Space Vector Modulation Strategy and Related Improvement Technology of Matrix Converter

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Abstract. Based on the modeming strategy, the paper studies the influence of three different pulse output modes on the input and output performance of matrix converter (MC) and obtains the result analysis by simulation results: Pulse output mode II is better in output low frequency and high frequency, and the pulse output mode II is selected as the pulse output mode of spatial vector modulation strategy in the process of impedance load experiment. Experiments verify the correctness of control policies.

Keywords: Matrix converter · Spatial vector modulation strategy · Pulse output

1 Introduction

Three-phase - Three-phase MC space vector modulation (SVM) strategy by Yugoslav scholar L. Professor Huber D. Borojevic proposed in 1989, this modulation method will be the traditional concept of spatial vector pulse wide modulation for MC control, simple and easy to implement, greatly reducing the requirements of the control circuit, the use of this method does not need to introduce low-frequency harmonics in the output phase voltage, the MC voltage utilization rate can reach a maximum of 0.866, to achieve arbitrary control of the input current phase difference.

MC SVM through the introduction of vector concept to achieve the control of output voltage and input current, not directly using instantaneous voltage, current to calculate the duty-to-duty ratio of each switch, so in the case of interference with the input voltage source control effect is slightly inferior. In the process of MC industrial application, there is imbalance of industrial power supply and interference factors such as harmonics, coupled with the MC input side for filtering out the high-level harmonics in the input current, there is a second-order low-pass filter, the input voltage of the switch matrix must have a certain degree of asymmetrical harmonic distortion. Therefore, it is necessary to analyze the operating performance of the MC when the input grid voltage is abnormal and adopt the corresponding control strategy to ensure the normal operation of the transformer load equipment.

The operating performance of the MC under the conditions of input voltage imbalance, non-sine, and instantaneous drop is analyzed respectively, and the abnormal conditions have a serious effect on the input, output performance, and load equipment of the

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MC. A SVM control strategy of spatial vector modulation is adopted to keep the output voltage of the MC as normal by compensating for the change of virtual DC voltage, and the simulation and experiment verify the correctness and effectiveness of the SVM control strategy.

2 Topology and Modulation Principle of 3-Phase to 3-Phase Matrix Converter

2.1 The Topology of a Three-Phase-Three-Phase Matrix Converter

As a new type of interchange-interchange converter, the MC transforms the sine wave of the AC utility grid constant frequency amplitude into a sine wave of the variable frequency amplitude, and its topology is shown in Fig. 1, wherein S11toS33 these nine bidirectional switches form a 3 × 3 switch matrix. MC in the process of operation, the switching device's on-off state constantly changes, three-phase output through a two-way switch can be connected to any one-phase input, according to a certain strategy to control S11to S33 these 9 bidirectional switches, you can get the frequency and amplitude are continuously adjustable sine wave.

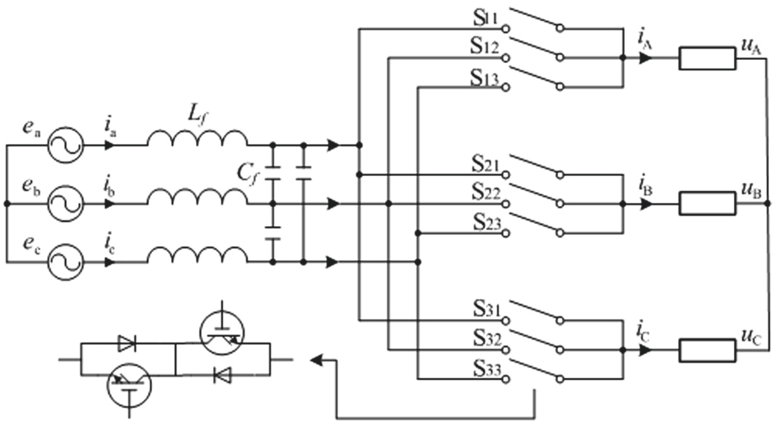


Fig. 1. The main circuit of MC

In the figure, e_ a, e_ b, e_ C is the three-phase input phase voltage, I_ a, i_ b, i_ C is the current of three-phase input phase, l_ f, C_ F is the filter inductance and the filter capacitance of the input filter; u_ A, u_ B, u_ C is the three-phase output phase voltage, I_ A, i_ B, i_ C is the current of three-phase output phase. First, define switch S_ The control function of JK is:

In the figure, e_a, e_b, e_c is the three-phase input phase voltage, i_a, i_b, i_c is the three-phase input phase current, respectively, $L_f,\ C_f$ is the filter inductor and filter capacitor of the input filter; u_A, u_B, u_C is the three-phase output phase voltage. i_A, i_B, i_C is the current of three-phase output phase. First, define switch S_{jk}, the control function of S_{jk} is:

$$S_{jk}(t) = 1\ or\ 0, j \in \{1, 2, 3\},\ k \in \{1, 2, 3\} \tag{1}$$

When $S_{jk}(t) = 1$, indicates that the switch is closed; $S_{jk}(t)S_{jk}(t) = 0S_{jk}(t)$.

The voltage source characteristics of the MC power supply require that the input side cannot be shorted, and the perceptic characteristics of the load require that the output side cannot open, so that at any one time, the three bidirectional switches connected to each output must have and only one switch is closed, which can be expressed as:

$$\sum\nolimits_{k=1}^{3} S_{jk} = 1, j \in \{1, 2, 3\} \tag{2}$$

Under these constraints, there are 27 combinations of MC switches that meet the requirements, given in Table 1. The three output phases in Group 1 are connected to three different inputs, consisting of six switch combinations, the three outputs in Group 2 are connected to two different inputs, containing 18 switch combinations, and the three outputs in Group 3 are short with only one input, consisting of three switch combinations.

2.2 Modulation Principle of Matrix Converter

The three-phase input power supply phase voltage of the MC is:

$$U_{\mathrm{iPh}} = \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = U_{\mathrm{im}} \begin{bmatrix} cos(\omega_i t) \\ cos(\omega_i t - 120^{\circ}) \\ cos(\omega_i t + 120^{\circ}) \end{bmatrix} \tag{3}$$

U_{im} is the magnitude of the input phase voltage and ω_i is the input voltage angle frequency.

The base wave sine value of the three-phase output line voltage of the desired MC is:

$$U_{\mathrm{oL}} = \begin{bmatrix} u_{\mathrm{AB}} \\ u_{\mathrm{BC}} \\ u_{\mathrm{CA}} \end{bmatrix} = \sqrt{3} U_{\mathrm{om}} \begin{bmatrix} cos(\omega_o t - \phi_o + 30^{\circ}) \\ cos(\omega_o t - \phi_o + 30^{\circ} - 120^{\circ}) \\ cos(\omega_o t - \phi_o + 30^{\circ} + 120^{\circ}) \end{bmatrix} \tag{4}$$

U_{om} is the magnitude of the output phase voltage, ω_o is the output voltage angle frequency, and ϕ_o is the phase shift angle of the output voltage relative to the input voltage.

Table 1. The switching combinations of MC

Grouping	Switch connection status	Output line voltage			Enter the phase current		
	$S_{11}S_{12}S_{13}S_{21}S_{22}S_{23}S_{31}S_{32}S_{33}$	u_{AB}	u_{BC}	u_{CA}	i_a	i_b	i_c
1	1 0 0 0 1 0 0 0 1	e_{ab}	e_{bc}	e_{ca}	i_A	i_B	i_C
	1 0 0 0 0 1 0 1 0	$-e_{\mathrm{ca}}$	$-e_{\mathrm{bc}}$	$-e_{\mathrm{ab}}$	i_A	i_C	i_B
	0 1 0 1 0 0 0 0 1	$-e_{\mathrm{ab}}$	$-e_{\mathrm{ca}}$	$-e_{\mathrm{bc}}$	i_B	i_A	i_C
	0 1 0 0 0 1 1 0 0	e_{bc}	e_{ca}	e_{ab}	i_C	i_A	i_B
	0 0 1 1 0 0 0 1 0	e_{ca}	e_{ab}	e_{bc}	i_B	i_C	i_A
	0 0 1 0 1 0 1 0 0	e_{cb}	e_{ba}	e_{ac}	i_C	i_B	i_A
2–1	1 0 0 0 0 1 0 0 1	$-e_{\mathrm{ca}}$	0	e_{ca}	i_A	0	$-i_A$
	0 1 0 0 0 1 0 0 1	e_{bc}	0	$-e_{\mathrm{bc}}$	0	i_A	$-i_A$
	0 1 0 1 0 0 1 0 0	$-e_{\mathrm{ab}}$	0	e_{ab}	$-i_A$	i_A	0
	0 0 1 1 0 0 1 0 0	e_{ca}	0	$-e_{\mathrm{ca}}$	$-i_A$	0	i_A
	0 0 1 0 1 0 0 1 0	$-e_{\mathrm{bc}}$	0	e_{bc}	0	$-i_A$	i_A
	1 0 0 0 1 0 0 1 0	e_{ab}	0	$-e_{\mathrm{ab}}$	i_A	$-i_A$	0
2–2	0 0 1 1 0 0 0 0 1	e_{ca}	$-e_{\mathrm{ca}}$	0	i_B	0	$-i_B$
	0 0 1 0 1 0 0 0 1	$-e_{\mathrm{bc}}$	e_{bc}	0	0	i	$-B_B$
	1 0 0 0 1 0 1 0 0	e_{ab}	$-e_{\mathrm{ab}}$	0	$-i_B$	i_B	0
	1 0 0 0 0 1 1 0 0	$-e_{\mathrm{ca}}$	e_{ca}	0	$-i_B$	0	i_B
	0 1 0 0 0 1 0 1 0	e_{bc}	$-e_{\mathrm{bc}}$	0	0	$-i_B$	i_B
	0 1 0 1 0 0 0 1 0	$-e_{\mathrm{ab}}$	e_{ab}	0	i_B	$-i_B$	0
2–3	0 0 1 0 0 1 1 0 0	0	e_{ca}	$-e_{\mathrm{ca}}$	i_C	0	$-i_C$
	0 0 1 0 0 1 0 1 0	0	$-e_{\mathrm{bc}}$	e_{bc}	0	i_C	$-i_C$
	1 0 0 1 0 0 0 1 0	0	e_{ab}	$-e_{\mathrm{ab}}$	$-i_C$	i_C	0
	1 0 0 1 0 0 0 0 1	0	$-e_{\mathrm{ca}}$	e_{ca}	$-i_C$	0	i_C
	0 1 0 0 1 0 0 0 1	0	e_{bc}	$-e_{\mathrm{bc}}$	0	$-i_C$	i_C
	0 1 0 0 1 0 1 0 0	0	$-e_{\mathrm{ab}}$	e_{ab}	i_C	$-i_C$	0
3	1 0 0 1 0 0 1 0 0	0	0	0	0	0	0
	0 1 0 0 1 0 0 1 0	0	0	0	0	0	0
	0 0 1 0 0 1 0 0 1	0	0	0	0	0	0

As shown in Table 1 and Fig. 1, the relationship between three-phase output line voltage U_{oL} of the MC and the three-phase input phase voltage U_{iPh} is:

$$U_{oL} = \begin{bmatrix} u_{AB} \\ u_{BC} \\ u_{CA} \end{bmatrix} = \begin{bmatrix} S_{11} - S_{21} & S_{12} - S_{22} & S_{13} - S_{23} \\ S_{21} - S_{31} & S_{22} - S_{32} & S_{23} - S_{33} \\ S_{31} - S_{11} & S_{32} - S_{12} & S_{33} - S_{13} \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{5}$$

The relationship between the input phase current and the output phase current is:

$$i_{iPh} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} S_{11} & S_{21} & S_{31} \\ S_{12} & S_{22} & S_{32} \\ S_{13} & S_{23} & S_{33} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} \tag{6}$$

According to the high-frequency synthesis theory, when the switching frequency f_s is high enough, the high-frequency components of variables in formulas (5) and (6) can be ignored, and the remaining low-frequency components are represented as the average of the variables in a switching cycle T_s. The average of a switching cycle of a switch function is the duty cycle of the switch S_{jk}, which can be reworded as d_{jk}:

$$U_{oL} = \begin{bmatrix} u_{AB} \\ u_{BC} \\ u_{CA} \end{bmatrix} = \begin{bmatrix} d_{11} - d_{21} & d_{12} - d_{22} & d_{13} - d_{23} \\ d_{21} - d_{31} & d_{22} - d_{32} & d_{23} - d_{33} \\ d_{31} - d_{11} & d_{32} - d_{12} & d_{33} - d_{13} \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} = T_{PhL} U_{iPh} \tag{7}$$

$$i_{iPh} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} d_{11} & d_{21} & d_{31} \\ d_{12} & d_{22} & d_{32} \\ d_{13} & d_{23} & d_{33} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = T_{PhPh}^T i_{oPh} \tag{8}$$

In the formula, the upper angle label T represents transpose, T_{PhL} is the switch transfer function matrix from the MC input side phase variable to the output sideline variable, and T_{PhPh} is the switch transfer function matrix from the MC input side phase variable to the output side phase variable. $T_{PhL} T_{PhPh}$ is also known as the duty-ratio matrix, each element represents the instantaneous duty-to-duty ratio of the corresponding switches in the main circuit of the MC, reflecting the control method of the MC. According to the duty-ratio matrix T_{PhL}, T_{PhPh}, the determination method is different, then the MC can get a variety of different modulation strategies.

Depending on the formula (3), (4), and (7), the duty-to-duty matrix T_{PhL} of the MC can be selected as:

$$\overline{T}_{PhL} = m \begin{bmatrix} cos(\omega_o t - \phi_o + 30^{\circ}) \\ cos(\omega_o t - \phi_o + 30^{\circ} - 120^{\circ}) \\ cos(\omega_o t - \phi_o + 30^{\circ} + 120^{\circ}) \end{bmatrix} \begin{bmatrix} cos(\omega_i t - \phi_i) \\ cos(\omega_i t - \phi_i - 120^{\circ}) \\ cos(\omega_i t - \phi_i + 120^{\circ}) \end{bmatrix}^T \tag{9}$$

m is the modulation coefficient of the MC, $0 \leq m \leq 1$; and ϕ_i is the phase difference between the input phase voltage and the phase current. (3), (4), (9) need to satisfy (7), and the relationship between the input phase voltage amplitude and the output phase voltage amplitude is:

$$U_{om} = \frac{\sqrt{3}}{2} U_{im}\, m\, cos(\phi_i) \tag{10}$$

It can be seen from Eq. (10) that when the modulation coefficient $m = 1$, the input power factor $cos(\phi_i) = 1$, i.e. input phase difference $\phi_i = 0$, the voltage transfer rate of MC will reach the maximum value $\sqrt{3}/2$, which is 0.866.

Because the load in a MC system is typically an inductive device, the output phase current waveform is also a sine and can be represented as:

$$i_{\mathrm{oPh}} = \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} = I_{\mathrm{om}} \begin{bmatrix} cos(\omega_o t - \phi_o - \phi_L) \\ cos(\omega_o t - \phi_o - \phi_L - 120^{\circ}) \\ cos(\omega_o t - \phi_o - \phi_L + 120^{\circ}) \end{bmatrix} \tag{11}$$

I_{om} is the amplitude of the output phase current and ϕ_L is the phase difference between the output phase voltage and the phase current, i.e. the load phase difference.

Similar to the output voltage, the base wave value of the three-phase input phase current of the MC you want is:

$$i_{\mathrm{iPh}} = \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = I_{\mathrm{im}} \begin{bmatrix} cos(\omega_i t - \phi_i) \\ cos(\omega_i t - \phi_i - 120^{\circ}) \\ cos(\omega_i t - \phi_i + 120^{\circ}) \end{bmatrix} \tag{12}$$

In the formula, I_{im} is the input phase current amplitude, and the formula (11), (12) needs to satisfy (8), thus obtaining:

$$I_{\mathrm{im}} = \frac{\sqrt{3}}{2} I_{\mathrm{om}}\, m\, cos\,(\phi_L) \tag{13}$$

The duty-to duty matrix T_{PhL} shown in the formula (9) can be represented as the product of two matrices:

$$\overline{T}_{\mathrm{PhL}} = \overline{T}_{\mathrm{VSI}}(\omega_o)\overline{T}_{\mathrm{VSR}}^{T}(\omega_i) \tag{14}$$

$\overline{T}_{\mathrm{VSR}}(\omega_i)$ is virtual rectifier matrix on the input side and $\overline{T}_{\mathrm{VSI}}(\omega_o)$ is virtual rectifier matrix on the output side. Take $\overline{T}_{\mathrm{VSR}}^{T}(\omega_i)$ by multiplying with the input phase voltage formula (3), a constant voltage is obtained as follows:

$$\overline{T}_{VSR}^{T}(\omega_1)U_{iPh} = \frac{3}{2}U_{im}\, cos(\varphi_i) = constant \tag{15}$$

(15) can be used to represent how a voltage source rectifier works, multiplying the constant voltage obtained in formula (15) by the matrix $\overline{T}_{\mathrm{VSI}}(\omega_o)$, and representing the operation of a voltage source inverter. Thus, a MC can theoretically be equivalent to a series connection between a virtual rectifier and a virtual inverter, as shown in Fig. 2, which records the intermediate virtual DC voltage as U_{pn}.

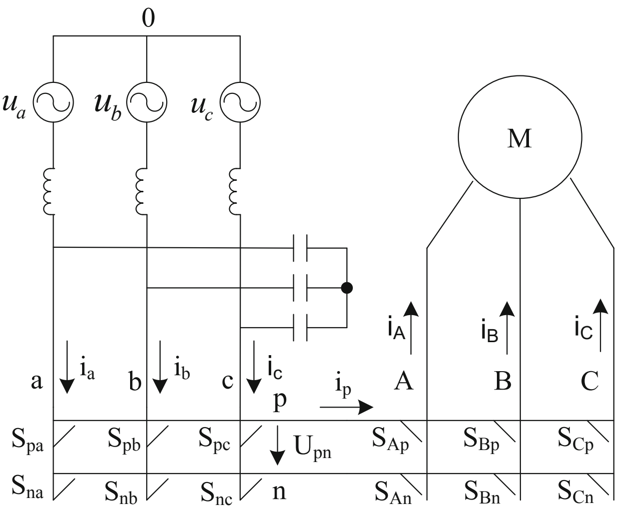


Fig. 2. Equivalent topology of MC VSR and VSI in series

3 Traditional Matrix Transformer Space Vector Modulation Strategy of Matrix Converter

According to the analysis of Sect. 2.2, the MC can be equivalent to a virtual voltage source rectifier (VSR) and a virtual voltage source inverter (VSI) series connection as shown in Fig. 2, which is the basis of the MC indirect spatial vector modulation strategy. According to this equivalent circuit model, the traditional SVM technology is applied to the virtual rectifier and virtual inverter respectively, the virtual rectifier is fed phase current SVM, the virtual inverter is output line voltage SVM, and then the intermediate DC link is eliminated, and finally, the SVM strategy of the MC is integrated.

3.1 Input Phase Phase Current Space Vector Vector Modulation of VSR

The circuit of the virtual rectifier of the MC is shown in Fig. 3. In the figure, only one of the three switches connected with positive and negative buses is closed, and six switches have nine combined states, corresponding to nine current basic space vectors I_0–I_8. Among them, I_1–I_6 is the effective basic vector, and the corresponding switch states are (a, c), (b, c), (b, a), (c, a), (c, b) and (a, b), respectively. The phase difference between adjacent effective vectors is 60; I_0, I_7, I_8 is the zero vector, and the corresponding switch states are (a, a), (b, b) and (c, c) respectively. By I_1–I_6 get a regular hexagon of switch vector, and the zero vector is located in the center of the regular hexagon. The spatial position and relationship of each vector are shown in Fig. 4.

In the spatial vector modulation of virtual rectifiers, a new current space vector can be generated by a linear combination of 9 basic current vectors. The spatial vector that defines the reference input phase current is:

$$I_{\text{ref}} = \frac{2}{3}\left(i_a + i_b \cdot e^{j120^\circ} + i_c \cdot e^{-j120^\circ}\right) = I_{\text{im}} \cdot e^{j(\omega_i t - \phi_i)} \tag{16}$$

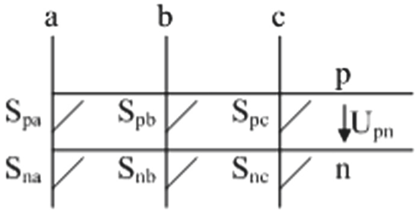


Fig. 3. VSR conversion part of MC

The spatial vector modulation of the input phase current can be performed in each sector of the space vector positive hexagon, and the input phase current reference space vector I_{ref} can be synthesized by two valid current vectors I_μ and I_γ zero vectors I_0 in the sector at a certain time, as shown in Fig. 5, the expression of the input phase current reference space vector is:

$$I_{\mathrm{ref}} = d_\mu I_\mu + d_\gamma I_\gamma + d_{0\mathrm{c}} I_0 \tag{17}$$

where

$$\begin{cases} d_\mu = T_\mu / T_s = m_c sin(60^\circ - \theta_{\mathrm{sc}}) \\ d_\gamma = T_\gamma / T_s = m_c sin(\theta_{\mathrm{sc}}) \\ d_{0\mathrm{c}} = T_{0\mathrm{c}} / T_s = 1 - d_\mu - d_\gamma \end{cases} \tag{18}$$

In Eq. (2–18), m_c is the SVM coefficient of input phase current, $0 \le m_c \le 1$; T_s is the switching period; T_μ, T_γ And $T_{0\mathrm{c}}$ is the current vector I_μ, I_γ And I_0, d_μ, d_γ And $d_{0\mathrm{c}}$ is the corresponding duty cycle; θ_{sc} is the phase angle of the reference current vector in its sector.

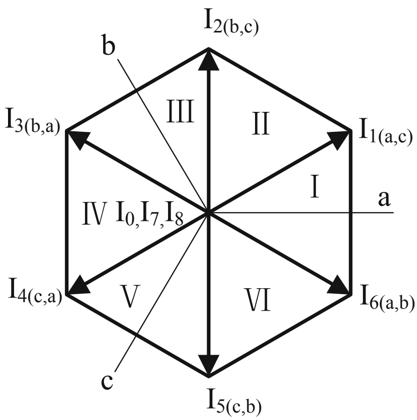


Fig. 4. Input phase current space vector hexagon of VSR

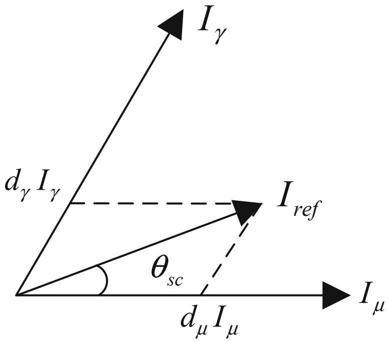


Fig. 5. Input phase current space vector synthesis of VSR

3.2 Virtual Inverter Output Line Voltage Space Vector Vector of VSI

The circuit diagram of the virtual inverter of the MC is shown in Fig. 6. In the figure, only one of every two switches connected from the positive and negative buses to the three-phase outputs of A, B and C is closed. Six switches have eight combined states, corresponding to eight voltage basic space vectors U_0–U_7. Where, U_1–U_6 is the effective basic vector, and the corresponding switch states are (p, n, n), (p, p, p, n), (n, p, n), (n, p, n), (n, p, p, p), (n, n, p), and (p, n, p) respectively. The phase difference between adjacent effective vectors is 60°; U_0 and U_7 is the zero vector, and the corresponding switch states are (n, n, n) and (p, p, p) respectively. By U_1–U_6 get a regular hexagon of switch vector, and the zero vector is located in the center of the regular hexagon. The spatial position and relationship of each vector are shown in Fig. 7.

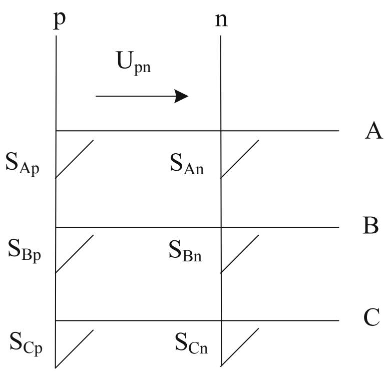


Fig. 6. VSI conversion part of MC

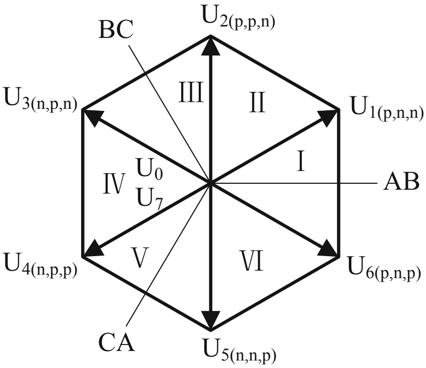


Fig. 7. Output line voltage space vector hexagon of VSI

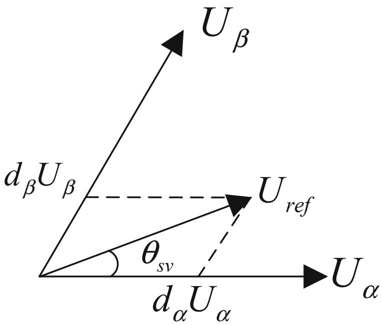


Fig. 8. Output line voltage space vector synthesis of VSI

In the spatial vector modulation of virtual inverters, a new voltage space vector can be produced by a linear combination of 8 basic voltage space vectors. The desired output line voltage space vector is defined as:

$$U_{\text{ref}} = \frac{2}{3}\left(u_{\text{AB}} + u_{\text{BC}} \cdot e^{\text{j}120^{\circ}} + u_{\text{CA}} \cdot e^{-\text{j}120^{\circ}}\right) = \sqrt{3}U_{\text{om}}e^{j(\omega_o t - \phi_o + \frac{\pi}{6})} \tag{19}$$

The spatial vector modulation of the output line voltage can be performed in each sector of the space vector positive hexagon, and at some point the output line voltage reference space vector U_{ref} can be synthesized by two effective voltage vectors, $U_\alpha U_\beta$ and zero vectors U_0 in the sector, as shown in Fig. 8. The expression of the composited output line voltage reference space vector is:

$$U_{\text{ref}} = d_\alpha U_\alpha + d_\beta U_\beta + d_{0\text{v}} U_0 \tag{20}$$

Where

$$\begin{cases} d_\alpha = T_\alpha / T_s = m_v sin(60^0 - \theta_{\text{sv}}) \\ d_\beta = T_\beta / T_s = m_v sin(\theta_{\text{sv}}) \\ d_{0\text{v}} = T_{0\text{v}} / T_s = 1 - d_\alpha - d_\beta \end{cases} \tag{21}$$

In Eq. (21), m_v is the voltage modulation ratio of SVM strategy, $0 \leq m_v = \sqrt{3}U_{\mathrm{om}}/U_{\mathrm{pn}} \leq 1$; T_α, T_β And $T_{0\mathrm{v}}$ is the voltage vector U_α, U_β And U_0, d_α, d_β And $d_{0\mathrm{v}}$ is the corresponding duty cycle; θ_{sv} is the phase angle of the reference line voltage vector in its sector.

3.3 Space Vector Modulation Strategy of Matrix Converter

By combining the input phase current SVM of the virtual rectifier and the voltage SVM of the output line of the virtual inverter, the spatial vector modulation strategy of the MC can be obtained by eliminating the intermediate DC link. If both the output line voltage space vector and the input phase current space vector are in sector I, then in one switching period Within T_s, the synthetic duty cycle of SVM strategy is:

$$\begin{aligned} d_1 = d_{\alpha\mu} = d_\alpha d_\mu = m\,sin(60^\circ - \theta_{\mathrm{sv}})sin(60^\circ - \theta_{\mathrm{sc}}) \\ d_2 = d_{\alpha\gamma} = d_\alpha d_\gamma = m\,sin(60^\circ - \theta_{\mathrm{sv}})sin\theta_{\mathrm{sc}} \\ d_3 = d_{\beta\mu} = d_\beta d_\mu = m\,sin\theta_{\mathrm{sv}}sin(60^\circ - \theta_{\mathrm{sc}}) \\ d_4 = d_{\beta\gamma} = d_\beta d_\gamma = m\,sin\theta_{\mathrm{sv}}sin\theta_{\mathrm{sc}} \\ d_0 = 1 - d_1 - d_2 - d_3 - d_4 \end{aligned} \tag{22}$$

Where, the modulation coefficient of MC is $m = m_v \cdot m_c = \frac{2}{\sqrt{3}} \cdot \frac{U_{\mathrm{om}}}{U_{\mathrm{im}}} \cdot \frac{1}{cos\phi_i}$. The duty cycle time of each period is $T_1 = T_s \cdot d_1$, $T_2 = T_s \cdot d_2$, $T_3 = T_s \cdot d_3$, $T_4 = T_s \cdot d_4$ and $T_0 = T_s \cdot d_0$. Since the input and output of the MC can be set to AC of different frequencies, the duty cycle, and the corresponding duty cycle time t are calculated for each switching cycle T_0–T_4 are constantly changing, so it needs real-time calculation.

Since the input phase current and output line voltage of the spatial vector modulation strategy each have six effective spatial vectors, there may be 36 combined states, each corresponding to one of the 27 switch combinations, as shown in Table 2. The three letters in the table represent the connection state of the output phase to the input phase, such as acc indicating that output A is connected to input a, output B is connected to input c, and output C is connected to input c.

Table 2. 36 Kinds of switching combinations.

Current vector → Voltage vector ↓	I_1	I_2	I_3	I_4	I_5	I_6
U_1	acc	bcc	*baa*	caa	cbb	abb
U_2	aac	bbc	bba	cca	ccb	aab
U_3	cac	cbc	aba	aca	bcb	bab
U_4	caa	cbb	abb	acc	bcc	baa
U_5	cca	ccb	aab	aac	bbc	bba
U_6	aca	bcb	bab	cac	cbc	aba

The vector combination in different sectors is different, so it is necessary to judge the combination of the sectors in real-time. Taking virtual rectifier and virtual inverter working in sector I as an example, the space vector used to synthesize input phase current is $I_6,\ I_1$ and I_0, the space vector used to synthesize the output line voltage is $U_6,\ U_1$ and U_0, so the synthesis process of input phase current vector and output line voltage vector has $I_6 - U_6, I_6 - U_1, I_1 - U_6, I_1 - U_1$ and $I_0 - U_0$. The duty cycle of each combination is the product of the duty cycle of each vector in the combination.

4 Study on the Mode of Output Pulse on Space on Vector Modulation Strategy

In each spatial vector switch cycle T_s, the duty cycle of the five vector combinations involved in the synthesis is calculated, and the control switch switching in some vector sequence can be used to achieve control of the MC. The sequence of vector action within each switching cycle and the position of the zero vector in the vector sequence affect the switching loss and input and output waveform quality of the MC. Depending on the location of the zero vector in the vector sequence, it can be divided into three different pulse output modes. The first vector sequence, within each switching cycle, starts with zero vector and ends with zero vector, called pulse output mode I; This section analyzes and compares the input and output waveforms and the spectrum obtained by the simulation to select the ideal pulse output mode.

4.1 Mode I of Output Pulse

In each switching cycle, the selection of vector action sequence follows two principles: one is the principle of minimum switching loss, that is, only one switching device is switched to minimize the switching loss each time the switching state is switched; The second is the symmetry principle, that is, in each switching cycle, the vector sequence is symmetrically distributed and the vector action time is evenly distributed, so that the harmonic content of input and output waveforms is less.

Assuming that the reference input phase current space vector and the reference output line voltage space vector are in the first sector, the effective vector combination is: $I_6\,U_1, I_6U_6, I_1U_6$ and I_1U_1. The corresponding switch combination is: abb, aba, aca, acc. According to the principle of minimum switching loss and symmetry, the switch combination sequence is: abb–aba–aca–acc–aca–aba–abb. According to the pulse output mode I, if the zero vector is inserted at the beginning and end of the switch combination sequence, the switch combination sequence is bbb–abb–aba–aca–acc–aca–aba–abb–bbb, and the corresponding vector action sequence is I_0U_0–I_6U_1–I_6U_6–I_1U_6–I_1U_1–I_1U_6–I_6U_6–I_6U_1–I_0U_0. The vector action sequences of other sectors can be obtained by the same method.

Let I be the effective vector of the sector where the reference vector of the input phase current of the MC is located I_μ And I_γ, The effective vector of the sector where the output line voltage reference vector is located is U_α And U_β. Then the five vector combinations of SVM are: $I_\mu U_\alpha$ (abbreviation μα), $I_\mu U_\beta$ (abbreviation μβ), $I_\gamma U_\alpha$ (abbreviation γα),

$I_\gamma U_\beta$ (abbreviation γβ) And $I_0 U_0$ for short. Considering the optimization strategy of reducing switching loss, the general vector sequence in a switching cycle is obtained as follows:

When the sum of current sector number and voltage sector number is even, 0–μβ–μα–γα–γβ–γα–μα–μβ–0; When the sum of current sector number and voltage sector number is odd, 0–μα–μβ–γβ–γα–γβ–μβ–μα–0.

When the SVM of MC is in the combination of I-I sectors, the pulse waveform of three output phases in a switching cycle is shown in Fig. 9. In the figure, level 1 indicates that the output phase is connected with input a, level 2 indicates that the output phase is connected with input b, level 3 indicates that the output phase is connected with input c, and the time constant $T_1 = T_0$, $T_2 = T_{\mu\beta}$, $T_3 = T_{\mu\alpha}$, $T_4 = T_{\gamma\alpha}$ = T_ γβ and $T_5 = T_{\gamma\beta}$.

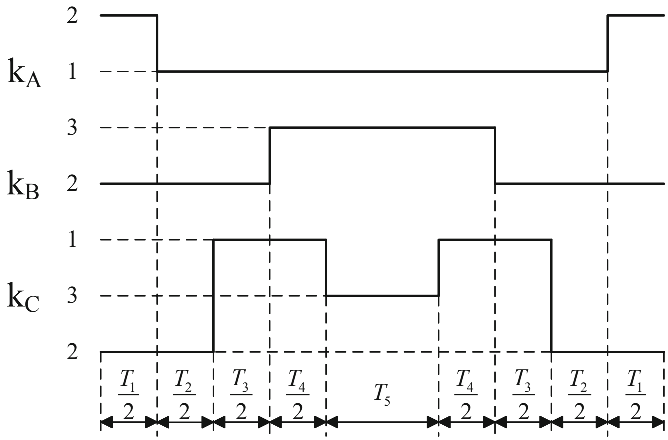


Fig. 9. Output phase pulse waves of I-I sector of mode I

4.2 Mode II of Output Pulse

According to the pulse output mode II, the zero vector is inserted in the middle of the switch combination sequence. When the reference input phase current vector and the reference output line voltage vector are in the first sector, the switch combination sequence in a switching cycle is: abb–aba–aca–acc–ccc–acc–aca–aba–abb, and the corresponding vector sequence is: I_6U_1–I_6U_6–I_1U_6–I_1U_1–I_0U_0–I_1U_1–I_1U_6–I_6U_6–I_6U_1. By synthesizing the vector sequence of each sector combination, the general vector sequence in a switching cycle can be obtained.

When the sum of current sector number and voltage sector number is even, μβ–μα–γα–γβ–0–γβ–γα–μα–μβ; When the sum of current sector number and voltage sector number is odd, μα–μβ–γβ–γα–0–γα–γβ–μβ–μα.

When the SVM of MC is in the combination of I-I sectors, the pulse waveform of three output phases in a switching cycle is shown in Fig. 10, and the time constant $T_1 = T_{\mu\beta}$, $T_2 = T_{\mu\alpha}$, $T_3 = T_{\gamma\alpha}$, $T_4 = T_{\gamma\beta}$ And $T_5 = T_0$.

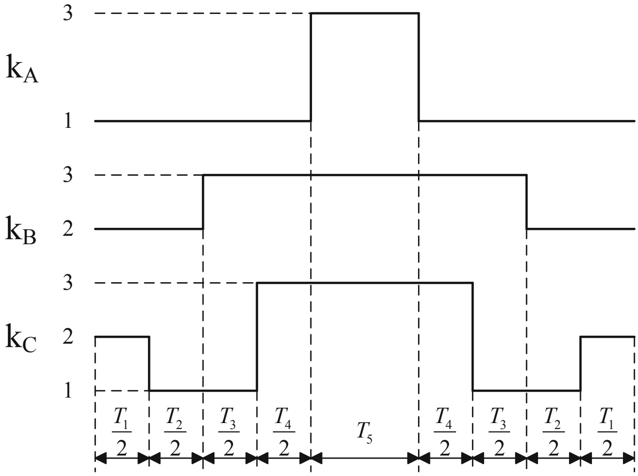


Fig. 10. Output phase pulse waves of I-I sector of mode II

4.3 Mode III of Output Pulse

According to the pulse output mode III, a zero vector is inserted in the middle of the first half and the second half of the switch combination sequence. When the current vector of the reference input phase and the voltage vector of the reference output line is in sector I, the switch combination sequence in a switching period is: abb–aba–aaa–aca–acc–aca–aaa–aba–abb, and the corresponding vector sequence is: I_6U_1–I_6U_6–I_0U_0–I_1U_6–I_1U_1–I_1U_6–I_0U_0–I_6U_6–I_6U_1. By synthesizing the vector sequence of each sector combination, the general vector sequence in a switching cycle can be obtained.

When the sum of current sector number and voltage sector number is even, μβ–μα–0–γα–γβ–γα–0–μα–μβ; When the sum of current sector number and voltage sector number is odd, μα–μβ–0–γβ–γα–γβ–0–μβ–μα.

When the SVM of MC is in the combination of sector I-I, the pulse waveform of three output phases in a switching period is shown in Fig. 2–11, and the time constant $T_1 = T_{\mu\beta}$, $T_2 = T_{\mu\alpha}$, $T_3 = T_0$, $T_4 = T_{\gamma\alpha}$ And $T_5 = T_{\gamma\beta}$.

4.4 Simulation Analysis

The input and output performances of the MC in three pulse output modes are simulated by Matlab/Simulink. The simulation parameters are input filter $L_f = 5\,\text{mH}$, $C_f = 10\,\mu\text{F}$, $R_f = 15\,\Omega$; Three phase symmetrical resistive load, $R = 11\,\Omega$, $L = 5$ mH

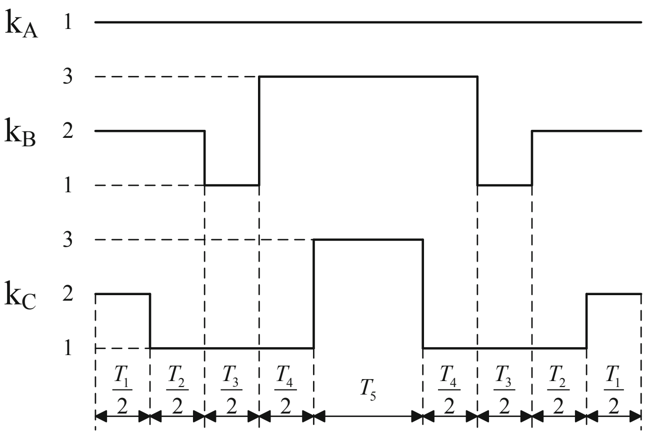


Fig. 11. Output phase pulse waves of I-I sector of mode III

for each phase, with star connection; The input phase voltage amplitude is 100 V, the frequency is 50 Hz, and the input power factor is 1; Modulation coefficient $m = 0.75$; The switching frequency is 5 kHz; The simulation algorithm is ode15 s; Two-way switch is composed of ideal switch. To study the influence of three pulse output modes on the input and output performance of MC at high frequency and low frequency of output voltage, the simulation is carried out when the expected output voltage frequency is 30 Hz and 80 Hz respectively. The simulation model is shown in Fig. 12.

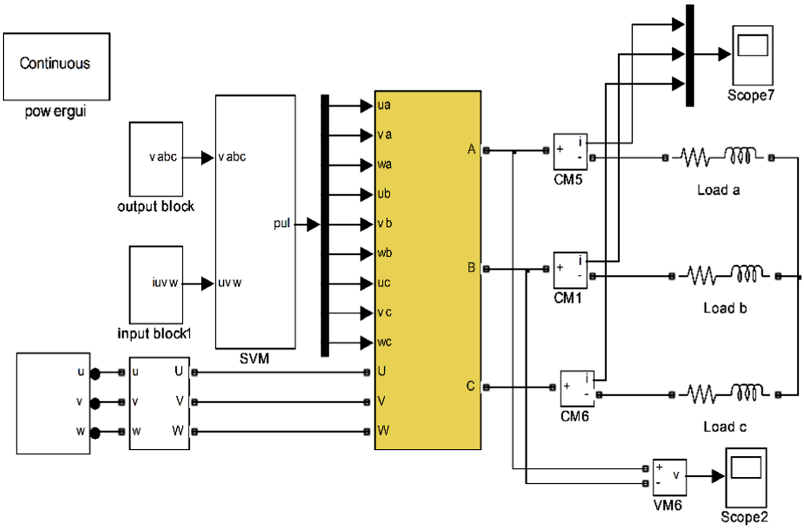
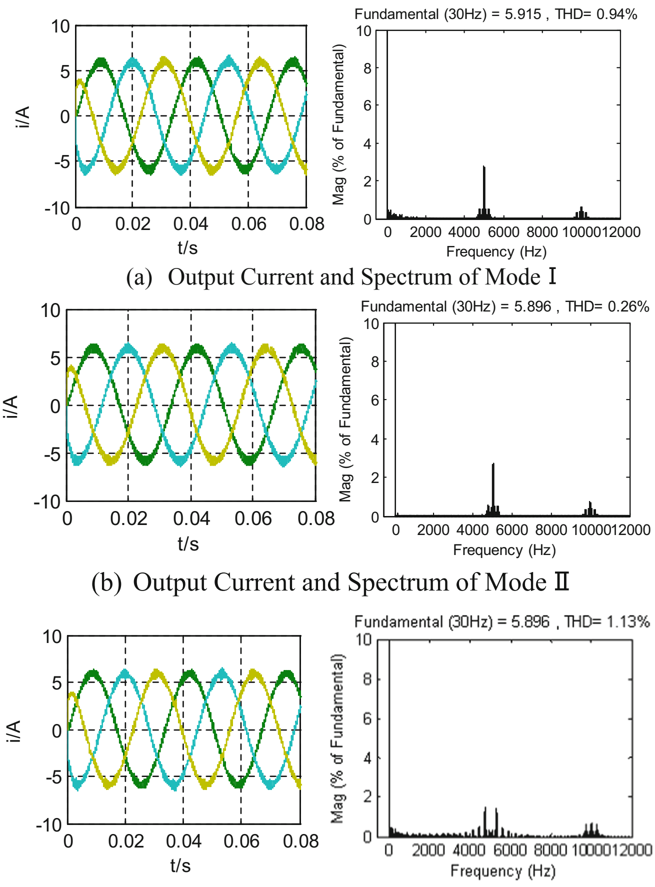


Fig. 12. The Matlab/Simulink simulation model of MC

Due to the limited space, only the simulation waveform with an output frequency of 30 Hz is given. Figure 13 shows the expected output frequency of 30 Hz. The current waveform of three-phase output phase and the spectrum of phase an output current of MC is respectively adopted in three pulse output modes; Fig. 14 shows the input current waveform and spectrum of MC under three pulse output modes with an expected output frequency of 30 Hz; Fig. 15 shows the output line voltage u_{AB} waveform and spectrum of MC under three pulse output modes with an expected output frequency of 30 Hz.

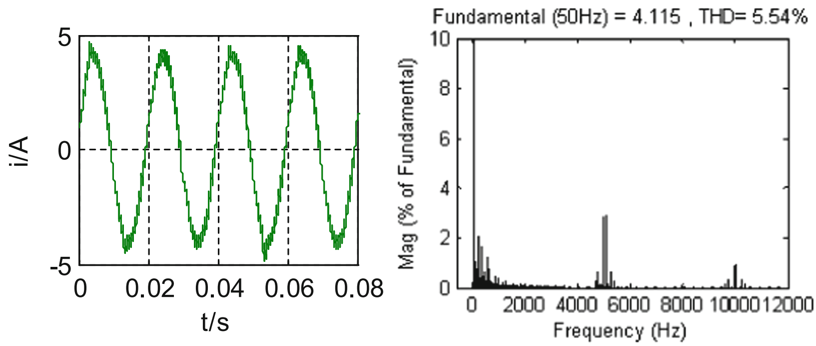


(a) Output Current and Spectrum of Mode Ⅰ

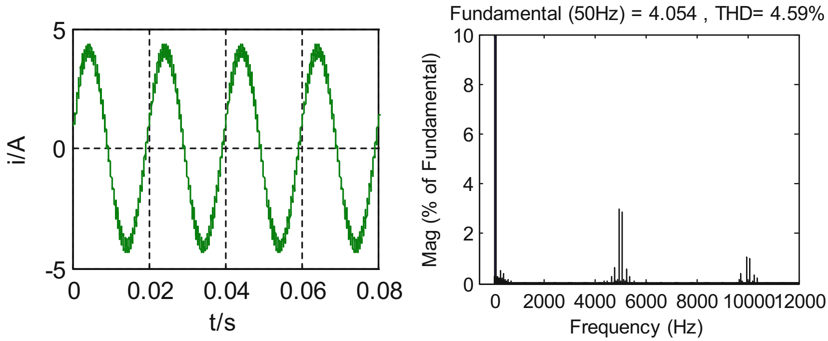
(b) Output Current and Spectrum of Mode Ⅱ

(c) Output Current and Spectrum of Mode Ⅲ

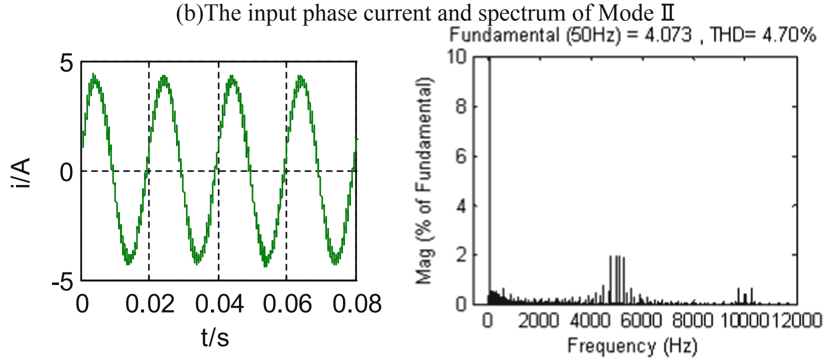
Fig. 13. Output current waveforms and spectrums under three modes of output pulse



(a)Input Current and Spectrum of Mode Ⅰ

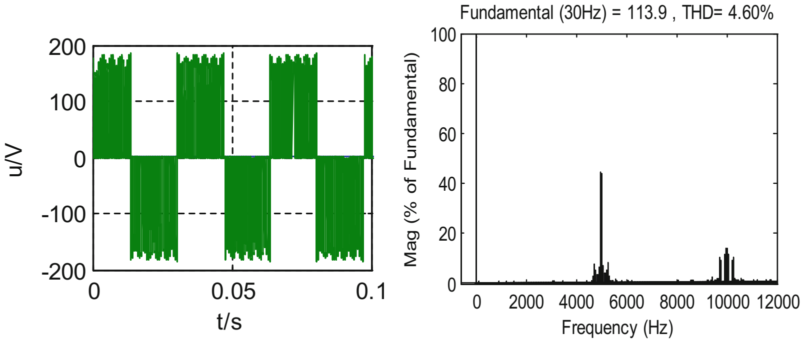


(b)The input phase current and spectrum of Mode Ⅱ

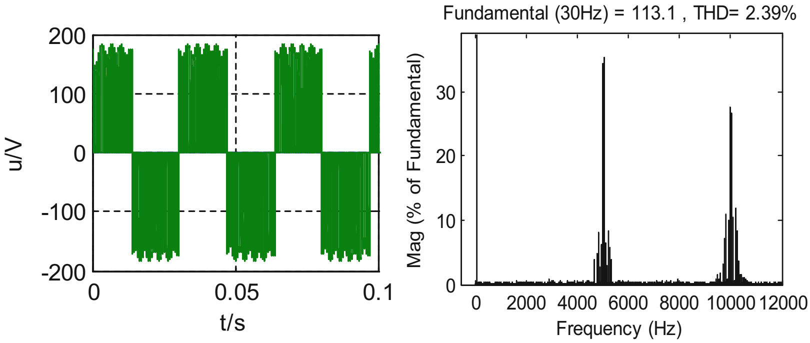


(c) Input Current and spectrum of Mode Ⅲ

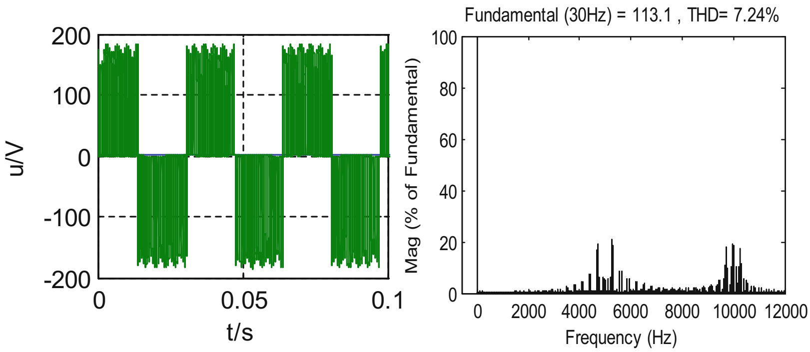
Fig. 14. Input current waveforms and spectrums of phase a under three modes of output pulse



(a) Output voltage and spectrum mode Ⅰ



(b) Output voltage and spectrum of mode Ⅱ



(c) Output voltage and spectrum of of mode Ⅲ

Fig. 15. Waveforms and spectrum in three pulse output u_{AB} modes

Table 3 and Table 4 list 30 Hz and 80 Hz, respectively. As can be seen from Table 3 and Table 4, waveform harmonic content and better waveform quality in the output frequencies of 30 Hz and 80 Hz, and pulse output mode III is output low-frequency 30 Hz and high-frequency 80 Hz The input current harmonic content is close to mode II, less than the harmonic content in mode I, and the output current harmonic content of pulse output mode I at low frequency 30 Hz and high frequency 80 Hz is close to mode II and less than the harmonic content of mode III. Pulse output mode II the output line voltage harmonic content at low frequency 30 Hz is smaller than mode I and mode III, but greater than mode I and mode III when output high frequency 80 Hz. In general, pulse output mode II in the output of low frequency and high frequency, MC input and output waveform quality are better, is the best pulse output mode of the three typical modes, the subsequent study using pulse output mode II to control the MC.

Table 3. Harmonic comparison of input and output waves when the output frequency is 30 Hz

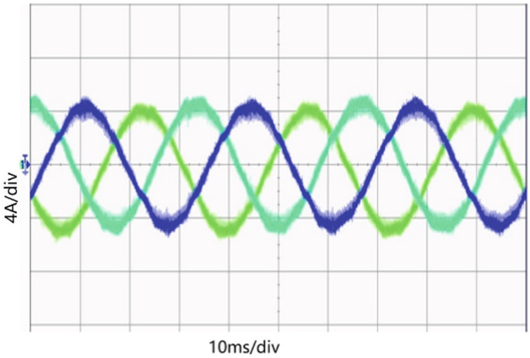
Pulse output mode	A Phase input current THD (%)	The A-phase output current is THD (%)	The B-phase output current is THD (%)	The C-phase output current is THD (%)	Output line voltage u_{AB} THD (%)
Mode I	5.54	0.94	2.13	2.47	4.60
Mode II	4.59	0.26	1.65	1.83	2.39
Mode III	4.70	1.13	2.19	2.53	7.24

Table 4. Harmonic comparison of input and output waves when the output frequency is 80 Hz

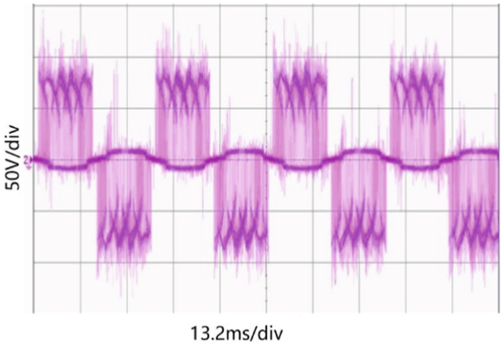
Pulse output mode	A Phase input current THD (%)	A-phase output current THD (%)	The B-phase output current THD (%)	The C-phase output current is THD (%)	Output line voltage u_{AB} THD (%)
Mode I	5.10	1.56	2.56	3.22	30.54
Mode II	4.56	1.47	2.46	3.12	34.09
Mode III	4.73	1.93	2.86	3.48	30.30

5 Experimental Results

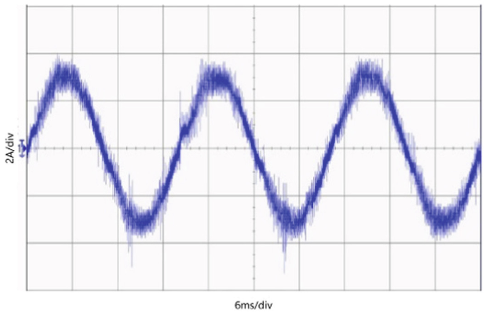
With dSPACE hardware real-time simulation platform as the main control unit, the experimental device of MC is designed. Experimental parameters: input filter $L_f = 5\,\text{mH}$, $C_f = 6\,\mu\text{F}$, $R_f = 15\,\Omega$; Three phase symmetrical resistive load,$R = 12\,\Omega$, $L = 5\,\text{mH}$ for each phase, with star connection; The effective value of input line voltage is 120 V, the frequency is 50 Hz, and the input power factor is 1; The modulation coefficient $m = 0.75$, and the expected output line voltage frequency is 30 Hz; The sampling frequency is 5 kHz. Figure 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15 and 16 shows the experimental waveform of SVPWM strategy using pulse output mode II, in which Fig. 16 (a) is the three-phase output current waveform of MC, Fig. 16(b) is the output PWM line voltage waveform, and Fig. 16 (c) is the A-phase input current waveform. It can be seen that the quality of input and output waveforms of MC is better with pulse output mode II.



(a) Three-phase output current waveform



(b) Output line voltage waveform



(c) A-phase input current waveform

Fig. 16. Experimental waveforms of mode II of output pulse based on SVM strategy

6 Conclusion

This paper analyzes the principle of the spatial vector modulation strategy of the MC, studies the influence of three different pulse output modes on the input and output performance of the MC, obtains the pulse output mode II as the ideal pulse output mode through simulation analysis, and selects the pulse output mode II as the pulse output mode of spatial vector modulation strategy in the resistance load experiment.

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