Modeling of 3-D Tri-level Power Quality Conditioner

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Abstract: In this paper, Tri-level shunt connected converter is under consideration in 3-phase 4-wired system as power quality compensators and motor drivers. Mathematical model of Tri-level Shunt Converters is addressed in detail first. A novel analysis of 3 dimension 3-level converters is achieved and the generalized theory of 3D Space Vector PWM including the 2D 2-level one is studied and developed such that 2D 2-level converters is a subset of 3 D one. A new approach control method is performed and called "Sign Cubical Hysteresis Control Strategy" in 3-phase 4-wired systems. Simulation of 3-level 3-phase 4-wired system for motor drivers and power quality compensation are achieved.

Keywords: 3-level Inverter, Pulse Width Modulation, Four-Wire Active Power Filter

1. Introduction

For the high voltage power applications where no semiconductor devices are available, the multi-level VSI topologies are good alternatives. The multi-level structure not only reduces voltage stress across the switches but also has many more available vectors. Therefore, it improves harmonic contents of the VSI by selecting appropriate switching vectors. The most popular topology is the three-level inverter. The number of vectors, which can be implemented with the three-level VSI, is 27. These can be categorized into four different vectors: large-, mid-, small-, and zero-vectors.

In this paper, a new focal point was taken for the control of the Three-Phase Four-Wire 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, the mathematical model of Tri-level converter model is presented in Section 2. The shunt converter can be used as a current source controller to compensate the harmonics, reactive current and imbalance, especially the zero sequence in 3-phase 4-wire system.

A novel prototype of three-level converters is studied too. The space vector pulse width modulation of 3-phase 4-wired 3-level converters will give more degree of freedom for the switching patterns so that 3-Deminsional Space Vector Pulse Width Modulation (3D-SVPWM) will be addressed in Section 3. Within recent decades, Neutral-Pointed-Clamped multilevel converters can achieve an overall effective switch frequency modulation and consequent ripple reduction through the cancellation of the lowest order switch frequency terms. However, traditional approach of PWM current regulation is mainly focused on the two-level converter with 3-phase 3-wired system. Based on the recent survey of the active filters, static VAR compensators and motor drivers, zero sequence component of the unbalanced effect is usually ignored by reason of the simplicity. Development of 3-phase 4-wired 2-level converter is already achieved in [1] but it still has some drawbacks. It may come from that there are only 8 vectors existed in 2-level converters. One more step that can be improved by using 3-level converters can be achieved due to the 27 space vectors available in 3-level converters. It means that more degree of freedom can be chosen so that the compensation of harmonics and unbalance especially in zero sequence will be succeeded. Moreover, there are seldom papers to discuss about the 3-phase 4-wired converter system [2]-[10]. According to the above view points, the 3-level 3-phase 4-wired converter system model will retain very high prospective to have further development in future so that modeling of 3-Phase 4-Wired 3-Level converter is addressed in 3 dimension aspect.

2. 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

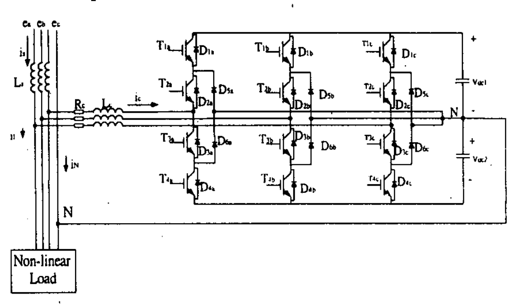

Fig. 1

the switching devices and snubber circuits, and process of commutation are ignored so that the equivalent switched-circuit can be obtained as Figure 2.

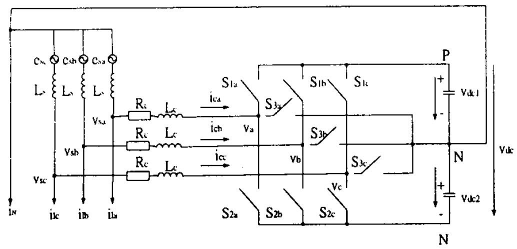

Fig. 2

The model of shunt 3-phase 4-wire 3-level converter is investigated in the abc frame. Switching functions can be considered as equivalent switched devices such as IGBT's, e.g., in phase A, 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 $S_{1a} = 0$, $S_{2a} = 0$, $S_{3a} = 1$; (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 :

$$\begin{cases} S_{1a} + S_{2a} + S_{3a} = 1 \\ S_{1a} = 1 \; or \; 0, S_{2a} = 1 \; or \; 0, S_{3a} = 1 \; or \; 0 \end{cases} \tag{2}$$

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

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

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).

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

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

$$\boldsymbol{Z\dot{X}} = \boldsymbol{AX} + \boldsymbol{BU} \tag{5}$$

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

, where

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

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

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

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

3. 2-Level and 3-Level 3 Dimension Space Vectors in 3-Phase 4-Wire System

In three-phase three-wire systems, two-dimensional (2-D) vector control is utilized [2]-[5]. This control method cannot be used in three-phase four-wire systems due to the presence of neutral current (zero-sequence component). This section presents equations that relate to three-dimensional (3-D) vector control not only for the 2-level converter but also for the 3-level one. This proposed technique could be used to control the 3-level VSI as an Active Filter for power quality improvement.

The instantaneous voltage in α,β and 0 frames can be transferred from a, b and c frames by the matrix [P], such as shown in (6).

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = [P] \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \tag{6}$$

, where $[P] = \sqrt{\dfrac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix}$.

The instantaneous voltage vector can be expressed as (7).

$$\vec{V}_S = \sqrt{\frac{2}{3}}\left(V_{SA} + \alpha \cdot V_{SB} + \alpha^2 \cdot V_{SC}\right) \tag{7}$$

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

According to the switching functions defined in (1), (7) can be expressed in $\alpha\beta0$ frames as shown in (8). It is assumed that $V_{dc1} = V_{dc2} = V_{dc}$.

$$V_s = V_{dc}\left[i\sqrt{\frac{2}{3}}\left(S_a - \frac{1}{2} \cdot S_b - \frac{1}{2} \cdot S_c\right) + j\frac{1}{\sqrt{2}}(S_b - S_c) + k\left(\frac{1}{\sqrt{3}}(S_a + S_b + S_c)\right)\right] \tag{8}$$

Furthermore, equation (8) can be defined as (9).

$$V_s = V_{dc}\left[i\sqrt{\frac{2}{3}}S_\alpha + j\frac{1}{\sqrt{2}}S_\beta + k\frac{1}{\sqrt{3}}S_0\right] \tag{9}$$

, where

$$S_\alpha = S_a - \frac{1}{2}S_b - \frac{1}{2}S_c$$

$$S_\beta = S_b - S_c$$

$$S_0 = S_a + S_b + S_c$$

However, the balancing of the neutral-point voltage variation is out of the discussion of this paper so that it is assumed that $v_{dc1} = v_{dc2}$. The 3D PWM is the main discussed topic in this paper so that $v_{dc1} = v_{dc2}$ is assumed to simplify the analysis, although it is not practical.

Figure 3 shows the Space Vector Allocation for 3-level converters. According to equation (9), there are 4 tables expressing the large, medium, small and zero voltage space vector allocation in $\alpha\beta0$ frames respectively. If the network has accessible neutral wire, a zero-sequence current component can exit. It is desired that the load current zero-sequence component be compensated by the active power filter or by the unbalance current compensator. For these cases, the zero-sequence converter current component, as well as the other components, must be controlled.

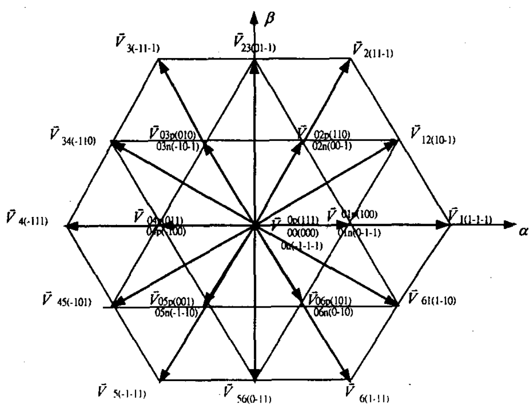

Fig. 3 (S_a, S_b, S_c)

Table 1 (Large Vectors)

	S_a	S_b	S_c	S_α	S_β	S_0
$\vec{V}_1$	1	-1	-1	2	0	-1
$\vec{V}_2$	1	1	-1	1	2	1
$\vec{V}_3$	-1	1	-1	-1	2	-1
$\vec{V}_4$	-1	1	1	-2	0	1
$\vec{V}_5$	-1	-1	1	-1	-2	-1
$\vec{V}_6$	1	-1	1	1	-2	1

Table 2 (Medium Vectors)

	S_a	S_b	S_c	S_α	S_β	S_0
$\vec{V}_{12}$	1	0	-1	1.5	1	0
$\vec{V}_{23}$	0	1	-1	0	2	0
$\vec{V}_{34}$	-1	1	0	-1.5	1	0
$\vec{V}_{45}$	-1	0	1	-1.5	-1	0
$\vec{V}_{56}$	0	-1	1	0	-2	0
$\vec{V}_{61}$	1	-1	0	1.5	-1	0

Table 3 (Small Vectors)

	S_a	S_b	S_c	S_α	S_β	S_0
$\vec{V}_{01\,p}$	1	0	0	1	0	1
$\vec{V}_{01\,n}$	0	-1	-1	1	0	-2
$\vec{V}_{02\,p}$	1	1	0	0.5	1	2
$\vec{V}_{02\,n}$	0	0	-1	0.5	1	-1
$\vec{V}_{03\,p}$	0	1	0	-0.5	1	1
$\vec{V}_{03\,n}$	-1	0	-1	-0.5	1	-2
$\vec{V}_{04\,p}$	0	1	1	-1	0	2
$\vec{V}_{04\,n}$	-1	0	0	-1	0	-1
$\vec{V}_{05\,p}$	0	0	1	-0.5	-1	1
$\vec{V}_{05\,n}$	-1	-1	0	-0.5	-1	-2
$\vec{V}_{06\,p}$	1	0	1	0.5	-1	2
$\vec{V}_{06\,n}$	0	-1	0	0.5	-1	-1

The voltage vectors in Tables 1 to 4 can be referred in Figure 3 to express the actual location in αβ frames. For simplicity, zero-axis does not show in Figure 3. When we further have consideration between 2-level 3D and 3-level 3D systems, it can be found that actually in 2-level system, what we have are the Table 1 and Table 4 only. It will be obvious to conclude that a set of 2-level 3D Voltage Space Vectors is a subset of 3-level 3-D system.

Table 4 (Zero Vectors)

	S_a	S_b	S_c	S_α	S_β	S_0
$\vec{V}_{000}$	0	0	0	0	0	0
$\vec{V}_{00\,p}$	1	1	1	0	0	3
$\vec{V}_{00\,n}$	-1	-1	-1	0	0	-3

4. Sign Cubical Hysteresis Current Controller for Shunt Power Quality Conditioner

In this section, the control strategy for this 3 dimension voltage vectors in 3-phase 4-wired system is described by using Sign Cubical Hysteresis Current Control.

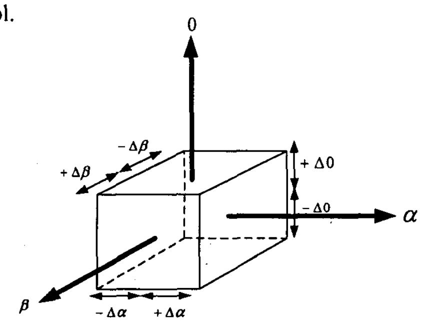

Fig. 4

Figure 4 shows the basic concept of this Sign Cubical Hysteresis Control Method. When the different between the reference signal and actual input signal is larger than Hysteresis limited value, it will trigger to positive and, vice versa, to negative. However, when the difference valve is less than the Hysteresis limit, it will be zero.

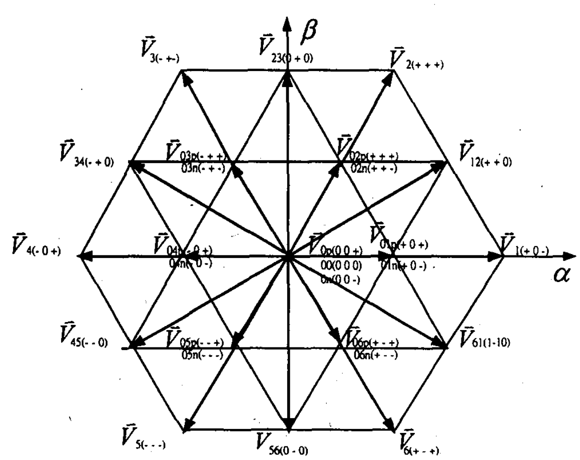

Fig. 5 (S_α,S_β,S_0)

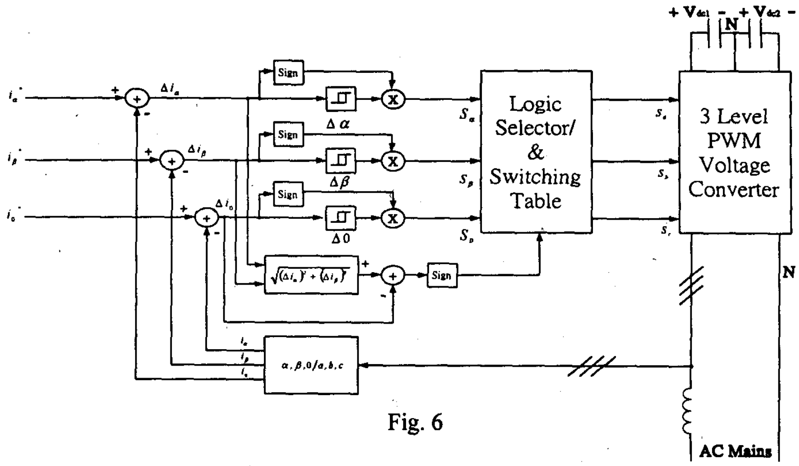

Fig. 6

Further analysis is taken for Tables 1 to 4 and Figure 3 can be redrawn for S_α, S_β, S_0 in Figure 5. It is obvious that this Sign Cubical Hysteresis Control will have two vectors in same manner such as $\vec{V}_1$ and $\vec{V}_{01n}$, $\vec{V}_2$ and $\vec{V}_{02p}$, $\vec{V}_3$ and $\vec{V}_{03n}$, $\vec{V}_4$ and $\vec{V}_{04p}$, $\vec{V}_5$ and $\vec{V}_{05n}$, and, $\vec{V}_6$ and $\vec{V}_{06p}$. For example, $\vec{V}_5$ and $\vec{V}_{05n}$, both vectors will occur at $S_\alpha < 0$, $S_\beta < 0$ and $S_0 < 0$. However, actually, $S_\alpha = -1$, $S_\beta = -2$ and S_0 -1 for $\vec{V}_5$, but $S_\alpha = -0.5$, $S_\beta = -1$ and S_0 -2 for $\vec{V}_{05n}$, in this case, $\vec{V}_{05n}$ will take more action than $\vec{V}_5$ in zero sequence compensation. At any moment, when these pair-vectors need to choose only one vector from them to take action. The amplitude of $\sqrt{(\Delta i_\alpha)^2 + (\Delta i_\beta)^2}$ is compared with Δi_0 so that it can be decided to activate which vector from those pair-vectors. Figure 6 shows the final control strategy. The neutral point voltage between V_{dc1} and V_{dc2} needs to consider to keep the difference between them as small as possible however, in this paper, the neutral point voltage balancing control is not included in this analysis. By the way, the Neutral-point voltage balancing can be performed by choosing $\vec{V}_{0Xn}$ or $\vec{V}_{0Xp}$ vectors, where X = 1,2,3,4,5 and 6.

5. Simulation Results

The simulation is preformed by MATLAB /SIMULINK for motor-drivers and power quality compensation.

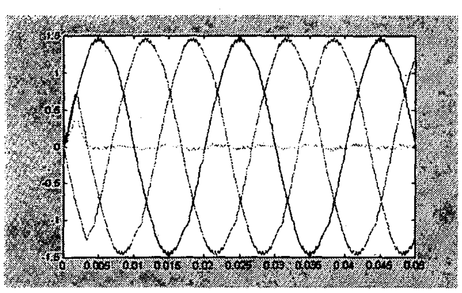

Fig. 7 (Load Current)

From Figure 7 to Figure 12, all of them are the simulation results for simple motor drive's operation in 3-phase 4-wired system. Figure 7 is the line current in a, b c and 0. Figure 8 is the 3-level voltage waveforms. Fig. 9 is the voltage space vectors in α and β axes. Fig. 10 is the 3-dimensional voltage vectors in α,β and 0 axes.

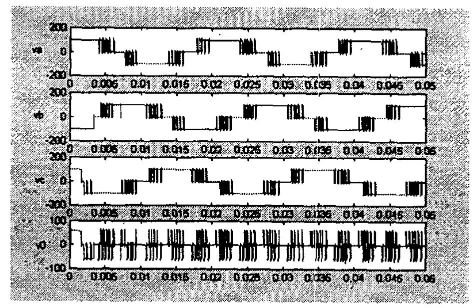

Fig. 8

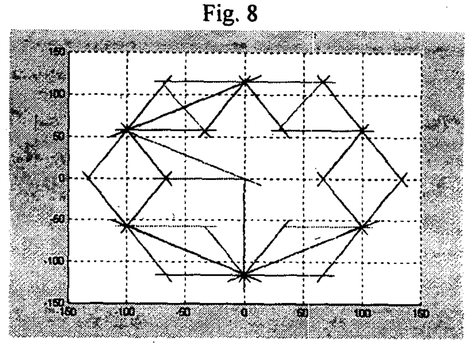

Fig. 9

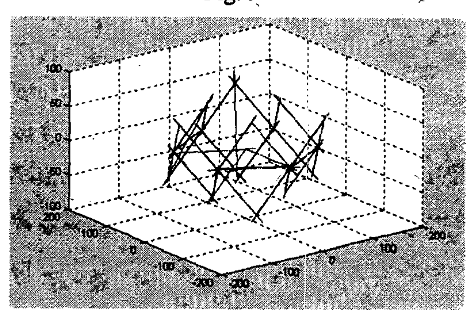

Fig. 10

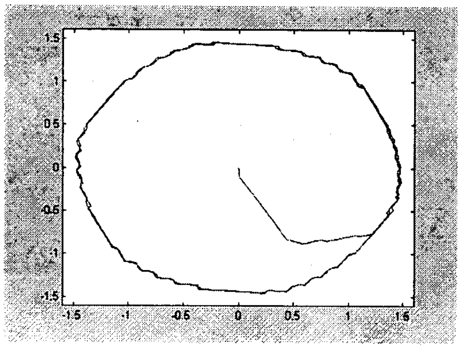

Fig. 11

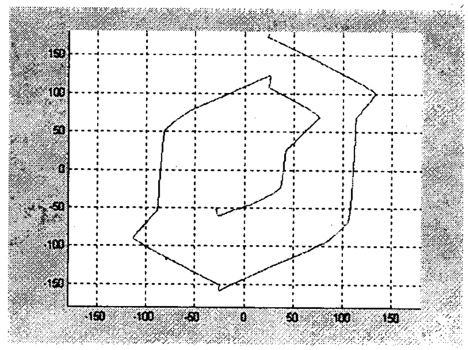

Fig. 15

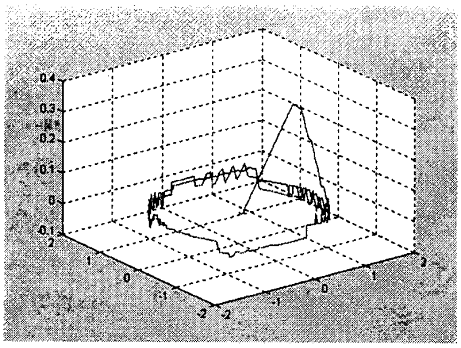

Fig. 12

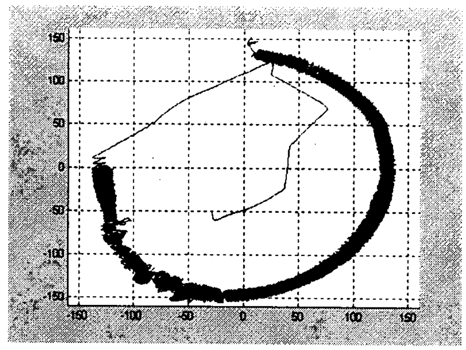

Fig. 16

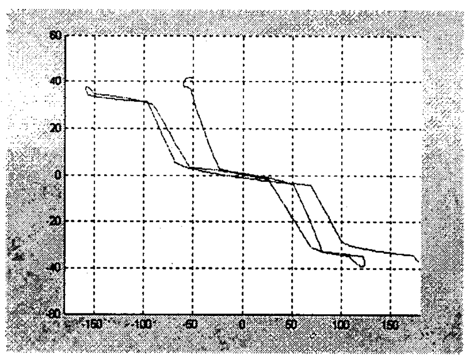

Fig. 13

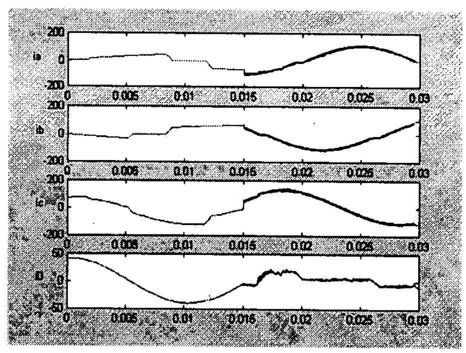

Fig. 17

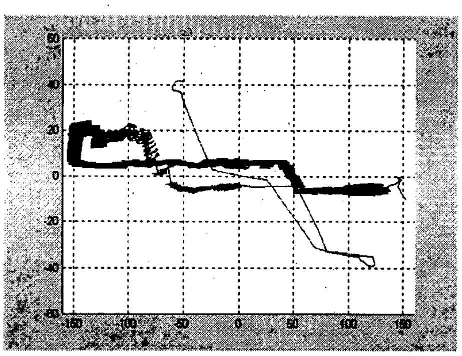

Fig. 14

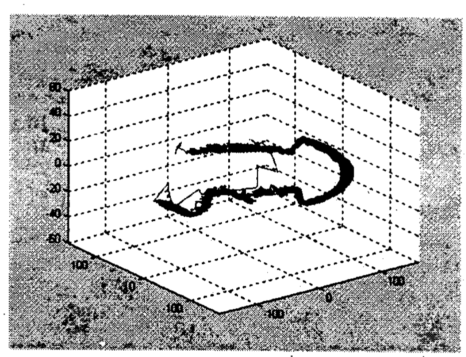

Fig. 18

Load current in a,b,c frames can be transferred into α,β frames in Fig. 11. It is obvious that the locus in Fig. 11 is almost circular so that the system works in balance case now. Fig. 12 is the current waveform in α,β and 0 axes. It is in 3 dimensional graph. In the beginning of this system, there is large zero current in zero axis. However, after sometime, it returns to almost horizontal level so that the current in line a, b, c and 0 are shown in Fig. 7 as a nearly sinusoidal and balanced waveforms.

Another simulation is performed as a power quality compensator. The simulation results are shown from Figure 13 to Figure 18. Figure 13, vertical axis is the zero axis, is the side view of 3 dimensional load current in α,β and 0 axes without any compensation. However, Fig. 14 shows side view of 3 D line current in α,β and 0 axes with compensation and the compensation begins at t=0.015s. It reduces the amplitude of zero current.

Fig. 15 shows the top view of load current in α,β and 0 axes without compensation. The locus is not circular so that the current contains harmonics and unbalance components. Fig. 16 shows the locus of line current after compensation and compensation activated at t =0.015s. It is obvious that the line current forced to follow the circular locus. It means that the line current turns back into balance case and the lower order harmonics are reduced. Fig. 16 shows the line current in phase a,b,c and 0. It is noticed that the compensation started at t=0.015s. Fig. 18 is the 3-D line current waveform in α,β and 0 axes. In the right side of this Fig. 18, it is clear that the system can perform enough compensation, as it seems to be a circular locus.

6. Conclusion

The Shunt-Connected 3-Level Converter in 3-Phase 4-Wired System is studied with the 3 dimensional voltage vectors consideration. Mathematical model of Tri-level converter is addressed. The novel theory of 3-D 3 level Voltage Vectors is proposed with the control of Sign Cubical Hysteresis Strategy. It shows that the validity of this 3-D 3-level converter theory can be applied to compensate power quality problems as well as motor divers in 3-Phase 4-Wired System. The 2-D 2-Level Voltage Vector is a subset of 3-D 3-Level one. The same consideration can be performed for 5-level converters or more. The basic background of multi-level converter in 3 dimensional aspect is performed.

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