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Research Article

Research on Matrix Converter Based on Space Vector Modulation

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Abstract: In this study, we study the control strategy for matrix converter. Through absorbing ideas about virtual rectification put forward by P.D.Ziogas, the common control idea of AC-DC-AC convertor is introduced into control of matrix converter; SPWM modulation strategy and space vector modulation strategy for matrix converter are studied respectively. In terms of SPWM modulation strategy, it has some advantages: for example, main circuit structure is simple; control program is simple; control switch function does not need complex mathematical derivation and calculation. In terms of space vector modulation strategy, it has advantages as follows: the physical conception is clear; input power factor can be adjusted; output voltage and current sine degree are high. In this chapter, an in-depth analysis will be conducted for this control method.

Keywords: Matrix convertor, SPWM modulation, simulation, space vector modulation

INTRODUCTION

The transformation process of matrix converter can be considered to be composed of "rectification" and "inversion" (Brenna *et al*., 2009). Sinusoidal input current and adjustable input power factor are obtained by using space vector modulation for input phase current in the rectification part and the amplitude value and sinusoidal output voltage with an adjustable frequency are obtained by using space vector modulation for output line voltage in the inversion part (Brooks, 1986); then the middle DC link is eliminated through the principle of equal middle DC voltage and DC current; thus, the method of space vector modulation of matrix converter is obtained (Brooks and Kaupp, 2007).

The classical SPWM modulation mainly focuses on making the output voltage of inverter approaching sinusoidal wave as much as possible, or expecting the fundamental wave component of output PWM voltage to be as large as possible and the harmonic component to be as small as possible (Cao and Dai, 2008). If PWM voltage is controlled by tracking the circular magnetic field and a constant electromagnetic torque is produced, it will have a better effect. As the trajectory of flux linkage is obtained by voltage space vectors versus time integration, it is also called "voltage space vector modulation" (Carmine *et al*., 2006). It is proved that the maximum amplitude value of output voltage of inverter is DC side voltage, which is 15% higher than general SPWM inverter output voltage and the utilization rate of DC voltage is relatively high while using voltage space vector modulation (Chella *et al*., 2010).

Voltage space vectors can be obtained by Park transformation of three-phase output voltage in complex plane:

$$U = \frac{2}{3}(U_{AB} + \alpha U_{BC} + \alpha^2 U_{CA}) \tag{1}$$

where, $\alpha = ej_{120^\circ}$.

When the power of a motor with symmetric three-phase winding is supplied by three-phase equilibrium sinusoidal voltage, the voltage equation for using blended space vectors to represent stator is as follows:

$$U = RI + \frac{d\Psi}{dt} \tag{2}$$

where, U is a blended space vector of three-phase voltage of stator, I is a blended space vector of three-phase current of stator and Ψ is a blended space vector of three-phase flux linkage.

When the revolving speed is not very low, the pressure drop of stator resistance occupies a small proportion which can be ignored. So the approximate relationship between stator voltage and flux linkage is:

$$U \approx \frac{d\Psi}{dt}\text{, i.e., } d\Psi = Udt \tag{3}$$

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The equation above shows that voltage space vector U equals to the change rate of Ψ as a function of time, while its direction is consistent with the direction of motion of Ψ. Therefore, the motion trail of flux linkage can be controlled by voltage space vectors.

It can be known from the above that a matrix converter can equal to a virtual AC-DC-AC converter. Therefore, a relatively mature space vector modulation mode with superior performance can be adopted.

SPACE VECTOR MODULATION OF OUTPUT LINE VOLTAGE OF MATRIX CONVERTER (VSI SVM)

Now space vector modulation is conducted for the inversion part on the right half of the Fig. 1. The power of this part is supplied by a DC voltage. Enable U_{pn} = U_{dc}. There are 8 permissible switch combination modes in VSI, among which 6 will produce non-zero output voltage and 2 will product zero output voltage. Voltage space vector of output line is defined as:

$$\bar{u}_{oL} = \frac{2}{3}(u_{AB} + u_{BC}e^{j120^\circ} + u_{CA}e^{-j120^\circ}) \tag{4}$$

Assume that $U_0 \sim U_6$ are seven voltage switch state vectors as shown in Fig. 1b. $U_0 \sim U_6$ six vectors divide a cycle into six sectors, i.e., I, II, III, IV, V and VI. Each sector accounts for 60°. U_0 and U_7 represent zero voltage vectors. Table 1 shows the relationship between $U_0 \sim U_7$ space vectors and the switch state.

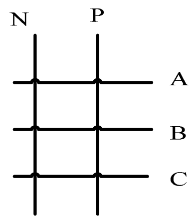
Any voltage space vector of output line $\vec{U}_{\mathrm{oL}}$ can be expressed by two adjacent switch state vectors $\vec{U}_\alpha$ and $\vec{U}_\beta$ and zero voltage vector $\vec{U}_0$, as shown in Fig. 3. Assume that the included angle between $\vec{U}_{\mathrm{oL}}$ and the subsequent component is θ_{SV}, therefore:

$$\vec{U}_{oL} = d_\alpha \vec{U}_\alpha + d_\beta \vec{U}_\beta + d_{ov}\vec{U}_{ov} \tag{5}$$

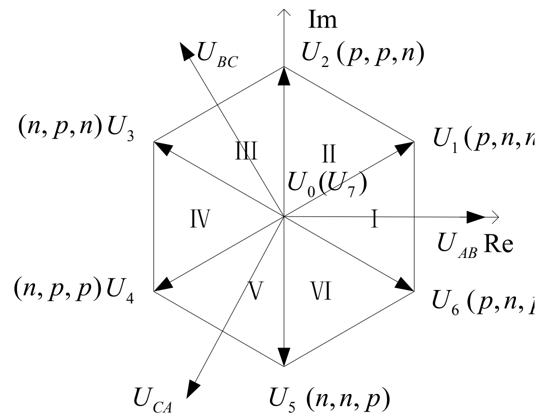
where, d_α, d_β and d_{ov} are respectively the duty cycle of $\vec{U}_\alpha$, $\vec{U}_\beta$ and zero vector $\vec{U}_{ov}$. It can be obtained through sine theorem within the switching period T_s that:

$$\begin{aligned} d_\alpha &= T_\alpha / T_S = m_v \sin(60^o - \theta_{sv}) \\ d_\beta &= T_\beta / T_s = m_v \sin(\theta_{sv}) \\ d_{0v} &= T_{ov} / T_s = 1 - d_\alpha - d_\beta \end{aligned} \tag{6}$$

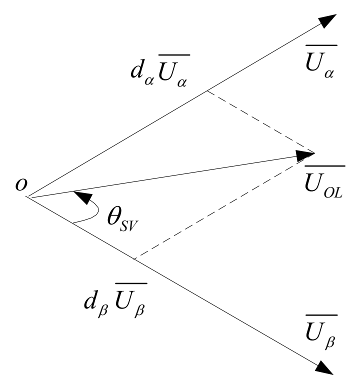
where: T_s refers to a PWM switching period; m_v is voltage modulation factor. Modulation factor $0 \le m_v = \sqrt{3U_{om}}/U_{dc} \ge 1$; θ_{sV} is the included angle between



(a) Virtual inversion structure



(b) Diagram of sectors of voltage space vectors of output line



(c) Vector synthesis schematic diagram

Fig. 1: Diagram of voltage space vectors of output line

Table 1: Relationship between VSI space vectors and switch state

Space vectors	Switch state					
	S_{AP}	S_{BP}	S_{CP}	S_{AN}	S_{BN}	S_{CN}
0	1	1	1	0	0	0
1	1	0	0	0	1	1
2	1	1	0	0	0	1
3	0	1	0	1	0	1
4	0	1	1	1	0	0
5	0	0	1	1	1	0
6	1	0	1	0	1	0
7	0	0	0	1	1	1

(1: represents switch on, 0: represents switch off) output voltage vector and the initial position of sectors and U_{PN} is the voltage between buses.

When the voltage space vector of output line is located in sector I, the local average of output line voltage is:

$$\begin{bmatrix} \bar{u}_{AB} \\ \bar{u}_{Bc} \\ \bar{u}_{cA} \end{bmatrix} = \begin{bmatrix} U_{dc} \\ -U_{dc} \\ 0 \end{bmatrix} d_\alpha + \begin{bmatrix} U_{dc} \\ 0 \\ -U_{dc} \end{bmatrix} d_\beta = \begin{bmatrix} d_\alpha + d_\beta \\ -d_\alpha \\ -d_\beta \end{bmatrix} U_{dc} = m_v \begin{bmatrix} \cos(\theta_{SV} - 30^\circ) \\ -\sin(60^\circ - \theta_{SV}) \\ -\sin(\theta_{SV}) \end{bmatrix} U_{dc} \tag{7}$$

-30°≤$\omega_o t$-φ_o+30°≤30° in the first sector and θ_{sv} = ($\omega_o t$-φ_o+30°) +30°. Therefore, Eq. (3-7) changes into:

$$\begin{bmatrix} \bar{u}_{AB} \\ \bar{u}_{Bc} \\ \bar{u}_{cA} \end{bmatrix} = m_v \begin{bmatrix} \cos(\omega_o t - \varphi_o + 30^\circ) \\ \cos(\omega_o t - \varphi_o + 30^\circ - 120^\circ) \\ \cos(\omega_o t - \varphi_o + 30^\circ + 120^\circ) \end{bmatrix} U_{dc} = \bar{T}_{VSI} U_{dc} \tag{8}$$

where, $\bar{T}VSI$ represents the transfer matrix of voltage source inverter at a low frequency.
The local average of input current of VSI is:

$\bar{\imath}_P$ = $\bar{T}_{VSI}^T \cdot$ i_{oL}= $\frac{\sqrt{3}}{2} \cdot I_{om} \cdot$ $m_v \cdot$ $\cos(\varphi_L)$ = CONST (9)

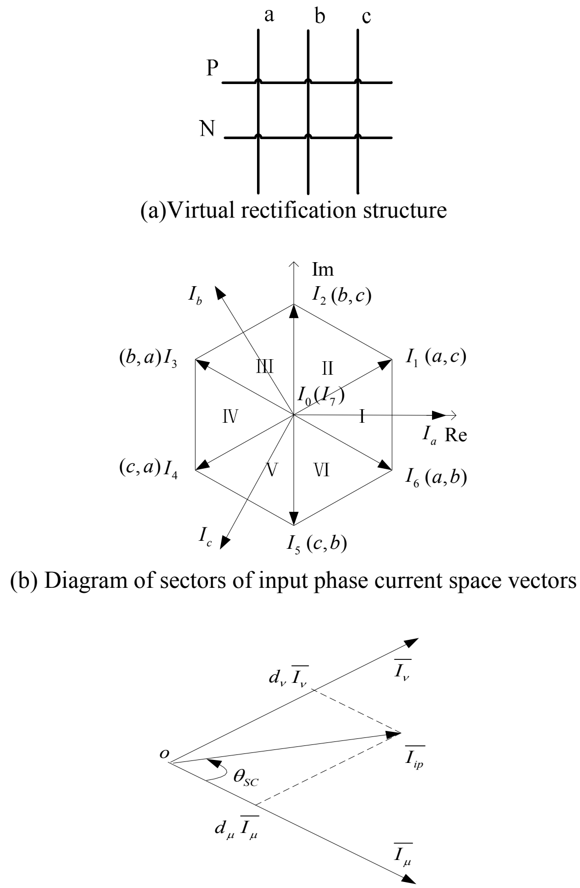
SPACE VECTOR MODULATION OF INPUT PHASE CURRENT OF MATRIX CONVERTER (VSR SVM)

The left half of Fig. 2 to 4 is a virtual rectifier (VSR). Enable it to produce direct current i_P = I_{dc}, similar to VSR input current space vector and VSI output voltage space vector as shown in Fig. 3.

If $\vec{I}\mu$ and $\vec{I}v$ are used to represent two adjacent phase current space vectors and $\vec{I}_0$ is used to represent zero current space vectors, in each VSR switching period:

$$\vec{I}_{iP} = d_\mu \bar{I}_\mu + d_v \vec{I}_v + d_{0c} \vec{I}_{0c} \tag{10}$$

where, d_μ, d_v and d_{0c} are respectively the duty cycle of $\vec{I}\mu$, $\vec{I}v$ and $\vec{I}_{0c}$ and:



(a)Virtual rectification structure

(b) Diagram of sectors of input phase current space vectors

(c) Vector synthesis schematic diagram

Fig. 2: Diagram of input phase current space vectors

$$\begin{aligned} d_\mu &= T_\mu / T_s = m_c \sin(60^o - \theta_i) \\ d_v &= T_v / T_s = m_c \sin(\theta_i) \\ d_{0c} &= T_{oc} / T_s = 1 - d_\mu - d_v \end{aligned} \tag{11}$$

where, m_c is current modulation factor and $0 \le m_c$ = I_{im}/I_{dc}≤1. θ_{SC} is the included angle between output voltage vector and the initial position of sectors (Table 2).

For example, switch state vector is located in the first sector of VSR hexagon. The local average of input phase current is:

$$\begin{bmatrix} \bar{i}_a \\ \bar{i}_b \\ \bar{i}_c \end{bmatrix} = \begin{bmatrix} I_{dc} \\ -I_{dc} \\ 0 \end{bmatrix} d_\mu + \begin{bmatrix} I_{dc} \\ 0 \\ -I_{dc} \end{bmatrix} d_v = \begin{bmatrix} d_\mu + d_v \\ -d_\mu \\ -d_v \end{bmatrix} I_{dc} = m_c \begin{bmatrix} \cos(\theta_{SC} - 30^\circ) \\ -\sin(60^\circ - \theta_{SC}) \\ -\sin(\theta_{SC}) \end{bmatrix} I_{dc} \tag{12}$$

Substitute Eq. (3-12) with $-30^\circ \le \omega_i t - \varphi i \le +30^\circ$ and $\theta_{SC} = (\omega_i t - \varphi i) + 30^\circ$. It can be obtained that:

$$\begin{bmatrix} \bar{i}_a \\ \bar{i}_b \\ \bar{i}_c \end{bmatrix} = m_c \begin{bmatrix} \cos(\omega_i t - \varphi) \\ \cos(\omega_i t - \varphi - 120^\circ) \\ \cos(\omega_i t - \varphi + 120^\circ) \end{bmatrix} I_{dc} = \overline{T}_{VSR} I_{dc}$$

where, $\overline{T}_{VSR}$ represents the transfer matrix of voltage source rectifier at a low frequency. While the local average output voltage of VSR is:

$$\bar{u}_{\text{pn}} = \overline{T}_{VSR}^{T}.u_{iPh} = \frac{3}{2}.\, m_c.U_{im}.\cos(\varphi_i) = \text{CONST} \qquad (13)$$

EQUIVALENT DIRECT SPACE VECTOR MODULATION

It is inferred from the above that VSR space vector modulation and VSI space vector modulation can be directly linked from the perspective of local average since the local average output voltage in VSR space vector modulation and the local average input current of VSI space vector modulation are constants.

An equivalent (i.e., actual) direct space vector modulation method can be obtained by combining VSR and VSI space vector modulation and eliminating the middle DC link. The synthesis method of switch control law is as shown in Fig. 3 to 5. Since input current and output voltage respectively have six

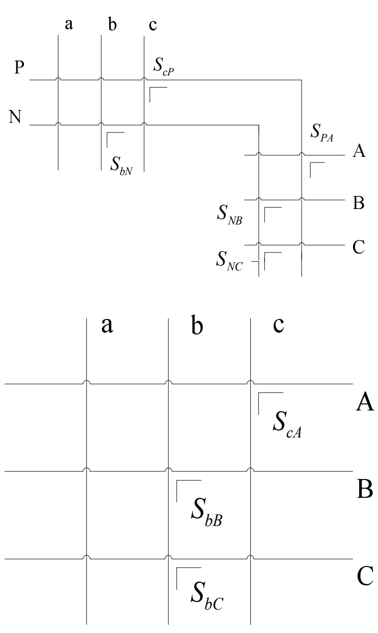


Fig. 3: Synthesis of switch control law

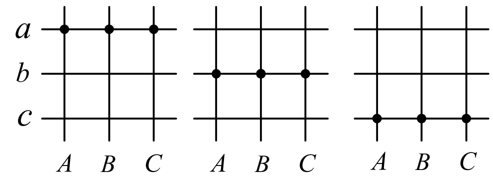
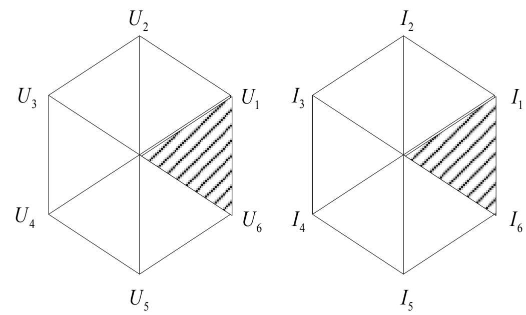
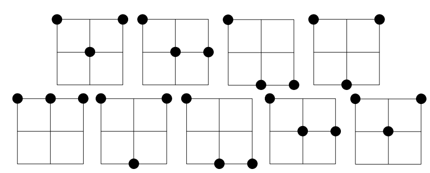


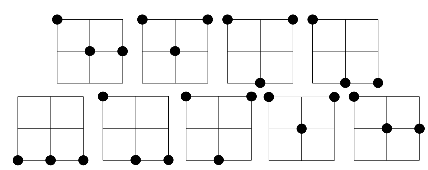
Fig. 4: Three switch states of zero vectors



(a) Sectors where voltage vectors and current vectors locate



(b) General (standard) vector transformation order



(c) Optimized vector transformation order

Fig. 5: Space vector modulation order (1)

effective static vectors, 36 possible switch combination states can be obtained according to the law shown in Fig. 3 to 5 and Table 3 each state corresponds to a combination mode of 9 switches, as shown in Table 3. In the table, acc represents that input phase a and output phase A, I nput phase c and output phase B, input phase c and output phase C respectively connect through break-over switch. Three zero vectors not included in the table are aaa, bbb and ccc.

It is required to first find the switch combination of matrix converter corresponding to the equivalent AC-DC-AC structure in order to realize space vector modulation in real matrix converter and accomplish

Table 2: Relationship between VSR space vectors and the switch state

Space vectors	Switch state S_{Pa}	S_{Pb}	S_{Pa}	S_{Na}	S_{Nb}	S_{Nc}
1	1	0	0	0	0	1
2	0	1	0	0	0	1
3	0	1	0	1	0	0
4	0	0	1	1	0	0
5	0	0	1	0	1	0
6	1	0	0	0	1	0
7	1	0	0	1	0	0
8	0	1	0	0	1	0
9	0	0	1	0	0	1

(1 represents switch on, 0 represents switch off, and vectors 7, 8 and 9 are zero vectors)

Table 3: 36 kinds of switch combination

	I1	I2	I3	I4	I5	I6
V1	acc	bcc	baa	caa	cbb	abb
V2	aac	bbc	bba	cca	ccb	aab
V3	caa	cbc	aba	aca	bcb	bab
V4	caa	cbb	abb	acc	bcc	baa
V5	cca	ccb	aab	aac	bcc	bba
V6	aca	bcb	bab	cac	cbc	aba

direct transformation of AC-AC power. There are 27 kinds of switch combination of matrix converter through which input voltage is not subject to short circuit and output current is not subject to sudden open circuit, as shown in Table 3. Six of them cannot find a correspondence in the equivalent AC-DC-AC transformation, which are switch combinations where three output phases respectively connect to three input phases. Therefore, 21 kinds of switch combination are available, which are divided into two groups. In group I, three output phases respectively connect to two input phases; in group II, three output phases only connect to one in out phase, resulting in short circuit. Matrix converter has an only switch state corresponding to each legal switch state of the equivalent AC-DC-AC transformation.

After obtaining the switch combination of matrix converter corresponding to the equivalent AC-DC-AC structure, it is also necessary to obtain the action time (duty cycle) of each switch combination so as to realize AC-AC direct transformation control of matrix converter. AC-AC direct transformation control mode of matrix converter (i.e., double space vector PWM modulation) can be obtained according to the corresponding relation of switch functions after adopting output line voltage space vector modulation for the inversion part of the equivalent AC-DC-AC transformation and adopting input phase current space vector modulation for the rectification part. In the implementation of double space vector PWM modulation, the ideal output line voltage reference vector circle of the inversion part and the ideal input phase current reference vector circle of the rectification part are both divided into 6 sectors. Therefore, there are 36 possible kinds of combination.

The virtual VSI space vector modulation and virtual VSR space vector modulation in matrix converter are independently conducted in the virtual AC-DC-AC equivalent structure. However, in the real matrix converter, the same switch conducts not only output line voltage space vector modulation but also input phase current space vector modulation and one PWM period corresponds to 5 duty cycles of voltage and current and each comprehensive duty cycle corresponds to one switch combination, respectively:

$$\begin{aligned} T_1 &= T_{\alpha\mu} = d_\alpha \cdot d_\mu \cdot T_s \\ T_2 &= T_{\beta\mu} = d_\beta \cdot d_\mu \cdot T_s \\ T_3 &= T_{\alpha\nu} = d_\alpha \cdot d_\nu \cdot T_s \\ T_4 &= T_{\beta\mu} = d_\beta \cdot d_\nu \cdot T_s \\ T_0 &= T_s - T_1 - T_2 - T_3 - T_4 \end{aligned} \tag{14}$$

Take the following example to explain the high-frequency synthesis steps of double space vector modulation of matrix converter, in which the output line voltage space vector is located in the first sector and the input phase current space vector is located in the first sector. It can be obtained through Eq. (3-8) and Eq. (3-13) that:

$$m_v m_c \begin{bmatrix} \cos(\theta_{SV} - 30^\circ) \\ -\sin(60^\circ - \theta_{SV}) \\ -\sin(\theta_{SV}) \end{bmatrix} \begin{bmatrix} \cos(\theta_{SC} - 30^\circ) \\ -\sin(60^\circ - \theta_{SC}) \\ -\sin(\theta_{SC}) \end{bmatrix}^T = T_{VSI} T_{VSR}^T \tag{15}$$

Enable $m = m_v m_c$ and $T_{PhL} = T_{VSI} T_{VSR}^T$, thus

$$T_{PhL} = m \begin{bmatrix} \cos(\theta_{SV} - 30^\circ) \\ -\sin(60^\circ - \theta_{SV}) \\ -\sin(\theta_{SV}) \end{bmatrix} \begin{bmatrix} \cos(\theta_{SC} - 30^\circ) \\ -\sin(60^\circ - \theta_{SC}) \\ -\sin(\theta_{SC}) \end{bmatrix}^T \tag{16}$$

To simplify work, enable $m_c = 1$ and $m = m_v$ and substitute the equation above with Eq. (3-5 and 3-10). Thus, the local average of output line voltage is:

$$\begin{bmatrix} \bar{u}_{AB} \\ \bar{u}_{BC} \\ \bar{u}_{CA} \end{bmatrix} = \begin{bmatrix} d_\alpha + d_\beta \\ -d_\alpha \\ -d_\beta \end{bmatrix} \cdot \begin{bmatrix} d_\mu + d_\nu \\ -d_\mu \\ -d_\nu \end{bmatrix} \cdot \begin{bmatrix} u_{ao} \\ u_{bo} \\ u_{co} \end{bmatrix} \tag{17}$$

Because: $u_{ab} = u_{ao} - u_{bo}$ and $u_{ac} = u_{ao} - u_{co}$, therefore,

Table 4: Switches of matrix converter corresponding to equivalent AC-DC-AC transformation

G	S_{Aa} S_{Ab} S_{Ac}	S_{Ba} S_{Bb} S_{Bc}	S_{Ca} S_{Cb} S_{Cc}	A B C	U_{AB} U_{BC} U_{CA}	i_a i_b i_c
I	1 0 0	0 1 0	0 0 1	a b c	U_{ab} U_{bc} U_{ca}	i_A i_B i_C
	1 0 0	0 0 1	0 1 0	a c b	$-U_{ca}$ $-U_{bc}$ $-U_{ab}$	i_A i_C i_B
	0 1 0	1 0 0	0 0 1	b a c	$-U_{ab}$ $-U_{ca}$ $-U_{bc}$	i_B i_A i_C
	0 1 0	0 0 1	1 0 0	b c a	U_{bc} U_{ca} U_{ab}	i_B i_C i_A
	0 0 1	1 0 0	0 1 0	c a b	U_{ca} U_{ab} U_{bc}	i_C i_A i_B
	0 0 1	0 1 0	1 0 0	c b a	$-U_{bc}$ $-U_{ab}$ $-U_{ca}$	i_C i_B i_A
II	1 0 0	0 0 1	0 0 1	a c c	$-U_{ca}$ 0 U_{ca}	i_A 0 $-i_A$
	0 1 0	0 0 1	0 0 1	b c c	U_{bc} 0 $-U_{bc}$	0 i_A $-i_A$
	0 1 0	1 0 0	1 0 0	b a a	$-U_{ab}$ 0 U_{ab}	i_A i_A 0
	0 0 1	1 0 0	1 0 0	c a a	U_{ca} 0 $-U_{ca}$	i_A 0 i_A
	0 0 1	0 1 0	0 1 0	c b b	$-U_{bc}$ 0 U_{bc}	0 $-i_A$ i_A
	1 0 0	0 1 0	0 1 0	a b b	U_{ab} 0 $-U_{ab}$	i_A $-i_A$ 0
	0 0 1	1 0 0	0 0 1	c a c	U_{ca} $-U_{ca}$ 0	i_B 0 $-i_B$
	0 0 1	0 1 0	0 0 1	c b c	$-U_{bc}$ U_{bc} 0	0 i_B $-i_B$
	1 0 0	0 1 0	1 0 0	a b a	U_{ab} $-U_{ab}$ 0	$-i_B$ i_B 0
	1 0 0	0 0 1	1 0 0	a c a	$-U_{ca}$ U_{ca} 0	$-i_B$ 0 i_B
	0 1 0	0 0 1	0 1 0	b c b	U_{bc} $-U_{bc}$ 0	0 $-i_B$ i_B
	0 1 0	1 0 0	0 1 0	b a b	$-U_{ab}$ U_{ab} 0	$-i_B$ i_B 0
	0 0 1	0 0 1	1 0 0	c c a	0 U_{ca} $-U_{ca}$	i_C 0 $-i_C$
	0 0 1	0 0 1	0 1 0	c c b	0 $-U_{bc}$ U_{bc}	0 i_C $-i_C$
	1 0 0	1 0 0	0 1 0	a a b	0 U_{ab} $-U_{ab}$	$-i_C$ i_C 0
	1 0 0	1 0 0	0 0 1	a a c	0 $-U_{ca}$ U_{ca}	$-i_C$ 0 i_C
	0 1 0	0 1 0	0 0 1	b b c	0 U_{bc} $-U_{b}$	0 $-i_C$ i_C
	0 1 0	0 1 0	1 0 0	b b a	0 $-U_{ab}$ U_{ab}	i_C $-i_C$ 0
III	1 0 0	1 0 0	1 0 0	a a a	0 0 0	0 0 0
	0 1 0	0 1 0	0 1 0	b b b	0 0 0	0 0 0
	0 0 1	0 0 1	0 0 1	c c c	0 0 0	0 0 0

$$\begin{bmatrix} \bar{u}_{AB} \\ \bar{u}_{BC} \\ \bar{u}_{CA} \end{bmatrix} = \begin{bmatrix} d_{\alpha\mu} + d_{\beta\mu} \\ -d_{\alpha\mu} \\ -d_{\beta\mu} \end{bmatrix} u_{ab} + \begin{bmatrix} d_{\alpha\nu} + d_{\beta\nu} \\ -d_{\alpha\nu} \\ -d_{\beta\nu} \end{bmatrix} u_{ac}$$

where,

$$\begin{aligned} d_{\alpha\mu} &= d_\alpha d_\mu = m\sin(60^\circ - \theta_{SV})\sin(60^\circ - \theta_{SC}) = T_{\alpha\mu}/T_S \\ d_{\beta\mu} &= d_\beta d_\mu = m\sin(\theta_{SV})\sin(60^\circ - \theta_{SC}) = T_{\beta\mu}/T_S \\ d_{\alpha\nu} &= d_\alpha d_{\alpha\nu} = d_\alpha \sin(60^\circ - \theta_{SV})\sin(\theta_{SC}) = T_{\alpha\nu}/T_S \\ d_{\beta\nu} &= d_\beta d_\nu = m\sin(\theta_{SV})\sin(\theta_{SC}) = T_{\beta\nu}/T_S \\ d_0 &= 1 - d_{\alpha\mu} - d_{\beta\mu} - d_{\alpha\nu} - d_{\beta\nu} = T_0/T_S \end{aligned} \tag{18}$$

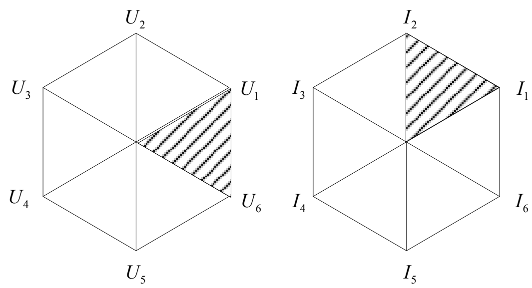
It can be seen from the analysis above that each output line voltage can be made up of input line voltage combination within each switching period. It can be obtained from equation 3-18 that:

$$\begin{bmatrix} \bar{u}_{AB} \\ \bar{u}_{BC} \\ \bar{u}_{CA} \end{bmatrix} = \begin{bmatrix} d_{\alpha\mu} \\ -d_{\alpha\mu} \\ 0 \end{bmatrix} u_{ab} + \begin{bmatrix} d_{\beta\mu} \\ 0 \\ -d_{\beta\mu} \end{bmatrix} u_{ab} + \begin{bmatrix} d_{\alpha\nu} \\ -d_{\alpha\nu} \\ 0 \end{bmatrix} u_{ac} + \begin{bmatrix} d_{\beta\nu} \\ 0 \\ -d_{\beta\nu} \end{bmatrix} u_{ac} \tag{19}$$

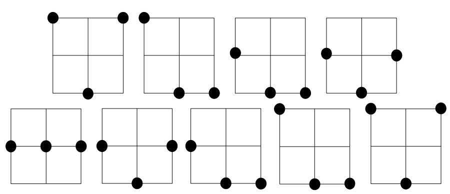
There are five different kinds of combination corresponding to five duty cycles in each PWM period. The control of matrix converter can be concluded as the determination of 5 duty cycles and their corresponding 5 kinds of switch combination state. Mutually nested double space vector PWM modulation strategies can not only ensure good sinusoidal property of output line voltage but also ensure that of input phase current, which realize the purpose of applying space vector modulation in control strategies of matrix converter and provide matrix converter with the effect of double PWM converter. The analysis above actually reflects the process of AC-AC direct transformation control of matrix converter (Table 4).

OPTIMIZED SPACE VECTOR MODULATION OF MATRIX CONVERTER

The section above introduces space vector synthesis methods of matrix converter. Assume that the adjacent basic vectors in the section where output voltage vectors of matrix converter locates are V_M (vector M for short) and V_N (vector N for short) and the adjacent basic vectors in the section where input current vectors of matrix converter locates are I_α (vector α for short) and I_β (vector β for short). So the comprehensive modulation of both space vectors is realized by using mutual nesting method. The overall vector synthesis process of input phase current and output line voltage has 5 kinds of combination in total, i.e., α-M, α-N, β-N, β-M and zero vector I_0 - U_0.



(a) Sectors where voltage vectors and current vectors locate



(b) General (standard) vector transformation order

Fig. 6: Space vector modulation order (2)

The action time of each vector combination is expressed by duty cycle.

Since matrix converter is working under high-frequency PWM modulation mode and the switching loss in the switching process cannot be neglected, how to reduce the switching loss of matrix converter has become a significant problem. We adopt a new nine-section optimized modulation strategy on the basis of common space vector modulation methods introduced above.

Using the common space vector modulation method, the vector transformation order in one switching period is: αM- αN - βN - βM- 0-βM-βN -αN-αM, while there are three switch states of zero vector: aaa, bbb and ccc, as shown in Fig. 3 to 6.

In the process of realizing the transformation of a vector sequence, the selection of zero vectors is related to the required switching times. Up to now, the selection principle of zero vectors is still focusing on reducing the switching times of MC.

As shown in Fig. 3 to 5a, assuming that voltage vectors and current vectors are both in their respective first section, first consider output voltage vector modulation and the order of voltage vectors is M -N - N - M – 0 in the first half of switching period based on the general (standard) vector transformation order; and then consider input current vector modulation and its order of vectors (in the first half of switching period) is α- β-0. As the last effective vector (in the first half of switching period) βM is aca, zero vector aaa is often selected because only one switching is required from vector βM to zero vector aaa. It can be known from Fig. 3 to 5b that the switching times necessary for realizing the order of vectors is 10. Assuming that the order of voltage vectors in the first half of switching period is changed into N-M-M-N-0, the order of input current vectors remains unchanged. As the last effective vector βN is acc, select ccc as zero vector similarly, as shown in Fig. 3 to 5c. The switching times necessary for realizing the order of vectors is 8. For a vector sequence
with nine-section and eight-step transformation, this is the least times that can be achieved. However, it can be known from the analysis above that such times cannot always be ensured in any situation.

As shown in Fig. 3 to 6a, the current vector enters into the second sector and the voltage vector is still in the first sector. Only 8 times of switching is required based on the general (standard) vector transformation order, that is, the minimum switching times.

The reason that the switching times are not the minimum one is that the transformation from the second vector to the third vector requires two times of switching instead of one. Similar situation occurs in the second half of switching period, making the total switching times twice more than the minimum times. It can be known from the analysis above that it is only necessary to change the order of voltage vectors, change the general (standard) transformation order M - N -N - M – 0 into N - M - M – N-0 and meanwhile change the selection of zero vector switch correspondingly when the switching times is not the minimum one. Thus, the switching times necessary for realizing vector transformation can be decreased to the minimum value-8 times. Figure 3 to 6b shows the transformation sequence diagram after the order of voltage vectors is changed.

In short, as long as an appropriate vector sequence and zero vector switches is selected, the switching times can be the minimum one. Through careful observation and analysis of all switching combinations using the method above, it is known that the minimum switching times can be ensured in any situation if the vector sequence and zero vector switches are selected according to the following rules.

- The order of input current vectors is maintained as α-β- 0
- If the sum of input sector number and output sector number is odd, the sequence of output vectors is M - N - N - M – 0
- If the sum of input sector number and output sector number is even, the sequence of output vectors is N - M - M - N – 0
- When the current sector number is 4 and 1, the output zero vector is aaa; When the current sector is 5 and 2, the output zero vector is bbb; otherwise, it is ccc

It is thus clear that the modulation of voltage vectors and current vectors are no longer mutually independent and that the selection of zero vectors is determined by current vectors. If the traditional (general) order of vectors is adopted for modulation, the switching period in which 10 transformation times occur will account for 50% among all switching periods, making the average switching times in a switching period as 9. If the optimized order of vectors is adopted, the average switching times is 8, with exceptions. When the sector where a reference vector locates in the switching period changes, the switching state of the first vector no longer equals to that of the last vector; thus, the switching times increases. The switching times corresponding to both modulation strategies above can be expressed as:

General method : $N = t[9f_S + 6(f_O + f_i)]$
Optimized method : $N_{opt} = t[8f_S + 6(f_O + f_i)]$

where, f_i is input frequency, f_o is output frequency. As f_i and f_i are much less than f_s (modulation frequency), the switching times increased due to sector change can be neglected. Then, the switching times corresponding to both modulation strategies above can be expressed as:

General method : $N = t \times 9 \times f_S$
Optimized method : $N_{opt} = t \times 8 \times f_S$

It is thus clear that the total switching times decreases by 11% (1/9) compared to the traditional strategy after the optimized modulation strategy is adopted and that it's switching loss will also decrease by the same proportion correspondingly.

CONCLUSION

This study studies the control strategies of matrix converter, introduces the control idea of general AC-DC-AC converters into the control of matrix converter through absorbing the virtual rectification idea put forward by P.D.Ziogas *et al*. and respectively studies SPWM modulation strategy and space vector modulation strategy of matrix converter. It also proposes the optimized method of space vector modulation strategy, that is, selecting an applicable vector sequence and zero vector based on a certain law can make the switching times reaching the minimum, thus achieving the purpose of reducing switching loss. The analysis in this study has significant theoretical meanings.

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