Zero common-mode voltage modulation in novel flying-capacitive VIENNA rectifier

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***Abstract*-- In this paper, the common-mode voltage (CMV) of VIENNA rectifier is analyzed, and a new modulation method using only zero CMV (ZCMV) vector is proposed. The voltage fluctuation of the neutral point is suppressed by introducing a flying-capacitive (FC) leg. The simulation results show that the amplitude of CMV is reduced by more than 90% and the common-mode conducted electromagnetic interference (EMI) is reduced by 30dB compared with conventional modulation. With the control of the FC leg, the amplitude of the voltage fluctuation at the neutral point is reduced significantly. This novel topology can be applied in three-phase AC-DC power conversion which considers EMI and power quality.**

***Index Terms*—Zero common-mode voltage, VIENNA, flying-capacitive leg.**

I. INTRODUCTION

With the wide application of power electronic devices in the field of electric energy conversion, a lot of harmonic pollution is brought to the power grid. Therefore, high-performance rectifiers has become the hot spot of research. Among them, VIENNA rectifier has the advantages of high power factor [1], no need to set dead zone for the bridge arm switch, and fewer power devices, but also has the characteristics of three-level converter output harmonics and switching voltage stress is small, so it is widely used in wind turbine systems, charging piles for electric vehicles [2] and power factor correction system [3] and other areas.

The rapid switching of the switch will generate electromagnetic interference (EMI). [4] Inevitably, higher dv/dt and di/dt will be generated. The pulse width modulation strategy based on the impulse equivalence principle can make the converter output the expected voltage, but there will be a large number of harmonic components in the high-frequency band, which is the noise source of EMI. Common-mode voltage (CMV) is defined as the voltage between the neutral point of the AC side and the neutral point of the DC side, which can be expressed as one-third of the sum of the voltages of the three phases. With the DC side neutral as the potential reference point, the AC side input phase voltage can be $\pm V_{dc}/2$ and 0 in a VIENNA rectifier with conventional modulation, resulting in the CMV with a maximum amplitude of $V_{dc}/3$. CMV will generate common-mode (CM) current in the stray circuit of the system, which will cause potential harm to the power electronic device and even the whole system. In addition, CM noise can also emit CM EMI, which threatens the reliable operation of the entire system [5].

EMI can be suppressed from two aspects: noise source [6] and propagation path [7]. The level of EMI can be greatly reduced by applied filters [8], but the introduction of passive devices will not only increase the volume and quality of the system, but also increase the cost. The active suppression method represented by the new pulse width modulation (PWM) strategy based on optimized switch combinations can reduce the conduction EMI at the source [9].

There are two main methods: spread spectrum modulation and zero common mode voltage modulation. [10] uses variable switching frequency to disperse EMI peaks caused by frequency concentration. In the special application background of MMC, [11] realizes EMI reduction through space spread spectrum. Zero-common-mode voltage modulation is often achieved by special vector fit and pulse alignment. [12] puts forward the carrier phase shifting method of SVPWM modulation combined with half-switched period, [13] puts forward the improved DPWM modulation combined with half-switched period carrier phase shifting method, both of which can only realize CMV suppression, but cannot realize the CMV elimination of the system. Each phase in a three-phase two-level inverter can output a voltage of $\pm V_{dc}/2$ (with the DC midpoint as the reference voltage). The three sums of these voltages are never zero. To achieve zero CMV, more degrees of freedom should be used. The CMV suppression of the four-bridge-arm current source converter is realized by vector combination [14]. [15] proposes a technical scheme to eliminate CMV by driving symmetrical six-phase motor with dual inverters. This method realizes synchronous cancellation of CMV by controlling the corresponding bridge arm output opposite voltage of the bridge arm of the two inverters, so as to suppress shaft current and common mode leakage current in the motor. For the study of VIENNA rectifier, the CMV vectors with smaller size were used for modulation to reduce the CMV amplitude from $V_{dc}/3$ to $V_{dc}/6$ [16]. But there is still a large CMV in VIENNA. It is very important to realize active suppression of VIENNA ZCMV by modulation technology.

So, in Chapter II, the influence of different vectors on CMV is analyzed. In Chapter III, a modulation method of ZCMV is proposed. Since only medium vectors are used, large fluctuation of neutral voltage is inevitable. Therefore, a flying-capacitive (FC) leg is introduced to suppress the voltage fluctuation of the neutral point. In Chapter IV, the VIENNA model with a FC leg is built in Matlab/Simulink. The simulation results show that, compared with the conventional space vector PWM (SVPWM), the amplitude of CMV is reduced by 98.5%, and the conducted EMI is reduced by 30 dB. With the control of the FC leg, the amplitude of the voltage fluctuation at the neutral point is reduced by 98.1%. The fifth chapter is the summary of the paper.

II. THE CIRCUIT AND CMV OF VIENNA

The circuit of VIENNA rectifier is shown in Fig. 1, e_a 、e_b、e_c are the voltage of the AC side of the grid, L is the AC filter capacitor, D_1-D_6 are the diodes, S_{a1}-S_{c2} are the switches, C_1 and C_2 are the DC link capacitor, R is the load. O is the neutral point on the DC side and O' is the neutral point on the AC side.

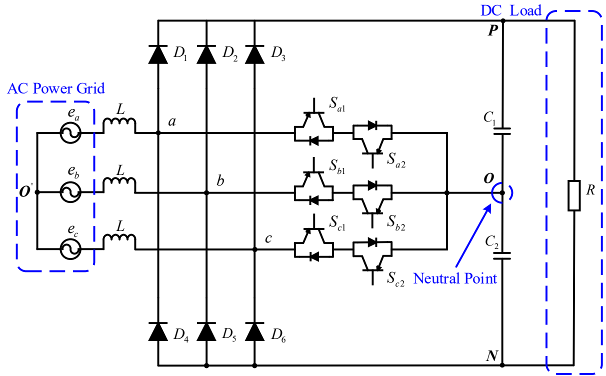


Fig.1. Circuit of VIENNA rectifier.

Taking phase a as an example, the neutral point O is used as the potential reference point. When the two switches in phase a are turned on, point a is clamped to the neutral point O and u_a=0, S_i=O (define the three states of the switch S_i, Where i =a, b, c.). When the two switches in phase a are off, if the current flows into point a from the AC side, it will continue to flow through the upper diode D_1 . In this case, point a is connected to point P, $u_a = V_{dc}/2$, S_i=P. If current flows from point a to the AC side, it will continue to flow through the lower diode D_2. In this case, point a is connected to point N, and $u_a = -V_{dc}/2$, S_i=N.

The current decoupling control strategy based on PI controller is widely used and its technology is mature. Firstly, the input voltage and current at the AC side are sampled, and then the direct flow in the d-q synchronous rotation coordinate system is obtained by coordinate transformation. The feedforward decoupling control is added to make the d and q axes independent of each other, thus controlling the active and reactive power components of the VIENNA rectifier respectively. The system control block diagram is shown in Fig.2. The decoupling governing equation based on PI controller can be expressed as

$$\begin{cases} u_d^* = -\left(K_{iP} + \dfrac{K_{iI}}{s}\right)\left(i_d^* - i_d\right) + \omega L i_q + u_d \\ u_q^* = -\left(K_{iP} + \dfrac{K_{iI}}{s}\right)\left(i_q^* - i_q\right) - \omega L i_d + u_q \end{cases} \tag{1}$$

where u_d^* and u_q^* are the expected value of modulation voltage in the D-Q synchronous rotating coordinate system, respectively. K_{iP} and K_{iI} are the proportional gain and integral gain of PI controller respectively. i_d^* and i_q^* are the current reference in the d-q synchronous rotation coordinate system. u_d and u_q are the direct flow of grid voltage in the d-q synchronous rotating coordinate system.

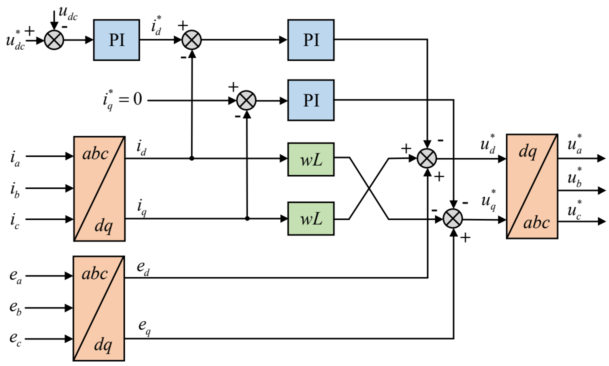


Fig.2. Double loop control of u and i.

The voltage reference generated by the control system is sent to the space vector modulation. The space vector diagram of VIENNA is shown in Fig.3. The output voltage vectors of VIENNA rectifier can be divided into four types: 6 large vectors, 6 medium vectors, 12 small vectors and one zero vector. The CMV can be expressed as:

$$u_{CMV} = \frac{1}{3}\left(u_a + u_b + u_c\right) \tag{2}$$

Therefore, the switching states of the VIENNA rectifier and the amplitude of the CMV can be obtained as shown in TABLE I.

TABLE I
SWITCH STATE AND CMV OF VIENNA

Large vector	CMV	Medium vector	CMV	Small vector	CMV	Small vector	CMV	Zero vector	CMV
PNN	$-V_{dc}/6$	PON	0	POO	$V_{dc}/6$	ONN	$-2V_{dc}/6$	OOO	0
PPN	$V_{dc}/6$	OPN	0	PPO	$2V_{dc}/6$	OON	$-V_{dc}/6$		
NPN	$-V_{dc}/6$	NPO	0	OPO	$V_{dc}/6$	NON	$-2V_{dc}/6$	PPP	$V_{dc}/2$
NPP	$V_{dc}/6$	NOP	0	OPP	$2V_{dc}/6$	NOO	$-V_{dc}/6$		
NNP	$-V_{dc}/6$	ONP	0	OOP	$V_{dc}/6$	NNO	$-2V_{dc}/6$	NNN	$-V_{dc}/2$
PNP	$V_{dc}/6$	PNO	0	POP	$2V_{dc}/6$	ONO	$-V_{dc}/6$		

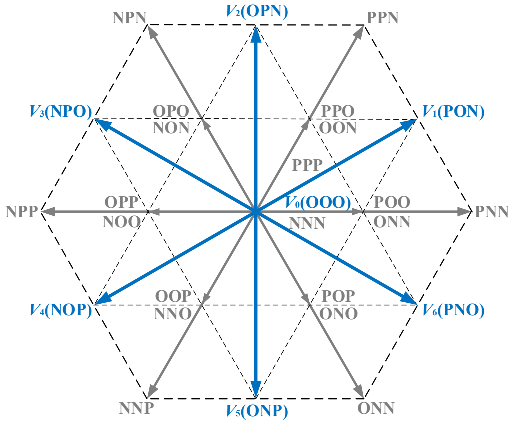
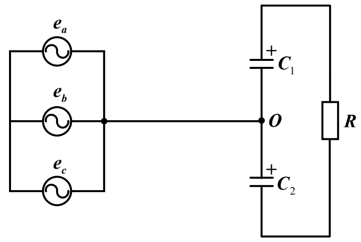
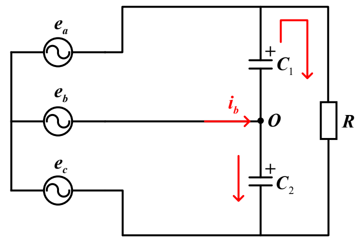


Fig.3. Space vector diagram of VIENNA.

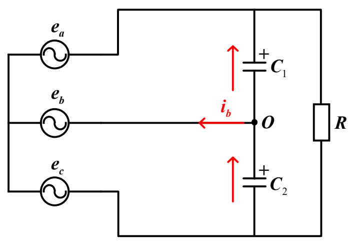
There is a CMV of $\pm V_{dc}/3$ in conventional SVPWM because of using small vectors. If only large, medium and zero vectors are used for modulation, there will be a CMV of $\pm V_{dc}/6$. In this paper, only medium vector and zero vector are used for modulation, which can theoretically reduce CMV to 0.



(a) zero vector (OOO)



(b) medium vector (PON)



(c) medium vector (PON)

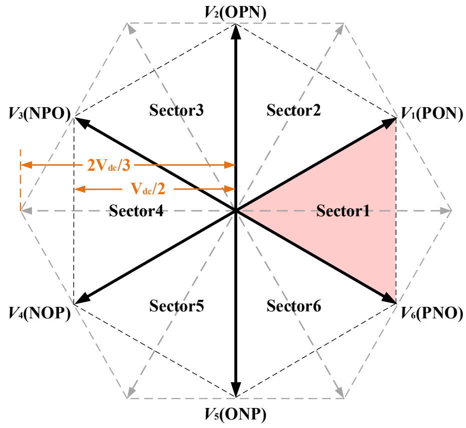
Fig.4. The effect of vectors on the voltage at the neutral point. (a)zero vector (b)medium vector (c)medium vector

The analysis of the influence of zero vector and medium vector on the voltage at the neutral point is shown in Fig.4. Fig.4 (a) shows the action of the zero vector, which doesn't affect the neutral voltage because i_o=i_a+i_b+i_c=0. Fig.4 (b) shows that when the current flows into the neutral point, capacitor C_1 discharges and capacitor C_2 charges. In this case, the medium vector will cause the potential of the neutral point to rise. Fig. 4 (c) shows that when the current flows out of the neutral point, capacitor C_1 charges and capacitor C_2 discharges. At this time, the medium vector will cause the potential of the neutral point to drop. Since the effect of the medium vector on the voltage at the neutral point depends on the direction of the current. Therefore, only zero vector and medium vector are used to modulate, and the voltage fluctuation of neutral point may be large or even unstable.

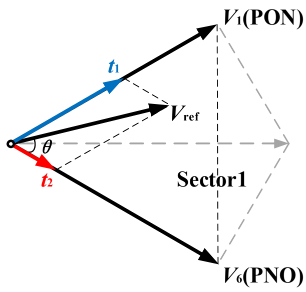
III. ZCMV Modulation and FC Leg

A. SVPWM-ZCMV

Assuming that the reference voltage vector is rotated to sector 1, the principle of vector synthesis is shown in Fig.5.



(a)



(b)

Fig.5. Principle of space vector synthesis.
(a) distribution of voltage vectors in ZCMV (b) vector synthesis in sector 1.

According to the volt-second equivalence principle, the following equation can be obtained:

$$T_s V_{ref} = t_1 V_1 + t_2 V_6 \tag{3}$$

$$T_s = t_1 + t_2 + t_0 \tag{4}$$

where V_{ref} is the space reference synthesis vector, t_1, t_2 and t_0 are respectively the action time of medium vector V_1, V_6 and zero vector V_0. Further according to the sine theorem, it can be obtained:

$$\frac{|V_{ref}|T_s}{\sin(2\pi/3)} = \frac{|V_1|t_1}{\sin(\theta)} = \frac{|V_6|t_2}{\sin(\pi/3-\theta)} \tag{5}$$

Where θ is the angle between the reference vector and the lagged medium vector in sector 1. Finally, the action time of each vector can be obtained as:

$$
\begin{cases}
t_1 = 2\left|V_{ref}\right| / V_{dc} T_s \sin(\theta) \\
t_2 = 2\left|V_{ref}\right| / V_{dc} T_s \sin(\pi/3-\theta) \\
t_0 = T_s - t_1 - t_2
\end{cases} \tag{6}
$$

B. Carrier-based PWM-ZCMV

Common three-level mainly adopts the same phase carrier cascade method, while ZCMV-PWM adopts the single carrier method similar to the two level. As shown in Fig.6, sinusoidal reference waves V_1, V_2 and V_3 with three-phase symmetry are compared with the triangular carrier V_r varying between ±1 to obtain reference signals V_{g1}, V_{g2} and V_{g3}. Then, the driving reference signals V_a, V_b and V_c of the three-phase bridge arm are determined according to formula (7). Obviously, the sum of three-phase voltage in (7) is constant zero, that is, the CMV is zero.

$$
\begin{cases}
V_a = \dfrac{V_{g1} - V_{g2}}{2} \\
V_b = \dfrac{V_{g2} - V_{g3}}{2} \\
V_c = \dfrac{V_{g3} - V_{g1}}{2}
\end{cases} \tag{7}
$$

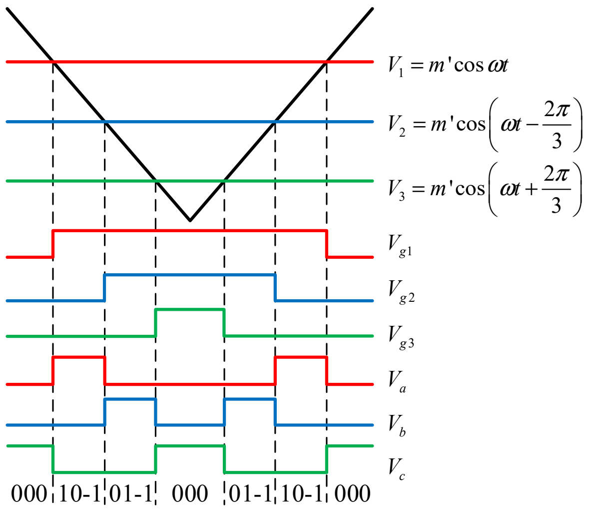


Fig.6. Principle of ZCMV for carrier PWM.

C. FC Leg

As shown in Fig.7, an auxiliary FC bridge is introduced to VIENNA rectifier, which consists of four switches S_1-S_4 and a capacitor. Fig.8(a) shows the situation when the switching state of S_1-S_4 is [0101], the capacitor is discharged and the voltage at the neutral point decreases. Fig.8(b) shows the situation when the switching state of S_1-S_4 is [1010], the capacitor is charged and the voltage at the neutral point increases. So, The PWM of S_1 and S_3 are consistent, which are both square waves with 50% duty cycle. The PWM of S_1 and S_2 are opposite, and the PWM of S_2 and S_4 are consistent. Through the control of the auxiliary switches S_1-S_4, the voltage at neutral O is maintains stable.

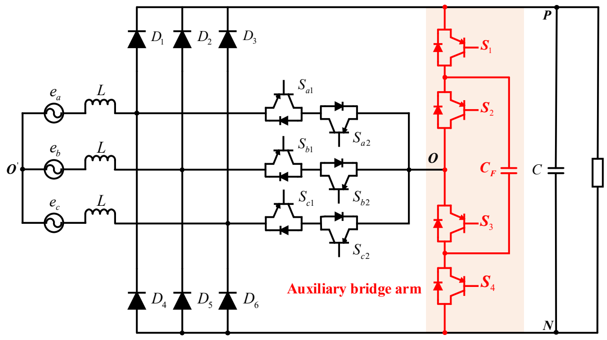


Fig.7. FC-VIENNA.

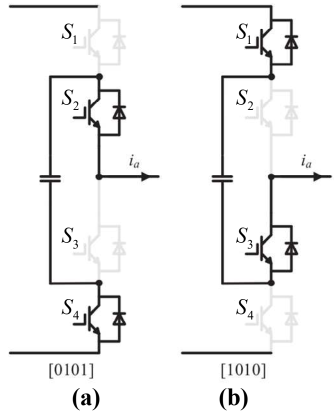


Fig.8. Status of the FC leg.

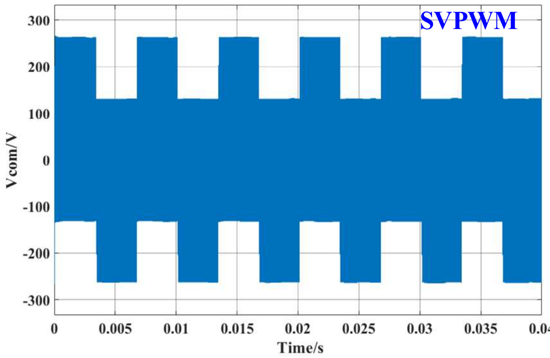
IV. SIMULATION

VIENNA model with FC leg is built in Matlab/Simulink, and the simulation parameters are shown in Table II. The simulation of conventional SVPWM modulation, ZCMV modulation and FC-ZCMV modulation are carried out respectively.

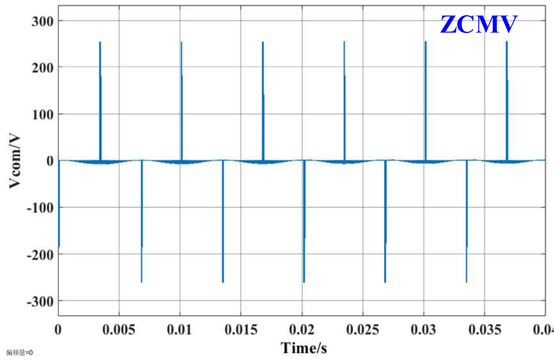
TABLE II
SIMULATION PARAMETERS

Symbol	Parameter	Value
e	RMS of the grid voltage	220V
L	Filter Inductor	3mH
V_{dc}^*	DC voltage	800V
C	Voltage regulator capacitor	88uF
C_F	Flying-Capacitor	88uF
R	Lord	100Ω
f_s	Switching frequency	20kHz
f	Modulated wave frequency	50Hz

The waveforms of CMV of the three modulation strategies are shown in Fig.9. There is a CMV with amplitude of 267V in conventional SVPWM. The two ZCMV modulations eliminate most of the CMV, except for a few spikes when the phase current crosses zero. This is because the upper and lower bridge arms of VIENNA are diodes, and the phase voltage is determined by the direction of the current. There are some ripples in actual phase current. It will inevitably fluctuate when crossing zero, so it is consistent with the theory.



(a)



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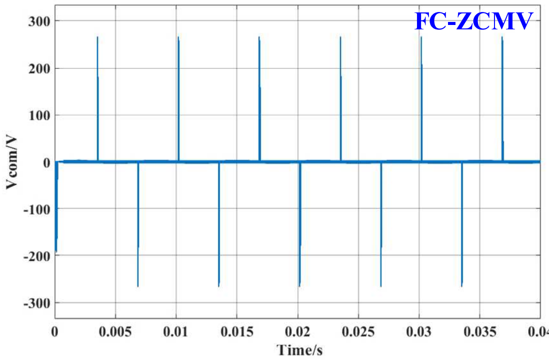


(c)

Fig. 9. Time domain waveform of CMV (a)ordinary SVPWM (b)ZCMV (c)FC-ZCMV

The frequency spectrum of CMV is shown in Fig.10, and FC-ZCMV modulation reduces the conducted EMI by 30dB.

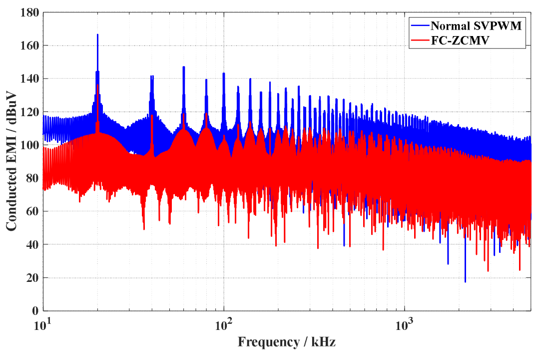
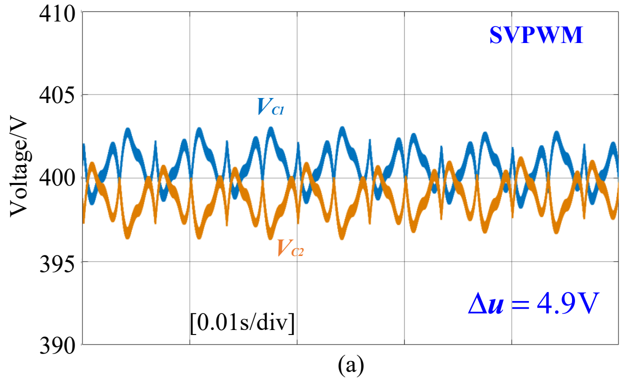
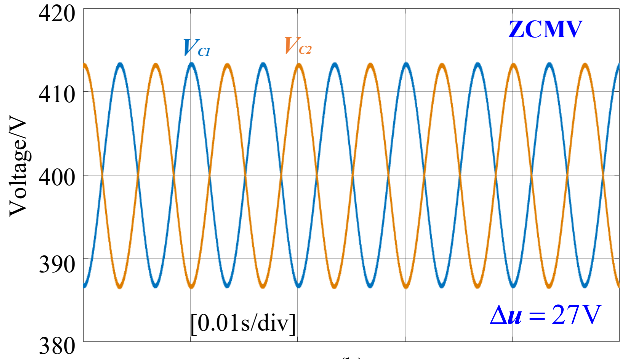


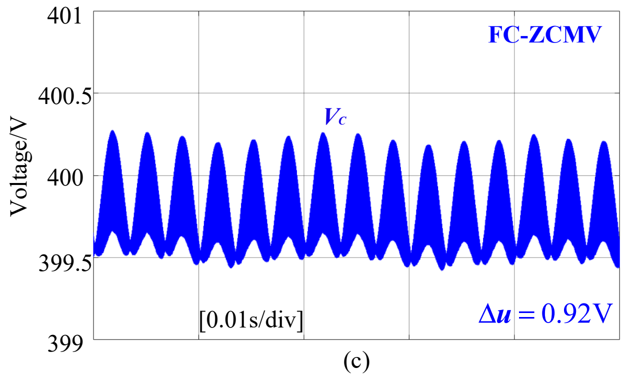
Fig. 10. The frequency spectrum of the CMV



(a)



(b)



(c)

Fig. 11. Capacitance voltage (a)ordinary SVPWM (b)ZCMV (c)FC-ZCMV

Fig.11 shows the voltage of the capacitance voltage of the three modulation strategies. ZCMV only uses the medium vectors, which leads to the increase of the voltage fluctuation of the neutral point. With the control of FC leg, the voltage fluctuation amplitude of neutral point is reduced by 98.1%.

V. CONCLUSIONS

By analyzing the CMV of VIENNA, this paper proposes a ZCMV modulation method using only medium vectors and zero vectors, and introduces a FC leg to suppress the voltage fluctuation of the neutral point. The simulation results show that ZCMV modulation reduces the CMV amplitude by 98.5% and reduces the CM conduction EMI by 30dB. The FC leg reduces the voltage fluctuation at the neutral point by 98.1% and improves the power quality. This modulation strategy is simple and reduces the harm of CMV greatly. It is suitable for various applications of VIENNA rectifiers.

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