
\]  

(27)

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where \( x = a, b, c, k = 0, 1, \ldots, 1 \); \( y = u, v, w, m = 0, 1, -1 \). From (26) and (27), the subconverter voltage ripples of FFS only contain components of \( 2f_s \) and those of PFS only contains components of \( 2f_s \).

The voltage ripple of the whole \( M^3C \) can be obtained by putting (21) into (23) as

\[
\bar{u}_d^{\text{all}} = 0
\]

From (28), there is no ripple voltage of the whole \( M^3C \).

### 4.3 Filter for each hierarchy

Here, the moving filter is adopted to filter the ripple voltages and to obtain the DC voltage of each hierarchy. The advantage of moving filter against other low-pass filters is that it can remove the ripples absolutely, and obtain the DC component for control.

#### 4.3.1 Filter for the average voltage of the whole \( M^3C \)

From (28), since there is no any ripple voltage of the whole \( M^3C \), only a low-pass filter with high cut frequency is adopted to remove the ripples with switching frequency.

#### 4.3.2 Filter for the average voltage of a subconverter

From (26) and (27), since the frequency of subconverter ripple voltages of FFS is \( 2f_s \) and those of PFS is \( 2f_s \), a moving filter with bandwidth 10 ms can be adopted for the average voltage of subconverter of PFS to remove the ripple with frequency \( 2f_s \).

#### 4.3.3 Filter for the average voltage of an arm

From (25), there are three kinds of ripple voltages of an arm, and the periods of corresponding ripple voltages satisfies

\[
f_s \neq f_f = \frac{2}{T_s + T_f} = \frac{2}{2f_s} = 30 \text{ ms}
\]

Therefore, a moving filter with bandwidth 30 ms can be adopted to remove three kinds of ripples for the average voltage of an arm.

#### 4.3.4 Filter for the voltage control of SMs within an arm

Since the nearest level modulation (NLM) method is adopted to balance the voltage of SMs within an arm, filter is unnecessary in this hierarchy.

From the analysis above, the frequencies of ripple voltages of three hierarchies and the corresponding power filters are shown in Table 1.

### 5 Simulation results

In order to verify the proposed control strategy for \( M^3C \), simulations are carried out by PSCAD/EMTDC with the circuit parameters listed in Table 2.

#### 5.1 Case one

In this case, \( M^3C \) operations at steady state and the results are shown in Fig. 6.

Fig. 6a shows the average capacitor voltages of, respectively, arm au \( (u_{aum}) \), subconverter au \( (u_{aum}) \), and the whole \( M^3C \) \( (u_{ave}) \). It is clearly shown that \( u_{aum} \) contains two kinds of voltage ripples, that is, 100/3 and 100 Hz, and the period of \( u_{aum} \) is 30 ms. The frequency of \( u_{ave} \) is 100 Hz, and the corresponding period is 10 ms. Voltage \( u_{ave} \) appears as a DC component. The frequencies of \( u_{aum} \), \( u_{ave} \), and \( u_{ave} \) correspond to the analysis in Section 4.3. Filters for each hierarchy are chosen according to Table 1, the filtered voltages of, respectively, \( u_{aum} \), \( u_{ave} \), and \( u_{ave} \) are shown as DC components, as the same with \( u_{ave} \). This shows the effectiveness of the filter design method.

Figs. 6b and c show the capacitor voltages of arm au, bu, cu and arm au, av, aw, respectively. The capacitor voltages of each arm are well balanced, which shows the effectiveness of the multi-hierarchy control strategy proposed in this paper.

Fig. 6d shows the currents of, respectively \( PFS \) and \( FFS \). It is clearly shown that the currents of both sides are symmetrical and there are hardly any harmonics.

Fig. 6e shows the arm currents and their corresponding references of arm au, bu, cu. The arm currents are symmetrical and perfectly track their references. This shows the effectiveness of arm current direct control method.

Fig. 6f shows the circulating current of arm au. The circulating current is adopted to balance the capacitor voltage of arm, and its frequency is the same with that of \( PFS \), that is, 50 Hz. Fig. 6f corresponds with Section 3.2.3.

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**Table 2** Circuit parameters

| Items | Values |
|-------|--------|
| rated Power \( P_N \) | 300 MW |
| rated line voltage of FFS | 110 kV |
| rated line voltage of PFS | 110 kV |
| SM Capacitor Voltage \( U_C \) | 5 kV |
| arm Inductance \( L \) | 30 mL |
| SM Capacitance \( C \) | 15,000 uF |
| number of SMs per Arm \( N \) | 40 |

---

**Fig. 5** Arm current direct control method and NLM
5.2 Case two

Case two shows a comparison between two kinds of filter adopted in multi-hierarchy control as shown in Figs. 7 and 8. In Fig. 7, all hierarchies adopt the same kind of moving average filter with bandwidth 30 ms. Fig. 8 adopts filters as shown in Table 1. The initial capacitor voltages of arm au, av, and aw are 180 kV, while the others are 200 kV. Control begins at $t = 0.1$ s.

Figs. 7a and 8a show the currents of PFS. In $t = 0.1$ s, the currents in Fig. 8a rise faster than those in Fig. 7a, and the peak values in Fig. 8a are also bigger than those in Fig. 7a. Current of PFS are used to control the average capacitor voltages of the whole $M^2C$ and subconverters. Fig. 8a shows a better performance in average capacitor voltage control of the whole $M^2C$ and subconverters of the proposed method.

Figs. 7b and 8b show the circulating current of arm au. It is clear that the peak value of circulating current in Fig. 8b is bigger than that in Fig. 7b, and current in Fig. 8b stabilises faster than that in Fig. 7b. Circulating current is used to control the capacitor voltage of an arm. Fig. 8b shows a better performance in arm capacitor voltage control of the proposed method.

Figs. 7c and 8c show the capacitor voltage of arm au, bu, cu, and aw. The capacitor voltages of all arms come to balance in about 1.8 s in Fig. 7c, and about 1.5 s in Fig. 8c.

Case two shows that the performance of the control strategy adopting filters proposed here is better than that adopting the same filters for all hierarchies.

6 Conclusion

A multi-hierarchy control strategy in abc coordinate is proposed for $M^2C$ in FFTS. The active power of $M^2C$ was analysed and four hierarchies are designed to balance the capacitor voltages. What is more, the capacitor voltage ripples of different hierarchies have different frequencies. According to this characteristic, different bandwidths of voltage filters are adopted in different hierarchies, resulting in different control speeds among four hierarchies. This not only speeds up the control but also assures the control accuracy. Two simulations based on PSCAD/EMTDC were designed to show the good static and dynamic properties of the proposed strategy.
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