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Robust Voltage Commutation of Conventional Matrix Converter

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***Abstract*– The three-phase ac-ac converter termed the matrix converter can provide high quality input/output waveforms and adjustable input power factor without any large energy storage component. However, it has not yet found much acceptance in industry. The main reason is that it requires a complicated commutation scheme to prevent input side short circuits and output side open circuits. This paper develops a new voltage commutation scheme for the conventional matrix converter. One advantage of this scheme is that it provides robust voltage commutations for the converter without sacrificing the quality of the line side current waveforms. The second advantage is that it needs the least information from the system than any algorithm yet reported. It only detects the line side synchronization angle which can have detection errors within ±p/6 radians under unity input power factor to provide accurate commutation. The last advantage of this scheme is that it can provide easier shut down sequences for the system. Theoretical analysis, simulation and experimental results are provided to verify its effectiveness in the paper.**

I. INTRODUCTION

The three phase ac-ac converter or matrix converter, M. Venturini [1] as shown in fig.1, can provide high quality input/output waveforms and adjustable input power factor without use of a large energy storage component. Subsequently, it has become an alternative candidate for three-phase AC/AC power conversion. However, it has not yet found much acceptance in industry. The main reason is that it needs complicated commutation scheme for the idea switches to prevent input side short circuits and output side open circuits.

Several solutions have been published to solve this issue [2]-[6]. In papers [2][3], voltage and current commutation schemes are proposed respectively. The main concept of these two papers is to introduce a multi-step voltage or current dependant switching procedure that can prevent false commutations. However, since the accuracy of these two methods is based upon the sign of either input line voltage or output load current, when these values are near zero, false commutations can still be generated and ultimately damage the power switches. Papers [4][5] proposed a robust voltage commutation scheme. It detects the magnitude of line side voltage dynamically, when the system operates at some critical region where two input phase voltages are nearly equal to each other, it creates new PWM sequences to prevent the commutation between these two phases. The advantage of this method is that the converter can operate safely. However, since the switching sequences are changed, the line side current is also distorted. References [6][7] proposed another intelligent commutation method. Its main principle is to build an intelligent circuit within the gate driver board to improve the accuracy of sign detection. However, a rather complicated circuit has to be added to the system.

This paper develops a robust voltage commutation scheme for the conventional matrix converter. One advantage of this scheme is that it provides robust voltage commutations for the converter without sacrificing the line side current waveform quality. The second advantage is that it needs only minimal information from the system. It only need detect the line side synchronization angle which can have detection errors within $\pm\pi/6$ radians under unity input power factor operation. The final advantage of this scheme is that it can provide easier shut down sequences for the system.

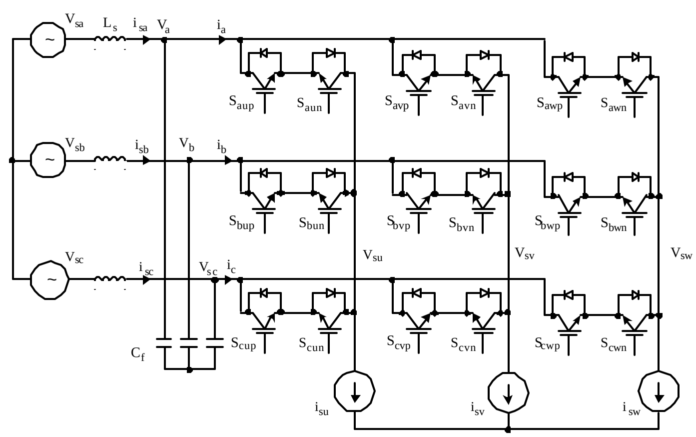


Fig. 1. Configuration of matrix converter system

The implementation of this scheme is based on the space vector PWM control of conventional matrix converter. By detecting the synchronization angle of line side voltage, six intervals are identified. In each interval, each switching cycle is subdivided into two portions. In each portion, the switches of the converter are classified into three types, named on-switch, off-switch, and modulated-switch. With this three switch types, the converter can be regarded as a DC/AC inverter. Finally, by applying appropriate voltage vectors in each portion, a robust voltage commutation scheme can be established.

This paper is organized into following steps. After a brief presentation of the input/output transforming equations of the circuit, the new voltage commutation scheme is proposed.

Meanwhile, the three switch types and equivalent circuit of the converter is demonstrated and the shut down of the converter is discussed. The paper then demonstrates the space vector PWM method of the matrix converter and proposes a corresponding PWM sequence for one switching cycle. Finally, simulation and experimental result on a clamp-less matrix converter are provided to prove its feasibility.

II. CIRCUIT AND SYSTEM CONFIGURATION

A simplified power circuit of matrix converter is shown in Fig.1. In this figure, each of the bilateral switches S_{jk} consists of two anti-series IGBTs (named S_{jxp}, S_{jxn}) and two anti-series diodes. The symbol $j\in\{a, b, c\}$ represents the phases at line side, $x\in\{u, v, w\}$ represents the phases on the load side, *p* designates the switches whose current flows from line side to load side, and *n* indicates the switches whose current flows from the load side to line side.

To simplify the analysis, it is assumed that there is no input filter on the line side. Hence, from Fig.1, the following equations can be obtained:

$$L_s = 0\,;\ C_f = 0\,;\ V_{sj} = V_j\,;\ i_{sj} = i_j \tag{1}$$

where V_j and i_j is the line side phase voltage and current at the converter side in phase j, L_s is the value of line side filter inductance, and C_f is the value of line side filter capacitor.

It is assumed that the line side voltage is a three phase balanced voltage source denoted as

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

and the load side is a three phase balanced current source described as

$$\begin{cases} i_{su} = I_o \cos\theta_{oi} = I_o \cos(\omega_o t + \varphi_o) \\ i_{sv} = I_o \cos(\omega_o t + \varphi_o - \frac{2\pi}{3}) \\ i_{sw} = I_o \cos(\omega_o t + \varphi_o + \frac{2\pi}{3}) \end{cases} \tag{3}$$

In (2) and (3), ω_i, ω_o are the input and output angular frequencies; φ_o is the initial electrical angle of the phase current; V_m, I_o are the amplitudes of input voltage and output current respectively; θ_a, θ_b, and θ_c are electrical angles of three phase input voltage.

For purposes of analysis, it is assumed that the switching frequency is far greater than fundamental frequencies of both the input and output of the converter. Thus, in each switching cycle, both the input voltage and output current can be considered as constant.

II. CIRCUIT AND SYSTEM CONFIGURATION

To simplify the analysis, it is assumed initially that the line side power factor is unity, thus the line side voltage and current has the same phase angle. The commutations while the line side power factor is not unity will be discussed later in this paper.

A. The six intervals

Six intervals are identified based on detection of the input current synchronization angle as shown in fig. 2. Because of unity power factor, during each interval, only one of the three-phase input voltages has the largest absolute value. For example, V_{sa} has the largest absolute voltage in interval 1, V_{sc} has the largest absolute voltage in interval 2, and so forth.

B. Two portions and three switch types

Each switching cycle is split into two portions and the switches in the converter are classified as three types, including on-switch, off-switch and modulated switch. In each portion, the on-switches and off-switches remain turn on and off respectively; the modulated switches commutate like the traditional DC/AC inverter.

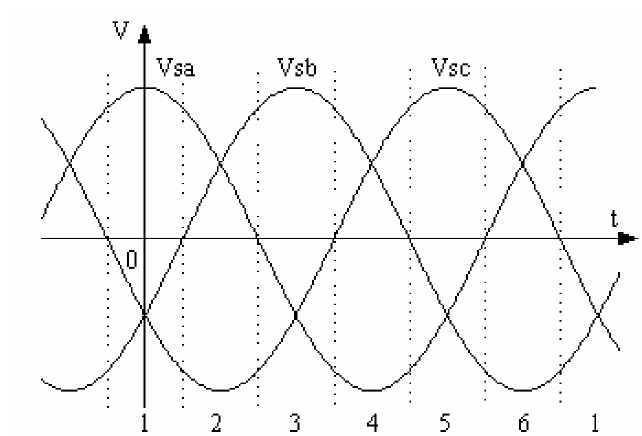
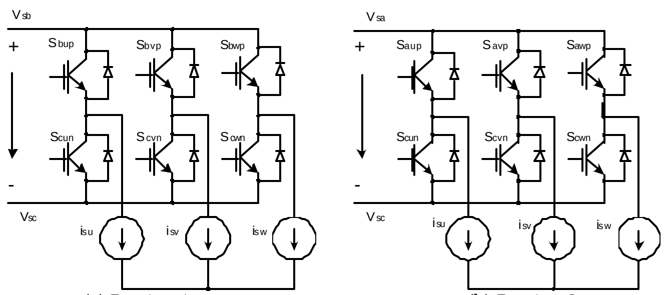


Fig. 2. Six intervals of the system

For example, V_{sc} in interval 2 has the largest absolute voltage and the two largest positive input line voltages are V_{sa} -V_{sc} and V_{sb} -V_{sc};. Then, the line side switching states in each portion can be determined by the following steps:

- In portion 1, defining S_{bxp} and S_{cxn} as modulated-switches and commutate in complimentary fashion, S_{axp} and S_{axn} as off-switches, and S_{bxn} and S_{cxp} as on-switches. With this definition, the matrix converter can be simplified as a DC/AC inverter as shown in fig.3 (a). In the inverter, the DC side voltage V_{dc} equals to line voltage V_{sb} -V_{sc}; the DC side current equals to input phase current i_{sb} and $-i_{sc}$, and input current i_{sa} is zero. The duty cycle of this portion is defined as d_{bc}.

- In portion 2, defining S_{axp} and S_{cxn} as modulated-switches, S_{bxp} and S_{bxn} as off-switches; and S_{axn} and S_{cxp} as on-switches. Again, the matrix converter can be simplified as a DC/AC inverter as illustrated in fig.3 (b). In this inverter, the DC side voltage V_{dc} equals to V_{sa} -V_{sc}; the DC side current equals to input phase current i_{sa} and $-i_{sc}$; and input current i_{sb} is zero. The duty cycle of this portion is defined as d_{ac}.

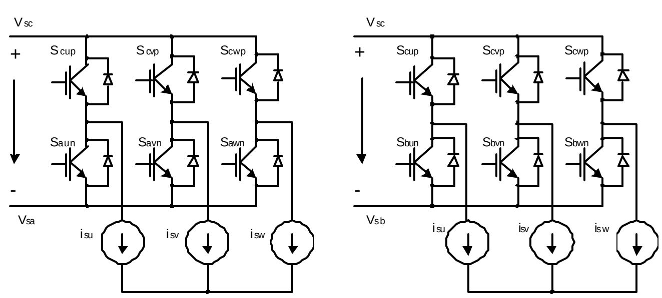


(a) Portion 1 (b) Portion 2

Fig. 3. Equivalent circuit in region 2

Similarly, in interval 5, V_{sc} has the highest voltage and the two absolute positive line voltages are V_{sc} -V_{sa} and V_{sc} -V_{sb} respectively. In this situation, the three switch types are defined in each portion through following steps:

- In portion 1, defining S_{axn} and S_{cxp} as modulated-switches, S_{bxp} and S_{bxn} as off-switches, and S_{axp} and S_{cxn} as on-switches. The converter is simplified as the third DC/AC inverter as shown in fig.4 (a). In this inverter, the DC side voltage V_{dc} equals to V_{sc} -V_{sa}, the DC side current equals to input current i_{sc} and $-i_{sa}$; the input phase current i_{sb} equals zero. The duty cycle of this portion is defined as d_{ac}.
- In portion 2, defining S_{bxn} and S_{cxp} as modulated-switches, S_{axp} and S_{axn} as always-off switches, and S_{bxp} and S_{cxn} as always-on switches. The fourth DC/AC inverter can be derived as illustrated in fig.4 (b). In this inverter, the DC side voltage V_{dc} equals to V_{sc} -V_{sb}, the DC side current equals input phase current i_{sc} and $-i_{sb}$, and i_{sa} equals to zero. The duty cycle of this portion is defined as d_{bc}.



(a) Portion 1 (b) Portion 2

Fig. 4. Equivalent circuit in region 5

Using the same method, when the system operates at other intervals, the same DC/AC inverter with different DC voltages can be obtained.

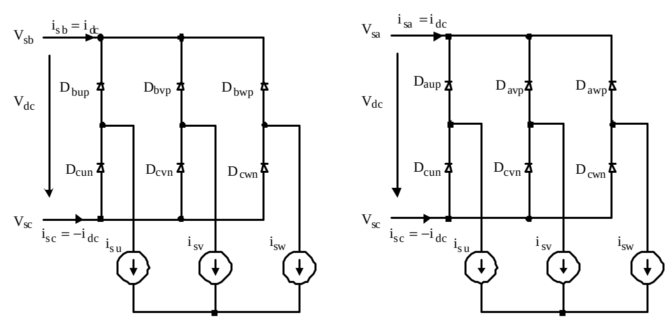
C. Voltage commutation scheme

With the six intervals and three switch types analyzed above, the commutation of the converter can be established by following policies.

- In each portion, dead time is applied between each pair of modulated switches as shown in fig. 3 and fig. 4. The commutations of these modulated switches are the same as that of the conventional DC/AC inverter.
- In each interval, the same zero vector which connects all outputs to the same input phase that has the highest absolute value is applied at both the beginning and ending of each portions. This implies that the same zero vector is utilized in both the beginning and ending of each portions in each interval. As a result, portion 1 and 2 can transit to each other automatically and the commutations of the on-switch and off-switch within each interval are all soft switching, thus multi-step commutation is not needed.
- The transition of different intervals involves the transition of different zero vectors. This can be achieved by utilizing the four-step voltage commutation scheme mentioned in [4]. For instance, if the system transits from interval 6 to interval 1, the matrix converter has to transit from zero vectors BBB to AAA. Since the sign of these two voltages are very easy to decide and no commutation errors will be generated.

III. CONVERTER SHUT DOWN

It can be shown that the shut down procedure for the matrix converter is also simplified. When the converter starts to shut down, all the modulated switches in each portion are turned off; the on-switches and off-switches operate similarly as in the running mode. Then, the matrix converter operates like an uncontrolled diode bridge with the output load as its input side. Fig.5 shows the equivalent circuit in each portion at interval 2 during shut down.



(a) Portion 1 (b) Portion 2

Fig. 5. Equivalent circuit in region 2 while the converter shut down

From fig.5, since the energy only flows from the load side to the line side, all the power at load side feeds back to the line side automatically. Finally, while all the energy of the load flows back to the source and output phase current reduces to zero, the system can turn off all other switches. Fig. 6 shows the gating signals of S_{aup} and S_{aun} at unity input power factor while the converter shuts down.

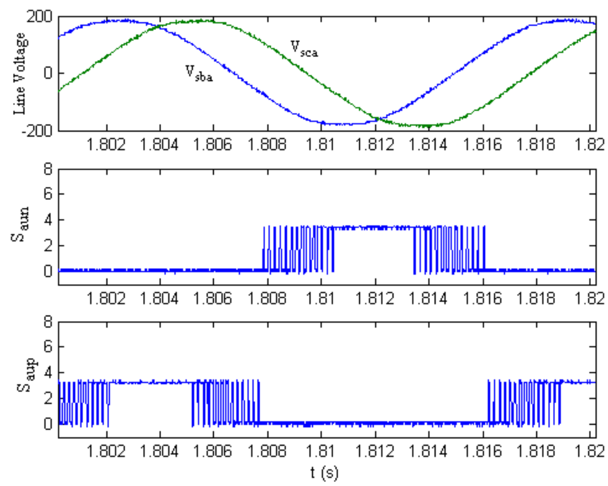


Fig. 6. Gating signal of switch S_{aup}, S_{aun} and the line voltage of the conventional matrix converter during shut down

IV. SVPWM AND THE CORRESPONDING PWM SEQUENCE

It is useful to initially consider the matrix converter as a conventional VSI inverter supplying output voltage V_{su}, V_{sv}, and V_{sw} by a dc voltage source V_{dc} = $3V_m/2$. In complex form, the space vector of the desired output voltages is

$$\vec{V}_{o\_ref} = V_{su} + V_{sv} \cdot e^{j\frac{2\pi}{3}} + V_{sw} \cdot e^{-j\frac{2\pi}{3}} = k \cdot \frac{3V_m}{2} \angle\theta_o \qquad (4)$$

Where $0 < k < \sqrt{3}/2$ is a constant.

Supposing $0 < q_o < p/3$ and that the system operates in interval 2, this vector can be approximated by its two adjacent voltage vectors (V_1 and V_2) and the zero voltage vector V_0 as shown in Fig. 6. The duty ratios of these vectors are

$$d_1 = \frac{2k}{\sqrt{3}} \sin(\frac{\pi}{3} - \theta_o)\,;\, d_2 = \frac{2k}{\sqrt{3}} \sin(\theta_o)\,;\, d_0 = 1 - d_1 - d_2 \qquad (5)$$

The average DC current of the inverter with the above duty cycles is determined as

$$i_{dc} = k \cdot I_o \cdot \cos(\theta_o - \theta_{oi}) = I_{im} \qquad (6)$$

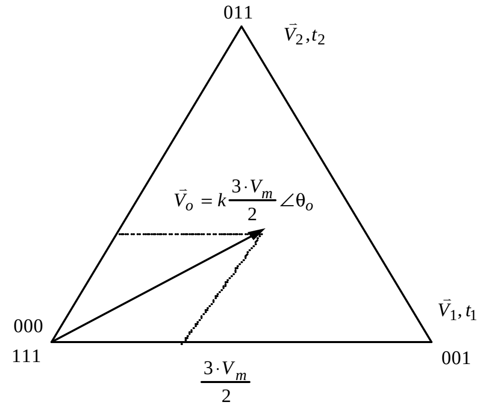


Fig. 7. Space vector PWM for inverter while $0 < q_o < p/3$

Because there are two portions during each switching cycle, the duty cycles V_1, V_2, and V_0 are also distributed to each portion.

In the first portion, they are:

$$d_{1bc} = d_1 \cdot |\cos\theta_b|\,; \qquad d_{2bc} = d_2 \cdot |\cos\theta_b|$$
$$d_{0bc} = d_0 / 2\,; \qquad d_{bc} = d_{1bc} + d_{2bc} + d_{0bc} \qquad (7)$$

In the second portion, they are

$$d_{1ac} = d_1 \cdot |\cos\theta_a|\,; \qquad d_{2ac} = d_2 \cdot |\cos\theta_a|$$
$$d_{0ac} = d_0 / 2\,; \qquad d_{ac} = d_{1ac} + d_{2ac} + d_{0ac} \qquad (8)$$

Combining Eqs. (5) to (8), the actual average output voltage vector and the input current can finally be derived as

$$\vec{V}_o = k \cdot \frac{3V_m}{2} \angle\theta_o \qquad (9)$$

$$i_{sa} = I_{im} \cdot \cos\theta_a \qquad (10)$$

$$i_{sb} = I_{im} \cdot \cos\theta_b \qquad (11)$$

$$i_{sc} = I_{im} \cdot \cos\theta_c \qquad (12)$$

This result verifies that the proposed space vector PWM control method generates the same actual output voltage as the reference voltage and the line side power factor can inherently remain at unity.

Figure 8 shows the PWM sequence of one switching cycle of the converter in interval 2. It shows that the rules specified in previous paragraph are strictly followed. When the system operates at the other intervals or when $\theta_o > \pi/3$, the corresponding duty cycle of voltage vectors, corresponding PWM sequences, and the same results like eqs (4) ~ (12) can also be obtained.

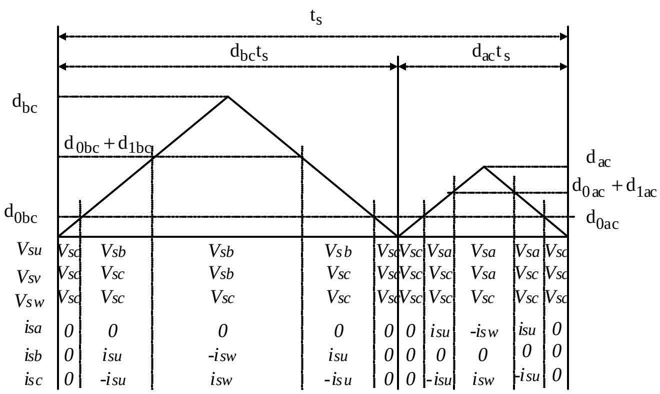


Fig. 8. PWM sequences in each switching cycle of interval 2

From the above analysis, the proposed PWM control method has the following characteristics:

- Under unity input power factor, all commutations during the operation occur between the input phase with highest absolute voltage value and one of the other two phases. Since the commutation voltage is never less than $0.866V_m$, accurate commutation can be guaranteed even the synchronization angle of input voltage is not accurate. In fact, this value can have detection errors between $-\pi/6$ to $\pi/6$ without commutation errors.
- The input current is pure sine waves with only high order harmonics around the switching frequency. Its magnitude under unity power factor is I_{im}.
- The output voltage remains pure sinusoidal with only high order harmonics around switching frequency. The magnitude of the output phase voltage is $kV_m(0<k<0.866)$.
- Since the commutation voltage can never be less than 0.866, the switching losses of the converter cannot be optimized. Moreover, because some zero vectors has to be utilized in each portion to make transitions, the highest voltage transfer ration is slightly smaller than 0.866.
- When the input power factor of the system is not unity, the same commutation can be applied. It can be demonstrated that the converter commutates safely if the line side power factor is grater than 0.866. If it is lower than the 0.866, this commutation scheme is not applicable. Fortunately, because the matrix converter generally operates near unity power factor, this commutation scheme can still be utilized.

V. SIMULATION AND EXPERIMENTAL RESULTS

The proposed PWM control method has been studied extensively with MATLAB/SIMULINK on the conventional matrix converter with R-L load. A clamp-less conventional matrix converter was also constructed in the lab. Both the simulation and experimental results are provided in this chapter to verify its effectiveness.

Fig. 9 shows the simulation results of the conventional matrix converter under unity power factor operation. The waveforms provided are line side phase voltage V_{sa} and current i_{sa}, load side voltage V_{suv} and load side phase current i_{su}. In fig. 10, the same waveforms of experimental results are provided. In fig.11, the experimental results of switch voltage and switch current are presented. Following conclusions can be observed:

- From fig. 9 and fig. 10, the simulation and experimental result agrees well with each other;
- In fig. 9. and fig. 10, both line side and load side currents are essentially sinusoidal, which proves that the proposed PWM method can provide high quality input current and output voltage;
- Because of the existence of line side filter, the power factor of line side voltage source has leading power factor. This is verified by both the simulation and experimental results;
- Since the proposed space vector PWM method can operate safely under normal operation without any clamp circuit, the robustness of the voltage commutation scheme and the effectiveness of the shut down scheme are verified.

VI. CONCLUSION

In this paper, a robust voltage commutation scheme is applied to the space vector PWM control of conventional matrix converter. With this method, the converter can provide robust voltage commutations with only the synchronization angle of line side voltage; thus it is possible to further reduce the cost of the conventional matrix converter. Moreover, the shut down sequence of the converter is also simplified. Analysis shows that the method can provide high quality input/output waveforms without degrading the input current waveforms. Finally, simulation and experimental results on a clamp-less matrix converter are both presented to demonstrate its effectiveness.

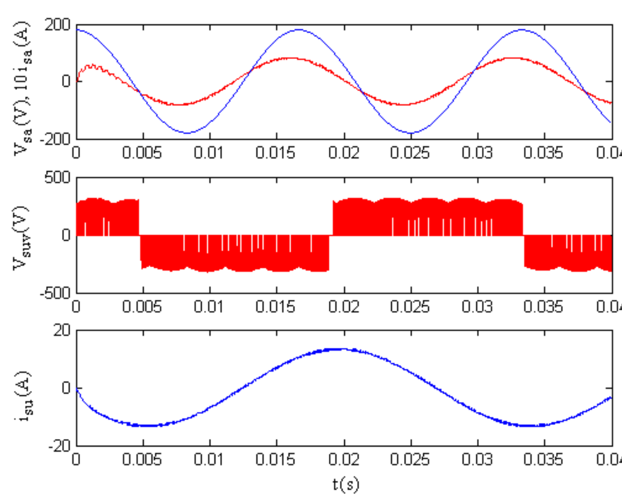


Fig. 9. Simulation result of the matrix converter

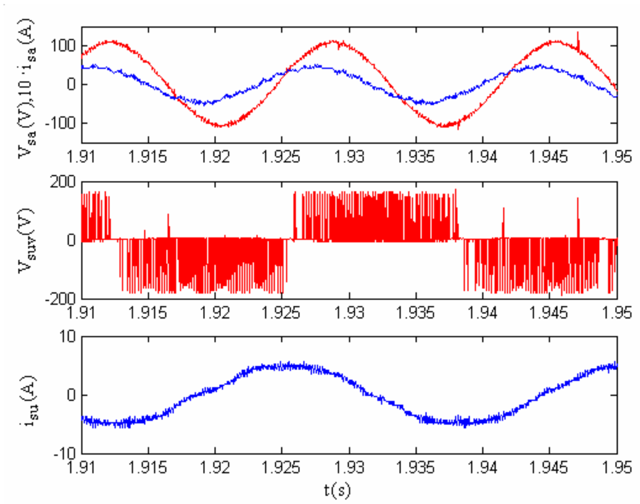


Fig. 10. Experimental result of the matrix converter

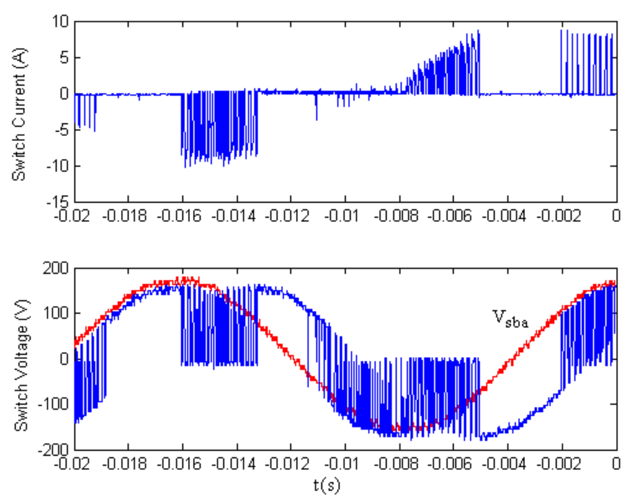


Fig. 11. Experimental result of switch voltage and switch current (Sau)

VII. ACKNOWLEDGEMENT

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