An Automatic Disturbance Rejection Controller for Matrix Converter

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Abstract –The scholars find great interest in matrix converter because of its great merits. But the researches mainly focus on open-loop control, and emphasis on the design of modulation strategy. Because the output and input lines are directly connected in matrix converter, the disturbance and unbalance of input lines affect the quality of the output waveform directly. Furthermore, in high efficient vector control systems, power converters are normally controlled to track reference output current in closed-loop. Apparently, it is necessary to control matrix converters in closed-loop. This paper establishes the model of matrix converters in *d-q* frame via PARK transformation. Since the closed-loop controller is relatively independent of the power electronic circuits, an automatic disturbance rejection controller (ADRC) for output current tracking is designed by applying ADRC algorithm to a matrix converter modulated by space vector modulation. Simulation results indicate that the controller have the advantages of good steady and dynamic performances, and it is strongly robust.
Keywords –Matrix Converter; Automatic Disturbance Rejection Control; Space Vector Modulation

INTRODUCTION

Inspired by the great merits of high power density, bi-directional energy flow and free power factor regulation, the scholars find great interests in matrix converters (MC). The researchers propose many control strategies. Among them, double line-to-line voltage synthesis [1] and space vector modulation [2] are mostly practical. But most of the present researches regard output voltage as control objective. And they are open-loop basically. The research on its closed-loop control is rarely reported [3,4,5]. In traditional voltage source inverter(VSI), the quality of output waveform is decided by the modulation strategy since the voltage of the DC-link is stable. In common motion control system, it's usually regarded as a unit gain component or delay component and controlled in open-loop. But in matrix converters, the output and input lines are directly connected. So the disturbance and unbalance of the inputs also affect the quality of the output waveform. Furthermore, in high efficient vector control system, power converter is normally controlled to track reference output current in close-loop. So it is obvious that it is very meaningful to control matrix converter in closed-loop.

The most classical technique in closed-loop control algorithm is no more than PID. Although simple, it occupies a leading position in process control. Advanced modern control theory is still difficult to find a right place in industrial control field. PID control eliminates error based on process error. Its mechanism is independent of plant model. But the simply dealing with the error between expected behavior and actual one is its limitation. The auto-disturbance rejection control [6,7] is a kind of non-linear robust control technique proposed by Jinqing Han. It absorbs the soul of PID, combines with the modern control theory's understanding in control system and the modern signal processing technique. Generally the Auto-Disturbance Rejection Controller(ADRC) consists of three parts: Tracking-Differential (TD), Extended State Observer (ESO) and Nonlinear State Error Feedback control law (NLSEF). It can track the input quickly without overshoot, estimate each order states of system and the disturbance effect to system in real time, and produce the correct controlled quantity. Then ADRC compensates the system parameter disturbance of the model, suppresses the disturbance outside the system at the same time. For the strong robustness, auto-disturbance rejection control gets the great concern [8,9,10].

This paper makes the series connection of rectifier and inverter as the equivalent circuit of matrix converter, based on the soul of undirected control. Via PARK transformation, the model of matrix converter is built in *d-q* coordinate frame. This paper introduces ADRC based on the virtue inverter modulated by voltage space vector to keep the output current track the reference current accurately and quickly. Two ADRCs in *d-q* coordinates respectively are designed, regarding the *d-q* axis cross-coupling and uncertain items of the matrix converter model as system's disturbance, and expecting output current as controller's reference signal, PWM modulation quantity as controlled quantity. Finally the simulation is carried out with MATLAB/Simulink.

UNDIRECTED CONTROL OF MATRIX CONVERTER

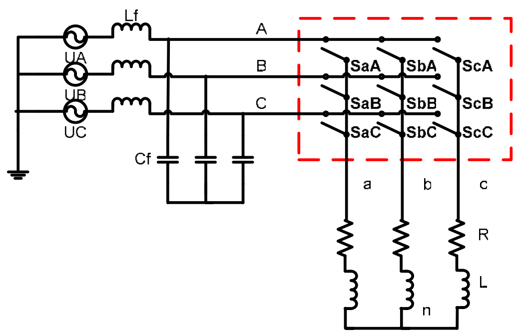

Fig. 1: Topology of matrix converter

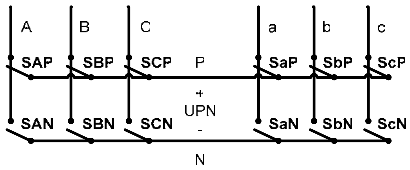

Fig. 2: Equivalent structure of matrix converter

The soul of undirected control of matrix converter makes the series connection of rectifier and inverter as the equivalent circuit of matrix converter. The topology of matrix converter is shown in Fig. 1.And Fig. 2 describes its equivalent structure. Define switch function S_{jk} ($j \in \{A,B,C,a,b,c\}, k \in \{P,N\}$): 1 for on and 0 for off. Because the input can't be short-circuited, and the output can't be interrupted, there is the restraint

$$\begin{cases} S_{Ak} + S_{Bk} + S_{Ck} = 1 \\ S_{jP} + S_{jN} = 1 \end{cases} \tag{1}$$

Then the transformation relationship of equivalent AC-DC -AC converter is

$$\begin{aligned} [u_a, u_b, u_c]^T &= [S_{aP}, S_{bP}, S_{cP}]^T u_P + [S_{aN}, S_{bN}, S_{cN}]^T u_N \\ &= \begin{bmatrix} S_{aP}\cdot S_{AP} + S_{aN}\cdot S_{AN} & S_{aP}\cdot S_{BP} + S_{aN}\cdot S_{BN} & S_{aP}\cdot S_{CP} + S_{aN}\cdot S_{CN} \\ S_{bP}\cdot S_{AP} + S_{bN}\cdot S_{AN} & S_{bP}\cdot S_{BP} + S_{bN}\cdot S_{BN} & S_{bP}\cdot S_{CP} + S_{bN}\cdot S_{CN} \\ S_{cP}\cdot S_{AP} + S_{cN}\cdot S_{AN} & S_{cP}\cdot S_{BP} + S_{cN}\cdot S_{BN} & S_{cP}\cdot S_{CP} + S_{cN}\cdot S_{CN} \end{bmatrix} \begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} \end{aligned} \tag{2}$$

And the direct transformation relationship of real matrix converter is

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} S_{aA} & S_{aB} & S_{aC} \\ S_{bA} & S_{bB} & S_{bC} \\ S_{cA} & S_{cB} & S_{cC} \end{bmatrix} \begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} \tag{3}$$

So, the relationship of switch functions below is easy to be derived.

$$S_{lm} = S_{lP}S_{mP} + S_{lN}S_{mN}, l \in \{a,b,c\}, m \in \{A,B,C\} \tag{4}$$

After this equivalent course, all kind of significant pulse width modulation (PWM) algorithms for rectifier and inverter can be contributed to the control of matrix converter. The real switch value of matrix converter can be got through (4) by the switch value of virtual rectifier and inverter in a certain instant

If the control objective is output current, the virtual inverter can be controlled by the current control algorithms of traditional inverter based on the soul of undirected control for matrix converter. In those algorithms, hysteresis control is simplest. And its response speed is fast, robustness is strong. But its switching frequency is not stable, and its harmonic random allocates. Triangle wave comparison algorithm is practical too. It amplifies the current error Δi between reference signal i^* and output signal i . Then Δi is compared with the triangle carrier wave. The amplifier is normally P- or PI-typed. Although the current response speed of latter algorithm is slower than the former one, the latter outputs less harmonic content and harmonic with the same frequency of carrier wave. The latter algorithm produces the modulating signal of output voltage by the current error after controlled by PID controller. Then the sine wave pulse modulation (SPWM) is done. It indicates a good way: to use close-looped control algorithms to make the output current track the reference current rapidly, and the control signal it produced is realized by common modulation strategy.

In 1989, Huber and Borojevic proposed the space vector modulation (SVM) of matrix converter. The virtual rectifier is modulated by current space vector to gain balancing sine wave input current and regulated power factor. The virtual inverter is modulated by voltage space vector to produce balancing output voltage with its amplitude and frequency regulated. Unfortunately they only did the research of open-looped control. But the noiseproof feature of SVM is poor. When the input voltage is unbalancing, the output voltage contain low frequency range of harmonic content which with the angular frequency of $\omega_o \pm 2\omega_i$ [11] and is very difficult to eliminated. Reference [12,13] proposed modulating rate time varied method and negative sequence injecting method to improve the output voltage waveform respectively. If the strongly robust control algorithm and highly efficient SVM are combined, it is not necessary to modify the modulation strategy to gain the aim of quickly and accurately tracking for output current.

ADRC FOR CURRENT TRACKING

A. d-q frame model of matrix converter

General, suppose the load of matrix converter is resistive and inductive as is shown in Fig. 1. Matrix converter is equivalent as a controlled current source to its input end, and a controlled voltage source to its output end based on the soul of undirected control. The delay feature can be neglected since the course of PWM is completed instantly. So in the output end

$$u_x = L\frac{di_x}{dt} + Ri_x + u_n \quad ,(x = a,b,c) \tag{5}$$

where, u_x is the output voltage of phase *abc*, and i_x is the current voltage of three phases, u_n is the voltage of Y connected point of load. The variables above are all in mean value. *R* and *L* is the resistance and induction of per phase of three phase balancing load.

The *d-q* frame model of matrix converter (see (6)) is derived by transforming (5) from *abc* frame to *d-q* frame by PARK transformation (shown in (7), and let ω equal to the expected output angular frequency ω_o). Because the voltage of Y connected point of load is not easy to be measured, look on u_{nd} and u_{nq} in the model of matrix converter as uncertain items. From (6), we can see, the model still contains coupled items and un-certain ones which may affect the accuracy of control system although after PARK transformation.

$$\begin{cases} L\dfrac{di_d}{dt} = u_d - Ri_d + \omega_o L i_q - u_{nd} \\ L\dfrac{di_q}{dt} = u_q - Ri_q - \omega_o L i_d - u_{nq} \end{cases} \quad (6)$$

$$C_{abc-dq} = \sqrt{\frac{2}{3}}\begin{bmatrix} \cos\omega t & \cos\left(\omega t - \dfrac{2\pi}{3}\right) & \cos\left(\omega t + \dfrac{2\pi}{3}\right) \\ \sin\omega t & \sin\left(\omega t - \dfrac{2\pi}{3}\right) & \sin\left(\omega t + \dfrac{2\pi}{3}\right) \end{bmatrix} \quad (7)$$

B. ADRC of matrix converter

Two current ADRCs are designed by looking on the sum of coupled items and uncertain items in the model: $\varpi_d(t) = \omega_o L i_q - u_{nd}$ and $\varpi_q(t) = -\omega_o L i_d - u_{nq}$ as system's inner disturbance. The control block diagram of system is shown in Fig. 3.

Construct a second order ESO

$$\begin{cases} \dot{z}_{2,1} = z_{2,2} - k_{21}\,\mathrm{fal}(\varepsilon_2, \alpha_2, \delta_2) + u_q \\ \dot{z}_{2,2} = -k_{22}\,\mathrm{fal}(\varepsilon_2, \alpha_2, \delta_2) \end{cases} \quad (10)$$

where, $\varepsilon_2 = z_{2,1} - i_q$ .The auto-disturbance rejection control law will be gained as (11) depending on the nonlinear function of system feedback state error $\varepsilon = z_{1,1} - z_{2,1}$

$$\begin{cases} u_0 = k\,\mathrm{fal}(\varepsilon, \alpha, \delta) \\ u_q = u_0 - z_{2,2} \end{cases} \quad (11)$$

All the parameters, that is k_1, α_1, δ_1, k_{21}, k_{22}, α_2, δ_2, k, α, and δ are all obtained by simulation attempting.

C. Undirected control algorithm

Close-looped controller is relatively independence from the power electronic circuits, Any kinds of modulation strategies can be regarded as a certain operation mode of the power electronic circuits. So the modulation strategy is only the means for close-looped controller to be imple mented.

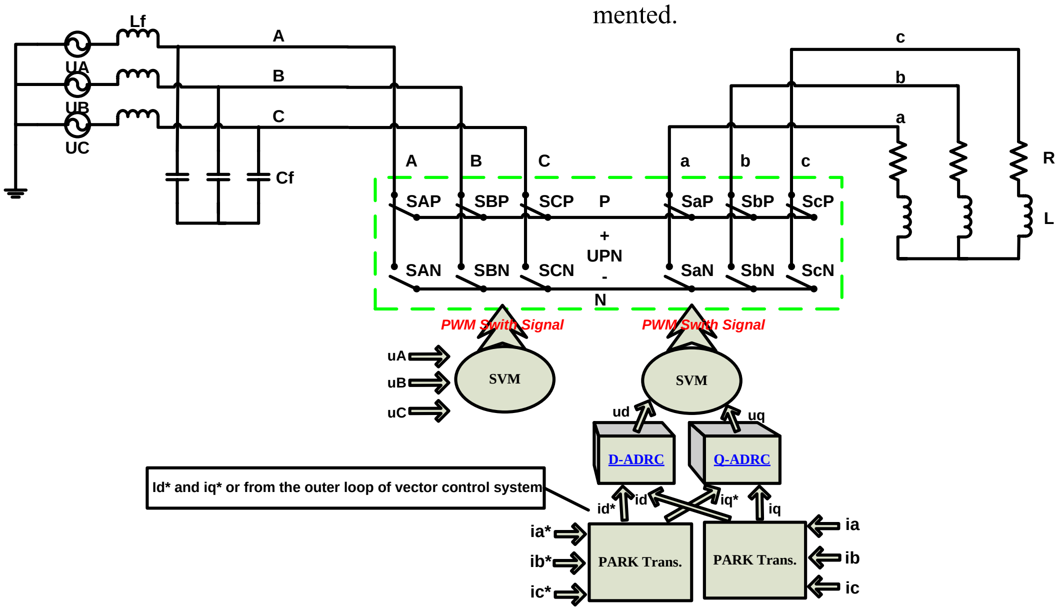

Fig. 3 Control block diagram of system

Because the principle and parameters of two axis controllers are in the same, the q-axis controller is illustrated below. Set the expected output current i_q^* as the reference input of ADRC, output current of matrix converter i_q as system output, modulation quantity of virtual inverter u_q as control value, and making output current i_q track the reference output i_q^* as control objective. Set the output of one order TD

$$\dot{z}_{1,1} = -k_1\,\mathrm{fal}((z_{1,1} - i_q^*), \alpha_1, \delta_1) \quad (8)$$

The definition of nonlinear function fal is

$$\mathrm{fal}(\varepsilon_i, \alpha, \delta) = \begin{cases} |\varepsilon_i|^{\alpha}\,\mathrm{sgn}(\varepsilon_i) & |\varepsilon_i| > \delta \\ \varepsilon_i / \delta^{1-\alpha} & |\varepsilon_i| \le \delta \end{cases} \quad (9)$$

The selection of modulation strategy is free, depending on varied aims of control. The control quantity of the d-q axis ADRCs, i.e. the pulse width modulation quantity of virtual inverter u_d and u_q can be modulated by two ways. One, they are transformed to *abc* frame, then are compared with triangle wave to produce the PWM switch value after amplitude adjusted. The other, they are synthesised to a voltage space vector then anticipate SVM. In steady state, the former is SPWM intrinsically. But the DC voltage utilization ratio of SPWM is not high. And it outputs high frequency harmonic which is ready to make the machine inverter loaded generate heat and the torque of machine ripple even the system oscillate. Reference [14] analysis three modulation strategies: SPWM, SVPEM, and THIPWM, of machine considered main flux saturated. It suggests that SVPWM increase the DC voltage utilization ratio, and decrease the torque ripple of machine. SVPWM is the optimal selection. Considered synthetically, SVM algorithm is selected to modulate the virtual inverter.

As for the virtual rectifier, SVM is adopted again. The detail of modulation course is described in many literatures [2] , so it is not necessary to be repeated in this paper. If the trigger method of three phase diode rectifier is applied to the virtue rectifier, though the input power factor is lower, the maximum DC voltage is so high to 514.8V that it can compensate the shortcoming of low voltage gain of matrix converter. In this case, the switch function is

$$\begin{cases} S_{AP}=1 & ,u_A=\max(u_A,u_B,u_C) \\ S_{BP}=1 & ,u_B=\max(u_A,u_B,u_C) \\ S_{CP}=1 & ,u_C=\max(u_A,u_B,u_C) \\ S_{AN}=1 & ,u_A=\min(u_A,u_B,u_C) \\ S_{BN}=1 & ,u_B=\min(u_A,u_B,u_C) \\ S_{CN}=1 & ,u_C=\min(u_A,u_B,u_C) \end{cases} \quad 0,\text{ the other time} \qquad (12)$$

SIMULATION RESULT

The simulation is done with the help of MATLAB/Simulink. The double PWM undirected controlled model is selected for matrix converter. The switches are substituted by the ideal switches. The power supply is 220V in 50Hz. Every phase of input filter is L_f =15mH and C_f =6μF. Every phase of the balancing load is R=2.8750Ω and L=8.5mH. The reference output current is 10A in amplitude, 50Hz in frequency, balancing in three phases, and in positive sequence. The sample cycle is 0.0002s for SVM. And the parameters of ADRC are k_1 =500000, α_1=0.8, δ_1=0.01; k_{21}=80000, k_{22}=3000000, α_2 =0.5, δ_2 = 0.01; k =700, α =1,and δ =0.01.

(1) Fig. 4 shows the real output current i_d and reference current i_d^* in d-axis. The q-axis ones are shown in Fig. 5.

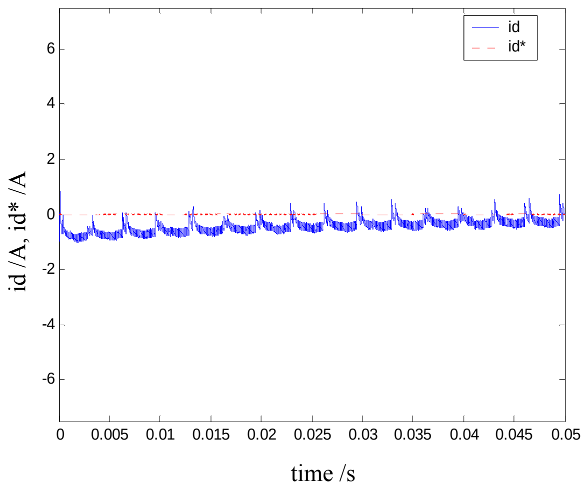

Fig. 4: The current of d-axis i_d and i_d^*

The minute tremble is due to the high frequency noise of switch devices. In fact, it indicates the noise doesn't affect the quality of output waveform too much after the real current value in d-q frame is transformed to abc frame. Fig. 6 shows the effect of the output current of phase a after transformation. What's more, the output waveform is still good when the reference output frequency is changed to 25Hz as is shown in Fig. 7. So the conclusion can be made that the steady performance of the controller is ideal.

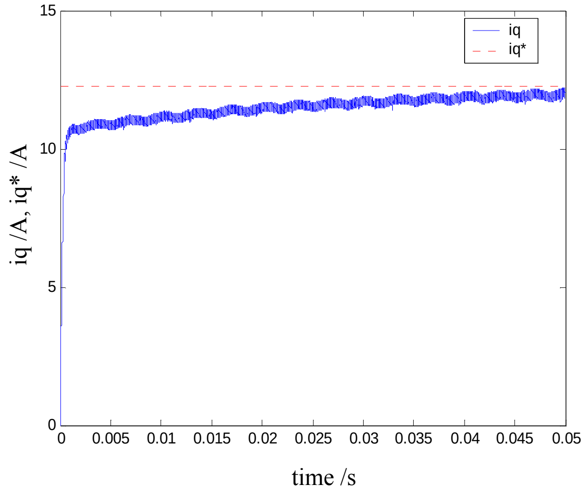

Fig. 5: The current of q-axis i_q and i_q^*

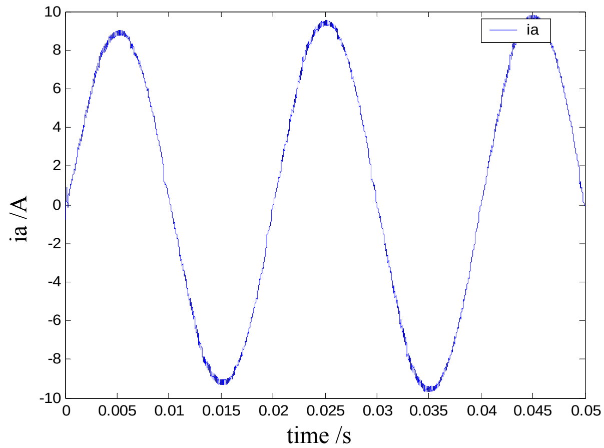

Fig. 6: The current of phase a i_a in 50Hz

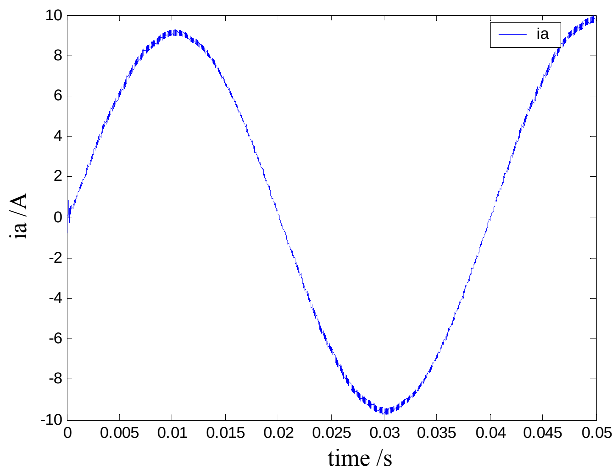

Fig. 7: The current of phase a i_a in 25Hz

(2) Do the simulation by setting the waveforms of i_d^* and i_q^* as square wave. Fig. 8 and 9 is i_d^* / i_d and i_q^* / i_q respectively. When the reference signal is rapidly changed, the output current can still keep tracking the reference accurately and quickly. So the dynamic performance of the controller is good.

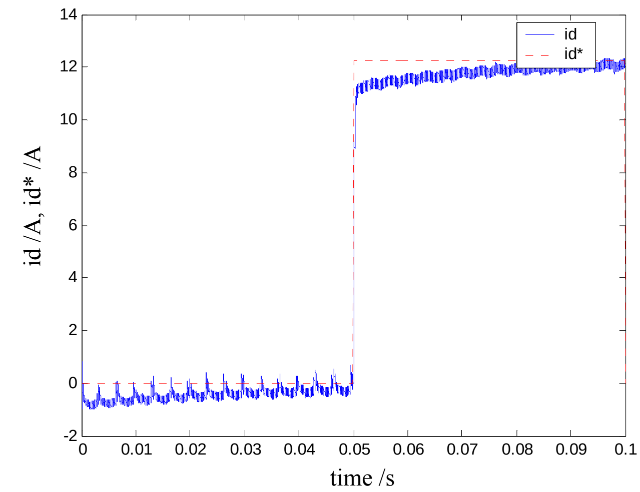

Fig. 8: The effect of tracking square wave in *d*-axis

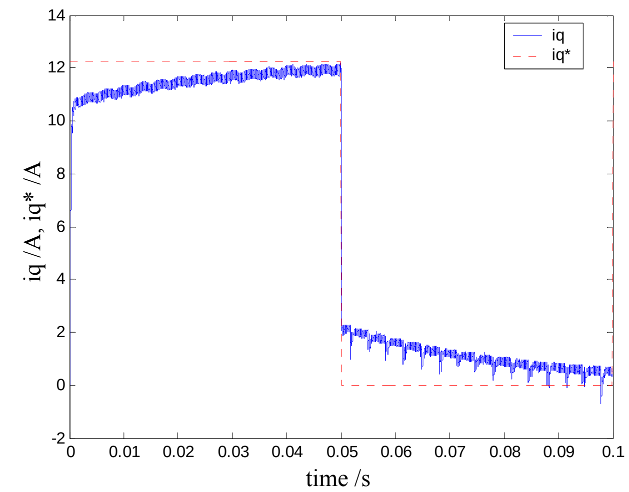

Fig. 9: The effect of tracking square wave in *q*-axis

(3) The disturbance of objective parameters and unbalance of power supply are the main disturbance of system worth considering. Fig. 10 shows the current of phase a when the load is changed to R =5Ω and L =10mH per phase. When

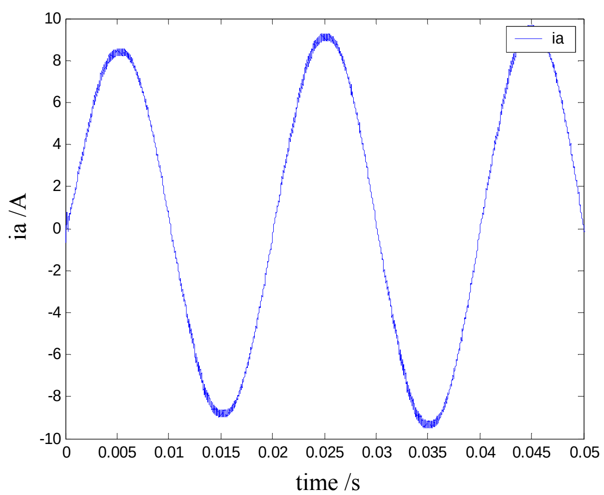

Fig. 10: The output current i_a when the load is changed

the power supply is changed to unbalancing as $\dot{U}_A = 436.8\angle16.7^\circ, \dot{U}_B = 394.8\angle-126.79^\circ, \dot{U}_C = 235.6\angle108.54^\circ$ but still in 50Hz, the real output current of phase a is shown in Fig. 11. Compared Fig.10/11 with Fig. 6, they are almost in the same. It proves the controller strongly robust.

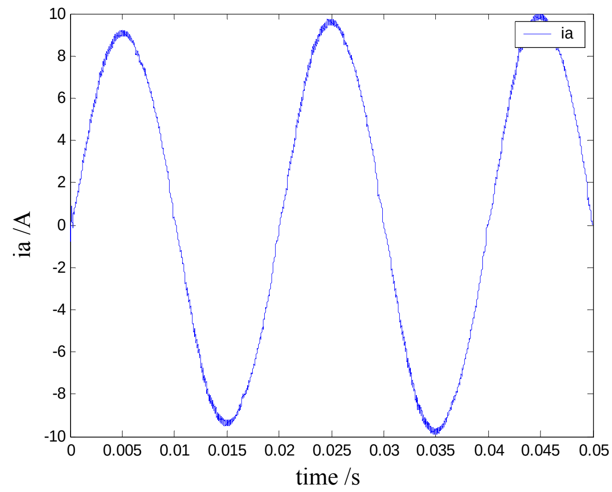

Fig. 11: The output current i_a when the power supply is unbalancing

CONCLUSION

(i) The *d-q* frame model of matrix converter decreases the number of controllers for system. And it's convenient to interface with the outer loop in vector control system. Especially, the significant virtue of this kind of model is the model composed by DC items after PARK transformation is convenient to apply modern control theory to the control of matrix converter.

(ii) The matrix converter doubly space vector modulated processes the virtue of power factor regulated freely. But the implementation of double SVM is somewhat troublesome. And its voltage gain is only 0.866. If the trigger method of three phase diode rectifier is applied to the virtue rectifier, although the input current contains many harmonic content and the input power factor is lower, the maximum DC voltage is higher which can compensate the shortcoming of low voltage gain of matrix converter. The selection of modulation strategy is free, depending on varied aims of control.

(iii) Closed-loop controller is relatively independence from the power electronic circuits, it's a good idea to combine strongly robust auto-disturbance rejection control with highly efficient space vector modulation to control matrix converter. .Furthermore, the disturbance rejection capability of SVM is poor, When the input voltage is unbalancing, the output voltage contain low frequency of harmonic which is very difficult to be eliminated. When the DC-link voltage ripples, the output voltage of inverter offset from the reference immediately. Because matrix converter contains no capacitor components in its virtual DC-link, the ripple of DC voltage is inevitable. The ADRC can compensate the error of modulation because of its strongly robustness. So the control effect is ideal.

(iv) The selection of parameters of ADRC must be attempted by simulation many times. The parameters once enter the stable zone, their range of selection is very wide. If the order of system is higher, the parameters that need be attempted increase markedly. Debug in hand becomes very trouble. In this case, the searching and optimizing methods such as Genetic Algorithm (GA) can be applied to search the best parameters.

ACKNOWLEDGMENT

This project is the Key Project of *Tenth Five* Science and Technology Layout of Guangdong Province (China) (A1050401), the project of Research Group of Fund of Natural Science of Guangdong Province (China) (003049), and supported by the Fund of Natural Science of Guangdong Province (China) (020906). The author would like to acknowledge these funds.

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