Research on Controlling of Tri-level Shunt Power Quality Conditioner

Man-Chung Wong* Chang-Jiang Zhan** Yu Han** Liang-Bing Zhao** Ying-Duo Han*
* Dept. of Electrical and Electronics Engineering
University of Macau,
Macau.
**Dept. of Electrical Engineering
Tsinghua University, Beijing, 100084
P. R. China.

Abstract: Controlling technology is the key problem to realize compensation of power quality with converter. A new method was proposed for the control of the Three-Phase Tri-level Voltage Source Shunt Power Quality Conditioner. The mathematical model of Tri-level Converter is addressed in detail. Reference current is calculated under synchronous d-q frame and advanced deadbeat control with Voltage Space Pulse Width Modulation is used to trace the reference current. Results of computer simulation under MATLAB show good dynamic performance of the proposed scheme to compete the function of compensating harmonics, reactive current and imbalance.

Keywords: Power Quality, Tri-level Converter, Deadbeat Control, Voltage Space Vector Pulse Width Modulation, Harmonics, Reactive Power, Imbalance

I. INTRODUCTION

To improve the power quality is one of the main research topics in power system. Recently, the power quality can be further improved due to the development of power electronics technology, digital signal processors and the control technique. However, controlling technology is the key issue to achieve compensation of power quality with converter. In this paper, a new method was proposed for the control of the Three-Phase Tri-level Voltage Source Shunt Converter as a power quality conditioner. The mathematical model of the Tri-level Shunt Converter is addressed in detail. Based on the concept of Switching Function and Space Vector and cited the coordinate transformation matrix on space reference frame in the unified theory of an AC motor, the mathematical model of Tri-level converter model is presented. The shunt converter can be used as a current source. However, battery is placed instead of dc-link capacitor in converter, it can work as an inverter to supply active power and one part of the peak-load current.

Reference current is calculated under synchronous d-q frame and advanced deadbeat control with Voltage Space Vector Pulse Width Modulation is used to trace the reference current. The system dynamics are represented by state-space model, which allows a computation of state variables at the end of a sampling interval from the initial values and the control and the distribution variables. By setting the system states to the desired values at the end of the sampling interval and by inverting the system model, a control vector can be computed, which shall drive the states to the reference signal in one T_s. Advanced deadbeat control is the modified version of deadbeat control method to overcome the drawback of it. The combination of Advanced Deadbeat Control and Vector Space PWM shows the robust operation of this new control method applied in Tri-level Shunt Converter can be achieved. Results of a computer simulation under MATLAB show good dynamic performance of the proposed scheme to compete the function of compensating harmonics, reactive current and imbalance.

II. TRI-LEVEL CONVERTER AND ITS MATHEMATICAL MODEL

The structure of Voltage Source Shunt Tri-level Converter is showed as the power quality compensator in Figure 1. The basic principle is to inject the same negative amplitude of harmonics into the load current in order to compensate the harmonic current. The losses of the switching devices and snubber circuits, and process of commutation are ignored so that the equivalent switched-circuit can be obtained as Figure 2.

A. Model in the abc Frame

Switching functions can be considered as equivalent switched devices such as IGBT's. e.g., in phase A,

$$S_a = \begin{cases} 1, & T_{1a} \text{ and } T_{2a} \text{ on} \text{ ,but } T_{3a} \text{ and } T_{4a} \text{ off} \\ 0, & T_{2a} \text{ and } T_{3a} \text{ on} \text{ ,but } T_{1a} \text{ and } T_{4a} \text{ off} \\ -1, & T_{3a} \text{ and } T_{4a} \text{ on} \text{ ,but } T_{1a} \text{ and } T_{2a} \text{ off} \end{cases} \quad (1)$$

S_a may be written as:

(1) if $S_a = 1$, then $S_{1a} = 1$, $S_{2a} = 0$, $S_{3a} = 0$;
(2) if $S_a = 0$, then $S_{1a} = 0$, $S_{2a} = 0$, $S_{3a} = 1$;
(3) if $S_a = -1$, then $S_{1a} = 0$, $S_{2a} = 1$, $S_{3a} = 0$;

In the Fig.2, the boundary condition of S_{1a}, S_{2a} and S_{3a} is defined as：

$$\begin{cases} S_{1a} + S_{2a} + S_{3a} = 1 \\ S_{1a} = 1 \text{ or } 0, S_{2a} = 1 \text{ or } 0, S_{3a} = 1 \text{ or } 0 \end{cases} \quad (2)$$

The relation among the ac-side compensating current, the terminal voltage of converter can be expressed as equation (3) according to Figure 2.

$$\begin{cases} L_c \dfrac{di_{ca}}{dt} = -R_c \cdot i_{ca} - v_a + v_{sa} \\ L_c \dfrac{di_{cb}}{dt} = -R_c \cdot i_{cb} - v_b + v_{sb} \\ L_c \dfrac{di_{cc}}{dt} = -R_c \cdot i_{cc} - v_c + v_{sc} \end{cases} \quad (3)$$

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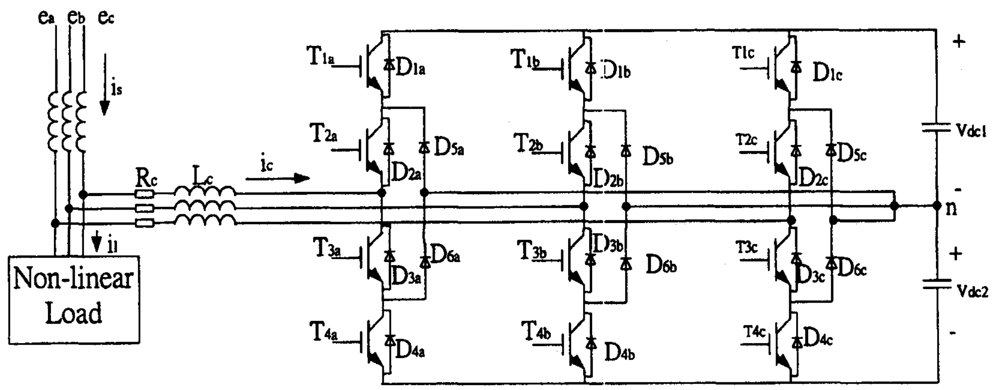

Figure 1

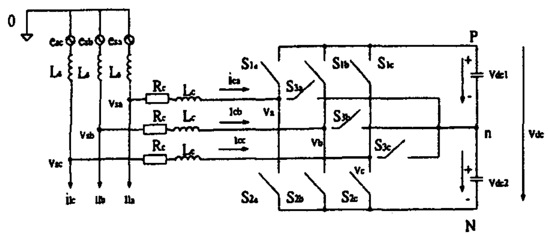

Fig.2 (Equivalent Circuit)

By using the switching functions, the relation between the terminal voltage (v_a, v_b, v_c) and the dc-link voltage (v_{dc1}, v_{dc2}) can be expressed as (4).

$$\begin{cases} v_a = \left(S_{1a} - \dfrac{S_{1a}+S_{1b}+S_{1c}}{3}\right)\cdot v_{dc1} - \left(S_{2a} - \dfrac{S_{2a}+S_{2b}+S_{2c}}{3}\right)\cdot v_{dc2} \\ v_b = \left(S_{1b} - \dfrac{S_{1a}+S_{1b}+S_{1c}}{3}\right)\cdot v_{dc1} - \left(S_{2b} - \dfrac{S_{2a}+S_{2b}+S_{2c}}{3}\right)\cdot v_{dc2} \\ v_c = \left(S_{1c} - \dfrac{S_{1a}+S_{1b}+S_{1c}}{3}\right)\cdot v_{dc1} - \left(S_{2c} - \dfrac{S_{2a}+S_{2b}+S_{2c}}{3}\right)\cdot v_{dc2} \end{cases} \quad (4)$$

A general mathematical model of the Tri-level Converter can be established as follows:

$$\boldsymbol{Z}\dot{\boldsymbol{X}} = \boldsymbol{A}\boldsymbol{X} + \boldsymbol{B}\boldsymbol{U} \quad (5)$$

, where

$$X = \begin{bmatrix} i_{ca} & i_{cb} & i_{cc} & V_{dc1} & V_{dc2} \end{bmatrix}^T$$

$$\boldsymbol{B} = \mathrm{diag}\begin{bmatrix} 1 & 1 & 1 & 0 & 0 \end{bmatrix}$$

$$\mathbf{U} = \begin{bmatrix} v_{sa} & v_{sb} & v_{sc} & 0 & 0 \end{bmatrix}$$

$$\mathbf{Z} = \mathrm{diag}\begin{bmatrix} L_c & L_c & L_c & C_d & C_d \end{bmatrix}$$

B. Model in the Stationary $\alpha\beta$ Frame

In studying AC machine, certain quantities are found to have variables in which are sinusoidal in the time and are often distributed in space. For the three-phase converter, all variables are defined in the time but not in space. However, it is still beneficial to quote the concept of space vector for studying rectifiers or inverters. Cited the coordinate transformation matrix on space reference frame in the unified theory of an AC motor, the "space" can be mathematically regarded as a complex plane rather than a "physical space". Define Park vector as follows:

$$A = \begin{bmatrix} -R_c & 0 & 0 & -\left(S_{1a} - \dfrac{S_{1a}+S_{1b}+S_{1c}}{3}\right) & \left(S_{2a} - \dfrac{S_{2a}+S_{2b}+S_{2c}}{3}\right) \\ 0 & -R_c & 0 & -\left(S_{1b} - \dfrac{S_{1a}+S_{1b}+S_{1c}}{3}\right) & \left(S_{2b} - \dfrac{S_{2a}+S_{2b}+S_{2c}}{3}\right) \\ 0 & 0 & -R_c & -\left(S_{1c} - \dfrac{S_{1a}+S_{1b}+S_{1c}}{3}\right) & \left(S_{2c} - \dfrac{S_{2a}+S_{2b}+S_{2c}}{3}\right) \\ S_{1a} & S_{1b} & S_{1c} & 0 & 0 \\ -S_{2a} & -S_{2b} & -S_{2c} & 0 & 0 \end{bmatrix}$$

$$\begin{cases} \vec{V}_S = \sqrt{\frac{2}{3}}\left(V_{SA} + \alpha \cdot V_{SB} + \alpha^2 \cdot V_{SC}\right) \\ \vec{i}_S = \sqrt{\frac{2}{3}}\left(i_{SA} + \alpha \cdot i_{SB} + \alpha^2 \cdot i_{SC}\right) \end{cases} \tag{6}$$

where $\alpha = e^{j\frac{2\pi}{3}}$, $\alpha^2 = e^{-j\frac{2\pi}{3}}$,

Then, $$\begin{cases} \vec{V}_S = L_c \frac{d\vec{i}_c}{dt} + R_c \vec{i}_c + \vec{V} \\ \vec{V} = \vec{V}_1 - \vec{V}_2 \end{cases} \tag{7}$$

and $$\begin{cases} \vec{V}_1 = V_{dc1} \cdot (S_{1\alpha} + jS_{1\beta}) \\ \vec{V}_2 = V_{dc2} \cdot (S_{2\alpha} + jS_{2\beta}) \end{cases} \tag{8}$$

with $$\begin{cases} S_{1\alpha} + jS_{1\beta} = \sqrt{\frac{2}{3}}\left[\left(S_{1a} - \frac{1}{2}S_{1b} - \frac{1}{2}S_{1c}\right) + j\left(\frac{\sqrt{3}}{2}S_{1b} - \frac{\sqrt{3}}{2}S_{1c}\right)\right] \\ S_{2\alpha} + jS_{2\beta} = \sqrt{\frac{2}{3}}\left[\left(S_{2a} - \frac{1}{2}S_{2b} - \frac{1}{2}S_{2c}\right) + j\left(\frac{\sqrt{3}}{2}S_{2b} - \frac{\sqrt{3}}{2}S_{2c}\right)\right] \end{cases} \tag{9}$$

and $$\begin{cases} C_d \frac{dV_{dc1}}{dt} = S_{1\alpha} \cdot i_{s\alpha} + S_{1\beta} \cdot i_{s\beta} \\ C_d \frac{dV_{dc2}}{dt} = -(S_{2\alpha} \cdot i_{s\alpha} + S_{2\beta} \cdot i_{s\beta}) \end{cases} \tag{10}$$

So a mathematical model of the tri-level system in the stationary $\alpha\beta$ frame is established as follows:

$$Z\dot{X} = AX + BU \tag{11}$$

where

$$Z = diag[L_c L_c C_d C_d]$$
$$X = [i_{s\alpha} i_{s\beta} V_{dc1} V_{dc2}]^T$$
$$B = diag[1100]$$
$$U = [V_{s\alpha} V_{s\beta}]^T$$

$$A = \begin{bmatrix} -R_c & 0 & -S_{1\alpha} & S_{2\alpha} \\ 0 & -R_c & -S_{1\beta} & S_{2\beta} \\ S_{1\alpha} & S_{1\beta} & 0 & 0 \\ -S_{2\alpha} & -S_{2\beta} & 0 & 0 \end{bmatrix}$$

C. Model in the Rotating dq Frame

The transformation relation can be given as followings for dq frame:

$$T_{dq/\alpha\beta} = T_{\alpha\beta/dq}^{-1} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \tag{12}$$

$$\begin{cases} L_c \frac{di_{cd}}{dt} = -R_c i_{cd} + \omega L_c \cdot i_{cq} - V_d + V_{sd} \\ L_c \frac{di_{cd}}{dt} = -R_c i_{cq} - \omega L_c \cdot i_{cd} - v_q + V_{sq} \end{cases} \tag{13}$$

$$\begin{cases} V_d = V_{d1} - V_{d2} \\ V_q = V_{q1} - V_{q2} \end{cases} \tag{14}$$

and $$\begin{cases} \begin{bmatrix} S_{d1} & S_{q1} \end{bmatrix}^T = T_{dq/\alpha\beta} \cdot \begin{bmatrix} S_{\alpha 1} & S_{\beta 1} \end{bmatrix}^T \\ \begin{bmatrix} S_{d2} & S_{q2} \end{bmatrix}^T = T_{dq/\alpha\beta} \cdot \begin{bmatrix} S_{\alpha 2} & S_{\beta 2} \end{bmatrix}^T \end{cases} \tag{15}$$

Then it will be

$$\begin{cases} L_c \frac{di_{cd}}{dt} = -R_c i_{cd} + \omega L_c i_{cq} - V_{dc1} \cdot S_{d1} + V_{dc2} \cdot S_{d2} + V_{Sd} \\ L_c \frac{di_{cq}}{dt} = -R_c i_{cq} - \omega L_c i_{cd} - V_{qc1} \cdot S_{q1} + V_{dc2} \cdot S_{q2} \end{cases} \tag{16}$$

With $$\begin{cases} C_d \frac{dV_{dc1}}{dt} = S_{d1} \cdot i_{cd} + S_{q1} \cdot i_{cq} \\ C_d \frac{dV_{dc2}}{dt} = -(S_{d2} \cdot i_{cd} + S_{q2} \cdot i_{cq}) \end{cases} \tag{17}$$

So a mathematical model of the tri-level system in the rotating *dq* frame is established as follows:

$$Z\dot{X} = AX + BU \tag{18}$$

where

$$Z = diag[L_c L_c C_d C_d]$$
$$X = [i_{cd} i_{cq} V_{dc1} V_{dc2}]^T$$
$$B = diag[1100]$$
$$U = \left[\sqrt{\frac{3}{2}} V_{sm} \, 0\right]^T$$

$$A = \begin{bmatrix} -R_c & \omega L_c & -S_{d1} & S_{d2} \\ -\omega L_c & -R_c & -S_{q1} & S_{q2} \\ S_{d1} & S_{q1} & 0 & 0 \\ -S_{d2} & -S_{q2} & 0 & 0 \end{bmatrix}$$

It should be pointed out that the power supply here is ideal. The further analysis can be achieved after we have this mathematical model of Tri-level converter in abc, $\alpha\beta$ and dq frames.

III. CONTROL STRATEGY

The control system of the Shunt Tri-level Power Quality Conditioner can be divided into two parts: inner current loop and outer voltage loop. The purpose of the outer voltage loop is to keep the dc-link voltage of the converter

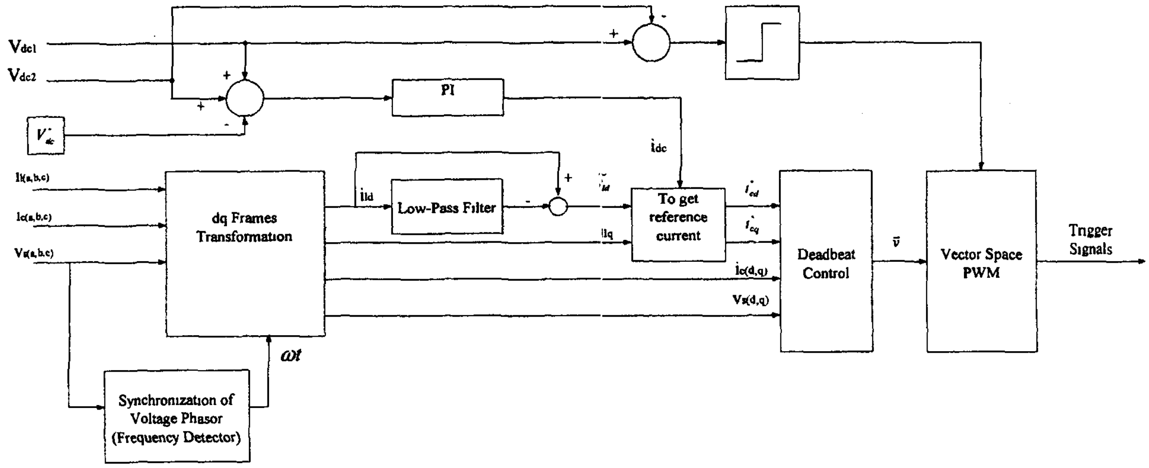

Figure 3

to be constant. The transient process of the outer voltage loop is much lower than the dynamic change of the inner current loop so that the proportional and integration control can fulfill the need. In Figure 3, it shows the control strategy. The voltage source, load current and the converter current are sampled and analyzed. The trigger pulses are generated at last by the combination of Deadbeat Control and Vector Space PWM Control. Low-pass filter is employed to obtain the oscillating components of i_{ld}.

To find the compensating current, dq-transformation of current (i_{la}, I_{lb} and i_{lc}) is needed first so that i_{cd} and i_{cq} can be obtained. The same-phase current, i_{cd} , with the voltage $\vec{e}_s$ will be the active current to supply the active power. On the other hand, the out-of-phase current, i_{cq}, with the voltage $\vec{e}_s$ is the reactive current. In the dq frame, the fundamental current will be transferred as a dc component. The load current can be decomposed into:

$$\begin{cases} i_{ld} = \bar{i}_{ld} + \tilde{i}_{ld} \\ i_{lq} = \bar{i}_{lq} + \tilde{i}_{lq} \end{cases} \qquad (19)$$

The purpose of compensation is to let the current in which exists only fundamental component and synchronizes with the $\vec{e}_s$ so that the compensating parameters are:

$$\begin{cases} i_{cd}{}^{*} = -\tilde{i}_{ld} + i_{dc} \\ i_{cq}{}^{*} = -i_{lq} \end{cases} \qquad (20),$$

where i_{dc} is the dc-link voltage control parameter as i_{dc} is used to keep the dc-link voltage to be constant due to the energy releasing from or storing into the dc-link capacitor in converter.

The dq compensating strategy can be utilized as the benefit of using it is that the voltage variation can be ignored comparing to the instantaneous real and imaginary power technique. However, the normalization of instantaneous real and imaginary power strategy where $e_\alpha^2 + e_\beta^2 = 1$ is assumed can be taken in order to take out the voltage variation effect and actually it is equivalent to dq compensating technique. Also, when only the reactive power is going to be compensated, the dc part of i_{lq} is taken only.

A. Deadbeat Control

By the state-of-art of the development of microprocessor or digital signal processors, the control of power electronics devices have been adopted to the digital control than the analog one. The DSP makes the achievement of very complicated control strategy possible.

The Dead Beat Control is employed with the Vector Space PWM to generate the pulse patterns for IGBT's. Usually, there are some papers to discuss the Deadbeat control [5], it is used in the rectifier mode operation and motor drive so that the perfect sinusoidal waveform is needed to produce by Deadbeat Control. But, in this paper, Dead Beat Control is considered to compensate the harmonics, reactive power and imbalance. The advantages of Deadbeat Control are the stiff mathematical deduction and its good dynamic response. The system dynamics are represented by (20) which is the equation (5), which allows a computation of the state variables at the end of a sampling interval from initial values, the control and disturbance variables.

$$\dot{X} = AX + BU \qquad (20)$$

By setting the system states equal to the desired values at the end of the sampling interval and by inverting the system model, a control vector can be computed, which shall drive the states to the reference signals in one T_s. The discrete state-space model can be obtained as (21).

$$X(k+1) = GX(k) + HU(k) \qquad (21)$$

where

$$\begin{cases} \mathbf{G} = e^{AT} \\ \mathbf{H} = \left(\int_0^T e^{At} dt\right) B = (e^{AT} - \mathbf{I})\mathbf{A}^{-1}\mathbf{B} \end{cases} \qquad (22)$$

X is the state variable matrix, U is the input variable matrix. By setting the reference states to X_{ref} instead of X(k+1), then equation (21) can be re-written as (23).

$$U(k) = H^{-1}(X_{ref}(k+1) - GX(k)) \qquad (23)$$

According to the equation (23), the control variables U(k) can be obtained and the estimated variable $X_{k+1} = X_{ref}$ is employed. However, it will generate one step delay and it just can ensure that the states at k+1 will equal to the states at k sample.

In dq frame, the mathematical model of system can be expressed as (24).

$$\begin{cases} L_c \dfrac{di_{cd}}{dt} = -R_c i_{cd} + \omega L_c i_{cq} - v_d + v_{sd} \\ L_c \dfrac{di_{cq}}{dt} = -R_c i_{cq} - \omega L_c i_{cd} - v_q + v_{sq} \end{cases} \tag{24}$$

The G and H can be computed according to equation (22) and discrete state variables are considered so that equation (25) can be obtained.

$$\begin{bmatrix} i_{cd}(k+1) \\ i_{cq}(k+1) \end{bmatrix} = G \begin{bmatrix} i_{cd}(k) \\ i_{cq}(k) \end{bmatrix} + H \begin{bmatrix} -v_d(k)+v_{sd}(k) \\ -v_q(k)+v_{sq}(k) \end{bmatrix} \tag{25}$$

When the actual load current is sampled at k and the reference current in d and q frames can be expressed (26).

$$\begin{cases} i_{cd}^*(k) = -\tilde{i}_{ld}(k) \\ i_{cq}^*(k) = -i_{lq}(k) \end{cases} \tag{26}$$

The reference current (26) puts into (25) instead of $i_{cd}(k+1)$ and $i_{cq}(k+1)$. Then, (27) can be deduced.

$$\begin{bmatrix} v_d(k) \\ v_q(k) \end{bmatrix} = H^{-1} G \begin{bmatrix} i_{cd}(k) \\ i_{cq}(k) \end{bmatrix} + H^{-1} \begin{bmatrix} i_{cd}^*(k) \\ i_{cq}^*(k) \end{bmatrix} + \begin{bmatrix} v_{sd}(k) \\ v_{sq}(k) \end{bmatrix} \tag{27}$$

At last, $v(k) = [v_d(k), v_q(k)]$ can be considered as the reference of voltage vector which can be generated by the vector space pulse width modulation at k sampling time so that $i_c(k+1) = i_c^*(k)$ can be achieved.

B. Advanced Deadbeat Control

Deadbeat Control can be used with acceptable error for the slow changing waveform due to the assumption that X_{ref} = X(k+1) is taken. However, there will be obvious error when the fast changing waveform exits such as sag. The sharp error will be adhered to the waveform when there is any sudden change. In this paper, the pervious period of waveform was recorded and this stored data used as the predicted picture for next period of signal so that the advanced deadbeat control was proposed such as (28), where n is the n^{th} period of fundamental component of waveform at k^{th} sample.

$$\begin{cases} i_{cd}^*(n,k) = -\tilde{i}_{ld}(n-1,k+1) \\ i_{cq}^*(n,k) = -i_{lq}(n-1,k+1) \end{cases} \tag{28}$$

As we know that in normal operation, the load may change in a short time. It may consider that after a few periods it may reach steady state and lasts long for some periods so that the above assumption can be acceptable to use in active filter. However, when there is random signals in the waveform, this kind of compensation technique is still needed to have further improvement.

IV. SIMULATION RESULTS

Fig. 4 shows the conventional simulation result of compensation of harmonics by Deadbeat Control method. However, it is obvious that it generate the current sag in compensated current. Fig. 5 shows the improvement made by Advanced Deadbeat Control method.

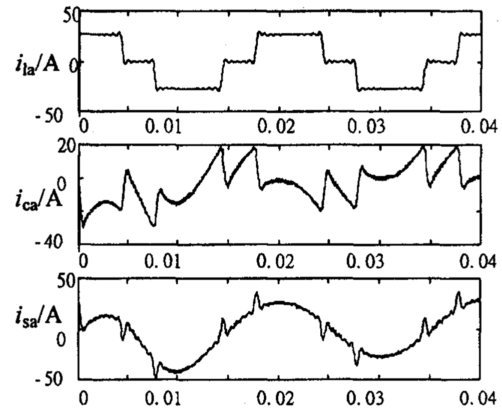

Fig. 4

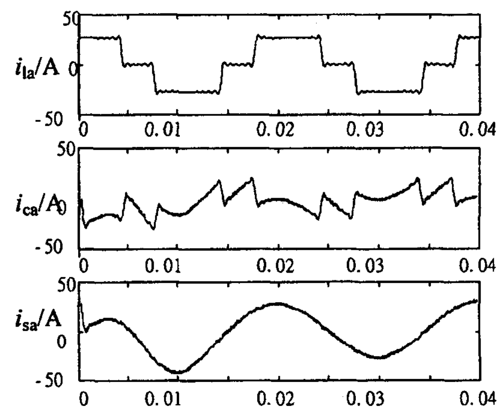

Fig. 5

The simulation parameters are: V_{sm}=311v (Peak voltage and Balanced 3-Phase Voltage), f=50Hz, L_s=0.6mH, R_c=0.5 Ω , L_c = 3mH, C_d=4700 μF and V_{dc}=1200V. The load is nonlinear: 3-Phase Bridge Rectifier Circuit with resistive and inductive loads. The sampling frequency is 4.8kHz.

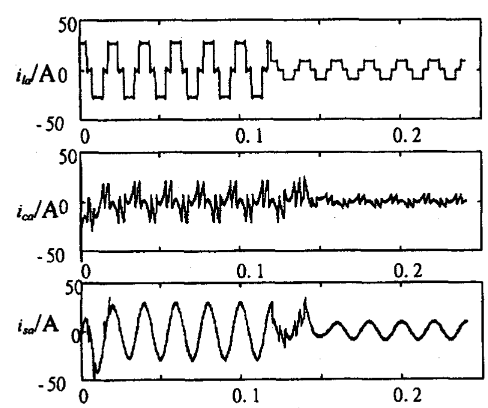

Fig. 6

Fig. 6 shows the dynamic response of this Shunt Tri-Level Power Quality Conditioner. The dynamic response is quite good and the THD is improved from 29.42% to 3.73%. Fig.

7 shows the dynamic current change in dq axes.

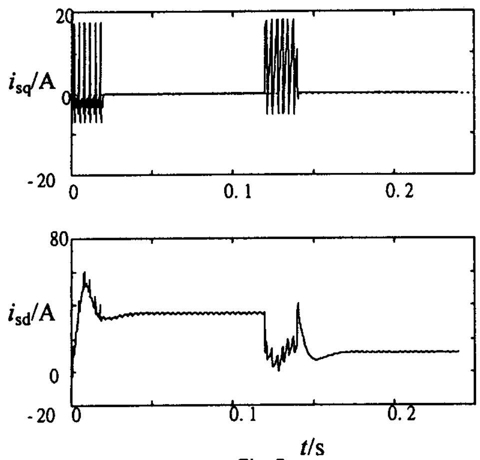

Fig. 7

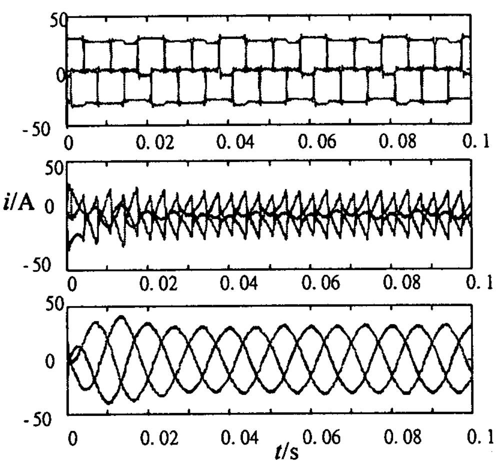

Fig.8

At last, Fig. 8 shows the compensation of Harmonics, Reactive Current and Imbalance. It is about 10% imbalance in the current.

V. CONCLUSION

In this paper, a new method was proposed for the control of the three-phase Tri-level Voltage Source Shunt Converter as a power quality conditioner. The mathematical model of the Tri-level shunt converter is addressed in detail. Advanced deadbeat Control is the modified version of deadbeat control method to overcome the drawback of it. The combination of the Advanced Deadbeat Control and Vector Space PWM shows the robust operation of this new control method applied in Tri-level Shunt Converter can be achieved. Results of computer simulation under MATLAB show good dynamic performance of the proposed scheme to complete the function of compensating harmonics, reactive current and imbalance.

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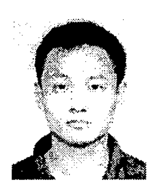
VII. BIOGRAPIES

Ying-Duo Han, Professor of the Dept. of Electrical Engineering of Tsinghua University, Member of the Chinese Academy of Engineering and Senior Research Center of Tsinghua University.
He was born in 1938 in Liaoning province of China. He received the electrical Engineering degree and Master degree from Tsinghua University in 1962 and in 1965 respectively, Doctor-degree from Erlangen-Nuernberg University, Germany in 1986. From 1986 to 1995 he was vice-chairman and chairman of the E.E. Dept.. From 1989 to 1999, he was the Head of Power Electronic Research Center of Tsinghua University. He has been engaged for more than35 years in education and research work on electric power system and automation field. He has published 2 books and more than 100 papers. Recent years he is engaged in FACTS, Intelligent Control, Regional Stability Control, Dynamic Security Estimation and Control based on GPS. Now he is working in University of Macau as a Visiting full professor and executive Director of Computer and System Engineering Institute of Macau.



Man-Chung Wong was born in Hong Kong in 1969 and obtained his B.Sc. and M.Sc. degrees in Electrical and Electronics Engineering at 1993 and 1997 respectively in University of Macau. He was a teaching assistant in University of Macau from 1993 to 1997. From 1998 up to now, he is a lecturer in University of Macau for Department of the Electrical and Electronics Engineering. Currently, he is a Ph.D. Student in Tsinghua University. His research interests are the power system, power electronics and instrumentation.

Zhan Changjiang was born in Hubei province, China in 1970. He received BSc, MSc and PhD from Huazhong University of Science and Technology, Wuhan China in 1991, 1994 and 1997 respectively. From 1997 to 1999, he worked in Tsinghua University on a subject of Distribution System Unified Conditioner (DS_Unicon) as a post-doctor. His research interests include Power Electronics, FACTS and Power quality.

Liang-Bing Zhao is the professor in the Tsinghua University, Beijing China. His research interests are the power electronics, motor drive and active filters.

Yu Han got his B.Sc degree in Tsinghua University and master degree in 1997, 1999 respectively. Her research interests are the power electronics and active filters.