Research on SVM strategy for Matrix Converter and Its Simulation

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Abstract: - This paper presents double space vector modulation (SVM) strategy for three-phase to three-phase matrix converter and discusses the modeling method based on Matlab/ Simulink in detail. The process of switches conversion is analyzed and a novel modulation mode is proposed. Simulation waveforms are presented which demonstrate the feasibility and validity of the proposed modulation mode. The method discussed in this paper lays strong basis for its further researches and approaching to applications and it can be directly implemented to practical matrix converter system.

Key-Words: - matrix converter, modulation, SVM, modeling, simulation

1 Introduction

Since the matrix converter (MC) topology was first proposed in 1976, people have obtained lots of achievements with great efforts [1-5]. Compared with traditional converter, matrix converter is a kind of direct AC-AC power conversion without energy storage in dc-link. It has many advantages such as bidirectional energy flow, controllable input power factor and a compact power circuit design [6].

The control strategy and modulation method are key points, which directly determine the performance of matrix converter. At present, the Matrix Converter control strategy can be generally categorized into four classes including direct transformation method, hysteresis current method, two-voltage method and space vector modulation method. Among all strategies, SVM is the most widely used and investigated in recent years. Because the SVM strategy can not only control the output voltage and the input current respectively, but also modify the input power factor conveniently. In this paper, dual space vector modulation strategy for three-phase to three-phase MC system is introduced at first. After that, the modelling method is explained in detail based on Matlab/Simulink. And a novel modulation mode is proposed when arranging the PWM sequences, which is superior to the commonly used one for MC. And this may lay strong basis for its further researches and approaching to applications.

2 Dual SVM Strategy of MC

2.1 Topology of Three-Phase to Three-Phase MC

The three-phase to three-phase matrix converter utilizes 9 bidirectional switches for connecting the input phases to the output phases as shown in Fig.1 (a). Each bidirectional switch can be replaced by two anti parallel unipolar turn-off power semiconductor such as insulated gate bipolar transistor (IGBT) with coupled diodes. The LC filter of the input grid side is adopted to prevent excessive voltages. Then, indirect matrix converter topology can be proposed with an imaginary DC-link without using any energy storage element as shown in Fig.1 (b). It can be observed that the virtual source rectifier (VSR) stage is connected to voltage-source while the virtual source inverter (VSI) is connected to current-source.

The indirect matrix converter topology are functionally equivalent to the standard matrix converter, and for each valid switching state of the equivalent indirect AC-DC-AC converter, there is a unique switch state of direct matrix converter corresponding to it. Therefore, the existing mature

space vector modulation algorithm can be applied to VSR and VSI respectively, both of them are finally integrated to obtain the modulation function matrix and to complete a transformation [7].
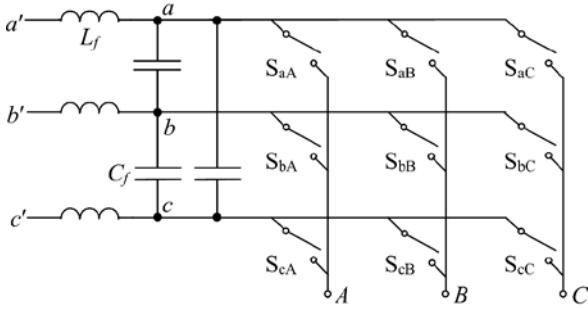
(a) Topology of three-phase to three-phase MC.
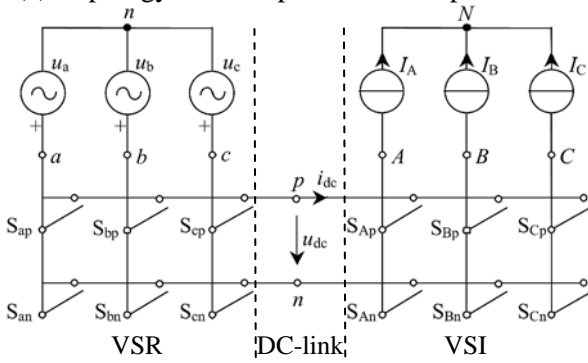
(b) Equivalent circuit of MC.
Fig.1 Topologies of MC and its equivalent circuit.

2.2 SVM of VSR
Considering that the VSR need to meet the requirements of short circuit avoidance between any two phases, and output current cannot be disconnected at the same time. There are 9 different combination switch states as shown in Table 1.

Table 1 Current space vector

Vector	S_{ap}	S_{an}	S_{bp}	S_{bn}	S_{cp}	S_{cn}
$\vec{I_1}$	1	0	0	1	0	0
$\vec{I_2}$	1	0	0	0	0	1
$\vec{I_3}$	0	0	1	0	0	1
$\vec{I_4}$	0	1	1	0	0	0
$\vec{I_5}$	0	1	0	0	1	0
$\vec{I_6}$	0	0	0	1	1	0
$\vec{I_7}$	1	1	0	0	0	0
$\vec{I_8}$	0	0	1	1	0	0
$\vec{I_9}$	0	0	0	0	1	1

In the above table, $\vec{I_1} \sim \vec{I_6}$ are effective vectors while $\vec{I_7} \sim \vec{I_9}$ are zero vectors. These 6 effective vectors divide coordinate plane into 6 equal sectors. The three-phase instantaneous input current can be mapped to rotating reference vector by Park transformation, while rotating space vector can be synthesized from pulse width modulation of static current vectors. That is, when the desired target vector is located in a certain sector, the rotating space vector can be synthesized from two static vectors and one zero vector which compose the sector triangle. In a single switching cycle, effective vectors operate for a period of time in accordance with the requirements of the reference current vector, and output line voltage. The rest of the time is allotted for zero vector duration, there is no voltage output and only provides free-wheeling load current [8].

The current space vectors of the rectifier are shown as in Fig.2. Static current space vectors are corresponding to Table 1. $\vec{I_i}$ is the target current space vector and θ_i is the sector angle of $\vec{I_i}$.
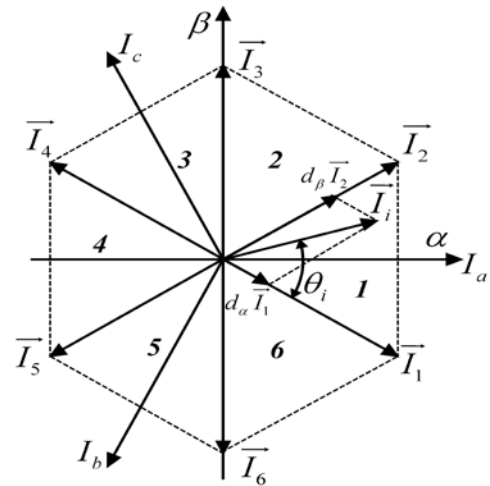

Fig.2 Synthesis of input current vector.

Assume that the target current space vector $\vec{I_i}$ falls into sector 1. It can be synthesized by $\vec{I_1}$, $\vec{I_6}$ and one zero vector according to current-second balance principle. The switching-on time represented by duty cycle of the selected vectors can be obtained as follows.

$$\begin{cases} d_\alpha = m_i \sin(60^\circ - \theta_i) \\ d_\beta = m_i \sin \theta_i \\ d_{0i} = 1 - d_\alpha - d_\beta \end{cases} \quad (1)$$

Where m_i is the modulation factor of VSR.

2.3 SVM of VSI
As for VSI, considering the output current of each phase must not be disconnected and the DC-link

must not be short-circuited, six switches can generate eight kinds of possible combinations including six effective space vectors and two zero vectors as shown in Table 2.

Table 2 Voltage space vector

Vector	S_{Ap}	S_{An}	S_{Bp}	S_{Bn}	S_{Cp}	S_{Cn}
$\vec{U_1}$	1	0	0	1	0	1
$\vec{U_2}$	1	0	1	0	0	1
$\vec{U_3}$	0	1	1	0	0	1
$\vec{U_4}$	0	1	1	0	1	0
$\vec{U_5}$	0	1	0	1	1	0
$\vec{U_6}$	1	0	0	1	1	0
$\vec{U_7}$	1	0	1	0	1	0
$\vec{U_8}$	0	1	0	1	0	1

The modulation of VSR and VSI are very similar, as shown in figure 3. $\vec{U_o}$ is the target voltage space vector and θ_u is the sector angle of $\vec{U_o}$.
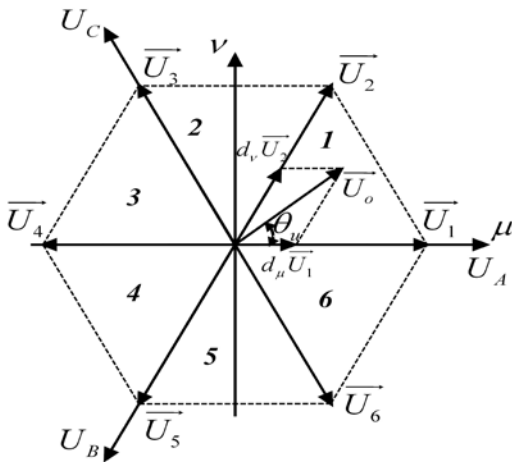

Fig.3 Synthesis of output voltage vector.

Assume that the target vector also falls into sector 1. When synthesizing the rotating voltage space vector from static vectors, there is:

$$\begin{cases} d_\mu = m_u \sin(60° - \theta_u) \\ d_\nu = m_u \sin \theta_u \\ d_{0u} = 1 - d_\mu - d_\nu \end{cases} \quad (2)$$

Where m_u is the modulation factor of VSI.

2.4 Synthesis of SVM for MC
The SVM of MC can be synthesized by the above two types of space vector modulation. For matrix converter, one switch is responsible for not only rectification but also inversion. In each PWM cycle,

it carries out both the output line voltage space vector modulation and the input current space vector modulation [9]. The switch state of VSR and VSI can be equalized to 9 switch states of Matrix Converter. Since the input phase current and output line voltage has six non-zero space vectors respectively, there are 36 kinds of combinations, each corresponding to one combination of the 9 switches, as table 3 shows it.

Table 3 Correspondence of switch combination

	$\vec{I_1}$	$\vec{I_2}$	$\vec{I_3}$	$\vec{I_4}$	$\vec{I_5}$	$\vec{I_6}$
$\vec{U_1}$	abb	acc	bcc	baa	caa	cbb
$\vec{U_2}$	aab	aac	bbc	bba	cca	ccb
$\vec{U_3}$	bab	cac	cbc	aba	aca	bcb
$\vec{U_4}$	baa	caa	cbb	abb	acc	bcc
$\vec{U_5}$	bba	cca	ccb	aab	aac	bcc
$\vec{U_6}$	aba	aca	bcb	bab	cac	cbc

In the above table, 3 lowercase letters indicate input connection with output in A, B, C phase order. Still, assume that both $\vec{I_i}$ and $\vec{U_o}$ fall into sector 1 respectively. There are five kinds of combination and one PWM cycle corresponds to five duty cycles of voltages and currents. Each duty cycle corresponds to one certain switch combination of matrix converter.

$$\begin{cases} \vec{I_1} - \vec{U_1}: & d_1 = d_\alpha \cdot d_\mu = m \sin(60° - \theta_i)\sin(60° - \theta_u) \\ \vec{I_1} - \vec{U_2}: & d_2 = d_\alpha \cdot d_\nu = m \sin(60° - \theta_i)\sin \theta_u \\ \vec{I_2} - \vec{U_1}: & d_3 = d_\beta \cdot d_\mu = m \sin \theta_i \sin(60° - \theta_u) \quad (3) \\ \vec{I_2} - \vec{U_2}: & d_4 = d_\beta \cdot d_\nu = m \sin \theta_i \sin \theta_u \\ \vec{I_0} - \vec{U_0}: & d_0 = 1 - d_1 - d_2 - d_3 - d_4 \end{cases}$$

So the corresponding switching-on time can be generalized as:

$$T_i = d_i T_S \quad (i = 0,1,2,3,4) \quad (4)$$

Where T_S is a switching period and $T_0 \sim T_4$ are time of switching on of 5 kinds of switch combinations respectively.

3 Modeling for MC System
3.1 Selection of Simulation Tools
Matrix Converter simulation requires a large number of power devices and many real-time computations of complex control strategy. In this paper, Matlab/Simulink is adopted to implement the models, which is very powerful for matrix and vector operations and is flexible and convenient in

programming. Simulink function blocks, embedded M-file as well as S-function can all be used in modelling. M-file and Simulink function block are often used in building simple models. For complex algorithm S-function is preferred as it runs 10 times faster or more than those implemented by Simulink function blocks [10].

The matrix converter is a hybrid system because the modulator is a digital discrete component while the grid, input filter, and load are continuous components. Hence discrete modulator should be built as a subsystem that is triggered in switching frequency. When discussing the performance of MC, the impact of discrete components like zero-order-holder and one-sample-delay which result from digital implementation of the modulation can't be ignored. Because it will leads to difference while study MC characteristics like stability [11-12]. Simulation step is another important setting that will affect the simulation results and should be chosen carefully in purpose of accuracy and speedy.

3.2 Time Calculation Module

According to formula (22), sector angle of output voltage and input current vector are needed when compute the switching-on time of different switch combination.

The phase angle of output line voltage vector $\theta_u{}'$ can be calculated as follows.

$$\begin{cases} \theta_u' = \varpi_o t + \varphi_o \\ \varpi_o = 2\pi f_o \end{cases} \tag{5}$$

Where ω_0 is the output angular frequency and φ_o is the initial phase angle of output line voltage vector. If phase angle is divided by $\pi/3$ and rounded, the sector number can be obtained. Meanwhile, its remainder should be the sector angle. Embedded M-file can be used to carry out the computation as follows.

$$\begin{cases} N_u = \mathrm{mod}(fix(\dfrac{\theta_u'}{\pi/3}),6)+1; \\ \theta_u = \mathrm{mod}(\theta_u',\pi/3) \end{cases} \tag{6}$$

In above formula, both 'fix' and 'mod' are functions provided by matlab. The 'fix' function rounds the element towards zero and the 'mod' function produce remainder after division. Notice that the syntax rules of M-file should be respected when programming the formula. Also, the sector angle and the vector number of input current vector can be obtained in a similar way. After that, the switching-on time of different switch combination can be calculated according to formula (3) and (4).

3.3 Modulation Mode Module

Most of published papers related to matrix converter are based on nine-step modulation mode shown as in Fig.3 [13-14]. It is symmetrical sequences centered by a zero vector. There are 10 times of commutation and only one zero vector to act in a switching period.
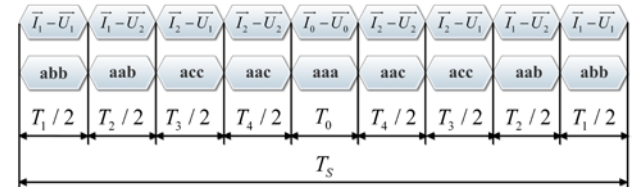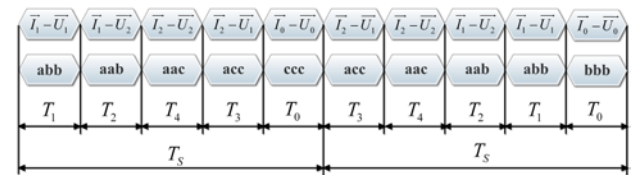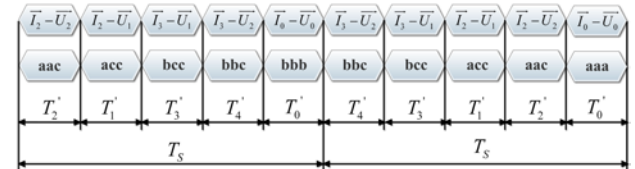

Fig.4 Common modulation mode for MC.

A novel modulation mode is adopted as is represented in Fig.5. When the sum of input and output sector numbers is even, the switch order is $T_1 \to T_2 \to T_4 \to T_3 \to T_0$. When the sum of input and output sector numbers is odd, the switch order is $T_2' \to T_1' \to T_3' \to T_4' \to T_0'$, as indicated by the arrow in table 3. Zero vector of the last step is selected according to the principle of minimum commutation. They are asymmetrical sequences and there are only 4 times of commutation in a switching period. There are two zero vectors act on for equal time respectively in a switching period, which is more reasonable than that of one zero vector for equal time. Besides, there are much fewer commutation times greatly reducing loss of switches. So, the modulation mode proposed here is obviously superior to the modulation mode which is often studied for MC.

(a) Modulation mode while the sum of sector numbers is even.

(b) Modulation mode while the sum of sector numbers is odd.
Fig.5 Novel modulation mode for MC.

Modulation mode is realized by S function. Different switch combinations are defined at first, and then look up table for switch combination according to each vector combination.

4 Simulation

Simulation study is carried out under the symmetrical three phase power supply and load condition. Followings are the parameters employed in simulations.

Table 4 Parameters Categories

Parameters	Value
Grid phase voltage(RMS)	220 V
Grid frequency	50 Hz
Input filter inductance	0.8mH
Input filter capacitance	20uF
Output frequency	100 Hz
Switching frequency	10kHz
Modulation factor	0.6
Resistance of load	3.5Ω
Inductance of load	10mH

The simulation results of output voltage, output current and input current waveforms are obtained as well as respective spectrum analysis. As are presented in Fig.6~Fig.11. According to the waveforms and their spectrum analysis, it can be seen clearly that the input and output current waveform are satisfying sinusoidal waveforms. And the output line voltage is fair to good quality of sinusoidal PWM wave despite that the THD is a little bit high.
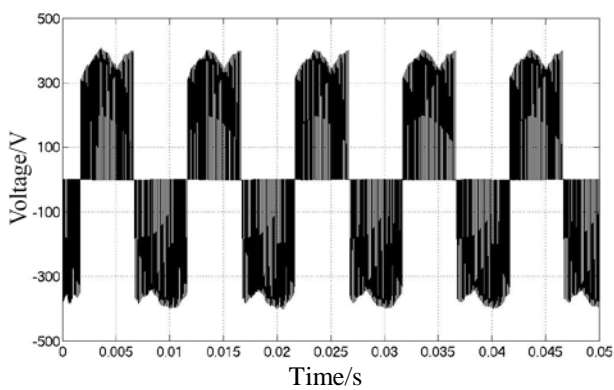

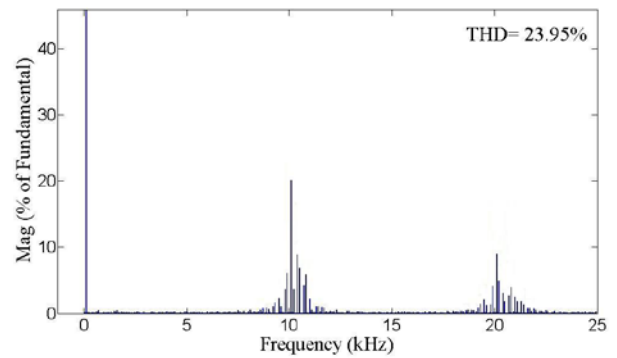Fig.6 Output line voltage of MC

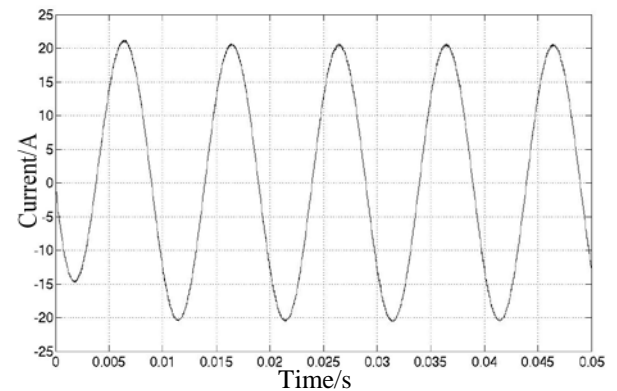Fig.7 Spectrum analysis of output line voltage
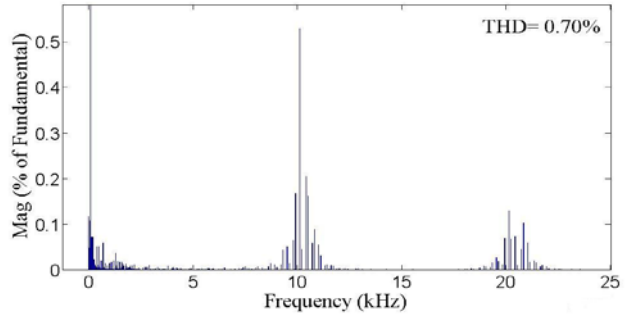

Fig.8 Output current of MC

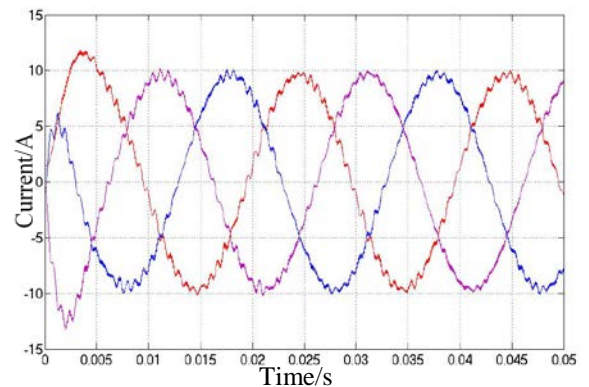Fig.9 Spectrum analysis of output current

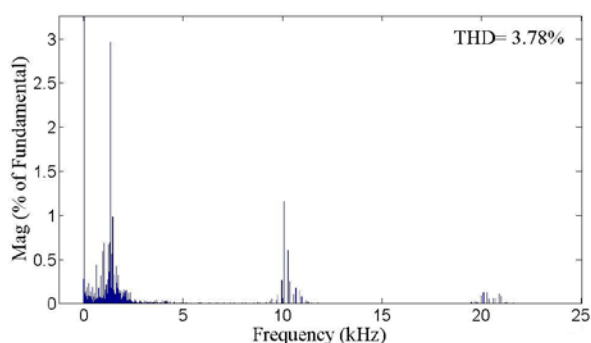
Fig.10 Input current drawn from grid

Fig.11 Spectrum analysis of input current

5 Conclusions

This paper introduces dual space vector modulation strategy for matrix converter and explains how the simulation models are built up. A novel optimized modulation mode is proposed which is superior to the commonly used one. Finally, simulation waveforms are presented which demonstrate the feasibility and validity of the proposed modulation mode. And the method can be directly implemented to practical MC system. It lay strong basis for its further researches and approaching to applications and is very helpful to the realization of MC.

Acknowledgement

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