A Current Regulated Switching Strategy with Auto-Restarting Ability During Power Grid Interruptions for Matrix Converter

Chen Der-fa[1] Liu Tian-hua[2]
[1] Department of Industrial Education and Technology
National Changhua University of Education
Changhua, Taiwan (R.O.C.)
dfchen@cc.ncue.edu.tw

Yao Kai-chao[1] Lee Yu-sen[2]
[2] Department of Electrical Engineering
National Taiwan University of Science and Technology
Taipei, Taiwan (R.O.C.)
Liu@mail.ntust.edu.tw

***Abstract*—Due to the properties of the matrix converter, the pseudo dc-link will provide with three different types of voltage. By suitably selecting switching pattern, the output current ripples are obviously reduced and unity power factor can be achieved. Using the switching strategy, the immune ability against disturbances is promoted. Thus power quality can be improved. In addition, to maintain the working ability of the control circuits and DSP under power grid interruptions is also investigated. When the power grid has returned to normal condition, the motor will restart automatically. The matrix converter is used to drive a PMSM servo motor. All the control loops, including the switching strategy, current-loop, and control law, are implemented by TMS320LF2407A digital signal processor. The hardware circuit is very simple. Several experimental results are shown to validate the theoretical analysis.**

***Index Terms*—matrix converter, power quality, power interruptions**

I. INTRODUCTION

In ac-ac converter applications, the two-stage converters with dc-link are widely used in traditional ac drive systems. A large capacitor as an energy storage element is required in the dc-link. The capacitor is large and expensive and can be a critical component. In addition, a braking resistance is required to absorb the energy during braking of the drive system. The matrix converters have become increasingly attractive in recent years due to several advantages. The matrix converter is a single stage converter. It does not require any dc-link energy storage component. In addition, it has a high-power-factor sinusoidal input current with a bi-directional power flow for the whole matrix converter drive system. In the past, the matrix converter was developed in research laboratory only and could not be popularly used in industry. The situation has been changed. A new technology for integrating the whole matrix converter power devices in a single package has been developed recently. In addition, the integrated power modules are now available commercially. This type of packaging can minimize the stray inductance and the size of the power devices [1]. Yaskawa Company has implemented a commercial matrix converter and has shown it has many advantages. For example, it requires small mounting place because the braking resistance or regeneration converter is unnecessary. It has lesser total current harmonic distortion and higher power factor at the input side when compared with the rectifier/dc-link/inverter. Moreover, it has longer life because no capacitance is used. As a result, one can predict that the applications of matrix converters will become more popular in the near future.

There are more and more papers being published in recent years. Different switching schemes for an ac/ac matrix converter have been proposed to achieve sinusoidal input and output current waveforms. For example, the space vector modulating method and input power factor correction were applied in a matrix converter [2]-[4]. Several methods have been proposed to improve the performance of the matrix converter [5]. Many researchers have studied the matrix converters that drive ac motors. For example, a matrix converter was developed to drive an induction motor [6]. These studies focused on the type of matrix converter and the field-oriented control in adjustable-speed induction drive systems. A method for using a matrix converter driving a permanent magnet synchronous motor (PMSM) was proposed in [7]. Most of the previous publications on matrix converters have dealt with modulation strategies [2]-[5], or with aspects of adjustable speed control [6]-[7]. Very few publications have considered the auto-restart ability during power grid interruptions for the matrix converter-fed ac drive system [8]. Due to lack of dc-link capacitor, this is more challenging than the conventional ac-ac converter.

Any disturbance in the input voltages will be immediately reflected to the output voltages and result in unwanted input harmonic currents due to the lack of dc-link energy storage elements in the matrix converter. In order to eliminate the harmonic contents of the input current and reduce the output current ripples, the paper proposes a new switching strategy for a matrix converter. In this control strategy, the pseudo dc-link voltage is modulated based on the input currents and the motor speed. By using the switching strategy, the immune ability against disturbances is promoted. Thus power quality can be improved. The matrix converter is also used to drive a PMSM servo motor. In addition, to maintain the working ability of the control circuits and DSP normally under power grid temporary interruptions is also effectively improved. All of the control loops, including the switching strategy, current-loop, and control law, are implemented by TMS320LF2407A digital signal processor. Several experimental results are shown to validate the theoretical analysis.

II. System Description

Fig. 1 shows the circuit diagram of matrix converter to be considered in this paper. The hardware part of the system consists of a three-phase PMSM with load, a current-regulated matrix converter, and a digital signal processor system. The digital signal processor reads the shaft angle and stator currents of the motor to execute the relative control algorithms. Finally, the digital signal processor outputs the nine signals to trigger the solid-state power switches S_1-S_9 to determine the switching patterns of the matrix converter. By using the switching strategy proposed in this paper, the ac-dc and dc-ac conversion signals are generated separately. Then, all of the switching patterns of the matrix converter can be obtained by synthesizing the signals of the ac/dc and dc/ac stages.

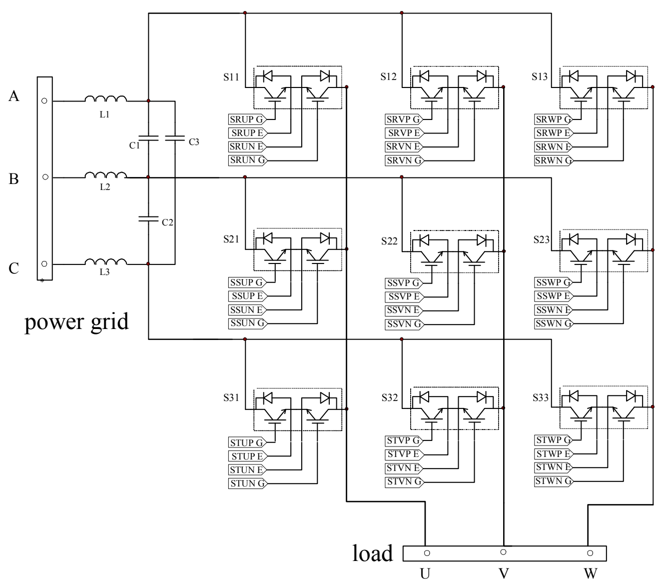


Figure 1. The circuit diagram of the matrix converter.

III. Switching Strategy

In the ac/dc stage, the dc-link voltage can be adjusted by suitably selecting different switching patterns. There are three different types of dc-link voltages: the high, the middle, and the low dc-link voltage. Their voltage waveforms are shown in Fig. 2.

In the dc/ac stage, the currents are regulated by an inverter. The inverter has three legs. Each leg with an upper switch and a lower switch independently controls one phase current. The current regulator controls the switches of the dc/ac stage to force the three-phase currents to track the current commands and the immune ability against the power disturbances is improved.

If the switching patterns of the matrix converter are suitably selected based on the input current commands, the unity power factor will be attained and power quality can be improved. In order to synthesize the input currents, the input currents of the matrix converter under different types of dc-link voltage should be described further. Assuming the pseudo dc-link current I_{dc} is constant, then, in one phase, the input currents of the matrix converter under different types of dc-link voltages can be shown in Fig. 3. These different types of dc-link voltage can be modulated by computing the switches duty cycle.

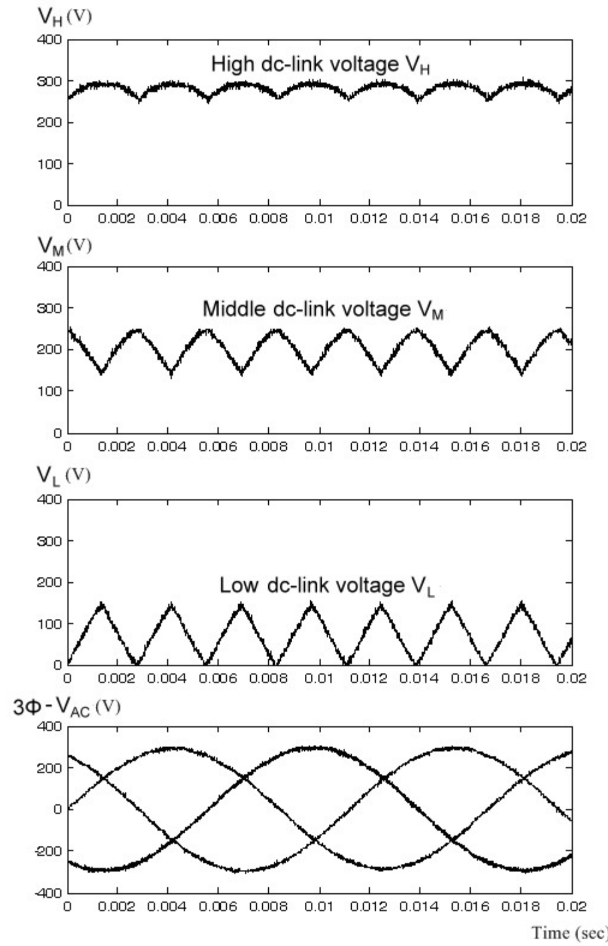


Figure 2. Three-type pseudo dc-link voltage.

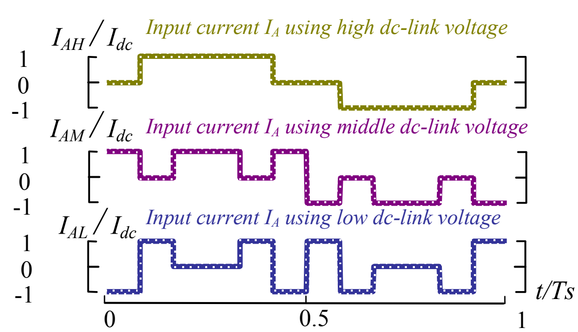


Figure 3. The input phase currents of the matrix converter under different types of dc-link voltage.

A higher dc-link voltage provides a wide adjustable speed range, however, it causes serious current deviations as well. When the dc-link voltage is adjusted relative to the motor speed, a better performance of the drive system can be obtained. It is possible to compute the required voltage value of the motor, and then determine the optimal selection of the dc-link voltage. This paper, therefore, adjusts the pseudo dc-link voltage based on the input currents and the motor speed to achieve unity power factor. In the proposed switching strategy, the pseudo dc-link voltage command V_{dc}^* is decided according to the operational condition of the PMSM. In addition, suppose the phase A and the phase B input current commands are i_A^* and i_B^* respectively. Due to consideration of input power factor, only the high dc-link voltage and middle dc-link voltage are used in this paper. The switches duty cycle of high dc-link voltage and middle dc-link voltage can be calculated in the following:

$$t_H V_H + t_M V_M = T_S V_{dc}^* \tag{1}$$

$$t_H I_{AH} + t_M I_{AM} = T_S i_A^* \tag{2}$$

$$t_H I_{BH} + t_M I_{BM} = T_S i_B^* \tag{3}$$

$$t_O = T_S - t_H - t_M \tag{4}$$

Where T_s is the sampling period, t_H and t_M are the on-time of switching patterns using high dc-link voltage and middle dc-link voltage respectively, t_O is the on-time of the zero vector. Once the switch duty cycle of each switching pattern is decided based on (1)-(4), the input power factor will be improved and the output current ripples will be reduced.

IV. AUTO-RESTARTING STRATEGY DURING INPUT POWER INTERRUPTIONS

The matrix converter has many advantages described as the previous session. Due to the lack of the dc-link capacitor in the main power stage, the ability of the power interruptions for a matrix converter is worse when compared to a conventional dc-link converter. In Fig. 4, a clamped circuit is used for the matrix converter. The clamped circuit is used to store the energy during the interrupting condition. The size of the capacitor in the clamped circuit is smaller than the dc-link capacitor [8]. To maintain the control circuits and DSP normally operate when the input power interrupting, the voltage value of the capacitor C_{clamp} should be kept within a suitable range. Otherwise, the voltage in the capacitor of the clamped circuit rapidly reduces and then the control circuits and DSP shut down immediately. When the input power returns to a normal condition, the motor can not restart automatically. As a result, the matrix converter drive system has to wait until the motor stops completely. Finally, the drive system can be operated again.

The required dc voltages of the control circuits and the DSP are provided by the capacitor C_{clamp}. As a result, the capacitor voltage has to be kept within a certain level. There are two major schemes to maintain the voltage in the capacitor C_{clamp} near a constant when the input power interrupts. The first method is to increase the capacitor of the clamped circuit. The second method is to use the continuously rotating mechanical energy of the motor and load. In this paper, the energy generating by the motor and load is used. The energy can keep the voltage of the capacitor C_{clamp} near a constant. As a result, it is not required to add any hardware circuit or increase the size of the capacitor of the clamped circuit. This scheme is easy to be adopted in the industry and is discussed as follows.

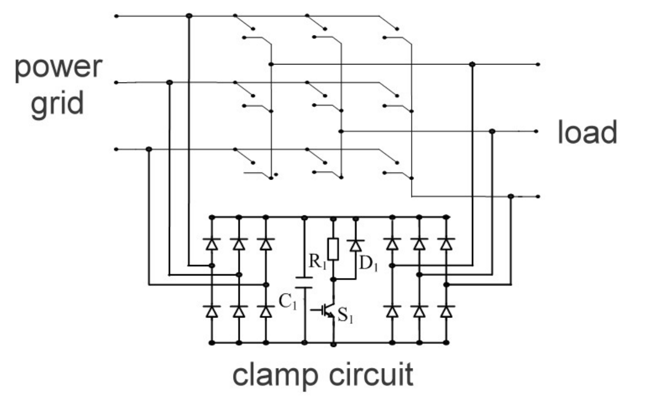


Figure 4. The clamped circuit of the matrix converter.

In the paper, the photograph of the proposed circuit is shown in Fig. 5. The circuit provides the required voltage for the control circuits and DSP. The voltage of the capacitor C_{clamp} is decreases when the input power interrupts. At that moment, the voltage generating from the motor is used to sustain and prolong the capacitor voltage level within a reasonable range. The energy transferred from motor to the capacitor is controlled by the matrix converter. Only two switching patterns are used in this control process. If all three switches on the same line are turned on, it is defined as a "closed" state. Then, the mechanical energy of the motor is transferred to the inductance of the motor. The stator currents of the motor are increased and the capacitor voltage of the clamped circuit is decreased. Fig. 6(a) shows the circuit of the "closed" state. The other switching pattern is all of switches of the matrix converter are turned off, It is defined as an "open" state. The energy stored in the motor is now released into the capacitor of the clamped circuit through the 3-phase rectifier circuit. The voltage of the capacitor is increased and the stator currents of the motor are decreased. Fig. 6(b) shows the circuit and the motor currents circulating path of the "open" state.

The constant voltage control method and hysteresis voltage control method are proposed in this paper to maintain the capacitor voltage keep as a constant under power interrupts. The first method is the constant voltage control. The matrix converter should alternate between "closed" state and "open" state in each sampling period. The drawback of this method is the switching losses are quite high. The second method is the hysteresis voltage control. For the hysteresis voltage control method, the voltage of the capacitor can be maintained within a suitable range. The voltage provides the control circuits and DSP to make them work properly. The maximum and minimum voltages of the range are expressed as $V_{c,max}$ and $V_{c,min.}$ In this method, the switching state is selected according to the voltage value of the C_{clamp}. If its voltage is below $V_{c,min}$, the "open" state should be executed; on the other hand, if the voltage of C_{clamp} is beyond $V_{c,max}$, then, the "closed" state is chosen.

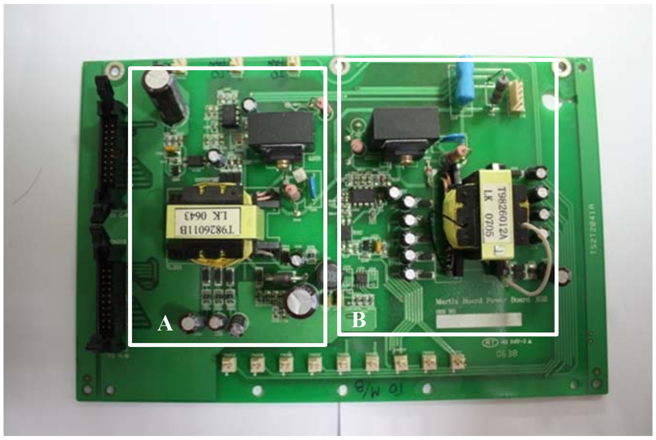
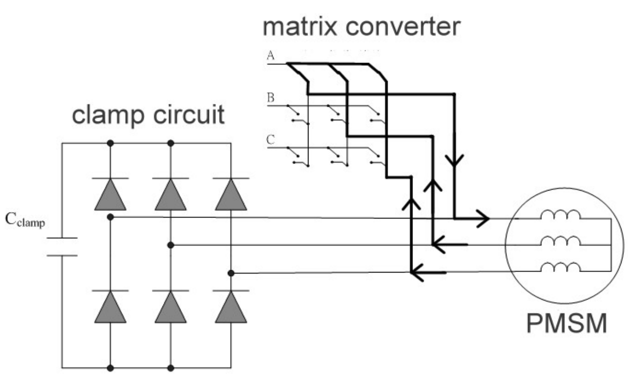
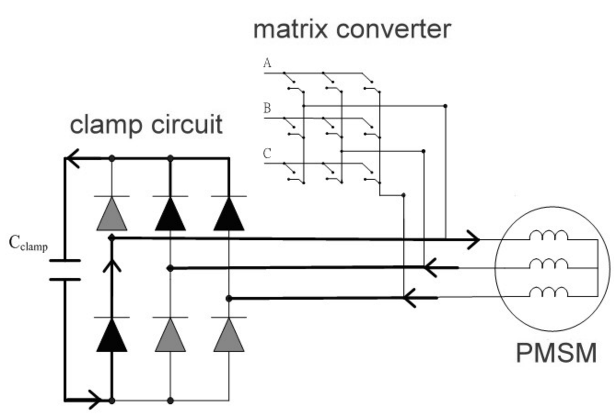


Figure 5. The photograph of the proposed circuit.



(a)



(b)

Figure 6. The currents circulating path in the matrix converter and clamped circuit (a) the "closed" state (b) the "open" state.

The currents of the motor are also detected. Once the current amplitude exceed the maximum current value, the switch in the clamped circuit turns on immediately to force the energy of the capacitor to be dissipated by the resistor. When capacitor voltage is below $V_{c,min}$, the "open" state is executed to decrease the currents of the motor.

V. Experimental Results

Some experimental results are shown here. Fig. 7 and Fig. 8 show photographs of the main power board and the control circuit board respectively. Fig. 9 shows the steady-state output current waveforms of the PMSM system under 2 N-m external load. Fig. 10 shows the voltages of the capacitor and power supply for DSP. The results reveal that the control methods can extend the sustaining ability of the power supplies for control circuits and DSP. The restarting ability of the motor during power interruptions is shown in Fig. 11. Fig. 12 shows the steady-state input current waveforms of the PMSM system under 2 N-m external load.

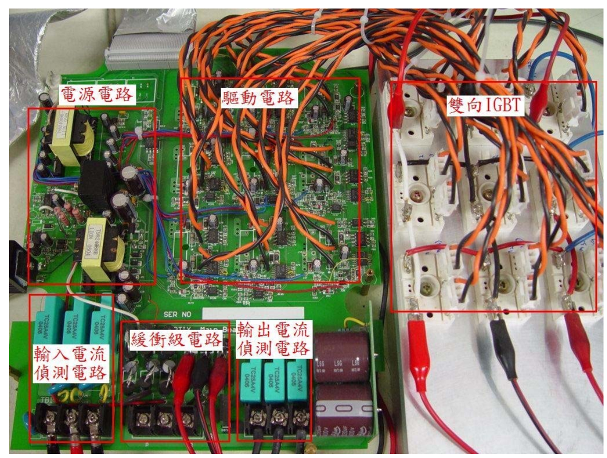


Figure 7. The photograph of the main power board.

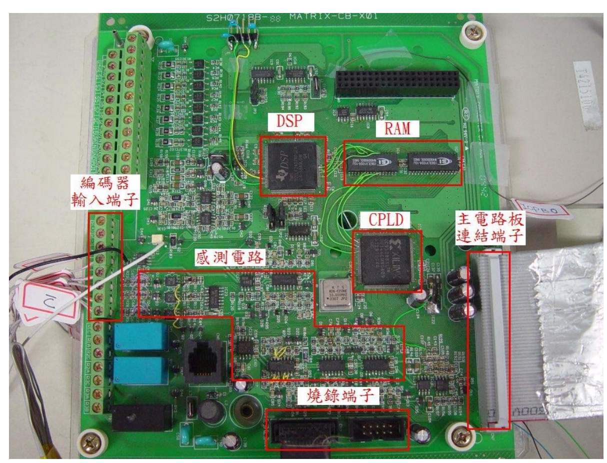
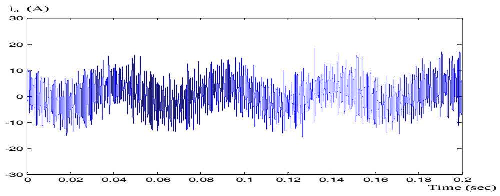
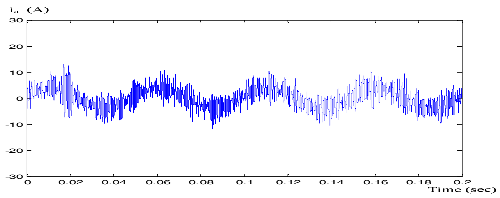


Figure 8. The photograph of the control circuit board.

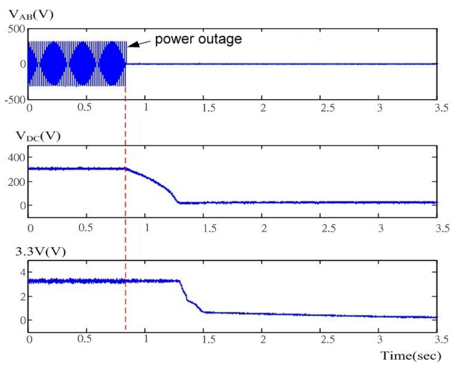


(a)

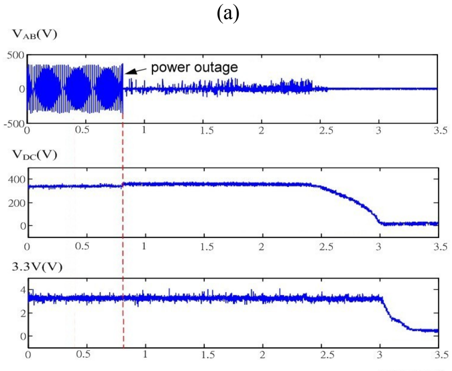


(b)

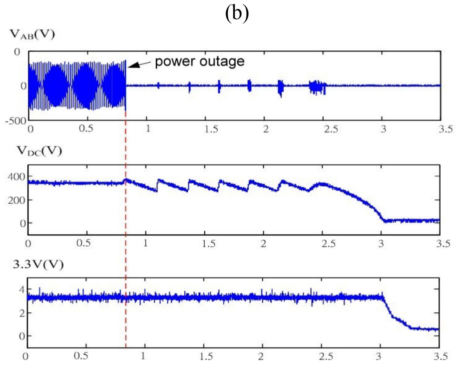
Figure 9. The output waveforms of the matrix converter (a) output current with fixed dc-link voltage (b) output current with adjusted dc-link voltage.



(a)

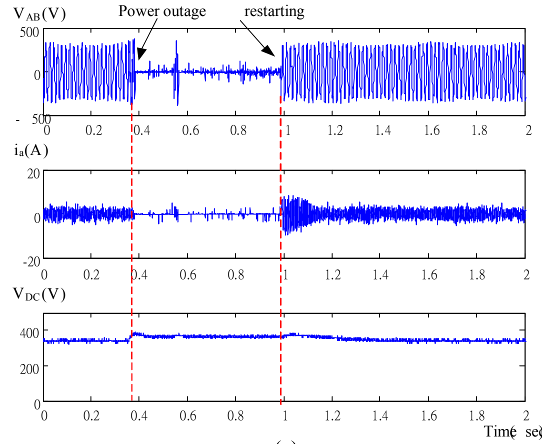


(b)

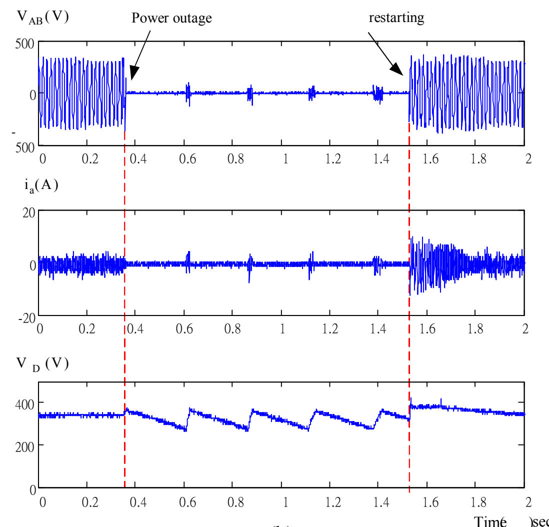


(c)

Figure 10. The sustaining ability of the control circuits and DSP (a) uncontrolled (b) constant voltage control method (c) hysteresis voltage control method.

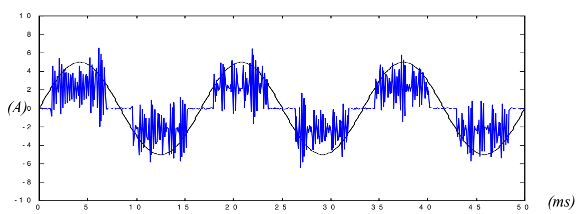


(a)

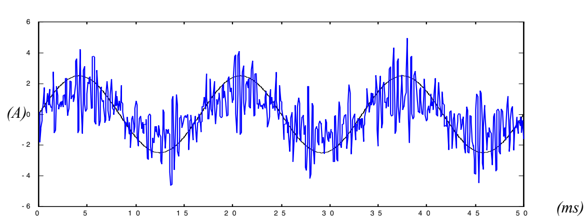


(b)

Figure 11. The restarting ability during power interruptions (a) constant voltage control method (b) hysteresis voltage control method.



(a)



(b)

Figure 12. The input waveforms of the matrix converter (a) input current with fixed dc-link voltage (b) input current with adjusted dc-link voltage.

VI. Conclusions

The paper proposes a current regulated switching strategy for a matrix converter. In this control strategy, the pseudo dc-link voltage is modulated based on the input currents and the motor speed. By using this strategy, the output current ripples are obviously reduced and unity power factor can be achieved. Power quality can be improved. The matrix converter is also used to drive a PMSM servo motor. In addition, the ability to maintain the working of the control circuits and DSP normally under power grid temporary interruptions is also effectively improved. When the power grid has returned to normal, the motor will restart automatically. All the control loops, including the switching strategy, current-loop, and control law, are implemented by TMS320LF2407A digital signal processor. As a result, the system has satisfactory performance as a servo drive system.

Acknowledgment

This study was supported by the National Science Council of R.O.C. under the grant NSC95-2221-E-018-030.

References

[1] P. W. Wheeler, J. Rodriguez, J. C. Chars, L. Empringham and A. Weinstein, "Matrix converters: a technology review," *IEEE Trans. Ind. Electron.*, vol. 49, no. 2, pp. 276-288. 2002.

[2] J. Vadillo, J. M. Echeverria, L. Fontan, M. Martinez-Iturralde, I. Elosegui, "Modeling and simulation of a direct space vector modulated Matrix Converter using different switching strategies," in *Proc. IEEE SPEEDAM'08*, June 2008, pp. 944-949.

[3] M. Milanovic and B. Dobaj, "Unity input displacement factor correction principle for direct AC to AC matrix converters based on modulation strategy," *IEEE Trans. Circuits Syst. I*, vol. 47, no. 2, pp. 221-230, Feb. 2000.

[4] Y. D. Yoon, S. K. Sul, "Carrier-based Modulation Method for Matrix Converter with Input Power Factor Control and under Unbalanced Input Voltage Conditions, " in *Conf. Rec. IEEE-APEC Annu. Meeting*, Feb./Mar. 2007, pp. 310-314.

[5] A. Arias, L. Empringham, G. M. Asher, P. W. Wheeler, M. Bland, M. Apap, M. Sumner, J. C. Clare, "Elimination of Waveform Distortions in Matrix Converters Using a New Dual Compensation Method, " IEEE Transactions on Industrial Electronics, Vol. 54, Iss. 4, pp. 2079-2087, 2007.

[6] S. Kim, S. K. Sul, and T. A. Lipo, "AC/AC power conversion based on matrix converter topology with unidirectional switches," *IEEE Trans. Ind. Applicat.*, vol. 36, no. 1, pp. 139-145, Jan./Feb. 2000.

[7] S. Bouchiker, G. A. Capolino, and M. Poloujadoff, "Vector control of a permanent-magnet synchronous motor using ac-ac matrix converter," *IEEE Trans. Power Electron.*, vol. 13, no. 6, pp. 1089-1099, Nov. 1998.

[8] C. Klumpner and F. Blaabjerg, "Short Term Breaking Capability During Power Interruptions for Integrated matrix converter—Motor Drives," *IEEE Trans. Power Electron.*, vol. 19, no. 2, pp. 303-311, Mar. 2004.

[9] J. K. Kang, H. Hara, A. M. Hava, E. Yamamoto, E. Watanabe, and T. Kume, "The matrix converter drive performance under abnormal input voltage conditions," *IEEE Trans. on Power Electron*., vol. 17, no. 5, pp.721-730. 2002.

[10] C. Klumpner, P. Nielsen, I. Boldea and F. Blaabjerg, "New solutions for a low-cost power electronic building block for matrix converters," *IEEE Trans. Ind. Electron.*, vol. 49, no. 2, pp. 336-342. 2002.