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Modular Multilevel Converter Control Strategy Under Unbalanced Grid Condition

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ABSTRACT: Upon the power analysis of modular multilevel converter (MMC), this paper proposed a comprehensive control strategy for the DC-link voltage, the capacitor voltages and the AC-side currents of MMC under unbalanced grid condition. Multi-hierarchy method was adopted to control the capacitor voltage. Under unbalanced grid condition, the AC-side currents were controlled to be symmetrical by adjusting active power distribution among three legs of MMC. Inner current loop employed arm current direct control, which can simultaneously control AC-side currents, DC bus current and circulating currents, removing the need for the three-sequence AC-side current controllers and the three-sequence circulating current suppressing controllers under unbalanced grid condition. A zero-sequence current canceller was proposed to add in arm current reference, and this could eliminate the zero-sequence fundamental-frequency current which is caused by the asymmetrical arm power losses and will flow to the DC-link. A 10kVA experimental prototype of the three-phase MMC was developed. The experiment results verify the feasibility and effectiveness of proposed strategy.

KEY WORDS: unbalanced grid condition; zero-sequence current canceller; modular multilevel converter (MMC); arm current control

(modular multilevel converter MMC)

MMC

MMC

10kVA

MMC

0

(modular multilevel converter MMC)[1]

[2-4] (high voltage direct current transmission HVDC)[5-20]

MMC

[9-16]

MMC

[9-16]

MMC

[11] MMC

( )

[12-15] MMC

[14]

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MMC
[15-16]

MMC

[17] [18]
MMC
MMC
[19]

(proportional resonant controller PR controller)

[15]
MMC
[19]
[20]
MMC

MMC

MMC
MMC

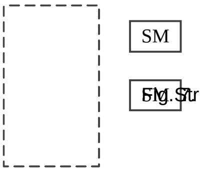


Fig. 1 Structure of three-phase MMC d[Tj<09bb19d7336647ff02c8

1 MMC

1 MMC MMC
N
L u_{sx}
i_{sx} U_d I_d
u_{px} u_{nx} x
i_{px} i_{nx} x
MMC L

$$\begin{aligned}&P_{sx}=\frac{1}{T}\int_0^T u_{sx}i_{sx}\mathrm{d}t=\frac{1}{T}\int_0^T u_{sx}(i_{spx}+i_{snx})\mathrm{d}t\\&P_{dcx}=\frac{1}{T}\int_0^T\frac{U_d}{2}i_{px}\mathrm{d}t-\frac{1}{T}\int_0^T\frac{U_d}{2}i_{nx}\mathrm{d}t=\\&\quad\frac{1}{T}\int_0^T U_d I_{dx}\mathrm{d}t\end{aligned}\tag{7}$$

$$\begin{aligned}&P_{px}=-\frac{1}{T}\int_0^T u_{px}i_{px}\mathrm{d}t=-\frac{1}{T}\int_0^T\frac{U_d}{2}I_{dx}\mathrm{d}t+\\&\quad\frac{1}{T}\int_0^T u_{sx}i_{spx}\mathrm{d}t\\&P_{nx}=\frac{1}{T}\int_0^T u_{nx}i_{nx}\mathrm{d}t=-\frac{1}{T}\int_0^T\frac{U_d}{2}I_{dx}\mathrm{d}t+\\&\quad\frac{1}{T}\int_0^T u_{sx}i_{snx}\mathrm{d}t\end{aligned}\tag{8}$$

1.1

MMC

$$P_{px}=P_{nx}\approx 0\tag{9}$$

(7) (8) MMC

$$\begin{aligned}&P_{sa}=P_{dca}\Rightarrow\frac{1}{T}\int_0^T u_{sa}i_{sa}\mathrm{d}t=\frac{1}{T}\int_0^T U_d I_{da}\mathrm{d}t\\&P_{sb}=P_{dcb}\Rightarrow\frac{1}{T}\int_0^T u_{sb}i_{sb}\mathrm{d}t=\frac{1}{T}\int_0^T U_d I_{db}\mathrm{d}t\\&P_{sc}=P_{dcc}\Rightarrow\frac{1}{T}\int_0^T u_{sc}i_{sc}\mathrm{d}t=\frac{1}{T}\int_0^T U_d I_{dc}\mathrm{d}t\end{aligned}\tag{10}$$

(10)

MMC

1.1.1 1

MMC

$I_{da}=I_{db}=I_{dc}=I_d/3$ i_{sa} i_{sb} i_{sc}

$I_{da}=I_{db}=I_{dc}$ (10)

$$\begin{aligned}&P_{dca}=P_{dcb}=P_{dcc}\Rightarrow P_{sa}=P_{sb}=P_{sc}\Rightarrow\\&\quad\frac{1}{T}\int_0^T u_{sa}i_{sa}\mathrm{d}t=\frac{1}{T}\int_0^T u_{sb}i_{sb}\mathrm{d}t=\frac{1}{T}\int_0^T u_{sc}i_{sc}\mathrm{d}t\end{aligned}\tag{11}$$

(11) u_{sa} u_{sb} u_{sc}

i_{sa} i_{sb} i_{sc}

[18]

1.1.2 2

i_{sa} i_{sb} i_{sc}

MMC

$I_{da}\neq I_{db}\neq I_{dc}$

i_{sa} i_{sb} i_{sc}

u_{sa} u_{sb} u_{sc} MMC

$$\begin{aligned}&P_{sa}\neq P_{sb}\neq P_{sc}\Rightarrow P_{dca}\neq P_{dcb}\neq P_{dcc}\Rightarrow\\&\quad\frac{1}{T}\int_0^T U_d I_{da}\mathrm{d}t\neq\frac{1}{T}\int_0^T U_d I_{db}dt\neq\frac{1}{T}\int_0^T U_d I_{dc}\mathrm{d}t\Rightarrow\\&\quad I_{da}\neq I_{db}\neq I_{dc}\end{aligned}\tag{12}$$

(12) ( )

MMC

1.1.3 1 2

1 2

$$\begin{aligned}&P_{sa}=P_{sb}=P_{sc}\Rightarrow P_{dca}=P_{dcb}=P_{dcc}\Rightarrow\\&\quad\frac{1}{T}\int_0^T U_d I_{da}\mathrm{d}t=\frac{1}{T}\int_0^T U_d I_{db}\mathrm{d}t=\frac{1}{T}\int_0^T U_d I_{dc}\mathrm{d}t\Rightarrow\\&\quad I_{da}=I_{db}=I_{dc}=I_d/3\end{aligned}\tag{13}$$

(13)

1 2

2 2

1 2

2

1

1.2

(7) U_d

I_{dx}

P_{dcx} i_{sx}

P_{sx}

(8)

1 I_{dx} 2

i_{spx} i_{snx} I_{dx} i_{spx} i_{snx}

Δi_{sxP}

$$P_{\mathrm{p}x}-P_{\mathrm{n}x}=\frac{1}{T}\int_0^T u_{\mathrm{s}x}(i_{\mathrm{sp}x}-i_{\mathrm{sn}x})\mathrm{d}t=\frac{1}{T}\int_0^T u_{\mathrm{s}x}\Delta i_{\mathrm{s}x\mathrm{P}}\mathrm{d}t \quad (14)$$

$$\begin{aligned} i_{\mathrm{sp}x} &= (i_{\mathrm{s}x}+\Delta i_{\mathrm{s}x\mathrm{P}})/2 \\ i_{\mathrm{sn}x} &= (i_{\mathrm{s}x}-\Delta i_{\mathrm{s}x\mathrm{P}})/2 \end{aligned} \quad (15)$$

2 MMC

2

MMC

2.1

I_{d} MMC

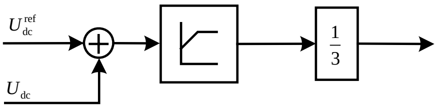
(

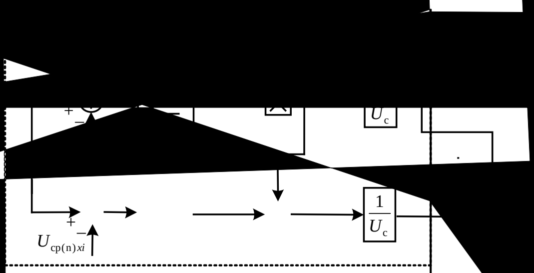
(16)) 2 $U_{\mathrm{dc}}^{\mathrm{ref}}$

$$I_{\mathrm{d}x}^{\mathrm{ctrl}} = I_{\mathrm{d}}^{\mathrm{ctrl}}/3 \quad (16)$$

$I_{\mathrm{d}}^{\mathrm{ctrl}}$ $I_{\mathrm{d}x}^{\mathrm{ctrl}}$

x




+
−
U_c
1
U_c
+
−
$U_{\text{cp(n)}xi}$

1

Tab. 1 Circuit and experimental parameters

N	4
L/mH	10
C/μF	2 400
U_{sab}/V	380
U_{dN}/V	800
I_{dN}/V	12.5
R/Ω	64
U_c/V	200
f_s/kHz	5
P_N/kW	10

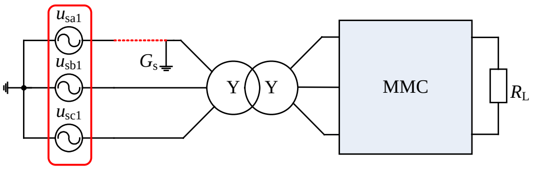


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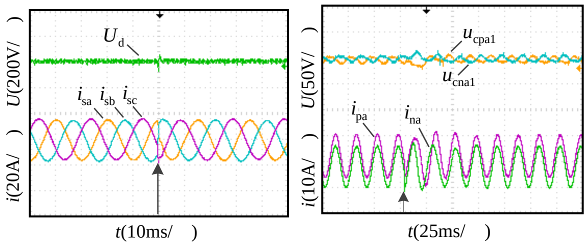
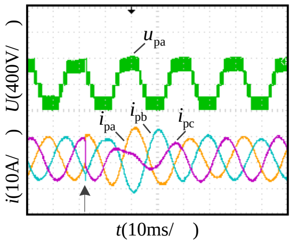
Fig. 10 Grid fault scheme



(a) U_d i_{sa}, i_{sb}, i_{sc}

(b) u_{cpa1}, u_{cna1} i_{pa}, i_{na}



(c) u_{pa} i_{pa}, i_{pb}, i_{pc}

11 MMC

Fig. 11 Experimental results of MMC with dynamic reactive power

11(b) a u_{cpa1} u_{cna1}

i_{pa} i_{na} 11(c) a

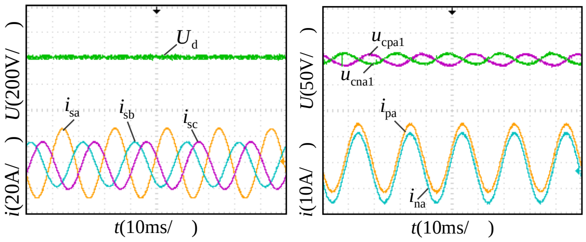
MMC

2 2

MMC 50%

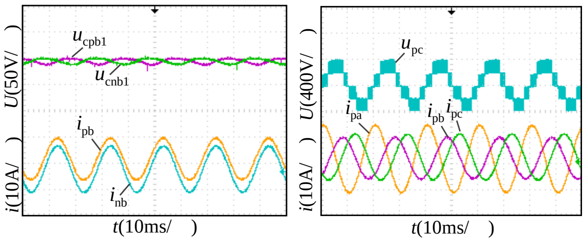
[18]

12 13



(a) U_d i_{sa}, i_{sb}, i_{sc}

(b) u_{cpa1}, u_{cna1} i_{pa}, i_{na}

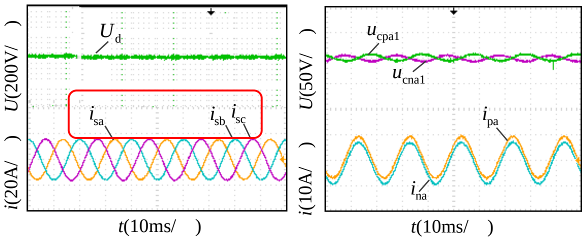


(c) u_{cpb1}, u_{cnb1} i_{pb}, i_{nb}

(d) u_{pc} i_{pa}, i_{pb}, i_{pc}

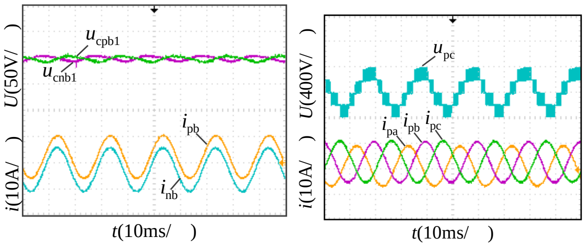
12 [18]

Fig. 12 Experimental result with the control strategy proposed in [18] under unbalanced grid condition



(a) U_d i_{sa}, i_{sb}, i_{sc}

(b) u_{cpa1}, u_{cna1} i_{pa}, i_{na}



(c) u_{cpb1}, u_{cnb1} i_{pb}, i_{nb}

(d) u_{pc} i_{pa}, i_{pb}, i_{pc}

13

Fig. 13 Experimental results with the control strategy proposed in this paper under unbalanced grid condition

12(a) 13(a)

12(a)

a i_{sa}

13(a)

12(b) (c) 13(b) (c)

a b

[18] (12(b) (c))a b (c b) (13(b) (c))a b (c b)

12(d) 13(d) c 12(d) 13(d) a a a 1.1.2 13(b) (c) a b

4

MMC

MMC

10kVA MMC

10

Y0/Y0

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Modular Multilevel Converter Control Strategy Under Unbalanced Grid Condition

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KEY WORDS: unbalanced grid condition; zero-sequence current canceller; modular multilevel converter (MMC); arm current control

The modular multilevel converter (MMC) is suitable for medium/high voltage applications, such as high-power motor drives, and high voltage direct current transmission (HVDC). However, when conventional ac-side current feedback control is applied under unbalanced grid condition, the comprehensive control of MMC is rather complicated.

In this paper, an MMC control strategy based on arm current control under unbalanced grid condition is proposed. This control strategy can greatly simplify the MMC control under unbalanced grid condition.

In MMC, the active power absorbed from ac-grid and output to dc bus by MMC should be equivalent.

$$\begin{aligned} &P_{\mathrm{sa}}=P_{\mathrm{dca}} \Rightarrow \frac{1}{T}\int_0^{\mathrm{T}} u_{\mathrm{sa}} i_{\mathrm{sa}}\mathrm{d}t=\frac{1}{T}\int_0^{\mathrm{T}} U_{\mathrm{d}} I_{\mathrm{da}}\mathrm{d}t \\ &P_{\mathrm{sb}}=P_{\mathrm{dcb}} \Rightarrow \frac{1}{T}\int_0^{\mathrm{T}} u_{\mathrm{sb}} i_{\mathrm{sb}}\mathrm{d}t=\frac{1}{T}\int_0^{\mathrm{T}} U_{\mathrm{d}} I_{\mathrm{db}}\mathrm{d}t \\ &P_{\mathrm{sc}}=P_{\mathrm{dcc}} \Rightarrow \frac{1}{T}\int_0^{\mathrm{T}} u_{\mathrm{sc}} i_{\mathrm{sc}}\mathrm{d}t=\frac{1}{T}\int_0^{\mathrm{T}} U_{\mathrm{d}} I_{\mathrm{dc}}\mathrm{d}t \end{aligned} \tag{1}$$

Under unbalanced grid condition, ac-grid voltage will be asymmetrical. In this paper, i_{sa}, i_{sb}, i_{sc} are controlled to be symmetrical, whereas $I_{\mathrm{da}} \neq I_{\mathrm{db}} \neq I_{\mathrm{dc}}$.

$$\begin{aligned} &P_{\mathrm{sa}} \neq P_{\mathrm{sb}} \neq P_{\mathrm{sc}} \Rightarrow P_{\mathrm{dca}} \neq P_{\mathrm{dcb}} \neq P_{\mathrm{dcc}} \Rightarrow \\ &\frac{1}{T}\int_0^{\mathrm{T}} U_{\mathrm{d}} I_{\mathrm{da}}\mathrm{d}t \neq \frac{1}{T}\int_0^{\mathrm{T}} U_{\mathrm{d}} I_{\mathrm{db}} dt \neq \frac{1}{T}\int_0^{\mathrm{T}} U_{\mathrm{d}} I_{\mathrm{dc}}\mathrm{d}t \Rightarrow \\ &I_{\mathrm{da}} \neq I_{\mathrm{db}} \neq I_{\mathrm{dc}} \end{aligned} \tag{2}$$

To realize the control, the AC-side current balancing controller is proposed, as shown in Fig.1.

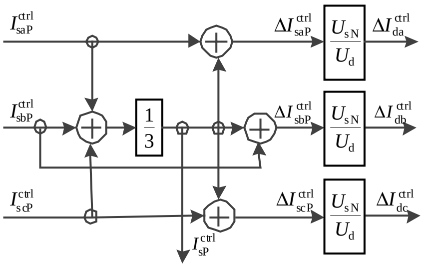
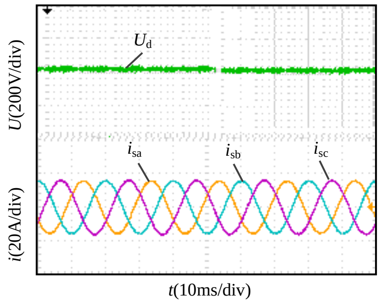
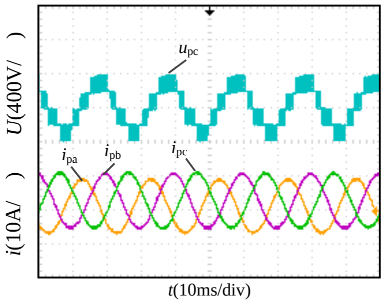


Fig. 1 AC-side current balancing control

Fig. 2(a) shows that ac-side currents are controlled to be symmetrical under unbalanced grid condition. Since dc bus voltage does not contain ac fluctuation, it also shows a good effect of the zero-sequence current canceller. Fig. 2(b) shows the upper arm currents of three phases and the upper arm output voltage of phase c. The peak-to-peak values of three-phase currents are almost the same, whereas the dc components of three phases are different. The DC current components of phase b and c are almost the same, while that of phase a is apparently smaller than those of phase b and c. This is in accordance with (2).



(a) U_{d} and i_{sa}, i_{sb}, i_{sc}



(d) u_{pc} and i_{pa}, i_{pb}, i_{pc}

Fig. 2 Experimental results with the proposed control strategy under unbalanced grid condition

In this control strategy, ac-side current is controlled to be symmetrical by adjusting active power distribution among three legs; the adoption of arm current control removes the need for the three-sequence ac-side current controllers and the three-sequence circulating current suppressing controllers; by adding zero-sequence current cancellers in arm current reference, the zero-sequence fundamental frequency current which is caused by the asymmetrical arm power losses and will flow to the dc-link is eliminated.