A new PWM method for instantaneous output current control of matrix converters with sinusoidal input current

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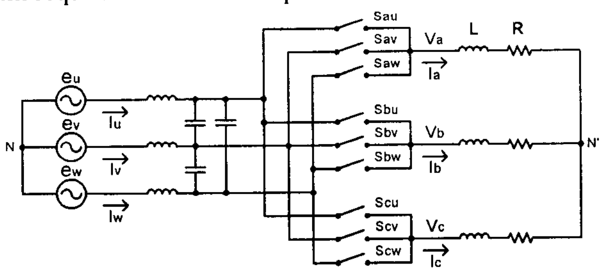
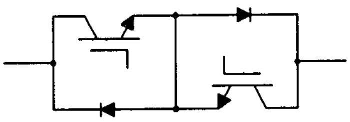
Abstract : *This paper presents a simple current control strategy for matrix converters based on the extension of PWM method for inverters. A novel and efficient PWM algorithm is developed. The algorithm is verified through simulation and experiments employing a 2-kVA prototype. The results of simulation and experiment prove the instantaneous control capability of the output current with the sinusoidal input current.*

I . INTRODUCTION

At present, a combination of a diode rectifier and a voltage-source inverter is widely used as a power converter for variable speed AC drives because of its low cost and simplicity. However, it has some problems such as the input current harmonics on the line side and necessity of bulky capacitors as DC link energy storage component. Recently, a PWM rectifier is increasingly used as the line side converter to overcome problems of the harmonics but it still requires the DC link capacitors.



(a) Main circuit



(b) Configuration of bi-directional switch

Fig. 1 Main circuit of matrix converter

As another type of power converters for AC drives, a matrix converter has been proposed [1]. The matrix converter is a three-phase AC–AC direct converter without any energy storage component in the converters. The typical circuit diagram of the matrix converter is illustrated in Fig. 1(a). S_{au}, S_{av}, • • •, S_{cw} are bi-directional switches. To realize each bi-directional switch, a pair of insulated gate bipolar transistors (IGBT) connected in anti-parallel are used as shown in Fig. 1(b). In the studies of the matrix converter so far, a few papers, the instantaneous control methods of the output current have been investigated. But they needed complicated computation for generation of the gate signals for nine bi-directional or eighteen unidirectional switches. Thus, it was difficult to realize the online instantaneous control of the output current even if a high-speed microprocessor was employed.

In this paper, we will discuss a new simple control method for the matrix converter that can realize the online instantaneous control of the output current. The proposed method of generating the switching pattern is regarded as an extension of the PWM pattern generation for the conventional voltage-source inverters. The hardware configuration to realize the proposed controller is simple comparatively. Therefore, the proposed control method can be effective for the realization of the practical matrix converters. The effectiveness of the proposed control method is confirmed by some results of the simulation and experimental investigations.

II . EXTENSION OF PWM STRATEGY FOR MATRIX CONVERTER

A. PRINCIPLE OF SWITCHING PATTERN GENERATION

A strategy to generate the switching pattern for the matrix converters was proposed in [2,3]. In this method, the commercial power source connected to the input side of the matrix converter was regarded as a voltage source. This method to generate the switching pattern was based on the PWM strategy for conventional voltage source inverters. The output terminal of the phase whose reference signal is the lowest is connected continuously to the phase of the supply whose voltage is the lowest. The other two phases are switched between the two phases of the supply whose voltage are the highest and the lowest by the PWM. In this method, two of the three phases of the supply are used. In other words, one of the input phases is left open. This condition is not desirable from the viewpoint of the input current waveform.

On the other hand, some consideration to introduce the use of the input phase whose voltage is middle (hereafter, middle voltage) are reported in [4,5]. The introduction of the middle voltage can reduce the sudden change in the input current. Thus, the input current waveform can be improved. But, these methods require the complex algorithm to generate the reference signal of the middle voltage. Therefore, it is difficult to control output current instantaneously. In this paper, a new simple method to generate the switching pattern using the middle voltage is proposed.

B. PROPOSED METHOD OF SWITCHING PATTERN GENERATION

In the proposed method, three-phase sinusoidal output voltage references V_a^*, V_b^*, and V_c^* are used to generate the switching pattern.

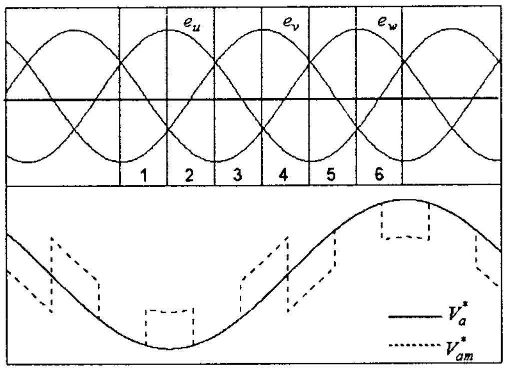


Fig. 2 Input phase voltage(Upper) and reference waveforms for output control(Lower)

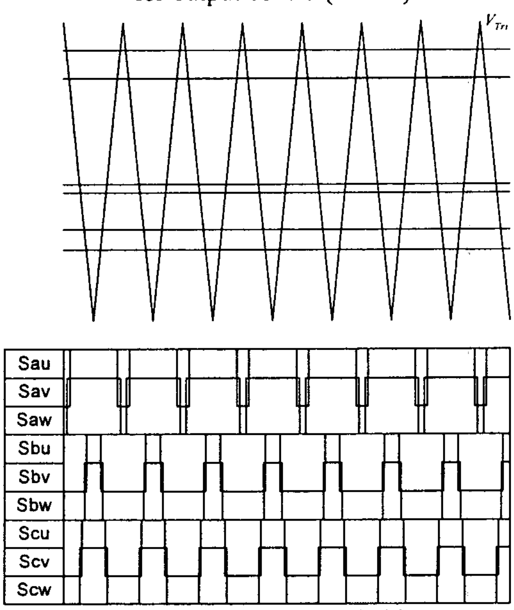


Fig. 3 Proposed method of switching pattern

Fig. 2 shows relationship between the input phase voltage waveforms (e_u , e_v , and e_w) and voltage references V_a^*, V_{am}^* which is used to control the output of phase-a. These two references are compared with a triangular signal. And then, three areas *X*, *Y* and *Z* are determined. These areas are defined by (1).

$$
\begin{aligned}
X &= (V_{tri} < V_a^*) \cap (V_{tri} < V_{am}^*) \\
Y &= \overline{(X \cup Z)} \qquad (1) \\
Z &= (V_{tri} > V_a^*) \cap (V_{tri} > V_{am}^*)
\end{aligned}
$$

In the area *X*, the output terminal of phase-a is connected to the input phase whose voltage is the maximum. And, it is connected to the middle voltage in the area *Y*. In area *Z*, base voltage (minimum voltage) is connected. Fig. 3 shows the resulting switching pattern for nine switches in the three phases.

As mentioned above, the introduction of the middle voltage can reduce the sudden change in the input current. Therefore, the input current can be improved. Fig. 4, 5 show the difference between two cases without and with using the middle voltage. We can see that the introduction of the middle voltage is effective in the reduction of the lower order harmonics in the input current. This proposed method is so simple that it can save the computation time. In addition, the proposed method can be adopted to the feedback control of the instantaneous output current. The implementation for the generation of the middle voltage references V_{am}^* , V_{bm}^* , and V_{cm}^* is discussed in next chapter.

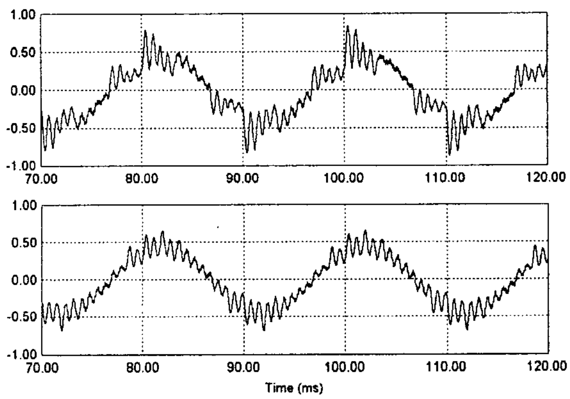


Fig. 4 Input current (Upper: without using middle voltage, Lower: with middle voltage)

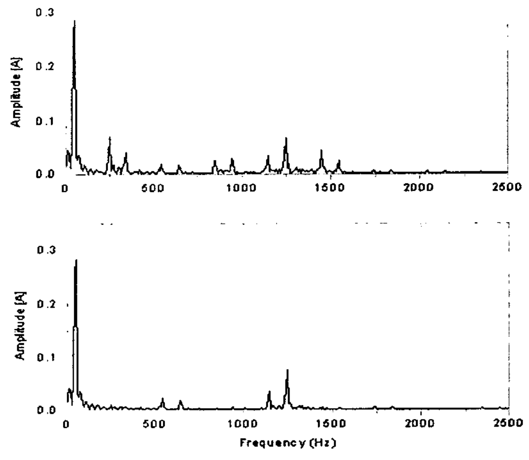


Fig. 5 Frequency components of input current (Upper: without using middle voltage,

Lower: with middle voltage)

Ⅲ. HARDWARE IMPLEMENTATION OF MATRIX CONVERTER

A. CURRENT CONTROLLER AND COMPUTATION OF MIDDLE VOLTAGE REFERNCE

Fig. 6 shows the configuration of the current controller. The detected signals of the output current I_a, I_b, and I_c are converted into a rotating d-q frame synchronized with the output frequency. A digital PI controller based on a DSP compensates for the error between the current reference and the actual value. Then, the output signals of the PI controller in the d-q coordinate are inversely converted into the three-phase voltage references V_a^*, V_b^*, and V_c^*. The middle voltage reference V_{am}^* for phase-a is obtained by equation (2). The references V_{bm}^*, and V_{cm}^* for phase-b and phase-c are obtained in the same way.

$$V_{am}^* = \begin{cases} V_a^* - K_m V_d^* & if(V_a^* > 0) \mathrm{I} (V_{mid} > 0) \\ V_a^* + K_m V_d^* & if(V_a^* < 0) \mathrm{I} (V_{mid} < 0) \\ V_a^* & others \end{cases} \qquad (2)$$

Where V_{mid} is,

$$V_{mid} = \begin{cases} e_u & if(e_v < e_u < e_w) and (e_v > e_u > e_w) \\ e_v & if(e_w < e_v < e_u) and (e_w > e_v > e_u) \\ e_w & if(e_u < e_w < e_v) and (e_u > e_w > e_v) \end{cases}$$

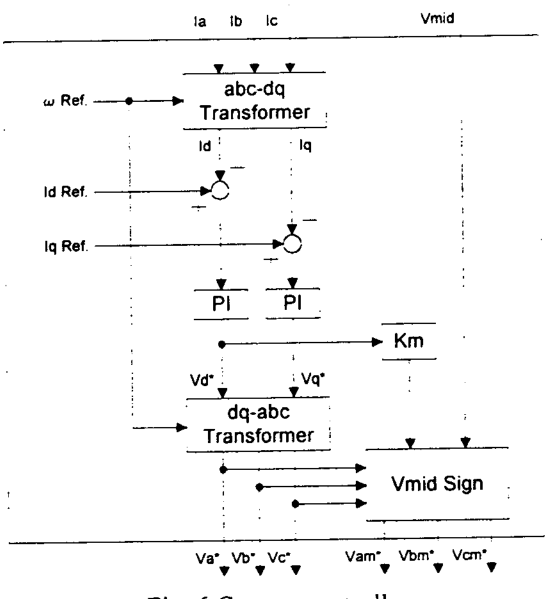
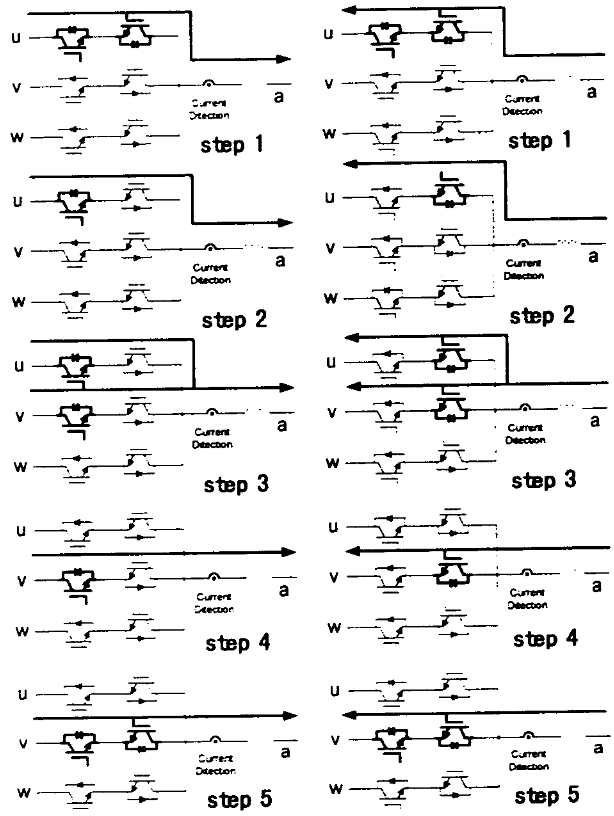


Fig. 6 Current controller

B. COMMUTATION STRATEGY

In the matrix converters, a special consideration is required for the operation during the commutation from one switch to another. Since the commercial power supply can be approximately regarded as a voltage source, the input phases of the matrix converter must never be short-circuited. On the other hand, due to the inductive nature of the load such as AC motors, the output phases must not be interrupted suddenly. To avoid short-circuit in the input side, a delay time is required practically in every commutation. But, this delay time makes a sudden interruption of the output current, so that a high spike voltage occurs due to the load inductance. As solutions to these problems, a few investigations of several approaches have been reported.[6,7] Typical efficient methods are a diode voltage clamping circuit and a step commutation strategy.



(a) Positive output current (b) Negative output current

Fig. 7 Step commutation strategy

The diode clamping circuit usually has a circuit configuration of a three-phase capacitor input diode bridge. In every commutation, a delay time is inserted. This causes the sudden interruption of the output current resulting in high spike voltage. The spike voltage is absorbed by the capacitor through the diode bridge connected to the output terminal of the matrix converter.

On the other hand, the delay time to avoid the short-circuit of the input lines are not inserted in the step commutation sequence. During the commutation periods, the turn on signals are applied to one of the IGBT's of each bi-directional switch according to the direction of the output current. In this case, the short circuit of the input lines does not occur essentially. Thus, the delay time is not required. Accordingly, the method to reduce spike voltage is not necessary because there is no possibility of sudden open-circuit of the output lines. Fig. 7 shows an example of the current commutation sequence. In the prototype, a programmable logic device is used for the implementation of step commutation strategy.

Fig. 8 shows the hardware configuration of matrix converter introduced in this paper.

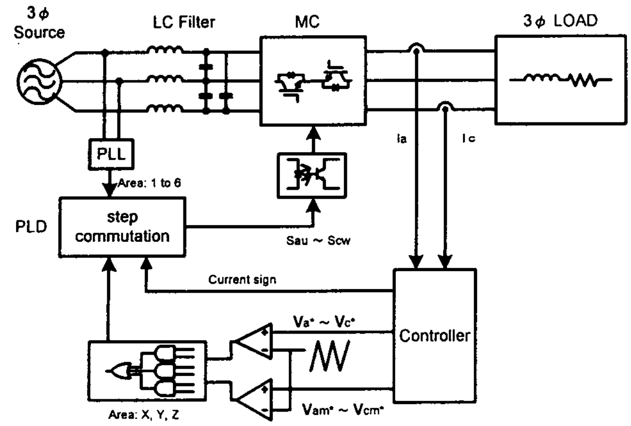


Fig. 8 The complete hardware diagram of experimental matrix converter

Ⅳ. SIMULATION

The effectiveness of the proposed switching pattern is inspected by simulation. The output line-to-line voltage, output current and input current in the steady state are shown in Fig. 9. The frequency of the output current is 30[Hz]. The parameters used in this simulation are listed in Table.1. The parameter to determine the middle voltage output ratio *Km* is 0.5, the PWM carrier frequency is 3[kHz]. The input currents have some harmonics near the resonant frequency of the LC filter, but it is verified that input and output currents become almost sinusoidal. The frequency components of the output and input currents are shown in Fig. 10.

Table. 1 Parameters

Source	$V_{Line\_to\_Line}$	100V
	f_{source}	50Hz
Input LC filter	L_{filter}	1mH
	C	4.8μF
Load	L_{Load}	5mH
	R_{Load}	5 Ω

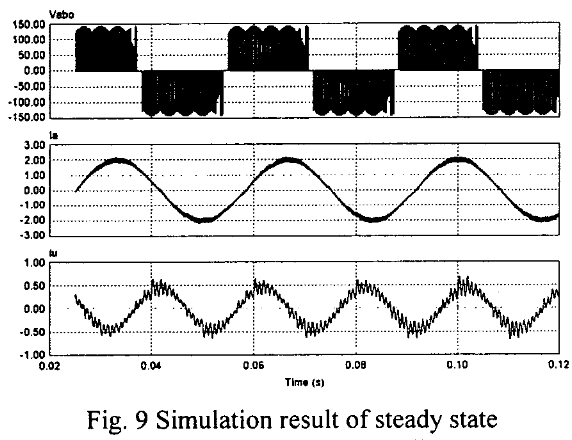


Fig. 9 Simulation result of steady state (Upper: output line-to-line voltage, Middle: output current, Lower: input current)

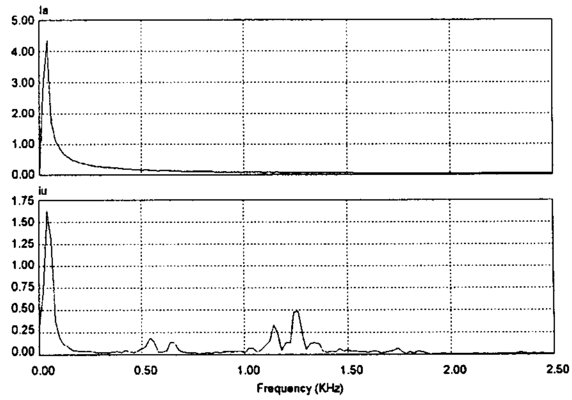


Fig. 10 Frequency components of current (Upper: output current, Lower: input current)

Next, the transient response is investigated. Fig. 11 shows the transient response of the currents when the amplitude of the output current reference changes from 2[A] to 3.8[A]. Fig. 12 shows the transient current waveforms when the frequency reference changes from 30[Hz] to 100[Hz]. It is verified that the output currents can be controlled instantaneously according to the change in the reference signal.

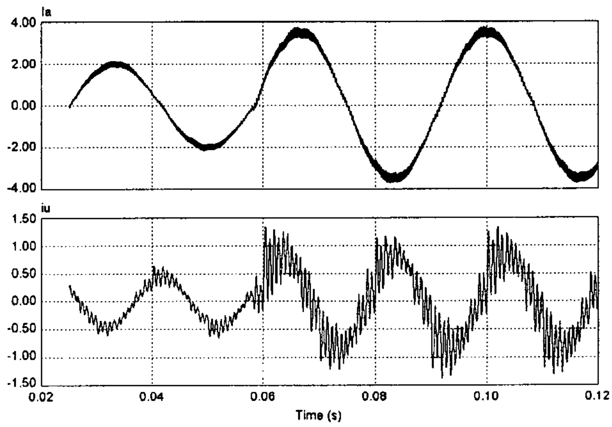


Fig. 11 Simulated current waveforms at sudden change in amplitude of output current reference (Upper: output current, Lower: input current)

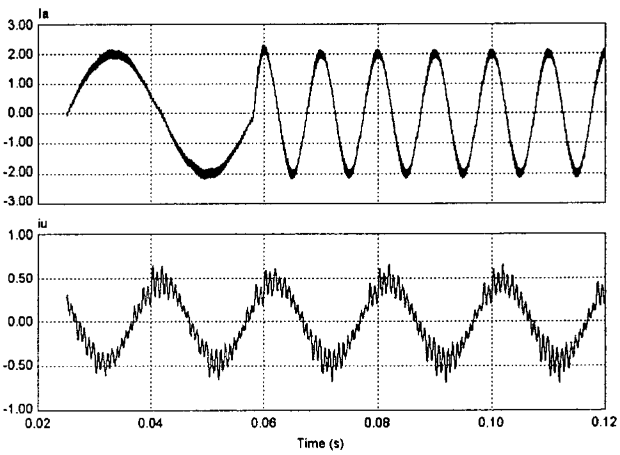


Fig. 12 Simulated current waveforms at sudden change in output frequency reference (Upper: output current, Lower: input current)

V. EXPERIMENTAL RESULTS

To confirm the effectiveness of the proposed control method, the experimental investigation has been made employing a prototype 2kVA matrix converter with RL load. The circuit and control parameters in the experiments are same as those in the simulation circuit.

Fig. 13 shows the experimental waveforms of the prototype matrix converter in the steady state. Both the output current and input current are almost sinusoidal. Fig. 14 and 15 shows the experimental current waveforms at the transient condition. In these experiments, the amplitude reference of the output current is changed from 2[A] to 4[A], and the reference value of the output frequency is suddenly changed from 30[Hz] to 100[Hz], respectively. We can see that the instantaneous output current control can be realized by the proposed control method.

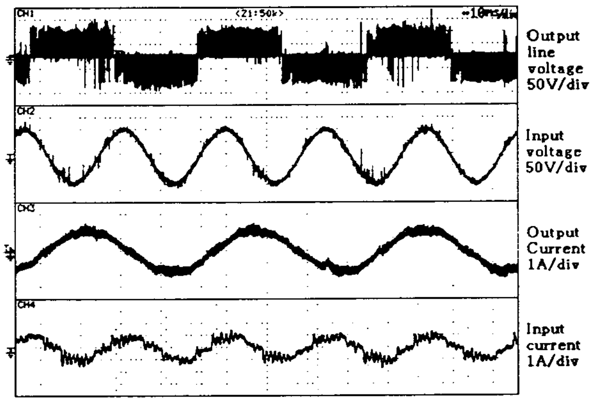


Fig. 13 Experimental waveforms in steady state

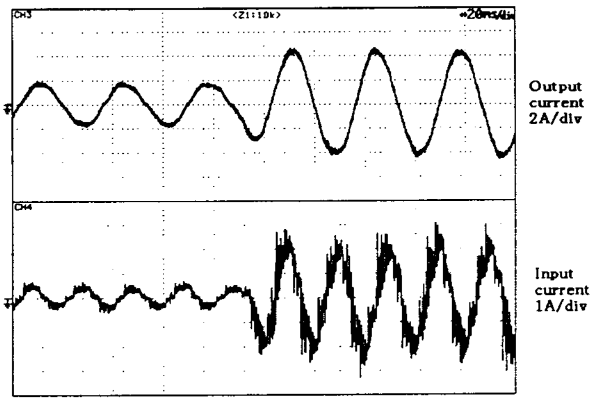


Fig. 14 Experimental waveforms in transient state (Sudden change in amplitude reference of output current)

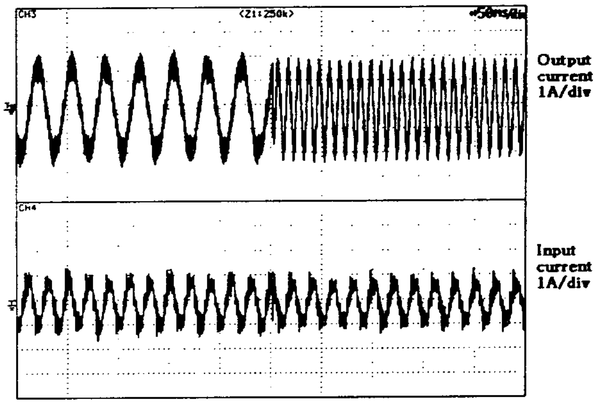


Fig. 15 Experimental waveforms in transient state (Sudden change in frequency reference of output current)

VI. CONCLUSIONS

In this paper, a new strategy to generate the switching pattern and output current control technique for the matrix converters have been proposed. The proposed methods are very simple to implement. The step commutation strategy to avoid the voltage spike is investigated. The effectiveness of the proposed switching strategy for the matrix converters has been confirmed by both the simulation and experiments employing the prototype system.

From the simulation and experiments, it is demonstrated that the proposed method can realize both the instantaneous control of the output current and the sinusoidal input current.

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