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Xiang Wu

wux@tongji.edu.cn

Tongji University

Yuyang Zhang

Tongji University

Zhixun Ma

Tongji University

Jieguang Li

China University of Mining and Technology

Shuo Chen

China University of Mining and Technology

Xiao Zhang

China University of Mining and Technology

Zhan Liu

Jiangsu Normal University

Research Article

Keywords: Pulse-width modulation, Inverter, Common-mode Voltage

Posted Date: August 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10053494/v1>

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Additional Declarations: No competing interests reported.

Optimal Common-mode Voltage Suppression Pulse-width Modulation Based on Adjacent-Four-Vector Synthesis Principle

Xiang Wu^{1,2} · Yuyang Zhang^{1,2} · Zhixun Ma^{1,2} · Jieguang Li³ · Shuo Chen³ · Xiao Zhang³ · Zhan Liu⁴

Abstract

The common-mode voltage (CMV) produced by voltage source inverters brings negative effects that cannot be ignored. Pulse width modulation (PWM) methods based on the nearest-three-vector synthesis principle face the problem of insufficient control freedom in CMV suppression. Therefore, an adjacent-four-vector (A4V) synthesis principle based CMV suppression PWM (A4V-CMVS-PWM) strategy is studied in this paper, where the switching sequence design method under the A4V synthesis principle is given and the control degrees of freedom are analyzed. The optimization methods of the switching sequence and the adjustment factor of the durations of A4V are studied, and the layer-by-layer optimization of the CMV volt-second characteristics and output harmonic performance is realized. Simulation and experimental results show that the proposed method can realize the targets of restricting the CMV peak and optimizing the CMV volt-second characteristics. On this basis, the optimization of output harmonic performance is realized by making full use of control degrees of freedom.

Keywords Pulse-width modulation · Inverter · Common-mode Voltage.

1 Introduction

With the increase of switching speed and frequency of power electronic devices, the common-mode voltage (CMV) generated by two-level voltage source inverters (2L-VSIs) [1]- [3] has caused some negative effects that cannot be ignored. In the field of photovoltaic power generation, leakage current [4] generated by high-frequency CMV can cause grid connected current distortion and even cause security problems. In the field of AC motor drive, the high frequency shaft voltage and shaft current caused by CMV reduce the service life of the motor [5]. CMV is also the source of common-mode electromagnetic interference [6], and the reliable operation of surrounding equipment may be affected to some extent.

The negative effects of CMV can be effectively reduced by adopting the method of hardware improvement [7]-[8], but it increases the system cost and volume, and generates additional losses. To address these problems, one approach to mitigate the negative impact of CMV at a lower cost is by optimizing the control mode of the power switching devices. In [9]-[10], CMV suppression methods based on finite-control-set model predictive control effectively restrain CMV amplitude by optimizing the selected voltage

vector or switching sequence. In [11]-[37], several CMV suppression PWM (CMVS-PWM) methods are proposed. According to the difference in optimization objective, the existing CMVS-PWM methods are mainly divided into three categories. The first category aims to limit the CMV amplitude, the second type aims to optimize the volt-second characteristics of CMV, and the third category considers the above two objectives at the same time.

For the first category of CMVS-PWM methods, the CMV amplitude can be reduced to 33.3% of the conventional space vector PWM (SVPWM) by avoiding the use of zero voltage vectors (ZVVs). For motor drive applications, the peak value of the shaft voltage is directly proportional to the peak value of CMV. Therefore, the use of the first category of CMVS-PWM is beneficial for reducing the probability of breakdown of the bearing oil film [36] and improving the service life of the motor. In [11]-[13], an active zero-state PWM1 (AZSPWM1) method using two reverse non-zero voltage vectors (NZVVs) of which the durations are the same to replace ZVVs is presented. On the basis of AZSPWM1, the dead-time effects to CMV reduction are considered in [14]. In [15], the output harmonic is optimized by adjusting the action time of the

✉ Xiang Wu
wux@tongji.edu.cn

¹ College of Transportation, Tongji University, Shanghai 201804, China

² State Key Laboratory of High-speed Maglev Transportation

Technology, Tongji University, Shanghai 201804, China

³ School of Electrical Engineering, China University of Mining and Technology, Xuzhou 221116, China

⁴ School of Electrical Engineering and Automation, Jiangsu Normal University, Xuzhou 221116, China

two reverse NZVVs based on the switching sequences of AZSPWM1. A MAZSPWM is presented in [16]-[17] based on AZSPWM1 to improve the issue. In [18]-[20], the near-state PWM (NSPWM) method synthesizing the reference voltage vector (RVV) with three nearest NZVVs is presented, which can achieve the CMV reduction and reduce the switching losses, but only applicable with the modulation degree (m , defined as the ratio of the amplitude of reference voltage to half of the dc-link voltage) is greater than 0.77. Thus, the application of NSPWM is limited to some extent. A virtual vector-based direct torque control method is proposed in [21] to suppress CMV amplitude while maintaining the simple structure and excellent dynamic performance. In [22], A modified single-edge modulation strategy considering the dead-time effects is proposed to reduce the CMV amplitude and CMV spikes, however, the range of m is limited in this method. In [23] and [24], the characteristics of common-mode current for AZSPWM1 and NSPWM in the field of photovoltaic grid connection and motor drive are studied, and it is indicated that the resonance frequency of the common-mode coupling circuit should also be considered in the design of the parameters for PWM.

By analyzing the mechanism of motor leakage current and common-mode choke saturation caused by CMV in [25], it is indicated that the problem of common-mode choke saturation and heating mainly be caused by the fluctuation of the voltage-second value of CMV, and the essential reason is that there are three-order low-frequency components in CMV. The CMV suppression method of the inverter with filters is analyzed in [26], it points out that the common-mode impedance of the common-mode filter is small and the low-frequency components of CMV caused by PWM can generate large common-mode current through the common-mode filter. To solve the above problems, the second type of CMVS-PWM method aims to optimize the volt-second characteristics of CMV by reducing the low-frequency components to reduce the volt-second value of CMV. Reference [27] proposes a method for optimizing the volt-second characteristics of CMV with injecting balanced zero-sequence voltage. A CMV low-frequency component suppression strategy is proposed with interleaved carriers based PWM in [28]. However, the bus voltage utilization of the methods in [27] and [28] is 13% lower than that of SVPWM. In [29], the three-order low-frequency components of CMV are minimized and its bus voltage utilization is the same as that of SVPWM by injecting the optimized zero-sequence component in the carrier.

The third type of CMVS-PWM method takes both the CMV amplitude and volt-second characteristics into account and it is more effective in mitigating the negative effects of CMV. A carrier-phase-shift PWM method is presented in [30] and it can restrict the amplitude of the

CMV within one sixth of the dc-link voltage and suppress the third-order low-frequency components, but it is only applicable with low m . A virtual SVPWM method is proposed in [31], which synthesizes the RVV with 3 virtual voltage vectors of which the volt-second value is 0. The third-order harmonic component in CMV is reduced, but the utilization ratio of the dc-link voltage is reduced by about 13% compared to AZSPWM1. In [32], a hybrid PWM strategy that integrates modified SPWM with NSPWM implementing with carrier modulation is proposed to achieve simultaneous suppression of high/low-frequency CMV while maintaining dc-link voltage utilization comparable to SVPWM. A CMVS-PWM method based on optimizing zero sequence voltage is proposed in [33], it can simultaneously limit CMV amplitude and low-frequency components while maintaining the same utilization ratio of the dc-link voltage as the AZSPWM1 method.

The conventional SVPWM adopts the nearest-three vectors (N3Vs) synthesis principle, which uses ZVVs and two NZVVs closest to the RVV to synthesize the RVV according to the principle of volt-second balance. There are two ZVVs for 2L-VSI, which can be used to realize the targets such as harmonic optimization and switching loss reduction by distributing the action time of ZVVs. The N3V synthesis principle has also been applied in CMVS-PWM methods, e.g., NSPWM adopts the three NZVVs closest to the RVV to synthesize the RVV [20]. However, due to the lack of redundant vectors in the NZVVs, it is not possible to optimize other goals while limiting the CMV amplitude, so the N3V synthesis principle has a problem of control degrees of freedom missing when considering the target of CMV suppression.

To address the above issues, a new adjacent-four vector (A4V) synthesis principle is proposed in this paper. Compared with N3V synthesis principle, the advantage of the proposed A4V synthesis principle is that it introduces two control degrees of freedom under the target of CMV reduction. The duration regulating factor of the selected A4Vs and the switching sequence of the A4Vs can be viewed as two control degrees of freedom for the proposed method, and the calculation method of these two control degrees of freedom is studied to realize the layer-by-layer optimization of the CMV volt-second characteristics and output harmonic performance. Through the simulation and experimental results, the effectiveness of the proposed method is verified in terms of CMV amplitude restriction, volt-second characteristic and output harmonic performance optimization. In addition, the comparative results indicate the advancement of the A4V synthesis principle.

2 Review of the Synthesis Principle of Existing PWMs

The main circuit structure of the three-phase 2L-VSI is shown in Fig. 1, where the dc-link voltage is denoted as V_{dc} , the midpoint of the dc-link is denoted as o, and the neutral point of the three-phase resistance-inductance load is denoted as n. There are two power switch devices in each bridge arm that work in complementary states. With the case that the upper power switch is conducting, it is referred to as the "1" state, otherwise it is referred to as the "0" state.

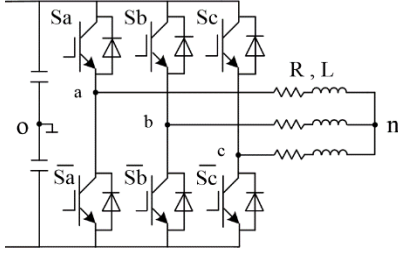


Fig. 1. Structure of 2-level VSI.

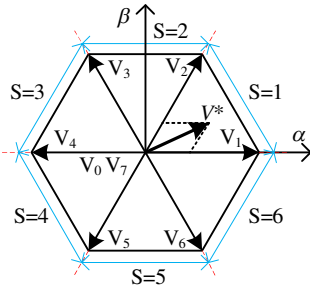


Fig. 2. Voltage space vector diagram.

The states of the three phases can form 8 voltage vectors (VVs), namely V_0 - V_7 in Fig. 2 where S is defined as the sector. V_0 and V_7 are ZVVs, of which the corresponding CMV are $-V_{dc}/2$ and $V_{dc}/2$, respectively. The CMV corresponding to the NZVVs of V_1 , V_3 , and V_5 is $-V_{dc}/6$, while the CMV corresponding to the NZVVs of V_2 , V_4 , and V_6 is $V_{dc}/6$.

2.1 The Conventional Nearest Three Vector Synthesis Principle

The conventional N3V synthesis principle selects the three VVs closest to the RVV and synthesizes the RVV by following the principle of volt-second balance. Taking the RVV V^* in sector 1 in Fig. 2 as an example, the N3V synthesis principle uses the ZVVs, V_1 and V_2 to synthesize V^* and calculates the action time of N3V according to equation (1).

$$\begin{cases} V^* T_c = V_1 t_1 + V_2 t_2 \\ t_1 + t_2 + t_0 = T_c \end{cases} \quad (1)$$

where T_c is the carrier period, t_0 , t_1 , and t_2 are the durations of ZVVs, V_1 , and V_2 , respectively. According to the N3V synthesis principle, when the RVV lies in the triangle surrounded by ZVVs, V_1 , and V_2 , there is a unique solution

to (1), and it satisfies the following formula:

$$0 \leq t_j \leq T_c, j = 0, 1, 2 \quad (2)$$

Since the conventional N3V synthesis principle selects ZVVs, the CMV amplitude reaches $0.5V_{dc}$ for the SVPWM algorithm that uses V_0 and V_7 with the same durations.

2.2 The Vector Synthesis Principle of Existing CMVS-PWMs

To suppress CMV, most existing CMVS-PWMs cancel the utilization of ZVVs and exclusively employ NZVVs to synthesize RVVs, thereby restricting the amplitude of CMV. The vector synthesis principles of existing CMVS-PWMs with S being 1 are shown in Fig. 3. For AZSPWM1 [11]-[14] as shown in Fig. 3(a), the RVVs are synthesized with two adjacent NZVVs (V_1 and V_2) which are nearest to the RVV and a pair of opposite NZVVs (V_3 and V_6). The durations of V_3 and V_6 are the same to equivalently synthesize the ZVVs. The vector synthesis principle of AZSPWM2 [18] is the same as AZSPWM1, but the sequence of the adopted 4 NZVVs are modified to reduce the number of jumps of CMV. To mitigate overvoltage at load terminals caused by line-to-line voltage polarity reversals, a modified AZSPWM1 (MAZSPWM) is proposed in [16]-[17] by adjusting the duration of vector located between voltage changes with the same vector synthesis principle as AZSPWM1.

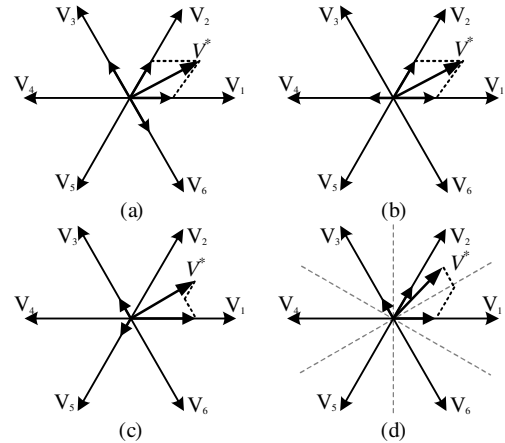


Fig. 3. The vector synthesis principles of existing CMVS-PWMs. (a) AZSPWM1, 2, and MAZSPWM (b) AZSPWM3, (c) RSPWM, (d) NSPWM.

AZSPWM3 [18] synthesizes the RVV using two adjacent NZVVs (V_1 and V_2) and a pair of opposite NZVVs (V_1 and V_4), achieving both reduced CMV amplitude and decreased CMV variation frequency, with its synthesis principle illustrated in Fig. 3(b). RSPWM mentioned in [37] synthesizes RVV through three non-adjacent NZVVs as shown in Fig. 3(c). For the NSPWM [18]-[20], RVVs are synthesized using three adjacent NZVVs as illustrated in Fig. 3(d).

By observing Fig. 3 (b), (c), and (d) carefully, AZSPWM3, RSPWM, and NSPWM essentially use three vectors to synthesize RVVs, however, the three selected vectors are not the N3Vs as shown in Fig. 2, which make the current ripples increased. It has been analyzed in [18] that the practicality of AZSPWM3, and RSPWM is limited

especially with long wires between the inverter and the motor owing to the problems such as requiring simultaneous switching in two legs and rapid reversals of the line-to-line voltages.

Unlike SVPWM, AZSPWM3, RSPWM, and NSPWM, the AZSPWM1, 2, and MAZSPWM adopts the adjacent four vectors (A4Vs) to synthesize RVVs, and it is in fact the basic of the proposed A4V synthesis principle. However, AZSPWM1, 2, and MAZSPWM share common limitations characterized by rigidly defined synthesis principle, unique switching sequence selection, and absence of additional control degrees of freedom, which makes it difficult to simultaneously optimize other objectives when reducing CMV. To solve the above problems, a more general A4V synthesis principle featuring with more control degrees of freedom and optional A4Vs will be studied in the next section.

3 Adjacent-Four-Vector Synthesis Principle

Without loss of generality, this paper takes the isosceles trapezoid formed by V_1 , V_2 , V_3 , and V_4 as shown in Fig. 4 as an example to illustrate the new A4V synthesis principle. If the RVV is located in the isosceles trapezoidal area surrounded by four non-zero vectors V_1 , V_2 , V_3 , and V_4 , the RVV can be equivalently synthesized by V_1 , V_2 , V_3 , and V_4 following the proposed A4V synthesis principle according to the volt-second balance formula in (3).

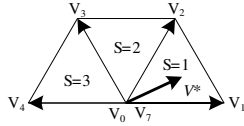


Fig. 4. Diagram of the adjacent-four-vector synthesis principle.

$$\begin{cases} V^* T_c = V_1 t_1' + V_2 t_2' + V_3 t_3' + V_4 t_4' \\ t_1' + t_2' + t_3' + t_4' = T_c \end{cases} \quad (3)$$

where t_1' , t_2' , t_3' and t_4' are the durations of V_1 , V_2 , V_3 , and V_4 , respectively, and they satisfy the following equation:

$$0 \leq t_j' \leq T_c, j=1,2,3,4 \quad (4)$$

In order to illustrate the correctness of the A4V synthesis principle, the proofs are provided as follows:

Case 1: If the RVV is located in the first sector ($S=1$), according to the conventional N3V principle, the volt-second balance equations in (1) have a unique solution.

According to the quadrilateral principle, we know that:

$$\begin{cases} V_3 = V_2 - V_1 \\ V_4 = -V_1 \end{cases} \quad (5)$$

Substituting (5) into (3), (6) can be obtained.

$$\begin{cases} V^* T_c = V_1 (t_1' - t_3' - t_4') + V_2 (t_2' + t_3') \\ t_1' + t_2' + t_3' + t_4' = T_c \end{cases} \quad (6)$$

By combining (1) and (6), (7) can be obtained.

$$\begin{cases} t_1' = t_1 + 0.5(t_0 + \Delta t) \\ t_2' = t_2 - \Delta t \\ t_3' = \Delta t \\ t_4' = 0.5(t_0 - \Delta t) \end{cases} \quad (7)$$

From (7), it can be concluded that (3) and (4) can be established at the same time only by satisfying (8).

$$0 \leq \Delta t \leq \min(t_0, t_2) \quad (8)$$

where Δt is defined as an adjustment factor for the action time of A4Vs.

That is to say, the volt-second balance equations in (3) derived from the A4V principle have solution sets with clear physical meaning. Accordingly, the validity of the A4V synthesis principle has been proved for the case where the RVV is located in the first sector.

Case 2: If the RVV is located in the second sector ($S=2$), according to the conventional N3V principle, the volt-second balance equations in (9) have a unique solution.

$$\begin{cases} V^* T_c = V_2 t_2 + V_3 t_3 \\ t_2 + t_3 + t_0 = T_c \end{cases} \quad (9)$$

where, t_0 , t_2 , and t_3 are the durations of zero vectors, V_2 and V_3 under the N3V synthesis principle.

According to the quadrilateral principle, we know that:

$$\begin{cases} V_1 = V_2 - V_3 \\ V_4 = V_3 - V_2 \end{cases} \quad (10)$$

Similarly, substituting (10) into (3), and then combining (9), the solution of (3) can be obtained as:

$$\begin{cases} t_1' = \Delta t \\ t_2' = t_2 + t_0 - 2\Delta t \\ t_3' = t_3 - t_0 + 2\Delta t \\ t_4' = t_0 - \Delta t \end{cases} \quad (11)$$

From (11), it is indicated that as long as (12) is satisfied, (3) and (4) can be established at the same time. Accordingly, the validity of the A4V synthesis principle has been proved for the case where the RVV is located in the second sector.

$$\max\left(0, \frac{t_0 - t_3}{2}\right) \leq \Delta t \leq \min\left(t_0, \frac{T_c - t_3}{2}\right) \quad (12)$$

Case 3: When the RVV is located in the third sector ($S=3$), according to the conventional N3V principle, the volt-second balance equation in (13) has a unique solution.

$$\begin{cases} V^* T_c = V_3 t_3 + V_4 t_4 \\ t_3 + t_4 + t_0 = T_c \end{cases} \quad (13)$$

where t_0 , t_3 and t_4 are the durations of zero vector, V_3 , and V_4 under the N3V principle.

According to the quadrilateral principle, we know that:

$$\begin{cases} V_1 = -V_4 \\ V_2 = V_3 - V_4 \end{cases} \quad (14)$$

Similarly, substituting (14) into (3), and then combining (13), the solution of the A4V principle in (3) can be obtained:

$$\begin{cases} t_1 = 0.5(t_0' - \Delta t) \\ t_2 = \Delta t \\ t_3 = t_3' - \Delta t \\ t_4 = t_4' + 0.5(t_0' + \Delta t) \end{cases} \quad (15)$$

It can be obtained from (15), as long as (16) is satisfied, then (3) and (4) can be established at the same time. Accordingly, the validity of the A4V synthesis principle has been proved for the case where the RVV is located in the third sector.

$$0 \leq \Delta t \leq \min(t_0', t_3) \quad (16)$$

Accordingly, the correctness of the A4V synthesis principle is effectively proved.

4 Optimized CMVS-PWM Based on Adjacent A4V Synthesis Principle

The A4V synthesis principle uses four NZVVs to synthesize the RVV, avoiding the use of zero vectors. The PWM strategy following the A4V synthesis principle can restrict the CMV amplitude within $V_{dc}/6$, which realizes 66.7% CMV reduction compared to the conventional SVPWM. Moreover, an A4V synthesis principle based CMVS-PWM (A4V-CMVS-PWM) strategy is studied in this paper, and the switching sequence and control degrees of freedom are analyzed, on this basis, the control degrees of freedom are made full use to achieve layer-by-layer optimization of CMV volt-second characteristics and output harmonic characteristics.

4.1 Design and Analysis of Switching Sequences

Through the analysis of Fig. 4, we can easily see that for a RVV at a particular location, it must be located in one of the three isosceles trapezoids. Taking the RVV in the first sector ($S=1$) as an example, Fig. 5 shows three synthesis methods of RVV with the A4V principle.

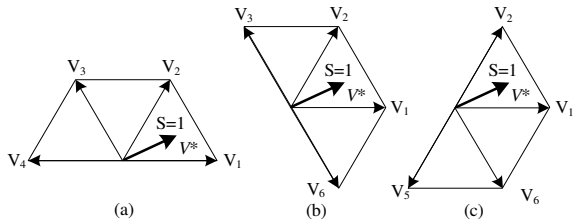


Fig. 5. Three types of the reference vector synthesis in sector 1.

In Fig. 5(a), V^* is located within the isosceles trapezoid formed by V_1 - V_2 - V_3 - V_4 , therefore, it can be synthesized by the A4Vs V_1 , V_2 , V_3 , and V_4 . In Fig. 5(b), V^* is located within the isosceles trapezoid formed by V_3 - V_2 - V_1 - V_6 , therefore, it can be synthesized by the A4Vs V_3 , V_2 , V_1 , and V_6 . In Fig. 5(c), V^* is located within the isosceles trapezoid formed by V_2 - V_1 - V_6 - V_5 , therefore, it can be synthesized by the A4Vs V_2 , V_1 , V_6 , and V_5 . In order to reduce the switching losses, the designed switching sequence should aim at minimizing the switching times, as shown in Fig. 6.

As with the method shown in Fig. 5 (a), the switching sequences in Fig. 6(a) and Fig. 6(b) are synthesized using the A4Vs V_1 , V_2 , V_3 , and V_4 , and the difference between them is the order of the vectors. The switching sequences shown in Fig. 6(c) and (d) correspond to the synthesis method in Fig. 5(b), and both switching sequences use the A4Vs V_3 , V_2 , V_1 , and V_6 , which differ in the order of the vectors. The switching sequences shown in Fig. 6(e) and (f) correspond to the synthesis method in Fig. 5(c), and both switching sequences use A4Vs V_2 , V_1 , V_6 , and V_5 , which differ in the order of the vectors.

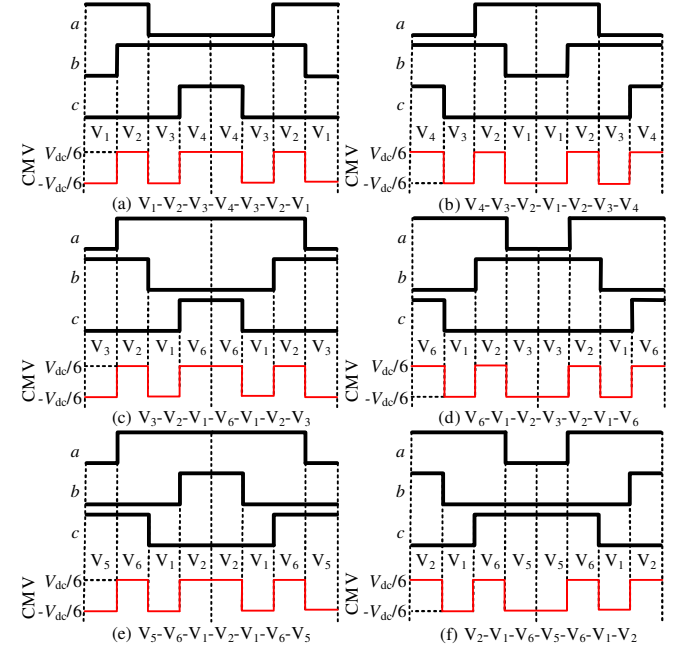


Fig. 6. Switching sequence of the proposed A4V principle in sector 1.

For cases where the RVV is located in other sectors, there are six different switching sequences with A4V synthesis principle.

4.2 Analysis of the Control Degrees of Freedom

According to (8), (12) and (16), it is known that the defined adjustment factor for the action time of A4Vs (Δt) is within a certain range, and its value is not unique. Therefore, we can consider Δt as a factor affecting the features of A4V-CMVS-PWM strategy and define it as the first control degree of freedom. According to (7), (11) and (15), different Δt values correspond to different durations of A4Vs. Therefore, these values of Δt can be used to optimize the volt-second characteristics of the CMV and the output harmonic characteristics.

In addition, the analysis in the last part indicates that a specific RVV can be synthesized with six different switching sequences. For different switching sequences, the CMV and output harmonic characteristics are not the same. Therefore, the available switching sequences can be regarded as factors that affect the A4V-CMVS-PWM strategy and it is defined as the second control degree of freedom.

4.3 Optimization Strategy of Volt-second Characteristics of CMV

Without losing generality, as shown in Fig. 5, the case where the RVV is located in the first sector is taken as an example to analyze the CMV volt-second characteristics of the A4V-CMVS-PWM. For the synthesis method shown in Fig. 5(a), the CMV volt-second can be calculated as (17).

$$V_{s_CMV} = V_{dc} (t_2' + t_4' - t_1' - t_3') / 6 \quad (17)$$

According to (7), (17) can be abbreviated as:

$$V_{s_CMV} = V_{dc} (t_2 - t_1 - 3\Delta t) / 6 \quad (18)$$

A mathematical programming model with constraints as shown in (19) is established, and it aims at minimizing the amplitude of the CMV volt-second.

$$\begin{cases} \text{minimize} & |V_{s_CMV}| \\ \text{subject to} & (8) \end{cases} \quad (19)$$

According to the synthesis method shown in Fig. 5 (a), the optimal Δt can be obtained by solving the mathematical programming model with constraints in (19), and the result is shown below:

$$\Delta t = \begin{cases} (t_2 - t_1) / 3, & \text{if } 0 \leq t_2 - t_1 \leq 3 \min(t_0, t_2) \\ 0, & \text{if } t_2 - t_1 < 0 \\ \min(t_0, t_2), & \text{if } t_2 - t_1 > 3 \min(t_0, t_2) \end{cases} \quad (20)$$

Similarly, for the synthesis methods in Fig. 5(b) and (c), the optimization of CMV volt-second can be achieved by solving a mathematical programming model with constraints similar to (19) to obtain Δt . When the RVV is located in the first sector, Fig. 7 shows minimal values of the amplitude of CMV volt-second for the three different synthesis methods. Types 1, 2, and 3 correspond to the synthesis methods in Fig. 5 (a), (b), and (c), respectively. The abscissa represents the angle of the RVV (θ), and the ordinate is the per-unit value of the volt-second amplitude of the CMV, where the base value is set to $V_{dc}T_c$.

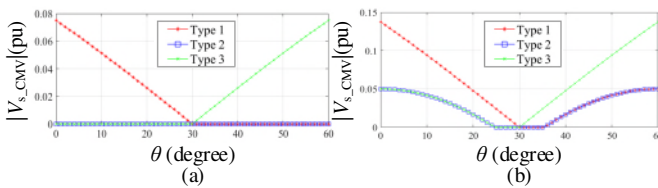


Fig. 7. Minimal values of the volt-second amplitude of CMV under three types of the reference voltage vector synthesis (a) $m=0.6$ (b) $m=1.1$.

In Fig. 7(a), the modulation degree ($m=2V_m/V_{dc}$, where V_m is the amplitude of the RVV) is 0.6. With θ in the range of 0-30 degrees, the minimal value of the CMV volt-second amplitude is close to 0, which corresponds to the synthesis method in Fig. 5 (b) and (c), and its CMV volt-second characteristic is better than the synthesis method in Fig. 5 (a). With θ in the range of 30-60 degrees, the minimal value of the CMV volt-second amplitude is close to 0, which corresponds to the synthesis method in Fig. 5 (a) and (b), and its CMV volt-second characteristic is better than the synthesis method in Fig. 5 (c).

In Fig. 7 (b), m is 1.1. With θ in the range of 0-30 degrees, the minimal value of the CMV volt-second amplitude for

the synthesis method in Fig. 5 (b) and (c) is smaller than Fig. 5 (a). With θ in the range of 30-60 degrees, the minimal value of the CMV volt-second amplitude for the synthesis method in Fig. 5 (a) and (b) is smaller than Fig. 5 (c).

The above analysis indicates that the optimization strategy of volt-second characteristics of CMV can be realized by solving the established mathematical programming model in (19) for various synthesis types and the optimal synthesis types with smallest CMV volt-second amplitude are finally selected. For any other m , the optimal switching sequence under the CMV volt-second optimization objective can be obtained by using numerical analysis method, and the result is shown in the following table.

Table 1 Optimal switching sequence in sector 1 under the target of CMV volt-second optimization

θ (degrees)	Optimal synthesis type	Optimal switching sequence
$0 < \theta < 30$	Fig 5 (b), (c)	Fig 6 (c), (d), (e), (f)
$30 < \theta < 60$	Fig 5 (a), (b)	Fig 6 (a), (b), (c), (d)

4.4 Selection of Optimal Switching Sequence

According to Table 1, there are multiple optimized switching sequences to select under the target of CMV volt-second characteristic optimization. Since the output harmonic characteristics with different switching sequences are not consistent, the constrained mathematical programming model in (21) can be further used to select the optimal switching sequence, so as to realize the optimization of output harmonics on the basis of CMV volt-second characteristic optimization.

$$\begin{cases} \text{minimize} & \lambda_{hn_rms} = \sqrt{\int_0^1 \lambda_{hn}^2 d\delta} \\ \text{subject to} & (20) \text{ and Table 1} \end{cases} \quad (21)$$

where δ is the duty cycle and λ_{hn_rms} is the root-mean-square (rms) value of the normalized harmonic flux vector over a PWM cycle, λ_{hn} is the normalized harmonic flux in the N th carrier cycle, which can be calculated according to (22).

$$\lambda_{hn} = \frac{\pi}{V_{dc}T_c} \int_{NT_c}^{(N+1)T_c} V_{kh} dt \quad (22)$$

where N is a non-negative integer, V_{kh} represents the harmonic voltage vector shown in Fig. 8 (a) which generates the inverter output current ripple.

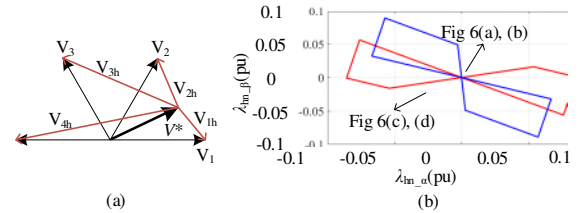


Fig. 8. Curves of flux ripples (a) Vector error (b) Trajectory of the flux ripples ($m=0.8$ and $\theta=45$ degrees).

In the case of $m=0.8$ and $\theta=45$ degrees, Fig. 8 (b) shows the trajectories of flux ripple corresponding to the four optimized switching sequences (Fig. 6 (a), (b), (c), (d)) in Table 1. In Fig. 8 (b), it can be seen that the trajectories of flux ripple of the optimized switching sequence in Fig. 6 (a) coincides with that in Fig. 6 (b), and that in Fig. 6 (c)

coincides with that in Fig. 6 (d), indicating that the action order of the selected A4Vs has no influence on λ_{hn} . In Fig. 8 (b), the output harmonic characteristics generated by two different λ_{hn} are also inconsistent, and by solving the mathematical programming model established in (21), the optimal switching sequence with the smallest λ_{hn_rms} can be obtained.

Taking $m=0.8$ as an example, Fig. 9 shows the curves of λ_{hn_rms} under different switching sequences. With θ in the range of 0-30 degrees, the values of λ_{hn_rms} corresponding to the switching sequences shown in Fig. 6 (e), (f) are equal, and they are smaller than the switching sequence in Fig. 6 (c), (d). With θ in the range of 30-60 degrees, the values of λ_{hn_rms} corresponding to the switching sequence in Fig. 6 (a), (b) are equal, and they are smaller than the switching sequence in Fig. 6 (c), (d). Accordingly, when θ belongs to the range of 0-30 degrees, the switching sequence is selected as Fig. 6 (e) or (f), and when θ belongs to the range of 30-60 degrees, the switching sequence is selected as Fig. 6 (a) or (b). In this way, the flux ripple can be optimized to obtain superior output harmonic performance.

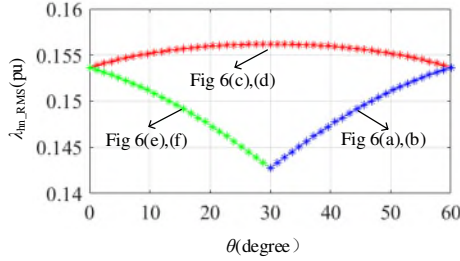


Fig. 9. Curves of λ_{hn_rms} under various switching sequences.

It can be seen from the above analysis that the volt-second characteristics of CMV and λ_{hn_rms} are not affected by selecting the action order of the A4Vs. However, under different action order, the start and end vectors of the switching sequences are not the same. In order to ensure that there is at most one phase change when the switching sequence is switched, it is necessary to arrange the action order of the A4Vs reasonably. For this reason, in the case of $m < 1$ and $m > 1$, Table 2 and Table 3 list the optimal switching sequences for different θ ranges, respectively. In Table 3, θ_0 can be calculated by (23).

$$\theta_0 = \arccos(1/m) \quad (23)$$

Table 2 Optimal switching sequence with various θ when $m < 1$

θ (degree)	Optimal switching sequence
$0 < \theta < 30$	$V_5-V_6-V_1-V_2-V_1-V_6-V_5$
$30 < \theta < 60$	$V_4-V_3-V_2-V_1-V_2-V_3-V_4$
$60 < \theta < 90$	$V_3-V_2-V_1-V_6-V_1-V_2-V_3$
$90 < \theta < 120$	$V_2-V_3-V_4-V_5-V_4-V_3-V_2$
$120 < \theta < 150$	$V_1-V_2-V_3-V_4-V_3-V_2-V_1$
$150 < \theta < 180$	$V_6-V_5-V_4-V_3-V_4-V_5-V_6$
$180 < \theta < 210$	$V_5-V_4-V_3-V_2-V_3-V_4-V_5$
$210 < \theta < 240$	$V_4-V_5-V_6-V_1-V_6-V_5-V_4$
$240 < \theta < 270$	$V_3-V_4-V_5-V_6-V_5-V_4-V_3$
$270 < \theta < 300$	$V_2-V_1-V_6-V_5-V_6-V_1-V_2$
$300 < \theta < 330$	$V_1-V_6-V_5-V_4-V_5-V_6-V_1$
$330 < \theta < 360$	$V_6-V_1-V_2-V_3-V_2-V_1-V_6$

Table 3 Optimal switching sequence with various θ when $m > 1$

θ (degree)	Optimal switching sequence
$0 < \theta < \theta_0$	$V_3-V_2-V_1-V_6-V_1-V_2-V_3$
$\theta_0 < \theta < 30$	$V_2-V_1-V_6-V_5-V_6-V_1-V_2$
$30 < \theta < 60$	$V_1-V_2-V_3-V_4-V_3-V_2-V_1$
$60 < \theta < 90$	$V_6-V_1-V_2-V_3-V_2-V_1-V_6$
$90 < \theta < 120-\theta_0$	$V_5-V_4-V_3-V_2-V_3-V_4-V_5$
$120-\theta_0 < \theta < 120$	$V_4-V_3-V_2-V_1-V_2-V_3-V_4$
$120 < \theta < 120+\theta_0$	$V_5-V_4-V_3-V_2-V_3-V_4-V_5$
$120+\theta_0 < \theta < 150$	$V_4-V_3-V_2-V_1-V_2-V_3-V_4$
$150 < \theta < 180$	$V_3-V_4-V_5-V_6-V_5-V_4-V_3$
$180 < \theta < 210$	$V_2-V_3-V_4-V_5-V_4-V_3-V_2$
$210 < \theta < 240-\theta_0$	$V_1-V_6-V_5-V_4-V_5-V_6-V_1$
$240-\theta_0 < \theta < 240$	$V_6-V_5-V_4-V_3-V_4-V_5-V_6$
$240 < \theta < 240+\theta_0$	$V_1-V_6-V_5-V_4-V_5-V_6-V_1$
$240+\theta_0 < \theta < 270$	$V_6-V_5-V_4-V_3-V_4-V_5-V_6$
$270 < \theta < 300$	$V_5-V_6-V_1-V_2-V_1-V_6-V_5$
$300 < \theta < 330$	$V_4-V_5-V_6-V_1-V_6-V_5-V_4$
$330 < \theta < 360-\theta_0$	$V_3-V_2-V_1-V_6-V_1-V_2-V_3$
$360-\theta_0 < \theta < 360$	$V_2-V_1-V_6-V_5-V_6-V_1-V_2$

5 Simulation Analysis and Experimental Verification

5.1 Simulation Analysis

In order to analyze the characteristics of A4V-CMVS-PWM and its advantages over existing PWM methods, a simulation model is built in Matlab/Simulink software. In the simulation, V_{dc} is set to 48V, T_c is set to 20 μ s, and the resistance-inductance load is set to 4 Ω , 1mH.

The curves of the volt-second value changing with time are plotted in Fig. 10. When m is equal to 0.3, the peak-to-peak values of the CMV volt-second fluctuation for SVPWM and AZSPWM1 are 0.9666mV.s and 0.8275mV.s, respectively. With the methods in [33] and this paper, the peak-to-peak values of the CMV volt-second fluctuation are only about 0.0806mV.s, and compared with SVPWM and AZSPWM1, the peak-to-peak values are reduced by 91.7% and 90.3%, respectively. When m is equal to 0.7, the peak values of the CMV volt-second fluctuation for SVPWM and AZSPWM1 are 1.9343mV.s and 1.8240mV.s, respectively. With the methods in [33] and this paper, the peak-to-peak values of the CMV volt-second fluctuation are only about 0.0806mV.s, and compared with SVPWM and AZSPWM1, the peak-to-peak values are reduced by 95.8% and 95.6%, respectively. When m is equal to 1.1, the peak values of the CMV volt-second fluctuation for SVPWM and AZSPWM1 are 2.9023mV.s. With the methods in [33] and this article, the peak-to-peak values of the CMV volt-second fluctuation are 1.1740mV.s, and compared with SVPWM and AZSPWM1, the peak-to-peak values are reduced by 59.5%. The CMV volt-second of the conventional SVPWM contains obvious low-frequency oscillation, which leads to a large peak-to-peak value. Although AZSPWM1 reduces the amplitude of the CMV, there are still obvious low-frequency ripples in the CMV volt-second. In addition, the methods in [33] and this paper are able to effectively reduce the fluctuation range of the CMV volt-second.

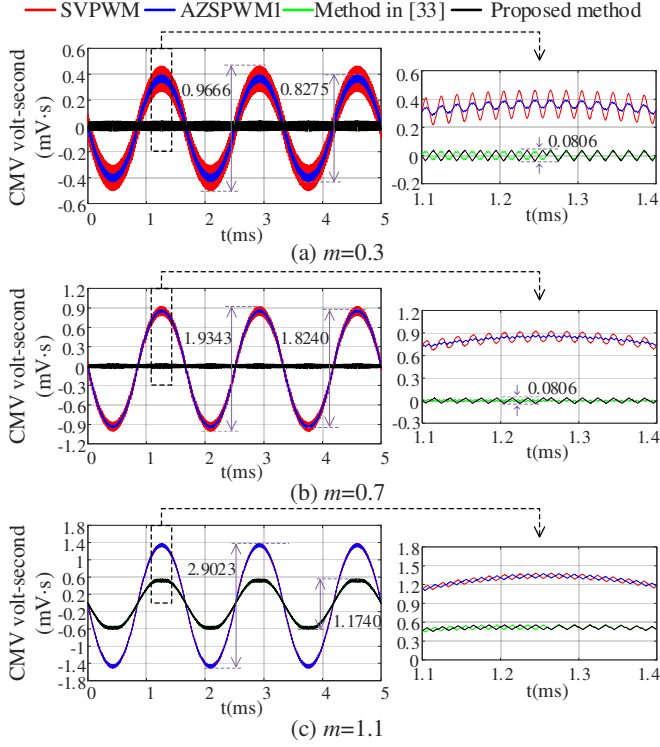


Fig. 10. Curves of the volt-second values of CMV.

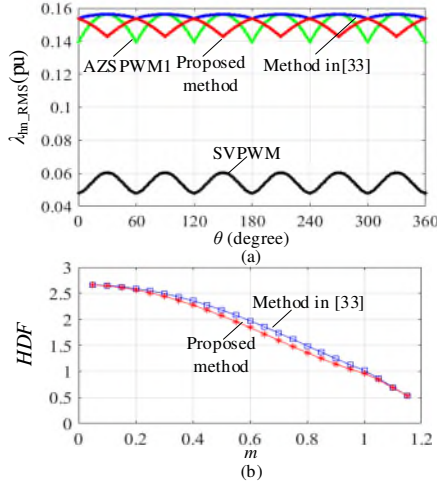


Fig. 11. Comparison results of the harmonic features (a) Curves of λ_{hn_rms} with m set as 0.7 (b) HDF curves with various m .

In order to compare the harmonic characteristics of different PWMs, Fig. 11 (a) shows the curves of λ_{hn_rms} for the four PWM methods when m is set as 0.7, and the values of λ_{hn_rms} with the three CMVS-PWM methods are all higher than SVPWM. It can be seen that the limitation of CMV amplitude is realized with the cost of increasing the output harmonics.

According to Fig. 10 (b) and Fig. 11 (a), it can be seen that the method proposed in this paper can not only achieve the CMV volt-second characteristics optimization similar to the method in [33], but also keep the values of λ_{hn_rms} smaller than the method in [33]. Therefore, more superior output harmonic characteristics can be achieved with the proposed method. Further, Fig. 11 (b) shows the curves of harmonic distortion factor (HDF)^[3] with different m , where HDF is calculated according to (24).

$$HDF = \frac{288}{\pi^2} * \frac{1}{2\pi} \int_0^{2\pi} \lambda_{hn_rms}^2 d\theta \quad (24)$$

It can be seen from Fig. 11 (b), for all m , the HDF of the proposed method is lower than that of the method in [33]. Accordingly, the proposed method in this paper can achieve better output harmonic characteristics compared to the PWM method in [33] with selection of the optimal switch sequence as shown in part D of Section IV.

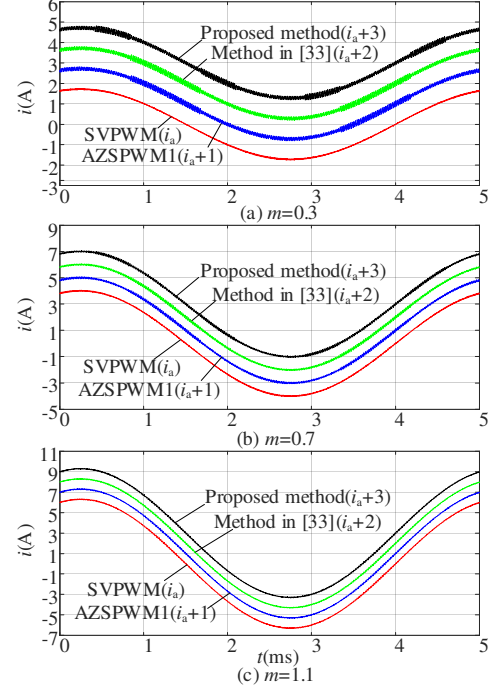


Fig. 12. Curves of the phase current.

Fig. 12 shows the phase current waveforms of the four PWM methods, where m is 0.3, 0.7, and 1.1 in Fig. 12(a), (b) and (c), respectively. For the current waveforms in Fig. 12 (a), the corresponding THD values of SVPWM, AZSPWM1, the method in [33] and the proposed method are 0.96%, 5.75%, 5.77% and 5.59%, respectively. For the current waveforms in Fig. 12 (b), the corresponding THD values of SVPWM, AZSPWM1, the method in [33] and the proposed method are 0.66%, 2.98%, 3.02% and 2.90%, respectively. For the current waveforms in Fig. 12 (c), the corresponding THD values of SVPWM, AZSPWM1, the method in [33] and the proposed method are 0.52%, 2.33%, 2.36% and 2.33%, respectively. In three modulation degrees, the proposed method can obtain smaller current THD than the method in [33].

The above simulation results show that the A4V-CMVS-PWM method studied in this paper can limit the peak-to-peak values of CMV within one-third of the dc-link voltage and realize the optimization of the CMV volt-second characteristics. In addition, it can obtain better output harmonic performance compared with the method in [33].

5.2 Experimental Verification

In order to verify the characteristics of the proposed A4V-CMVS-PWM and its advantages over the existing PWM methods, a 2L-VSI experimental platform is built of

which the main parameters are consistent with the simulation parameters.

In the experiments, the waveforms when $m=0.3$ are obtained, including the terminal voltage (v_{ao}), the line-to-line voltage (v_{ab}), the phase current (i_a), and CMV, as shown in Fig. 13.

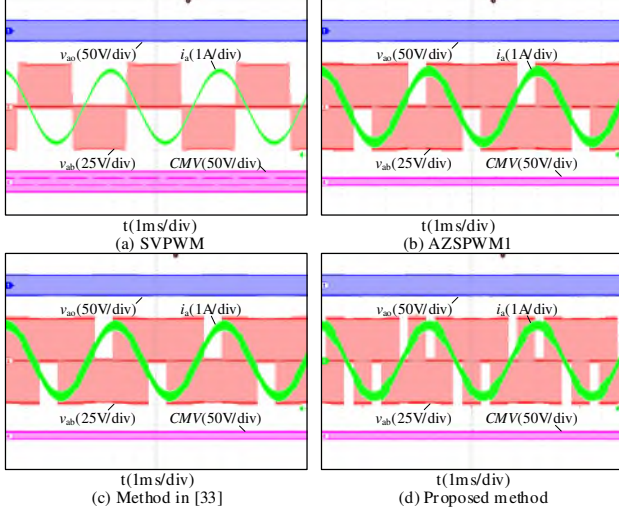


Fig. 13. Curves of experiment ($m=0.3$).

The experimental results of SVPWM, AZSPWM1, the method in [33], and the proposed method are shown in Fig. 13 (a), (b), (c), and (d), respectively. According to the CMV waveform, the peak-to-peak value of the CMV of SVPWM is about 48V, while the peak-to-peak value of the CMV can be restricted within about 16V by using the existing and the proposed CMVS-PWMs, and the peak-to-peak value of CMV is reduced by 66.7%.

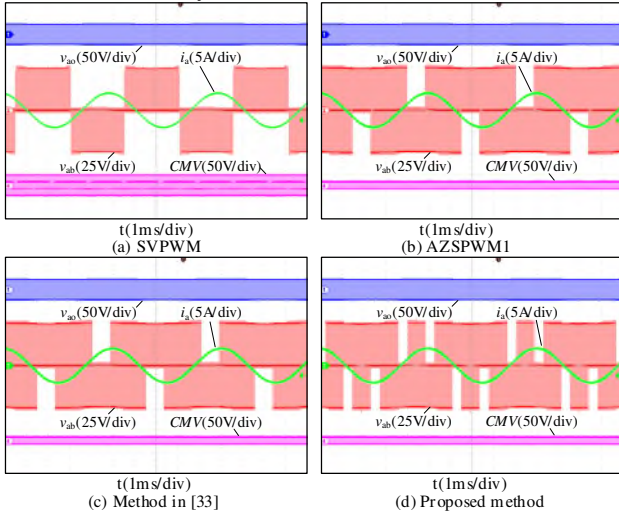


Fig. 14. Curves of experiment ($m=0.7$).

When m is 0.7 and 1.1, the experimental results of SVPWM, AZSPWM1, the method in [33] and the proposed method are shown in Fig. 14 and Fig. 15, respectively. In Fig. 14 and Fig. 15, the peak-to-peak value of the CMV of SVPWM is about 48V, while the peak-to-peak value of the CMV can be limited to 16V by using the existing and the proposed CMVS-PWMs. Compared with SVPWM, the peak-to-peak value of the CMV is reduced by 66.7%.

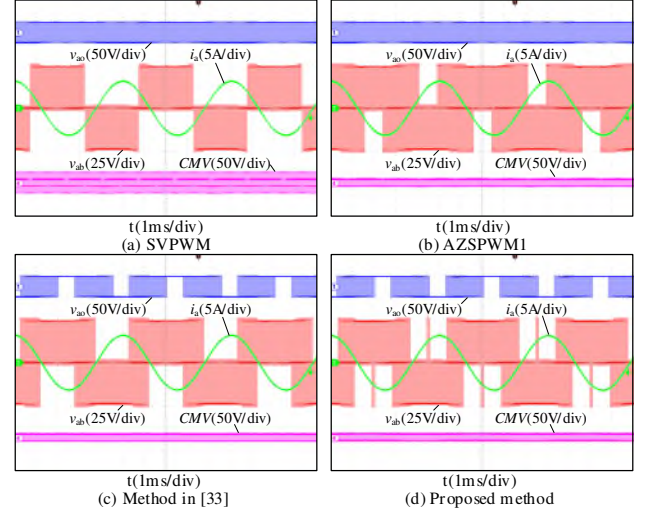


Fig. 15. Curves of experiment ($m=1.1$).

Table 4 Peak-to-peak values of the volt-second of CMV with various m

m	SVPWM (mV·s)	AZSPWM1 (mV·s)	[33] (mV·s)	Proposed method (mV·s)
0.1	0.48184	0.32896	0.08128	0.08304
0.2	0.72456	0.57856	0.07728	0.08376
0.3	0.96664	0.82752	0.06832	0.08072
0.4	1.20888	1.07696	0.06752	0.08208
0.5	1.44904	1.32400	0.06128	0.08248
0.6	1.69368	1.57552	0.05640	0.08184
0.7	1.93432	1.82400	0.05360	0.08056
0.8	2.17576	2.07776	0.05040	0.08232
0.9	2.41816	2.34752	0.04656	0.08072
1	2.65976	2.61712	0.05984	0.08088
1.1	2.90232	2.88736	1.16688	1.17400
1.15	3.02280	3.02128	2.04832	2.04832

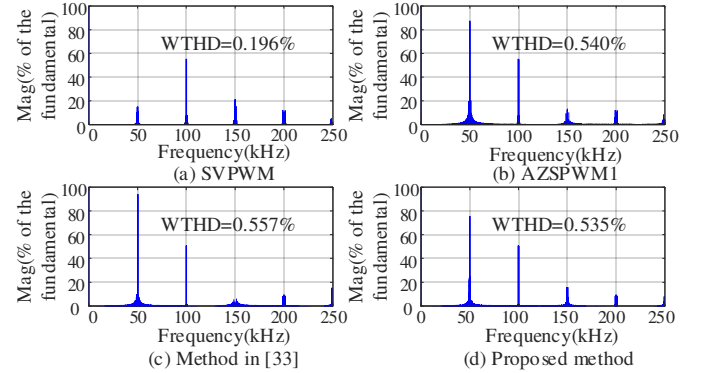


Fig. 16. Spectrum analysis results of the line-to-line voltage ($m=0.7$).

The data about the CMV waveforms gained from the experiment is imported into Matlab, and then the volt-second characteristics of CMV are calculated and the peak-to-peak values of the volt-second of CMV with various m are shown in Table 4. It can be seen that the proposed A4V-CMV-S-PWM method can significantly reduce the peak-to-peak values of the CMV volt-second compared to SVPWM and AZSPWM1.

The data of the line-to-line voltages obtained from the experiment is imported into Matlab, and fast Fourier transform (FFT) analysis is performed. Fig. 16 shows the

spectrum analysis results of the four PWM methods with m equal to 0.7 as shown in Fig. 14.

According to the spectrum in Fig. 16, the weighted total harmonic distortion ($WTHD$)^[3] is calculated by (25). The $WTHD$ values of SVPWM, AZSPWM1, the method in [33], and the proposed A4V-CMVS-PWM are 0.196%, 0.540%, 0.557% and 0.535%, respectively. It can be seen that the output harmonics of the three CMVS-PWMs are increased compared with SVPWM, so the suppression of CMV is based on sacrificing the output harmonic performance. In addition, the $WTHD$ of the proposed method is smaller than the method in [33], and the output harmonic performance is improved.

$$WTHD = \sqrt{\sum_{n=2}^{n_{\max}} \frac{V_n^2}{n^2}} / V_1 \quad (25)$$

where V_1 and V_n mean the fundamental and n order harmonic component in the output line-to-line voltage, respectively. $n_{\max}$ is the calculated maximal harmonic order, and it is selected as 1250 here.

The HDF and $WTHD$ values of the method in [33] and the proposed method are calculated under various m , and the results are shown in Table 5. The HDF and $WTHD$ values of the proposed method are smaller than the method in [33]. Therefore, on the basis of limiting the CMV amplitude and optimizing the volt-second characteristics of the CMV, the proposed method can obtain better output harmonic performance.

Table 5 Calculation results of HDF with various m

m	HDF of the method in [33]	HDF of the proposed method	$WTHD$ of the method in [33](%)	$WTHD$ of the proposed method(%)
0.1	2.649	2.641	4.823	4.816
0.2	2.593	2.566	2.385	2.372
0.3	2.495	2.442	1.560	1.543
0.4	2.357	2.274	1.137	1.117
0.5	2.181	2.071	0.875	0.852
0.6	1.972	1.841	0.693	0.669
0.7	1.739	1.599	0.557	0.535
0.8	1.492	1.359	0.452	0.431
0.9	1.246	1.140	0.367	0.351
1	1.016	0.962	0.298	0.290
1.1	0.693	0.685	0.224	0.223
1.15	0.5334	0.5332	0.188	0.188

6 Conclusion

An A4V-CMVS-PWM based on A4V synthesis principle is studied in this article. Compared with the conventional N3V synthesis principle, it can avoid the use of ZVV and has more control degrees of freedom for CMV suppression. Under the A4V synthesis principle, a layer-by-layer optimization method for the CMV volt-second and output harmonic characteristics is studied. The simulation and experimental results show that the proposed method can simultaneously realize the CMV peak limitation and the optimization of volt-second characteristics at the same time, and obtain better output harmonic performance on this basis.

Acknowledgements We do not have anyone to acknowledge.

Funding This work was supported in part by the National Natural Science Foundation of China under Grant 52007190.

Data Availability The results/data/figures in the submitted manuscript have not been published elsewhere, nor are they under consideration by another publisher.

Ethical declaration We hereby declare that the submitted manuscript does not involve any studies on humans or animals.

Conflict of interests We declare that the authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results reported in this paper.

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