Research on Common Mode Voltage Suppression of Three-phase Four-bridge Matrix Converter Considering Unbalance Inductance

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Firstly, the influence of the inductance unbalance degree of fourth leg on the common mode voltage (CMV) of three-phase four-leg matrix converter (TFMC) is proposed, and the optimal value of fourth leg inductance is given. By comparing the three-dimensional space vector modulation (3DSVM) with no zero vector selection, it is found that the proposed control strategy can reduce the amplitude of CMV by 50%. Secondly, the MATLAB/Simulink module simulation is used to verify the correctness of the CMV suppression strategy. Then DSP and FPGA algorithms are designed respectively in C language and VHDL to perform the proposed control strategy. Finally, not only a highly integrated TFMC is designed, but the dual processor control system based on TMS320F28377 and MAX10 is built. The proposed control strategy is verified by the experimental platform. Simulation and experimental results show that the proposed control strategy is correct and effective, and CMV is suppressed greatly.

Keywords—three-phase four-leg matrix converter; unbalanced load; common mode voltage

I. INTRODUCTION

Matrix converter is a kind of direct AC-AC topology, because it eliminates the intermediate DC link, so it has the characteristics of small volume and large power density. Secondly, the matrix converter has the advantage of unit power factor input. Grid pollution is small, the output voltage and frequency is adjustable, which is a "green high power density inverter" [1,2]. With the extensive in-depth study of domestic and foreign scholars, matrix converters have been used in the actual production activities, especially in the field of small size. However, space vector modulation techniques inevitably lead to high frequency ripple, resulting in a high common-mode voltage at the neutral point of the load. CMV has many hazards: generating high frequency electromagnetic interference; stray capacitance and parasitic coupling capacitance of the excitation system will produce leakage current; long time operation will destroy the motor the insulation winding and bearings [3].

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There are two main ways to suppress and eliminate CMV: (1) The software algorithm are as follows: based on the traditional SVPWM mode, select the non-zero vector modulation which generates the lower magnitude CMV; Adjusting the zero vectors corresponding to the switch state corresponding to the re-division space vector; using the rotation vector which generates zero common mode voltage; replacing the zero vector with a pair of opposite switching states. (2) Hardware implementation is mainly to increase the isolation transformer, output filter optimization and so on. But they increase the cost, size and weight of the system. Therefore, it is more meaningful to suppress the CMV at the software algorithm level. In [4], the CMV is reduced by changing the input phase voltage corresponding to the zero-output state based on the dual voltage synthesis strategy. The article [5] proposed the use of a pair of opposite effective vectors to replace the zero vectors to suppress the CMV, but increased the switching losses and reduced the output voltage performance. The article [6-8] proposed a CMV suppression method based on predictive control. however, the calculation is too complex. The article [9] proposed the use of three effective voltage vectors to synthesize the desired output voltage vector. But this only applies when the modulation ratio is higher than 0.577. These are the control strategies proposed for the traditional three-phase three-leg matrix converter (TTMC) common mode voltage suppression. However, there is limited research on the CMV suppression of TFMC in the references that can be found.

Based on the discussion of the conventional method of CMV suppression based on the traditional matrix converter, this paper proposes to select the zero vector by time-sharing partition without using the rotation voltage vector. The effect of the fourth leg inductance on the voltage of the load neutral point is proposed. The theoretical value of the fourth bridge is given by theoretical calculation and simulation and verified by experiment.

Based on the above analysis, the works are as follows：

•Putting forward the topology and control strategy of the TFMC.

• Analyzing the CMV generation mechanism and suppression method of the TFMC.

•Verifying the proposed control strategies by relevant simulation and experiment.

This paper is organized as follows. Section II introduces topology and control strategy of the TFMC. Section III introduces CMV generation mechanism and suppression method of the TFMC. Section IV presents reasonable simulation results to validate the effectiveness of the proposed method in mitigating CMV. Section V is experiment verification. Relevant conclusions show in section VI.

II. CONTROL STRATEGY OF TFMC

The fourth bridge arm N is added to connect the traditional 3×3 MC neutral point n, which constitutes 3×4 MC. Topology is shown in Fig.1.

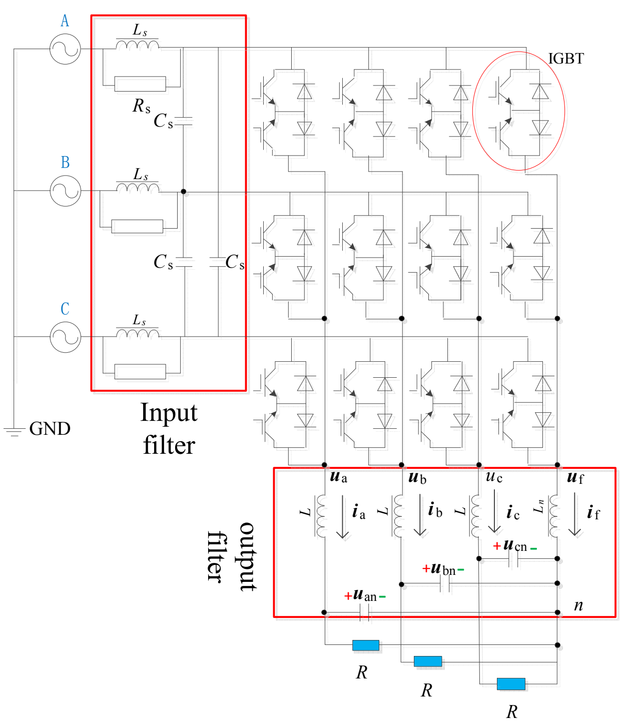


Fig.1. Topology of 3×4 MC

In order to make the matrix converter work properly, the following two important principles are required [5, 6]: (1) The TFMC cannot short-circuit between any two phases of the three-phase input (A, B, C); (2) the four-phase output (a, b, c, f) in any single phase cannot be broken [10,11].

Based on the above two important principles, it can be defined as follows:

$$S_{ij}(t)=\begin{cases}1 & S_{ij}\ \text{on}\\ 0 & S_{ij}\ \text{off}\end{cases} \tag{1}$$

Where $i\in\{A,B,C\}$，$j\in\{a,b,c,f\}$ in equation (1) and

$$S_{iA}+S_{iB}+S_{iC}=1 \quad i\in\{a,b,c,f\} \tag{2}$$

Defining the vector of input phase voltage and the input phase current:

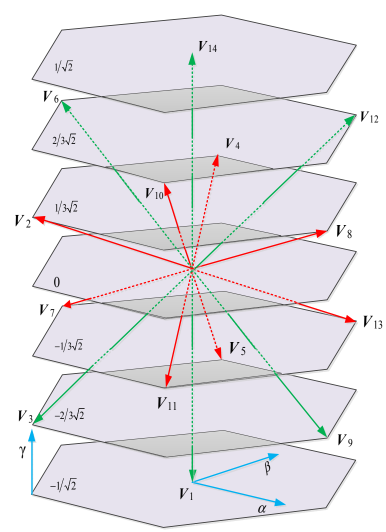
$$\boldsymbol{u}_i=\frac{2}{3}\left(\boldsymbol{u}_A+\boldsymbol{u}_B e^{j2\pi/3}+\boldsymbol{u}_C e^{j2\pi/3}\right)=U_{im}e^{j\alpha_i} \tag{3}$$

$$\boldsymbol{i}_i=\frac{2}{3}\left(\boldsymbol{i}_A+\boldsymbol{i}_B e^{j2\pi/3}+\boldsymbol{i}_C e^{j4\pi/3}\right)=I_{im}e^{j\beta_i} \tag{4}$$

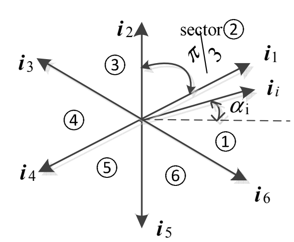
According to Fig.1, it is easy to get the relationship between the output phase voltages of TFMC.

$$\boldsymbol{u}_a+\boldsymbol{u}_b+\boldsymbol{u}_c+\boldsymbol{u}_f=0 \tag{5}$$

The TFMC with 3^4=81 switching states can be classified into three groups. The first group consists of 36 switch states, where the output vector of phase voltage and phase current with no fixed direction. The second group consists of 42 kinds of switch state, where the vector of output voltage and input phase current in a fixed direction. The third group consists of 3 kinds of switch state, zero voltage and current vector, as shown in Fig.2.



(a) The 3D voltage vectors



(b)Input current sector division

Fig.2 The voltage current vectors of TFMC

III. THE GENERATION MECHANISM OF CMV AND SUPPRESSIN METHOD OF TFMC

According to Fig.1, we can get the equation (6):

$$\begin{cases} \boldsymbol{u}_{\mathrm{a}} = L\dfrac{d\boldsymbol{i}_{\mathrm{a}}}{dt} + \boldsymbol{u}_{\mathrm{an}} + \boldsymbol{u}_{\mathrm{n}} \\ \boldsymbol{u}_{\mathrm{b}} = L\dfrac{d\boldsymbol{i}_{\mathrm{b}}}{dt} + \boldsymbol{u}_{\mathrm{bn}} + \boldsymbol{u}_{\mathrm{n}} \\ \boldsymbol{u}_{\mathrm{c}} = L\dfrac{d\boldsymbol{i}_{\mathrm{c}}}{dt} + \boldsymbol{u}_{\mathrm{cn}} + \boldsymbol{u}_{\mathrm{n}} \\ \boldsymbol{u}_{\mathrm{f}} = L_{\mathrm{n}}\dfrac{d\boldsymbol{i}_{\mathrm{f}}}{dt} + \boldsymbol{u}_{\mathrm{n}} \end{cases} \tag{6}$$

Where $\boldsymbol{u}_{\mathrm{a}}$, $\boldsymbol{u}_{\mathrm{b}}$, $\boldsymbol{u}_{\mathrm{c}}$ and $\boldsymbol{u}_{\mathrm{f}}$ denote the output voltage ; $\boldsymbol{u}_{\mathrm{n}}$ denote the CMV; $\boldsymbol{u}_{\mathrm{an}}$, $\boldsymbol{u}_{\mathrm{bn}}$, $\boldsymbol{u}_{\mathrm{cn}}$ are the voltage of the loads; $\boldsymbol{i}_{\mathrm{a}}$, $\boldsymbol{i}_{\mathrm{b}}$, $\boldsymbol{i}_{\mathrm{c}}$, $\boldsymbol{i}_{\mathrm{f}}$ represent output current; L and L_n denote the load inductance and fourth-leg inductance.

Owning to the output demand voltage is symmetrical, so

$$\boldsymbol{u}_{\mathrm{an}} + \boldsymbol{u}_{\mathrm{bn}} + \boldsymbol{u}_{\mathrm{cn}} = 0 \tag{7}$$

According to KCL,

$$\boldsymbol{i}_{\mathrm{a}} + \boldsymbol{i}_{\mathrm{b}} + \boldsymbol{i}_{\mathrm{c}} + \boldsymbol{i}_{\mathrm{f}} = 0 \tag{8}$$

Combining the equation (6) to (8), then

$$\boldsymbol{u}_{\mathrm{n}} = \frac{k(\boldsymbol{u}_{\mathrm{a}} + \boldsymbol{u}_{\mathrm{b}} + \boldsymbol{u}_{\mathrm{c}}) + \boldsymbol{u}_{\mathrm{f}}}{3k+1} \qquad k = L_{\mathrm{n}}/L \tag{9}$$

K is the ratio of the fourth leg inductance to the inductance of the other three arms. And the magnitude of CMV is closely related to the three-phase input voltage and k.

By summing up the CMV generated by all the 45 active switching states, the relationship between the CMV and the k value can be obtained, as shown in Fig3.

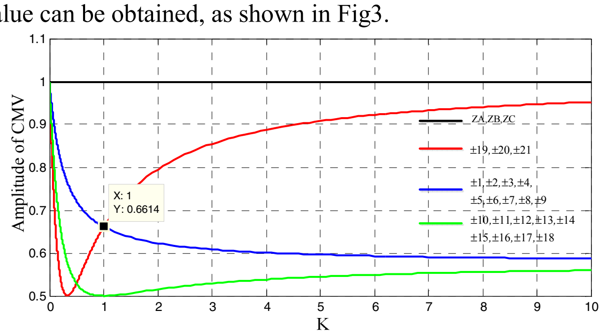


Fig.3 The graph of relationship between CMV and k

When the input vector is zero, the maximum CMV is amplitude of the input voltage. However, other vectors include fixed vectors and rotating vectors would generate CMV. The control strategy proposed in this paper does not use the rotating vectors, so it can be used to suppress the CMV by reducing number of zero vectors. Last but not least, when k equals 1, the CMV can be suppressed effectively.

Based on the above analysis, for the TFMC, 45 effective vectors are used to complete the 3DVSM and 36 rotation vectors are discarded. Each switch state produces the CMV greater than or equal to 0.5 times the input voltage. Therefore, based on the proposed optimization of the switch sequence and zero vector selection method can be the common mode voltage amplitude reduced by 0.5 times the input voltage.

(a)Non-optimized the zero vectors selection

According to the space vector modulation strategy of the TFMC, the input current and the output voltage vectors are divided into six sectors. Each output voltage sector is projected from six triangular prisms in the coordinate system. Each triangular prism consists of four tetrahedrons, so there are 144 combinations. We give the current vector in the sixth sector, the output voltage vector in the first sector, where the tetrahedron number 3 as an example to meet the 3DSVM switch sequence diagram, as shown in Figure 4.

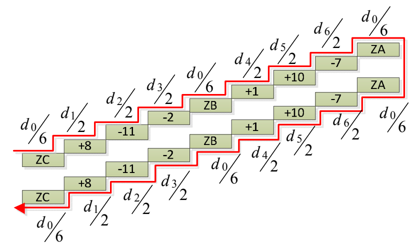


Fig.4 The non-optimized switching sequence

It can be seen from the above figure that the 3DSVM without zero vector is adopted 17-segment symmetric modulation. The advantage is that the number of times and turn on time are equal in each 12 groups interrupt cycle, so that the local switch temperature is not high, and the heat dissipation is more balanced. The disadvantage is that the switch on-state loss increases, the CMV cannot be suppressed. In order to suppress the amplitude of the CMV, this paper adopts the method of reducing the number of zero vectors and optimizing the zero vector selection. At the same time, the amplitude of the CMV is greatly suppressed while the 3DSVM is completed.

(b)Reducing and optimization the zero vectors selection

Removing the zero vectors, such as ZB or ZC, then the switching order becomes ZB, +1, +10, -7, +9, -12, -3 or +1, +10, -7, +9, -12, -3, ZC. Further, each input sector can be divided into two parts. One is [0 $\pi/6$], the other is [$\pi/6$ $\pi/3$]. Zero vectors can be selected by according to the principle of minimum CMV generating in every input sector, just as the Fig.5 shows.

When Sector_i is 1, ZC and ZB should be selected, hence the final switching sequence shown in Fig.8 and Fig.9.

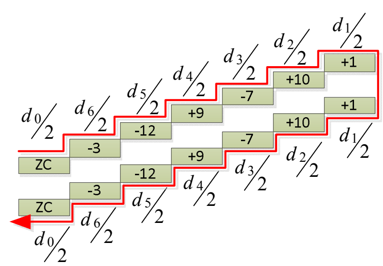


Fig.6. The switch sequence when use ZC

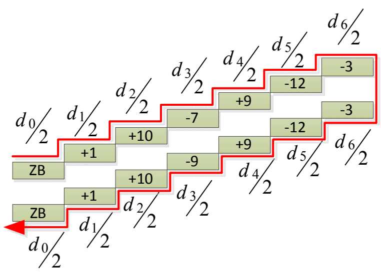


Fig.7. The switch sequence when use ZB

IV. SIMULATION RESULTS

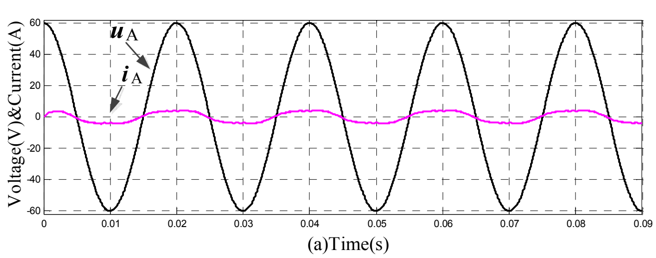
The simulation model of TFMC is built in MATLAB/Simulink to verify the correctness of optimized zero vectors selection theory proposed in this paper. Besides, the 24 switches are built by using insulated gate bipolar transistor (IGBT) switches and diodes. The input source voltage is assumed to be a three-phase symmetrical voltage source. And the other key parameters are listed in Table 1.

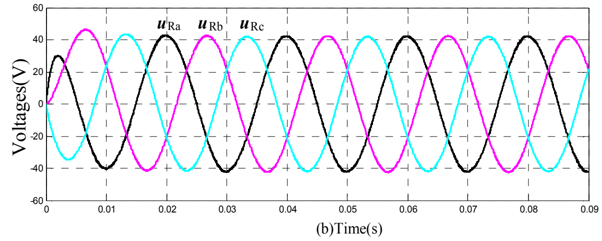
TABLE 1. SIMULATION PARAMETERS

Parameter	Symbol	Value	Parameter	Symbol	Value
Input voltage	U_{im}	60V	Resistance of Z_b	R_b	5Ω
Input frequency	f	50Hz	Inductance of Z_b	L_b	10mH
Modulation Index	m	0.7	Resistance of Z_c	R_c	5Ω
Switching frequency	f_s	20kHz	Inductance of Z_c	L_c	10mH
Output frequency	f_o	50Hz	Resistance of Z_N	R_N	0Ω
Resistance of Z_a	R_a	5ohm/ 10Ω	Inductance of Z_N	L_N	1mH/ 10mH
Inductance of Z_a	L_a	10mH	Input filter	L_S	1mH
Input filter capacitor	C_S	50uF	Input filter resistance	R_S	30Ω

(a)Non-optimized the zero vectors selection

The parameters are shown in Table 1, in which the inductance of the fourth leg is 1mH, so k=0.1. The simulation results are shown in Fig.8.





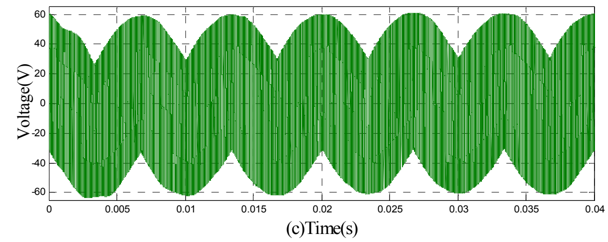
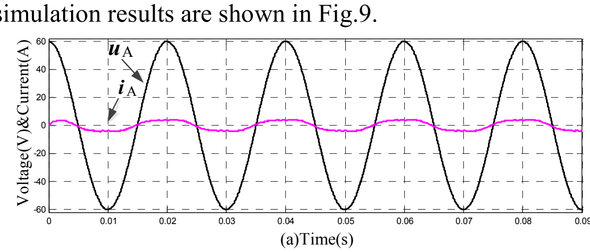


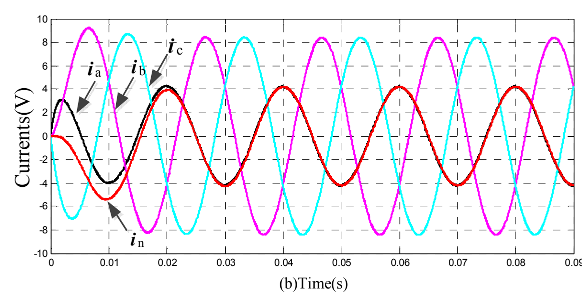
Fig.8. (a) Input Voltage and Current, (b) Output Voltage of three-phase load, (c) CMV.

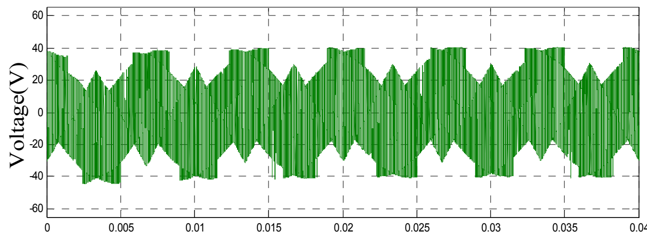
The output load voltage waveform of TFMC with output three-phase unbalanced load is showed in Fig.8(b), the voltage is sinusoidal and symmetrical. Moreover, Fig.8(a) shows that the TFMC satisfies unity power factor input. The CMV results show that when the traditional modulation strategy is used, the maximum CMV is the magnitude of the input voltage.

(b)Reducing and optimization the zero vectors selection

In order to suppress the CMV produced by the zero vectors, this paper proposes a method of using one zero vector and partitioning to select zero vectors，where the value of fourth leg inductance is 10mH, so k=1. The simulation results are shown in Fig.9.







(c)Time(s)

Fig.9. (a) Input Voltage and Current, (b) Output Current of three-phase Load, (c) CMV.

Obviously, the control strategy proposed in this paper can reduce the amplitude of CMV by 1/3, especially the CMV generated by the zero vectors is half of the input voltage amplitude. Due to the desired output voltage set symmetrically, the output current amplitude of a phase is half of b and c phase. The zero sequence component of fourth bridge arm is sine wave and satisfies the KCL, so $\boldsymbol{i}_{\mathrm{a}}+\boldsymbol{i}_{\mathrm{b}}+\boldsymbol{i}_{\mathrm{c}}+\boldsymbol{i}_{\mathrm{n}}=0$.

V. EXPERIMENT VERIFICATION

The experimental platform is shown in Fig.10. The whole set of experimental devices is concentrated on a 41cm by 56cm PCB circuit board, including three-phase input and output, diode clamp absorption circuit, voltage and four current detection modules and 12 groups of IGBT driver module. 12 bidirectional switches on the back of the PCB, showing a matrix distribution. The bidirectional diode clamp absorption circuit has the main function of absorbing the input and output instantaneous voltage spikes and releasing energy by resistors. The control system consists of the digital signal processor TMS320F28377 and the field programmable gate array control board MAX10.

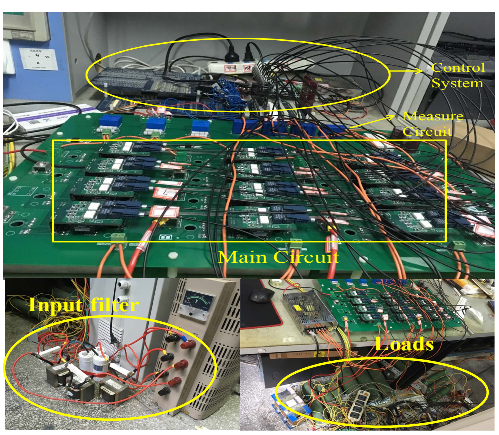
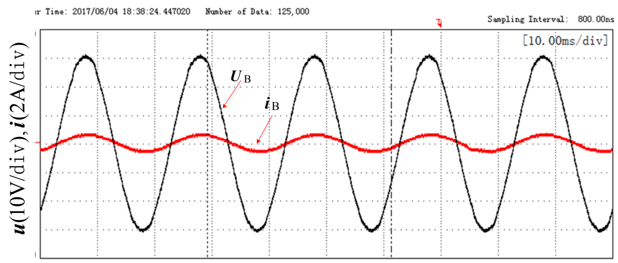


Fig.10. The whole experimental device

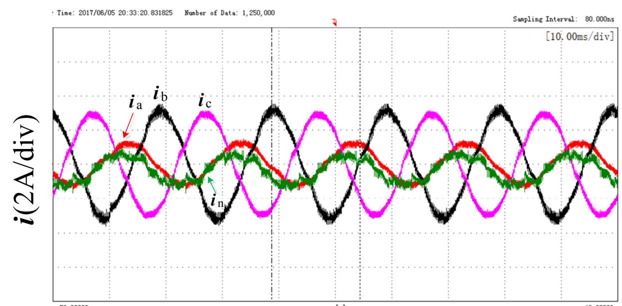
In this experiment, the switching frequency is 5kHz, the input line voltage is 40V, the four-step commutation time is 4.2us and the output voltage frequency is 50Hz. The other parameters are same as the simulation parameters.

(a)Non-optimized the zero vectors selection

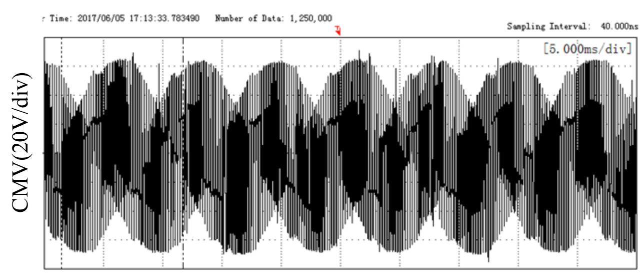
Fig.11 shows the experimental results of input voltage and current, output voltage and CMV when Ln = 1mH, respectively.



(a) t(10ms/div)



(b) t(10ms/div)



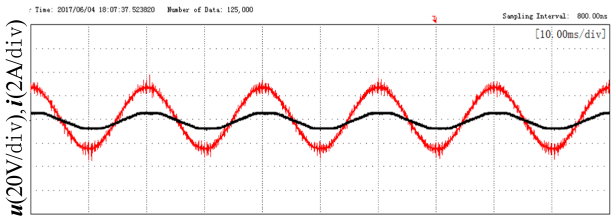
(c) t(5ms/div)

Fig.11. (a) Input Voltage and Current, (b) Output Current of three-phase Load, (c) CMV.

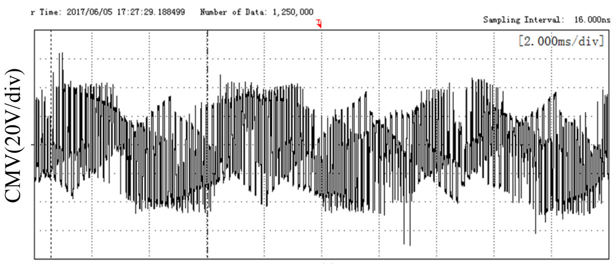
It can be seen from the experimental results that the amplitude of the CMV is the amplitude of the input phase voltage based on the modulation strategy with zero vector not optimized. The input current and voltage is same phase angle. The output phase current waves are basically sinusoidal, which is accordance with the simulation results. The experiment verifies the correctness of the control strategy

(b)Reducing and optimization the zero vectors selection

Fig.16 shows the experimental results of input voltage and current, output voltage and CMV when Ln = 1mH, respectively.



(a) t(10ms/div)



(b) t(2ms/div)

Fig.12. (a) Input Voltage and Current, (b) Output Current of three-phase Load, (c) CMV.

It can be seen from the experimental results that the output current and input phase current was sinusoidal waveform, and the waveform quality is good. Based on the zero vectors optimization of the modulation strategy, the CMV amplitude suppression is about 0.66 times of the input voltage. The CMV amplitude generated by the zero vector is 50%, and the waveform of the CMV is basically the same as the simulation waveform. The correctness of the control algorithm is verified by experiments.

Combining the experimental results of non-optimized zero vectors selection and optimized zero vectors optimization, the amplitude of CMV is reduced on the whole. At k=1, the magnitude of the CMV is the smallest. At this point, it is verified that k=1 is the optimal inductance condition when the desired output three-phase voltage vector is symmetrical.

VI. CONCLUSION

In this paper, the experimental platform of TFMC is built, the causes and suppression methods of CMV are studied. A method of selecting zero vectors according to time division optimization is proposed. The CMV generated by the zero vectors is suppressed by 50%. The simulation and experimental results show that when k=1, the control strategy proposed in this paper, not only makes the TFMC has excellent input and output characteristics, but largely suppress the amplitude of the CMV.

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