A Novel Matrix Converter Topology With Simple Commutation

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***Abstract*-Matrix converter is very simple in structure and has powerful controllability. However, commutation problem and complicated PWM method keep it from being utilized in industry. This paper discloses a novel matrix topology with advantages over the usual matrix converter topology. Firstly, it has the same performance as a conventional matrix converter in terms of voltage transfer ration capacity, four quadrant operation, unity input power factor, no DC capacitor and pure sine waveforms with only high order harmonics in both line and load side. Secondly, the PWM method utilized at conventional inverter can be used, which can largely simplify its control complexity. Thirdly, all the switches at line side turn on and turn off at zero current; the converter does not have any commutation problems as required by the conventional matrix converter. Theoretical analyses and simulation results are provided to verify its feasibility.**

I. INTRODUCTION

The matrix converter, first introduced in 1980 [1], has experienced revived attention recently. The matrix converter topology is shown in Fig. 1. Compared with the conventional AC/DC/AC converter, it has the following merits:

1) No large energy storage components, such as large DC capacitors or inductors, are needed. As a result, a large capacity and compact converter system can be designed.

2) Four-quadrant operation is straightforward, by controlling the switching devices appropriately, both output voltage and input current are sinusoidal with only harmonics around or above switching frequency [2].

However, this topology does not yet found much application in industry. The major reason is that it has potential commutation problems requiring a complex control circuit as well as, in general, a bipolar snubber. In addition the control algorithm, developed by Venturini [1], typically requires a PLA (programmable logic array) for efficient computation. Commutation problems are mainly caused by the need to adhere to the safe operation of four quadrant switches. Several solutions have been published to solve this issue[5][6]. However, they generally introduce a multi-stepped switching procedure or an additional protection circuit, which largely increases the complexity of the matrix converter. Until now, these solutions do not appear to be sufficient to enable the matrix converter leave the research labs into the industrial area. Besides commutation problem, in order to get sinusoidal waveform at both input and output sides, both the forward sequence and negative sequence component should be calculated and added together. It requires very complex computational burden and additional PWM circuits.

Other researchers have also focused on eliminating the DC capacitors in a traditional AC/DC/AC converter [3],[4]. These circuits can effectively eliminate the DC side capacitor, but the line current contains large amount of low order harmonics. Special problems arise in ensuring commutation as a result of the altered circuit topology.

In this paper, a matrix converter topology is developed which has not yet been previously reported. The new converter has following advantages:

- It has the same performance as the conventional matrix converter, such as good voltage transfer ratio capacity, four quadrant operation, unity input power factor, pure sine waveforms with only high order harmonics in both input current and output voltage.
- Pulse width modulation algorithms of conventional inverters can be utilized, which can greatly simplifies its control circuit.
- All switches at the line side turn on and turn off at zero current. Hence, this new converter does not experience the commutation problems of a conventional matrix converter.
- No large energy storage components are needed except relatively small size ac filter making these filter more easily to be integrated into a system package.

In this paper, the basic operation of this topology is first discussed. A suitable PWM algorithm is then developed. This algorithm maintains both input line current and output voltage waveforms as sinusoidal simultaneously as well as guaranteeing zero current turn-on and turn-off of the line side converter. Finally, both system and circuit level simulation results are provided to verify its feasibility. System level simulation study is conducted using MATLAB/ SIMULINK to verify its sinusoidal input and output performance. On the

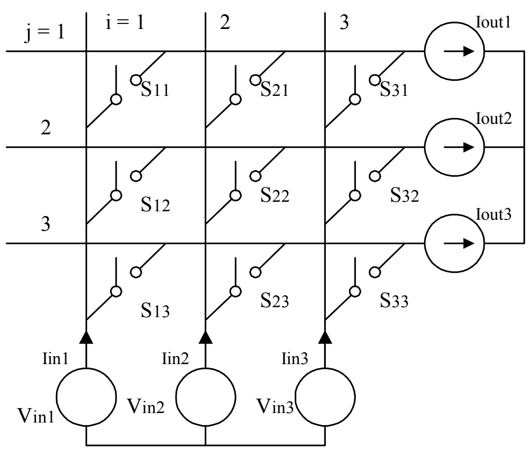

Fig. 1. Conventional matrix converter topology

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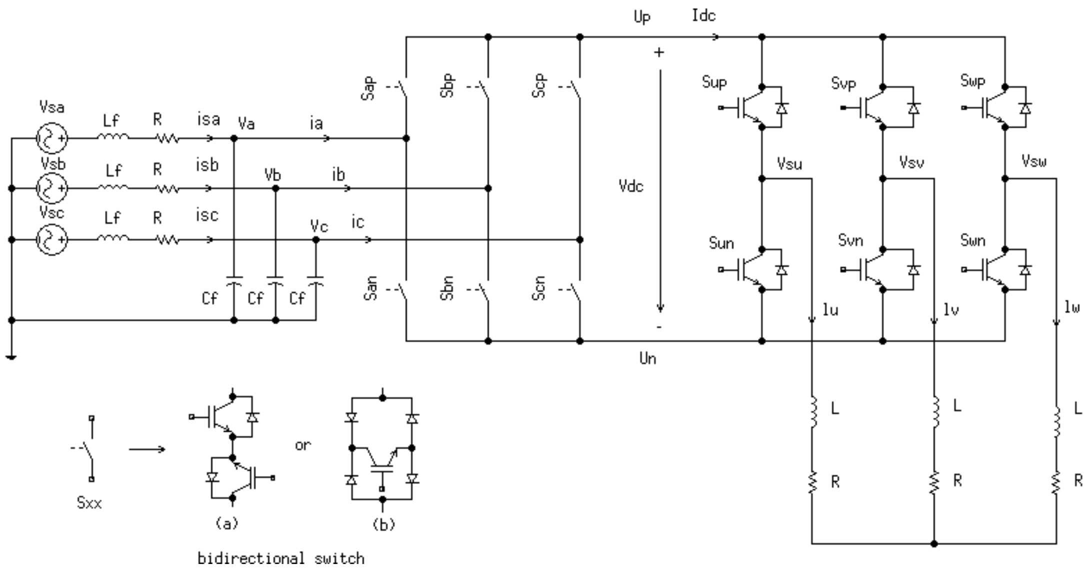

Fig. 2 Basic topology of the proposed matrix converter

other hand, the SABER simulation language is employed for a circuit level simulation to demonstrate zero current turn on and turn off characteristics, which ultimately leads to a simple snubber for both sides of the converter. The experimental results, not present in this article, are in progress and will be provided in the near future.

II. PROPOSED TOPOLOGY

Fig. 2 illustrates the modified matrix converter topology presented in this paper. Although it is still termed a matrix converter and has the same power switches as conventional switch layout, it is also similar to the traditional AC/DC/DC converter system and to previous proposed capacitorless DC link circuits [3],[4]. On the load side, the arrangement has the same conventional inverter as for the AC/DC/AC converter. As a consequence, traditional PWM methods may be used to generate the output voltage waveform. However, in order to ensure proper operation of this converter, the DC side voltage should always be positive. On the line side, the converter has a rectifier which is similar to traditional one except that the switches are all bidirectional. This modification also provides the distinguishing feature which differs this converter from circuits of previous researchers [3],[4]. The main objective of this rectifier is to maintain pure sinusoidal input current waveforms as well as maintain positive voltage on the DC side. In contrast to the AC/DC/AC converter, the DC capacitors can now be replaced by a small filter on the line side.

For purposes of analysis, one can assume that the switching frequency is far greater than fundamental frequencies of both the input voltage source and output current source. Thus during each switching cycle, both the input voltage and output current can be assumed as constant. Assuming a stiff voltage source on the line side and stiff current sink on the output side, the DC side voltage is essentially decided by the switching functions of the rectifier and the input voltage, the DC side current is determined by the combination of output switching functions and output current. It is assumed that, on the input side

$$\begin{cases} V_{sa} = V_m \cos\theta_a = V_m \cos(\omega_i t) \\ V_{sb} = V_m \cos\theta_b = V_m \cos(\omega_i t - \frac{2\pi}{3}) \\ V_{sc} = V_m \cos\theta_c = V_m \cos(\omega_i t + \frac{2\pi}{3}) \end{cases} \quad (1)$$

and on the load side,

$$\begin{cases} i_u = I_o \cos\theta_{oi} = I_o \cos(\omega_o t + \varphi_o) \\ i_v = I_o \cos(\omega_o t + \varphi_o - \frac{2\pi}{3}) \\ i_w = I_o \cos(\omega_o t + \varphi_o + \frac{2\pi}{3}) \end{cases} \quad (2)$$

In Eqs. (1) and (2) :

ω_i , ω_o are the input and output angular frequencies

φ_o : initial electric angle of the U phase output current.

V_m , I_o : amplitudes of input voltage, output current respectively.

III. PROPOSED PWM METHOD

A. *PWM Method for the rectifier side*

In order to simplify the analysis of the rectifier, it is supposed that there is no input filter in the line side. Hence:

$$L_f = 0 \,;\, R = 0 \,;\, C_f = 0$$

$$V_x = V_{sx} , \quad i_{sx} = i_x , \quad x = a,b,c$$

The aim of the pulse width modulation of the rectifier is to maintain positive voltage in the dc side as well as to maintain the input power factor as unity.

Since the input line voltages are balanced, there are two possible conditions for the input phase voltages.

1) Two voltages are positive, and one is negative

Supposing that phases A and B are positive, phase C is then negative. One can derive:

$$|V_{sc}| = |V_{sa}| + |V_{sb}|$$

Under this condition, switch S_{cn} must be maintained in the conducting state while S_{ap}, S_{bp} are modulated. All other switches keep in off state.

While S_{ap} is turned on, the DC voltage is equal to V_{ac} and is positive. The duty ratio of switch S_{ap} is given by,

$$d_{ac} = -\frac{\cos\theta_a}{\cos\theta_c} \quad (3)$$

While S_{bp} is turned on, the DC voltage equals to V_{bc} and is also positive. The duty ratio of S_{bp} is given by,

$$d_{bc} = -\frac{\cos\theta_b}{\cos\theta_c} \quad (4)$$

The average DC side voltage in this switching cycle is

$$V_{dc} = d_{ac} \cdot (V_{sa} - V_{sc}) + d_{bc} \cdot (V_{sb} - V_{sc}) \quad (5)$$

Substituting (1), (3), and (4) in (5), one can finally obtain

$$V_{dc} = \frac{3 \cdot V_m}{2 \cdot |\cos\theta_c|}$$

2) Two voltages are negative, one is positive

Supposing that phases A and B are negative, phase C is then positive. One can establish that

$$|V_{sc}| = |V_{sa}| + |V_{sb}|$$

Under this condition, switch S_{cp} remains in conducting state, switches S_{an}, S_{bn} are modulated. All other switches remain in off state.

During the time when S_{an} is turned on, the DC voltage equals V_{ca} and is positive. The duty ratio of S_{an} can be expressed as,

$$d_{ac} = -\frac{\cos\theta_a}{\cos\theta_c} \quad (6)$$

When S_{bn} is turned on, the DC voltage equal V_{cb} and is positive. The duty ratio of S_{bn} is

$$d_{bc} = -\frac{\cos\theta_b}{\cos\theta_c} \quad (7)$$

Finally, the average value of the DC voltage during this switching interval is

$$V_{dc} = d_{ac} \cdot (V_{sc} - V_{sa}) + d_{bc} \cdot (V_{sc} - V_{sb}) \quad (8)$$

Substituting Eqs. (1), (6), and (7) in (8), one obtains

$$V_{dc} = \frac{3 \cdot V_m}{2 \cdot |\cos\theta_c|}$$

Utilizing the same approach, one can obtain the corresponding duty ratio and switching state for all other circuit conditions. The average value of DC voltage during each of these switching cycle is

$$V_{dc} = \frac{3 \cdot V_m}{2 \cdot \cos\theta_{in}} \quad (9)$$

where, $\cos(\theta_{in}) = \max(|\cos(\theta_a)|, |\cos(\theta_b)|, |\cos(\theta_c)|)$.

Figure.3 shows the PWM sequence for both input and output side converters. One can determine from this figure that on the rectifier side, only two commutation events occur during each switching cycle.

The duty cycle d_1, d_2 and switching pattern while $-\frac{\pi}{6} < \theta_a < \frac{5\pi}{6}$ are shown in Table. I. While $\frac{5\pi}{6} < \theta_a < \frac{11\pi}{6}$, one can establish the corresponding values and patterns with the same approach.

B. PWM method for the inverter side

Once the PWM sequences of the rectifier have been decided, one can apply various PWM methods for the inverter, including space vector PWM, SPWM, etc. Here, the space vector PWM method will be utilized for the inverter side.

Initially, it is assumed that the DC voltage is $\frac{3 \cdot V_m}{2}$, and the expected output voltage is

$$\vec{V}_{o\_ref} = k \cdot \left(\frac{3 \cdot V_m}{2}\right) \cdot \angle\theta_o \; ; \; 0 < k < \sqrt{3}/2 \quad (10)$$

where: $\vec{V}_{o\_ref} = V_{su} + V_{sv} \cdot e^{j\frac{2\pi}{3}} + V_{sw} \cdot e^{-j\frac{2\pi}{3}}$

$\theta_o = \varphi_o + \psi$ is the output voltage angle

ψ is the angle between output voltage and current.

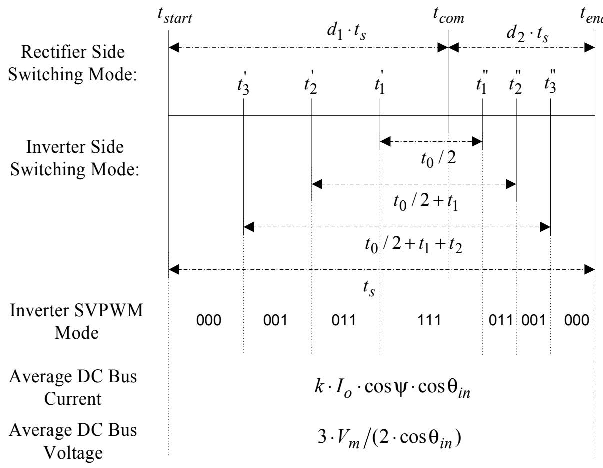

Fig. 3. PWM sequence for the proposed converter

TABLE I
DUTY CYCLE AND SWITCHING PATTERN OF THE RECTIFIER

θ_a	$-\frac{\pi}{6} \sim \frac{\pi}{6}$		$\frac{\pi}{6} \sim \frac{\pi}{2}$		$\frac{\pi}{2} \sim \frac{5\pi}{6}$	
Duty Cycle	d_1	d_2	d_1	d_2	d_1	d_2
Values	d_{ba}	d_{ca}	d_{bc}	d_{ac}	d_{cb}	d_{ab}
Conducting	S_{ap}		S_{cn}		S_{bp}	
Switches	S_{bn}	S_{cn}	S_{bp}	S_{ap}	S_{cn}	S_{an}

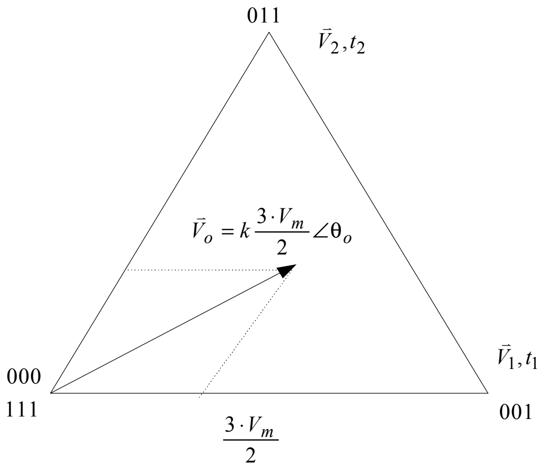

Fig. 4. Space vector PWM for inverter over the instant while $0 < \theta_o < \pi/3$

Figure 4 shows the space vector PWM for inverter while $0 < \theta_o < \frac{\pi}{3}$. The time duration of V_1, V_2 are

$$t_{10} = \frac{k\sin(\frac{\pi}{3} - \theta_o)}{\sin\frac{\pi}{3}} t_s \,; \quad t_{20} = \frac{k\sin(\theta_o)}{\sin\frac{\pi}{3}} t_s \tag{11}$$

In actual system, the average DC voltage is $\frac{3 \cdot V_m}{2 \cdot \cos\theta_{in}}$, so that the time durations of V_1, V_2 and V_0 for this case are;

$$t_1 = t_{10} \cdot \cos\theta_{in}\,;\; t_2 = t_{20} \cdot \cos\theta_{in}\,;\; t_0 = t_s - t_1 - t_2 \tag{12}$$

The time sequence of the inverter side switching is shown in Fig. 3. The various time intervals in the figure can be derived as:

$$\begin{aligned} &t_1^{'} = t_{com} - d_1 t_0/2\,;\quad t_2^{'} = t_1^{'} - d_1 t_1\,;\quad t_3^{'} = t_2^{'} + d_1 t_2 \\ &t_1^{''} = t_{com} + d_2 t_0/2\,;\quad t_2^{''} = t_1^{''} + d_2 t_1\,;\quad t_3^{''} = t_2^{''} + d_2 t_2 \\ &t_{com} = t_{start} + d_1 t_s\,;\quad t_{end} = t_{start} + t_s \end{aligned} \tag{13}$$

Since i_{dc} equals alternately i_u, $-i_w$ and 0 for vectors $\vec{V}_1$, $\vec{V}_2$ and $\vec{V}_0$ respectively, one obtains the average dc current for this switching period as:

$$i_{dc\_avg} = \frac{t_1 i_u - t_2 i_w}{t_s}$$

$$= \frac{kI_o\cos\theta_{in}}{\sin\frac{\pi}{3}}[\sin(\frac{\pi}{3} - \theta_o)\cos\theta_{oi} - \sin\theta_o\cos(\theta_{oi} + \frac{2\pi}{3})]$$

$$= kI_o\cos(\theta_o - \theta_{oi})\cos\theta_{in} = kI_o\cos\psi\cos\theta_{in} \tag{14}$$

Moreover, from (13), one can establish that the duty cycle of vectors $\vec{V}_1$, $\vec{V}_2$ and $\vec{V}_0$ equal each other over both intervals d_1, d_2.

When $\theta_o > \frac{\pi}{3}$, using the same method, one can again obtain the corresponding time durations for the relevant vectors. Moreover, it can be shown that the average dc current over each cycle always equals Eq. (14).

C. Waveforms of both input current and output voltage

Supposing $0 < \theta_o < \frac{\pi}{3}, -\frac{\pi}{6} < \theta_a < \frac{\pi}{6}$, from Fig. 3 and Table 1, it can be seen that during the d_1 period in which S_{ap}, S_{bn} are conducting, one obtains $i_{sa1} = -i_{sb1} = i_{dc}$, and $i_{sc1} = 0$; During the period d_2, switches S_{ap} and S_{cn} are conducting in which case $i_{sa2} = -i_{sc2} = i_{dc}$, and $i_{sb2} = 0$. Over this switching cycle $\theta_{in} = \theta_a$.

The average input currents during this switching cycle are

$$\begin{aligned} &i_{sa} = i_{dc\_avg} = k \cdot I_o \cdot \cos\psi \cdot \cos\theta_a \\ &i_{sb} = -d_1 \cdot i_{dc\_avg} = k \cdot I_o \cdot \cos\psi \cdot \cos\theta_b \\ &i_{sb} = -d_2 \cdot i_{dc\_avg} = k \cdot I_o \cdot \cos\psi \cdot \cos\theta_c \end{aligned} \tag{15}$$

The output voltage vector is:

$$\vec{V}_o = d_1 V_{sab}\cos\theta_a \cdot k\angle\theta_o + d_2 V_{sac}\cos\theta_a \cdot k\angle\theta_o \tag{16}$$

Substituting Eq. (5) into (16), one can finally determine that the actual output voltage vector is

$$\vec{V}_o = k \cdot \frac{3V_m}{2}\angle\theta_o \tag{17}$$

D. Commutation Problem

From Fig. 3, while the rectifier side is commutating, the inverter side vector is $\vec{V}_0$. This result indicates that during commutation the DC side current is zero. Hence, at this instant, all currents one the rectifier side are zero so that zero current turn-on and turn-off on the rectifier side can be guaranteed. This feature largely simplifies the commutating problems always associated with conventional matrix converters. In addition, switching losses of the input side devices are significantly reduced.

E. Discussion

From above analysis, with the proposed PWM method, the proposed matrix converter topology has the following characteristics:

- The input currents are pure sine waves with only high order switching harmonics, input power factor is maintained at unity and the maximum magnitude of the

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input phase current is $k \cdot I_o \cdot \cos\psi$.

- The output voltage remains a pure sine wave with only high order harmonics. The magnitude of output voltage vector is $k \cdot \frac{3V_m}{2}$, the maximum value of k is $\frac{\sqrt{3}}{2}$ or the same as the highest transfer ratio of the conventional matrix converter.
- All switches on the rectifier side turn on and turn off at instants of zero current so that the commutation problems of the traditional matrix converter are completely avoided.

IV. Simulation Results

The proposed topology has been extensively investigated under both system and circuit level simulations. The system level simulation is made utilizing MATLAB/SIMULINK. This software represents all the switches as ideal switches. The PWM signal, input current and output voltage waveforms are obtained to test the feasibility of proposed control method. The parameters of the converter for the MATLAB simulation are:

Input Line voltage: 480V;	Input frequency: 60Hz
Filter inductor: 200μH;	Resistor: 0.2Ω
Filter capacitor: 30μF;	Output resistor: 10Ω
Output inductance: 5mH;	Modulation level k: 0.80
Output frequency: 35Hz	

Fig. 5 shows MATLAB simulation results for the proposed matrix converter. In Fig. 5(a), the PWM signal, input converter phase current and output line voltage are shown. In Fig. 5(b), the waveforms listed are dc voltage, dc current, output current, input line voltage and line current.

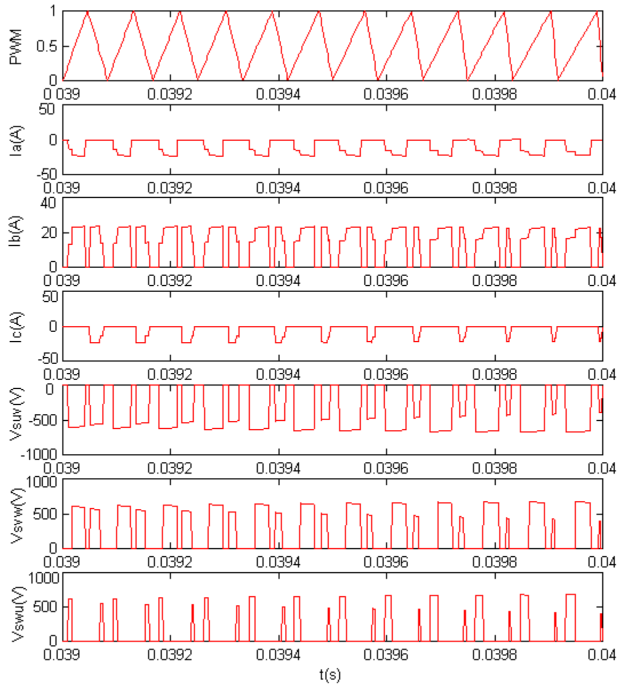
From Fig. 5(a), it can be noted that the phase currents of the rectifier are modulated during each cycle. Their values are comprised of the three phase output currents. On the other hand, the output voltages are also modulated, and are composed of portions of the three phase input voltages.

From Fig. 5(b), one can note the dc voltage and dc current traces. These waveforms are modulated in each switching cycle and are comprised of input voltage and output current respectively. Moreover, one can establish that the DC voltage fluctuates between the magnitude of the line voltage and one half of this value.

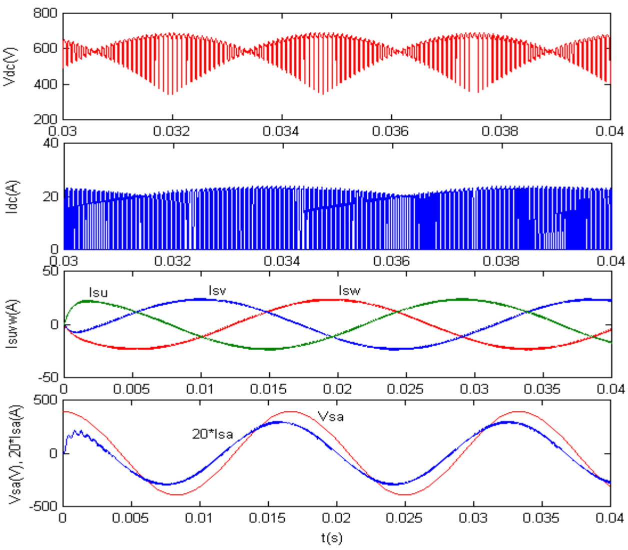
From Fig. 5(b), it can be noted that the waveforms of three phase output currents are essentially sinusoidal. This result, in turn, demonstrates that there are no low order harmonics in the output voltage.

Fig. 5(b) also shows the waveforms of input phase voltage and phase current. From this figure, it can be observed that the input phase current is also sinusoidal. It can be found in this figure that, the phase angle of current is leading the voltage. This result is caused by choice of the parameters of input filter.

Simulation studies using the SABER software were also made to investigate more detail with the switch zero-current turn-on and turn-off capability on the rectifier side. The circuit simulation uses diode models with a reverse recovery



(a)



(b)

Fig. 5. Simulation result for the proposed matrix converter

function. The IGBT model used is IRGB430U. It was assumed that during simulation, on the rectifier side, S_{ap} keeps conducting, and S_{bn} and S_{cn} are modulated. On the inverter side, it is assumed that S_{vp} and S_{wp} turn on, and S_{up} is modulated. The current I_a at this instant is 20A.

Fig. 6 shows the simulation result under SABER. The waveforms shown from top to bottom are V_{dc}, V_{su}, I_{dc}, PWM inverter and PWM rectifier gate voltages respectively. From this result, it can be found that the DC current is very small (0.063A - 0.1A) while the rectifier side is commutating. Thus in order to avoid voltage peaks while the rectifier is commutating, a small value of snubber capacitors can parallel with the rectifier side switches to eliminate the commutation voltage spikes.

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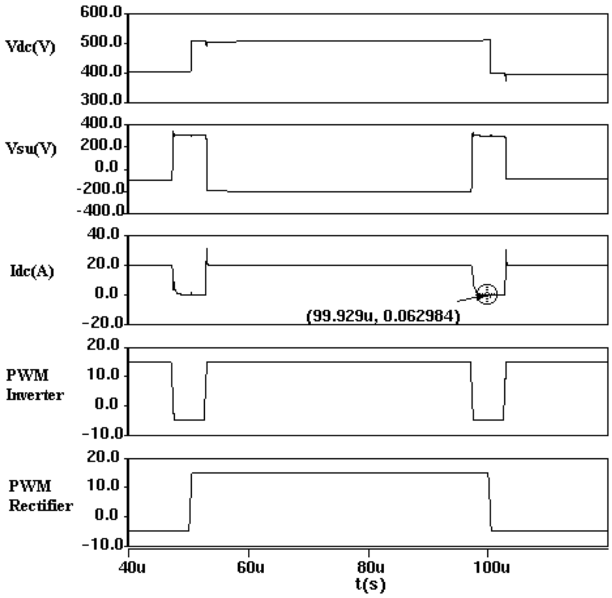

Fig. 6. Circuit level simulation using SABER

At present, a circuit realization of the new converter is being realized in hardware. It is expected that the experimental results will be obtained in the near future.

V. CONCLUSION

This paper presents a new matrix converter topology. It combines the control method of the traditional PWM method for AC/DC/AC system with the needs of a matrix converter and thus fulfills the functional advantages of the matrix converter. Theoretical analysis and simulation results show that the converter has following performance features:

- Both the input current and output voltage can be pure sine waveforms with only harmonics around or above switching frequency.
- The converter can provide a unity input power factor.
- Four quadrant operation is possible.
- No DC link capacitors are needed, which means that a large capacity, compact converter system can be designed.
- Has the same voltage transfer ratio capacity as conventional matrix converter.
- Conventional PWM methods can be applied for controlling the output side converter. This feature largely simplifies the complexity of control.
- The converter is completely free of the commutation problems associated with conventional matrix converters.
- The converter offers the possibility of better efficiency than the conventional matrix converter since switching of the input side converter only takes place during instant of zero dc link current.

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