THE DEVELOPMENT OF DIRECT SPACE VECTOR MODULATION METHOD FOR MATRIX CONVERTER

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ABSTRACT

Matrix converter has emerged as a best substitution of the conventional converters due to the capability of power regeneration, the sinusoidal input and output waveforms, and no need for energy storage. This paper describes direct space vector modulation method using in matrix converter, and then, the modified direct space vector modulation method without using zero-space vector is proposed to reduce the common-mode voltage which currently exists in the entire modern converters. The simulation and experimental results on three-phase inductive load are carried out to validate the theoretical analysis.

Keywords - Matrix converter (MC), direct space vector modulation (DSVM)

1 INTRODUCTION

In two recent decades, as the need to increase the quality and the efficiency of the power supply and the power usage, three phase matrix converter becomes a modern energy converter and has emerged as one of the best energy conversion substitution which fulfils all the requirements of the conventionally used rectifier/ dc link/ inverter structures. Some advantages of the matrix converter can be seen as follows: the use of a compact voltage source, providing sinusoidal voltage with variable amplitude and frequency beside the adjustable input power factor from power supply side. As shown in Fig. 1, matrix converter has the simple topology and allows a compact design due to the lack of dc-link capacitor for energy storage. The common-mode voltage produced by modern converters has been reported as a main source of early motor winding failure and bearing deterioration. The most common cause of this bearing damage is caused by the motor shaft voltages and the associated bearing currents resulted from dielectric breakdown and bearing lubricant. Since, there exists the leakage

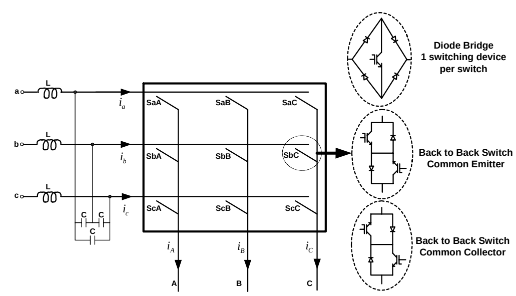

Fig. 1 The structure of ac-ac matrix converter

-current flow through parasitic capacitor between the stator core and stator winding, the life time of winding insulation is reduced and then, the motor insulation is easily broken beside the EMI is generated. As a result, it is very important to reduce common-voltage itself or to limit this voltage within certain bounds.

Due to the advantages of three-phase to three-phase matrix converter, several methods have been proposed to reduce the common-mode based on analyzing the indirect space vector modulation (ISV-PWM) rectifier-inverter system in [3], [5], [7]. However, this paper proposes a new modulation strategy which can restrict valuably to 42% the peak value of common-mode voltage beside lower high harmonic component compared to the conventional SVM method. This SVM technique is based on using a couple of active space vector instead of zero space vectors to complete the rest of sampling period.

2. MATRIX CONVERTER THEORY

Three-phase matrix converter module includes nine bidirectional switches and the structure of three-phase ac-ac matrix converter is shown in Fig. 1. The voltages and current at the input side of matrix converter are denoted by a, b, c while the output sides are denoted by A, B, C. There are 27 switching configuration states, which means 27 possible space vectors can be used to control IM and can be split respectively into 3 groups as shown in Table I. However, group III is not useful, only 18 non-zero space vectors in group I (±1, ±2,…, ±9) and 3 zero space vectors in group II (0_a, 0_b, 0_c) can be usually employed in the current control techniques for matrix converter such as space vector modulation, DTC methods in [1], [2], [4], [6],[8].

The three-phase matrix converter is supplied by sinusoidal voltage source

$$\begin{aligned} v_a &= V_m \cos(\omega_i t) \\ v_b &= V_m \cos(\omega_i t - 2\pi/3), \\ v_c &= V_m \cos(\omega_i t - 4\pi/3) \end{aligned} \tag{1}$$

Hence, for the space-vector modulation of matrix converter, the input and output phase space-vector voltages of matrix converter can be expressed in terms as

$$\vec{v_i} = \frac{2}{3}\left(v_a + v_b e^{j\frac{2\pi}{3}} + v_c e^{j\frac{4\pi}{3}}\right) = V_i e^{j\alpha_i} \tag{2}$$

$$\vec{v_o} = \frac{2}{3}\left(v_A + v_B e^{j\frac{2\pi}{3}} + v_C e^{j\frac{4\pi}{3}}\right) = V_o e^{j\alpha_o} \tag{3}$$

In the same way, the input and output phase space-vector currents result as follows

Table I Possible switching configurations

Group	Switching Configuration list	Switches on	V_0	α_0	I_i	β_i
I	+1	SaA SbB SbC	$2/3v_{ab}$	0	$2/\sqrt{3}i_A$	$-\pi/6$
	-1	SbA SaB SaC	$-2/3v_{ab}$	0	$-2/\sqrt{3}i_A$	$-\pi/6$
	+2	SbA ScB ScC	$2/3v_{bc}$	0	$2/\sqrt{3}i_A$	$\pi/2$
	-2	ScA SbB SbC	$-2/3v_{bc}$	0	$-2/\sqrt{3}i_A$	$\pi/2$
	+3	ScA SaB SaC	$2/3v_{ca}$	0	$2/\sqrt{3}i_A$	$7\pi/6$
	-3	SaA ScB ScC	$-2/3v_{ca}$	0	$-2/\sqrt{3}i_A$	$7\pi/6$
	+4	SbA SaB SbC	$2/3\ v_{ab}$	$2\pi/3$	$2/\sqrt{3}i_B$	$-\pi/6$
	-4	SaA SbB SaC	$-2/3v_{ab}$	$\pi/3$	$-2/\sqrt{3}i_B$	$-\pi/6$
	+5	ScA SbB ScC	$2/3v_{bc}$	$\pi/3$	$2/\sqrt{3}i_B$	$\pi/2$
	-5	SbA ScB SbC	$-2/3v_{bc}$	$2\pi/3$	$-2/\sqrt{3}i_B$	$\pi/2$
	+6	SaA ScB SaC	$2/3v_{ca}$	$2\pi/3$	$2/\sqrt{3}i_B$	$7\pi/6$
	-6	ScA SaB ScC	$-2/3v_{ca}$	$2\pi/3$	$-2/\sqrt{3}i_B$	$7\pi/6$
	+7	SbA SbB SaC	$2/3v_{ab}$	$4\pi/3$	$2/\sqrt{3}i_C$	$-\pi/6$
	-7	SaA SaB SbC	$-2/3v_{ab}$	$4\pi/3$	$-2/\sqrt{3}i_C$	$-\pi/6$
	+8	ScA ScB SbB	$2/3v_{bc}$	$4\pi/3$	$2/\sqrt{3}i_C$	$\pi/2$
	-8	SbA SbB ScC	$-2/3v_{bc}$	$4\pi/3$	$-2/\sqrt{3}i_C$	$\pi/2$
	+9	SaA SaB ScC	$2/3v_{ca}$	$4\pi/3$	$2/\sqrt{3}i_C$	$7\pi/6$
	-9	ScA ScB SaC	$-2/3v_{ca}$	$4\pi/3$	$-2/\sqrt{3}i_C$	$7\pi/6$
II	0_a	SaA SaB SaC	0	-	0	-
	0_b	SbA SbB SbC	0	-	0	-
	0_c	ScA ScB ScC	0	-	0	-
III	x	SaA SbB ScC	x	x	x	x
	x	SaA ScB SbC	x	x	x	x
	x	SbA ScB SaC	x	x	x	x
	x	SbA SaB ScC	x	x	x	x
	x	ScA SaB SbC	x	x	x	x
	x	ScA SbB SaC	x	x	x	x

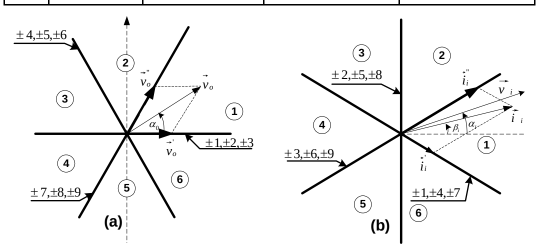

Fig. 2 (a) The output line-to-neutral voltage vector and (b) the input line current vector.

$$\vec{i_i} = \frac{2}{3}\left(i_a + i_b e^{j\frac{2\pi}{3}} + i_c e^{j\frac{4\pi}{3}}\right) = I_i e^{j\beta_i} \tag{4}$$

$$\vec{i_o} = \frac{2}{3}\left(i_A + i_B e^{j\frac{2\pi}{3}} + i_C e^{j\frac{4\pi}{3}}\right) = I_o e^{j\beta_o} \tag{5}$$

3. COMMON MODE VOLTAGE ANALYSIS

Fig. 3 shows a matrix converter connected to an induction motor. It is common to connect the induction motor to neutral of the secondary side of the input transformer and motor frame to the same ground. The common-mode voltage v_{sg} can be expressed as follows

$$\begin{aligned} v_A - v_{sg} &= Ri_A + L\frac{di_A}{dt} \\ v_B - v_{sg} &= Ri_B + L\frac{di_B}{dt}, \\ v_C - v_{sg} &= Ri_C + L\frac{di_C}{dt} \end{aligned} \quad (6)$$

Assuming that the induction motor has the symmetric equivalent resistance and inductance per phase. As a result, $i_A+i_B+i_C=0$ and the leakage current is zero, the common mode voltage becomes

$$v_{sg} = \frac{v_A + v_B + v_C}{3} \quad (7)$$

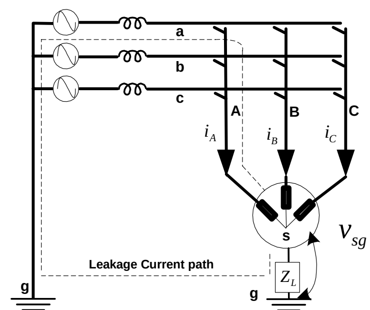

Fig. 3 Path of motor leakage current

Regardless of the ac source, as can be easily seen that the common mode voltage only depends on the switching state of matrix converter. From Table I, the possible common mode voltage is given as follows

$$v_{sg} = \begin{cases} \frac{1}{3} v_{phase-to-phase} & , GroupI \\ v_{phase} & , GroupII \\ 0 & , GroupIII\ (not\ used) \end{cases} \quad (8)$$

4. DIRECT SVM METHOD ANALYSIS

4.1 Conventional direct SVM method

In the conventional SVM algorithm for matrix converter, beside the inherent capability to achieve full control of output voltage vector, to obtain the unity input power factor, the direction of the input current space vector $\vec{i_i}$ must be the same of the input voltage space vector $\vec{v_i}$. The voltage sectors and current sectors are defined as in Fig. 2. In order to explain the modulation, reference will be made in Fig.2 (a).and (b), where the output voltage vector $\vec{v_o}$ and the input current vector $\vec{i_i}$ are assumed to be both lying in sector 1 ($-\pi/6 \le \alpha_i \le \pi/6$ and $0 \le \alpha_o \le \pi/3$) without missing the generality of the analysis. As can be seen, the output voltage vector $\vec{v_o}$ can be combined from two vectors $\vec{v_o}'$ and $\vec{v_o}''$. To get the vector direction as $\vec{v_o}''$, among the six possible switching configurations (±7, ±8, ±9) which have the output voltage vector in the same direction of $\vec{v_o}''$, only two higher voltage values and corresponding to vectors, -7 and +9 are selected to drive the matrix converter. By the similar analysis, the switching configurations used to obtain $\vec{v_o}'$ are -3, +1 and zero switching configuration is used to complete the rest of the cycle period. The entire SVM table is shown in Table II in which the duty cycle for each chosen vectors are computed as follows

$$\delta_1 = \frac{2}{\sqrt{3}} q \sin\left[\alpha_o - (k_v - 1)\frac{\pi}{3}\right] \sin\left[\frac{\pi}{6} - \left(\alpha_i - (k_i - 1)\frac{\pi}{3}\right)\right] \quad (9)$$

$$\delta_2 = \frac{2}{\sqrt{3}} q \sin\left[\alpha_o - (k_v - 1)\frac{\pi}{3}\right] \sin\left[\frac{\pi}{6} + \left(\alpha_i - (k_i - 1)\frac{\pi}{3}\right)\right] \quad (10)$$

$$\delta_3 = \frac{2}{\sqrt{3}} q \sin\left[k_v \frac{\pi}{3} - \alpha_o\right] \sin\left[\frac{\pi}{6} - \left(\alpha_i - (k_i - 1)\frac{\pi}{3}\right)\right] \quad (11)$$

$$\delta_4 = \frac{2}{\sqrt{3}} q \sin\left[k_v \frac{\pi}{3} - \alpha_o\right] \sin\left[\frac{\pi}{6} + \left(\alpha_i - (k_i - 1)\frac{\pi}{3}\right)\right] \quad (12)$$

The zero configurations are applied to complete the sampling period with the following duty cycle:

$$\delta_5 = 1 - \frac{2}{\sqrt{3}} q \cos\left[\alpha_o - (2k_v - 1)\frac{\pi}{6}\right] \cos\left[\alpha_i - (k_i - 1)\frac{\pi}{3}\right] \quad (13)$$

where $q=V_o/V_i$ is voltage transfer ratio, k_v and k_i are respectively the voltage sector and the current sector which voltage vector and current vector are currently located.

From equation (13), the interval time must be not negative to exist the zero space vector

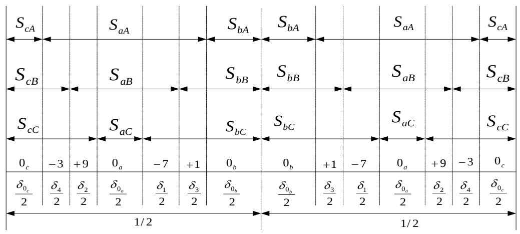

Fig. 4 Double side switching pattern in a sampling period, T_s

$$q \le \frac{\sqrt{3}}{2}\frac{1}{\cos\left[\alpha_o-(2k_v-1)\frac{\pi}{6}\right]\cos\left[\alpha_i-(k_i-1)\frac{\pi}{3}\right]} \quad (14)$$

Hence, assuming the unity input power factor, equation (14) gives the well-known maximum voltage transfer ratio of matrix converter to be $\sqrt{3}/2$.

According to the current SVM techniques, there are two particular cases of SVM techniques. The fist one, called symmetrical SVM (SSVM), utilizes all the three zero configurations in each cycle period with equal duty cycles. With reference to the particular case of the output voltage vector lying in sector 1 and input current in sector 1, the switching configurations selected are, in general, 0_a, 0_b, 0_c,-7, +9, +1, -3 as shown in Fig. 4. The use of three zero configurations leads to 12 switching commutations in each cycle period. The second case, called asymmetrical SVM (ASVM), utilizes only one of the three zero configurations, that is the configuration located in the middle of each half of the switching pattern as shown in Fig. 4 and only one zero configuration 0_a is used. In this case, the switches of one column of the matrix converter do not change their state, and the number of commutations in each cycle is reduced to 8.

4.2 Proposed SVM strategy

In order to explain about the proposed SVM technique, the switching configurations of matrix converter used in SVM techniques is assumed that the current and the voltage of matrix converter are entirely constant within one sampling period, T_s. As can be easily seen in Table I that the couple of switching configurations (±1, ±2 ,. . ., ±8, ±9) has the same characteristics: the output space voltage vector and the input space current vector have

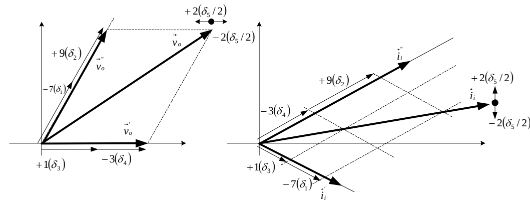

Fig. 5 Output voltage vector and input current vector principle

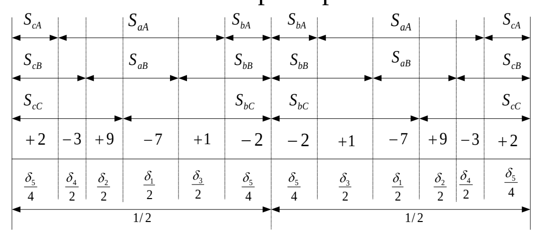

Fig. 6 Double side switching pattern with the proposed SVM technique in a sampling period

- the same magnitude but opposite in direction. As a result, if two opposite space vectors are used with the same interval time to contribute to the reference vector, they will not change the direction of the configurations to complete the cycle period, T_s, with the fixed output reference voltage vector and also the input reference current vector. Therefore, instead of using the zero cycle δ_5 , a couple of the opposite switching configuration is used with the same duty cycle $\delta_5/2$. However, with the proposed SVM method, the couple of selected vector should have the smallest magnitude between 18 vectors in group I.

For example, when the reference output voltage space vector $\vec{v}_o$ is in voltage switching hexagon sector 1 and the reference input current space vector $\vec{i}_i$ is in current switching hexagon sector 1 as previous assumption. Beside the four active switching configurations are chosen -7, +9, +1, -3 corresponding to duty cycle δ_1, δ_2, δ_3, δ_4 respectively. Among the six possible switching configurations which have the smallest space vector magnitude, ±2, ±5, ±8, the ones that optimize switching commutation must be selected. As a result, the most suitable couple of switching configuration is ±2, as shown in Fig. 5. It can be verified that there is only one switching configuration sequence characterized by only one switching commutation for each switching change that is the following sequences in a half side of

Table II Switching table for the half side of the proposed SVM method for MC

Cur. Sec.⇒	Sector 1 or Sector 4						Sector 2 or Sector 5						Sector 3 or Sector 6					
⇓ Vol. Sec.	$\delta_5/4$					$\delta_5/4$	$\delta_5/4$					$\delta_5/4$	$\delta_5/4$					$\delta_5/4$
Sector 1 or Sector 4	***+2***	-3	+9	-7	+1	***-2***	***+7***	-8	+2	-3	+9	***-7***	***+3***	-1	+7	-8	+2	***-3***
Sector 2 or Sector 5	***-5***	+4	-7	+9	-6	***+5***	***-7***	+9	-6	+5	-8	***+7***	***-6***	+5	-8	+7	-4	***+6***
Sector 3 or Sector 6	***+5***	-6	+3	-1	+4	***-5***	***+1***	-2	+5	-6	+3	***-1***	***+6***	-4	+1	-2	+5	***-6***
Sector 4 or Sector 1	***-8***	+7	-1	+3	-9	***+8***	***-1***	+3	-9	+8	-2	***+1***	***-9***	+8	-2	+1	-7	***+9***
Sector 5 or Sector 2	***+8***	-9	+6	-4	+7	***-8***	***+4***	-5	+8	-9	+6	***-4***	***+9***	-7	+4	-5	+8	***-9***
Sector 6 or Sector 3	***-2***	+1	-4	+6	-3	***+2***	***-7***	+6	-3	+2	-5	***+7***	***-3***	+2	-5	+4	-1	***+3***

-switching pattern, +2, -3, +9, -7, +1, -2 as shown in Fig. 6.

Finally, six switching configurations +2, -7, +9, +1, -3 and -2 are respectively used with the following duty cycles, $\delta_5/2$, δ_1, δ_2, δ_3, δ_4 and $\delta_5/2$ to get the reference voltage space vector and also keep the power factor to be unity at the input power supply.

To optimize the switching commutations, the compatible double side arrangement is also proposed. In this way, the extra active space vector is placed at two end side of sampling period and the position of the common active space vector is remained as conventional SVM. This leads the switching commutations to 10 during each sampling period.

Using the same procedure, it is possible to determine the two extra switching configurations related to any possible combination of output voltage and input current sectors, leading to the results summarized in Table II.

5. SIMULATION RESULTS

Some simulation results are carried out by Matlab/Simulink to validate the proposed space vector modulation. The system has been simulated with three-phase balanced R-L load (42Ω, 10mH) and the power source 380[V], 60Hz, the sampling frequency is 4KHz. Reference with the output voltage f_o=50 Hz q=0.841 in Fig. 7 and f_o=100 Hz q=0.45 in Fig 9. As can be easily seen that the peak value of v_{sg} in the conventional SVM is 311[V] corresponding to $V_{phase(peak)}$ while the peak value of v_{sg} in the proposed method is 179[V] corresponding to $V_{phase\text{-}tophase}/3$

The common-mode voltage v_{sg} decreases 42% regardless of transfer ratio modulation index, q and output frequency, f_o of the matrix converter in Fig. 8. Furthermore, in Fig. 7 and 9, the harmonic spectrum of v_{sg} shows that the proposed SVM method has the lower high harmonics components compared to the conventional SVM method.

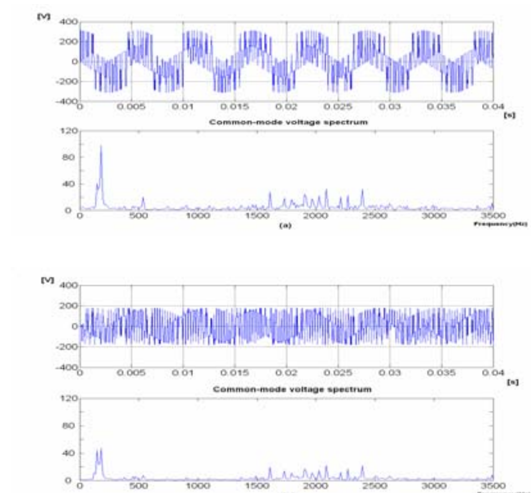

Fig. 7. Waveform and harmonic spectrum of v_{sg} with f_o=50[Hz] q=0.841 (a) Conventional SVM (b) Proposed SVM method.

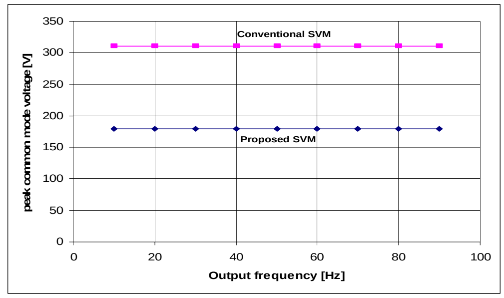

Fig.8. Peak value of v_{sg} comparison.

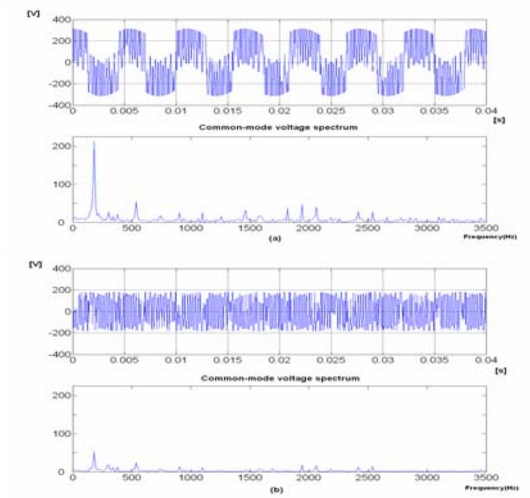

Fig. 9 Waveform and harmonic spectrum of v_{sg} with f_o=100 Hz q=0.45 (a) Conventional SVM (b) Proposed SVM method.

6. EXPERIMENTAL RESULTS

To validate the theoretical analysis and simulation, the experimental results are carried out on DSP board using TMS320C32. A FPGA board and a analog board to guarantee the safe current commutation, a Gate driver and 6-

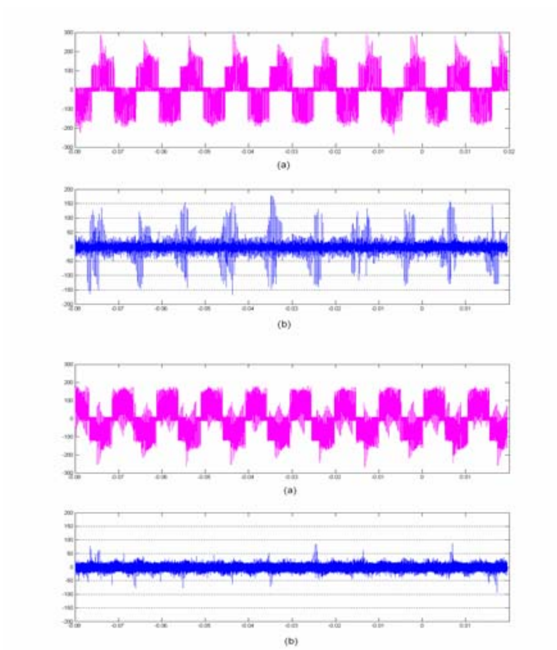

Fig. 10 (a) output line voltage and (b) common mode voltage $v_{sg,}$ with f_o=100 Hz q=0.45 of the conventional and the proposed SVM method respectively

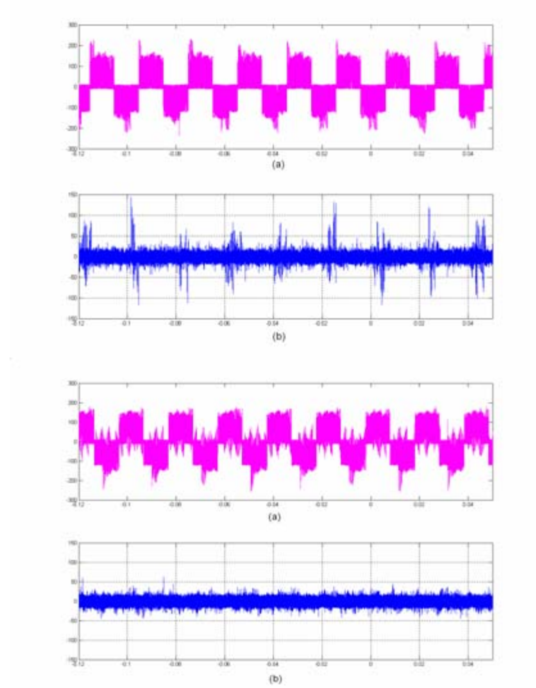

Fig. 11 (a) output line voltage and (b) common mode voltage $v_{sg,}$ with f_o=50 Hz q=0.84 of the conventional and the proposed SVM method respectively

-isolated power supplies board and a power board containing Eupec IGBT module (FM35R12KE3), voltage and current sensors and snubbers.

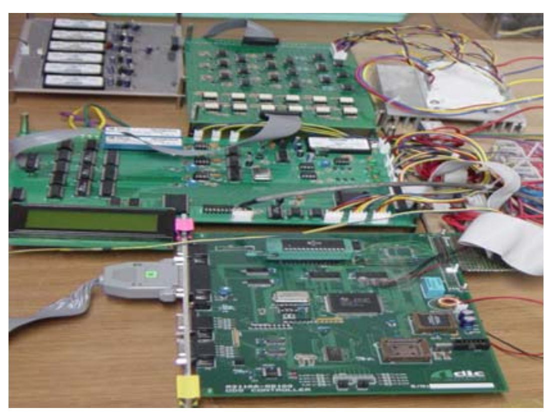

Fig. 12 The matrix converter experiment

The experimental results verify again the effectiveness of the proposed SVM method as compared to the conventional direct SVM method in reduction common mode voltage of matrix converter.

7. CONCLUSION

This paper has proposed a new SVM strategy which can restrict the peak value of common-mode voltage to 42% and lower high harmonic components compared to the conventional SVM method. It has been archived by replacing the zero space vectors by a couple of appropriate vectors and rearranging the suitable switching configurations in each sampling period. Thus, the voltage transfer ratio is unaffected by the proposed strategy. The simulation and experimental results have been carried out to validate the proposed method. With this proposed SVM method, only some extra C-code for software program is needed without any extra hardware.

8. ACKNOWLEDGMENT

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