Novel Five-Level Inverter PWM Control in 3-Phase 4-Wire System for Power Quality

Jing Tang, Man-Chung Wong, Yingduo Han

***Abstract*--** **During the past decades, 3-phase 3-wire system plays a very important role in the power electronics research, especially in the PWM studies. However, in the distribution site, there are many 3-phase 4-wire equipments are installed. In most recent researches, 4-arms Inverters are proposed to solve 3-phase 4-wires system issues [1]. In the PWM researches, almost all the studies are focused in 2-dimensional PWM techniques on α–β frame. [2][3] However, 3-Legs Inverter can be applied to compensate the power quality issues including the zero-sequence compensation by the novel PWM technique: 3 Dimensional PWM. [4] In this paper, novel 3DPWM control strategy is applied to reduce the control complexity of the 5-level Inverter system. With this novel control method, the 3-Arms 5-level inverter can be used in 3-Phase 4-Wired System, instead of 4-Arms 5-level inverter, to compensate the power quality issues as well as the neutral line current.**

***Index Terms*—5-level inverter, 3-phase, sign cubical, vectors**

I. Introduction

THE 3-Arm 5-level inverter is applied to 3-phase 4-wired system in order to compensate the power quality issues as well as the neutral zero sequence current. The 3DPWM of 5-level inverter control method is studied. The control of 5-level inverter is more complex than the 3-level one not only due to structure but also the complicated algorithm [13] [14]. In the 5-level inverters, the 5-level space vector PWM control method is one of the most popular methods [3] [4] [9]. It needs many computational steps and to determine the corresponding space vector according to the complex algorithm. First, the voltage vector must be determined in which area. But in the 3DPWM Hysteresis method, the vector can be used to determine the compensating vector. Secondly, the corresponding space vectors need many complicated computational steps to be found by space vector method. And how to determine the switching time of the space vector is the most difficult work. However, the 3DPWM Hysteresis method doesn't need to calculate the switching time. It simplifies the control method to increase the quality of the control system. By the way, the hardware DSP's requirement is high too. However, when the neutral line current existed, 4-Arms Inverters are needed and one arm of them is dedicated for compensating the zero-sequence current. In this report, the Novel 3-Dimensional Double Hysteresis PWM Inverter Control method is described with the advantages: simple and fast implementation. It doesn't need to calculate the switching times of switching components for a specific vector. The look-up table PWM vector selection is performed with the compensation of neutral current as well as the current harmonics, reactive current and unbalance. The corresponding switching vectors are chosen from simple look-up tables in order to limit the current error within the Hysteresis boundaries. The proposed controller in this report has good performance in the steady state as well as the good dynamic response. In this scheme, Sign Cubical Double-level Hysteresis Controller based on 3-Dimensional Voltage Vector PWM will be explained. The performance of the proposed control strategy will be tested. Simulation of 5-level 3-phase 4-wired system as an power quality compensator is achieved by 3D Double Hysteresis PWM Control Strategy. The simulation results demonstrate the validity of the proposed method.

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II. Basic Priciple

This part provides the basic principle of the novel control method.

A. Circuit and Switching Logic of the 5-level inverter

The main circuit configuration of the 3-phase 4-wired 5-level PWM converter is shown in the Fig. 1.

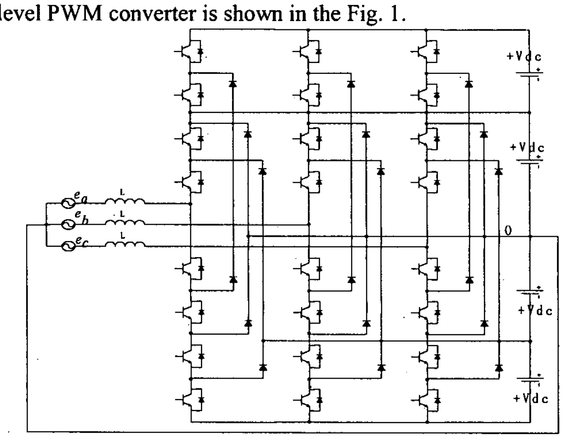


Fig.1 Circuit Configuration

Each phase of the converter consists of eight IGBT switches and six clamped diodes. Table I lists voltage levels and the corresponding states of the switches. In table I, 1 indicates the ON state, 0 indicates the OFF state. The x variable stands for A, B or C phase respectively. The losses of the switching devices and snubber circuits, and process of communication are ignored so that the equivalent switched-circuit can be obtained as shown in Fig. 2.

TABLE I
IBGT Gating Logic

Vox / Switch	+2Vdc	+Vdc	0	-Vdc	-2Vdc
Sx1	1	0	0	0	0
Sx2	1	1	0	0	0
Sx3	1	1	1	0	0
Sx4	1	1	1	1	0
Sx5	0	1	1	1	1
Sx6	0	0	1	1	1
Sx7	0	0	0	1	1
Sx8	0	0	0	0	1

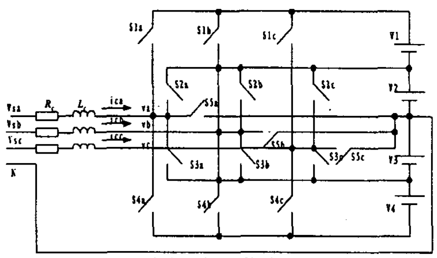


Fig. 2 (Equivalent Circuit)

According to the equivalent circuit shown in Fig. 2, the switching function in phase a, for instant, can be expressed as

$$S_a = \begin{cases} 2 & when \quad S_{1a} \quad closed \\ 1 & when \quad S_{2a} \quad closed \\ 0 & when \quad S_{5a} \quad closed \\ -1 & when \quad S_{3a} \quad closed \\ -2 & when \quad S_{4a} \quad closed \end{cases} \tag{1}$$

There are total 5 cases in one arm of the five-level converters, such as 2, 1, 0, -1 and -2.

At any moment there is only one equivalent switch that can be turned on. According to the Fig. 1 and Fig. 2, the relation among the ac-side compensating current, the terminal voltage of the inverter can be expressed as the following equations:

$$\begin{cases} L_c \dfrac{di_{ca}}{dt} = -R_c i_{ca} - v_a + v_{sa} \\ L_c \dfrac{di_{cb}}{dt} = -R_c i_{cb} - v_b + v_{sb} \\ L_c \dfrac{di_{cc}}{dt} = -R_c i_{cc} - v_c + v_{sc} \end{cases} \tag{2}$$

By using the switching functions, the relation between the terminal voltage (v_a, v_b, v_c) and dc-link voltage (V_1, V_2, V_3, V_4) can be expressed as:

$$\begin{cases} v_a = S_{1a}V_1 + (S_{1a}+S_{2a})V_2 - (S_{3a}+S_{4a})V_3 - S_{4a}V_4 \\ v_b = S_{1b}V_1 + (S_{1b}+S_{2b})V_2 - (S_{3b}+S_{4b})V_3 - S_{4b}V_4 \\ v_c = S_{1c}V_1 + (S_{1c}+S_{2c})V_2 - (S_{3c}+S_{4c})V_3 - S_{4c}V_4 \end{cases} \tag{3}$$

From the above equations, the whole system can be described as the following state equation.

$$Z\dot{X} = AX + BU \tag{4}$$

where

$$A = \begin{bmatrix} -R_c & 0 & 0 & -S_{1a} & -(S_{1a}+S_{2a}) & S_{3a}+S_{4a} & S_{4a} \\ 0 & -R_c & 0 & -S_{1b} & -(S_{1b}+S_{2b}) & S_{3b}+S_{4b} & S_{4b} \\ 0 & 0 & -R_c & -S_{1c} & -(S_{1c}+S_{2c}) & S_{3c}+S_{4c} & S_{4c} \end{bmatrix}$$

$$X = [i_{ca}, i_{cb}, i_{cc}, V_1, V_2, V_3, V_4]^T$$

$$Z = diag[L_c \quad L_c \quad L_c]$$

$$B = diag[1 \quad 1 \quad 1]$$

$$U = [v_{sa} \quad v_{sb} \quad v_{sc}]$$

B. Transforming Three-phase Quantities

In the 3DPWM Hysteresis control method, the current different values are all in the α-β-0 frame, so the voltage will be transferred form a-b-c frame to α-β-0 frame. It is assumed that $V_1 = V_2 = V_3 = V_4 = V_{dc}$. According to the switching functions, the instantaneous voltage vector can be given in (5) $\alpha - \beta - 0$ frame.

$$\vec{V_s} = V_{dc}\left[i\sqrt{\frac{2}{3}}\left(S_a - \frac{1}{2}S_b - \frac{1}{2}S_c\right) + j\frac{1}{\sqrt{2}}(S_b - S_c) + k\frac{1}{\sqrt{3}}(S_a + S_b + S_c) \right] \tag{5}$$

Furthermore,

$$\vec{V_s} = V_{dc}\left[i\sqrt{\frac{2}{3}}S_\alpha + j\frac{1}{\sqrt{2}}S_\beta + k\frac{1}{\sqrt{3}}S_0 \right] \tag{6}$$

, where

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

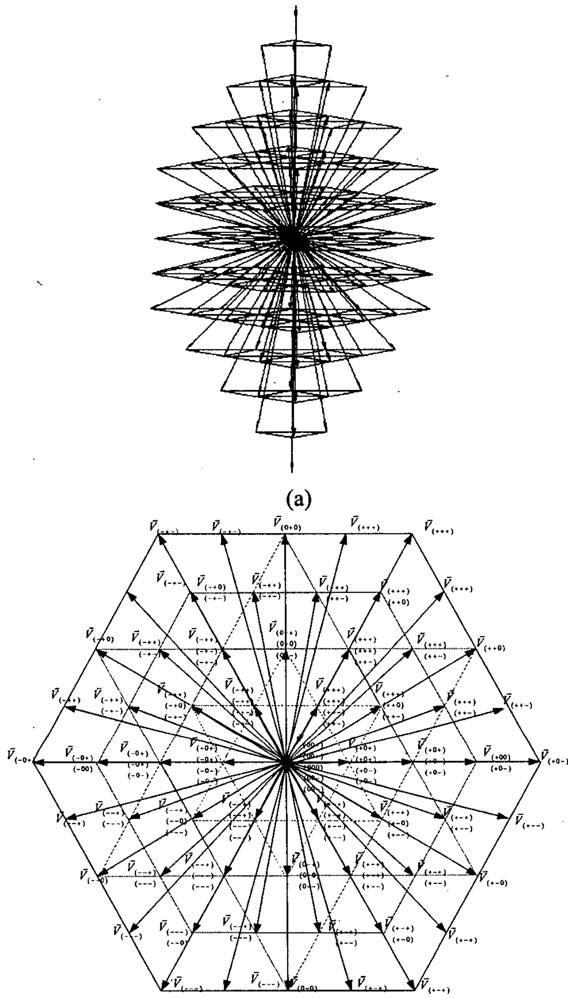
$$S_\beta = S_b - S_c$$

$$S_0 = S_a + S_b + S_c$$

C. 3-Dimension Voltage Vectors of Five-Level Inverter

For n-level inverter system, there will be n^3 voltage vectors. So the number of voltage vectors in 5-level inverter system is 125. The total voltage vectors in 3 dimensions can be shown as Fig.3 (a). Traditionally, if the DC supply voltage is divided into four equal sources and the effect of the zero axes is ignored, the 5-level inverter has 61 states corresponding to the apexes of the small triangles in Fig.3 (b), since the same voltage will be outputted by multiple switching modes. So the available vectors are not equal to the actual number of the states. But in the 3DPWM method, the vectors are 125. In order to simple the method, the categories are based on the

$\alpha-\beta$ frame. In Table III, there are 9 categories. The vectors in the same category have the same amplitude in the $\alpha-\beta$ frame. With the zero affection, the whole vectors can be available vectors in 3D PWM method which can be explained in the next section.



(a)

(b)

Fig. 3 (a) Total voltage vectors in 3 Dimensions
(b) Vectors in S_α-S_β frame

TABLE II
Vector Categories

Name	Amplitude of $\alpha-\beta$
MLV (Most Large Vector)	4
VLV (Very Large Vector)	$\sqrt{3}/2\times 4$
LV (Large Vector)	0.9×4
LMV (Large Medium Vector)	$\sqrt{3}/2\times 3$
SMV (Small Medium Vector)	0.9×3
SV (Small Vector)	2
VSV (Very Small Vector)	$\sqrt{3}/2\times 2$
MSV (Most Small Vector)	1
ZV (Zero Vector)	0

III. 3-DIMENSION VOLTAGE VECTOR DOUBLE-BAND SIGN CUBICAL HYSTERESIS CONTROL STRATEGY

Recent years, the control methods of multi-level inverters have developed very quickly. There are so many novel control methods such as [9][10][12]. Especially the Hysteresis method [11] is an easier method with good dynamic response. In this section, the application of Hysteresis control strategy in double-band Sign Cubical Control will be explained so as to perform the harmonics, unbalance and neutral line compensation by 3DPWM technique.

A. Basic Control Strategy

The basic principle of this control method is to inject the same negative amplitude of harmonics into the load current in order to compensate the harmonic current and the in-phase current into the system to reduce the peak-load power supply from the generator. The basic concept of this control strategy is similar to the 3-level system and other traditional Hysteresis PWM control system. Fig. 4 shows the control block diagram. In this figure, the injected current of the five-level converter is detected and transferred from a-b-c frame into α–β–0 one. The error between the current reference and the actual load current would be the signal to compare with the injected current signal.

$$i^{*}_{\alpha\beta 0} = i^{reference}_{\alpha\beta 0} - i^{load}_{\alpha\beta 0} \tag{7}$$

$i^{Reference}_{\alpha\beta 0}$ is the reference signal that can be obtained by Instantaneous Reactive Power Compensation Technique, $i^{load}_{\alpha\beta 0}$ is the actual load current that may be distorted by non-linear load, and the error between the reference signal and load current signal will be the tracking current ($i^{*}_{\alpha\beta 0}$) that should be injected by the inverter.

$$\Delta i_{\alpha\beta 0} = i^{*}_{\alpha\beta 0} - i_{c\alpha\beta 0} \tag{8}$$

The error between the tracking current ($i^{*}_{\alpha\beta 0}$) and the coupling current ($i_{c\alpha\beta 0}$) between the inverter and the load terminal will be the control signal ($\Delta i_{\alpha\beta 0}$) to the controller to control the action of inverter.

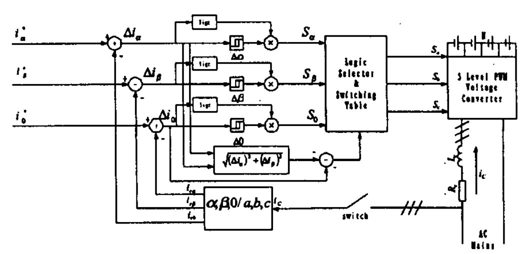
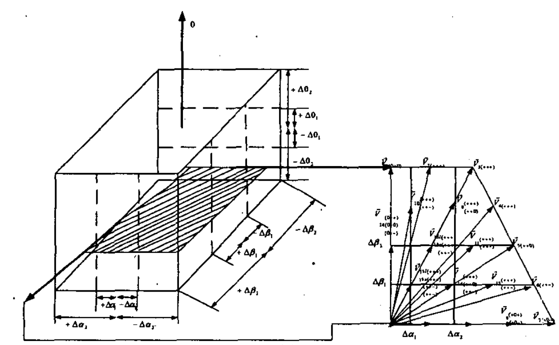


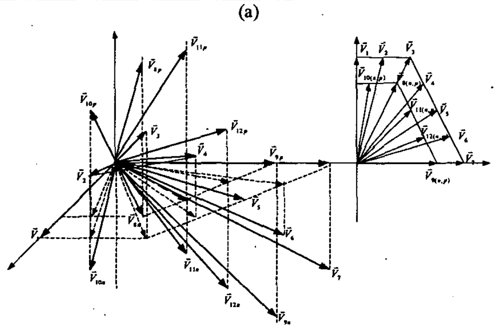
Fig.4 Control Strategy

Referring to Fig. 4, the basic control strategy is described by sign cubical Hysteresis current controller or sign rectangular bar Hysteresis current controller. But the Hysteresis limits are doubled such as $\Delta\alpha_1, \Delta\alpha_2, \Delta\beta_1, \Delta\beta_2, \Delta 0_1, \Delta 0_2$ and

$\Delta\alpha_1 < \Delta\alpha_2, \Delta\beta_1 < \Delta\beta_2, \Delta 0_1 < \Delta 0_2$ also $\Delta\alpha_1 = \Delta\beta_1 = \Delta 0_1$, $\Delta\alpha_2 = \Delta\beta_2 = \Delta 0_2$ so as to have cubical control technique. Double-level Hysteresis control method is employed and is shown in Fig. 5 (a). It can be seen that there are two hysteresis value on each axe. It is because that there are so many voltage vectors in the 5-level system. The two-level Hysteresis can let the selection of the voltage vector easier.



(a)



(b)

Fig. 5 Control Diagram of Double-Level Hysteresis Control

B. Switching Table and Selection

There are five voltage levels {2,1,0,-1,-2} in 5-level voltage inverter so that the sign of triggering pulses is an important parameter in tracking the current reference so as to choose the correct vectors. When the error between the reference signal and actual input signal is larger than the first Hysteresis limited value, it will trigger to positive 1 or, vice versa, to negative 1. If the error is larger than the second Hysteresis limited value, it will trigger to positive 2 or, vice versa, to negative 2. Then if the error is less than the first Hysteresis limited value, there will be the zero level. When the error current is larger than the $\Delta\alpha_2, \Delta\beta_2, \Delta 0_2$, the most large, very large, large, medium large and medium vectors would be selected. And if the error current is larger than the $\Delta\alpha_1, \Delta\beta_1, \Delta 0_1$ but less than the $\Delta\alpha_2, \Delta\beta_2, \Delta 0_2$, the small, very small and most small vectors would be chosen. Lastly, if the error current is less than the $\Delta\alpha_1, \Delta\beta_1, \Delta 0_1$, 5 zero vectors would be activated. Because in five-level system, there are many same direction or same amplitude vectors, which vector will be selected is determined by the main effect on the α-β frame or on the zero axes. Especially for the pair-vectors, they have the same directions respectively but with different amplitude in $v_{\alpha\beta}$ and v_0 Assume that the Vdc equals to 1.

$$|V_s| = V_{dc}\left[\sqrt{\left(\sqrt{\frac{2}{3}}S_\alpha\right)^2 + \left(\frac{1}{\sqrt{2}}S_\beta\right)^2 + \left(\frac{1}{\sqrt{3}}S_0\right)^2}\right] \tag{9}$$

$$= V_{dc}\sqrt{\left[V_{\alpha\beta}^{\ 2} + V_0^{\ 2}\right]}$$

where

$$V_{\alpha\beta} = \sqrt{\left(\sqrt{\frac{2}{3}}S_\alpha\right)^2 + \left(\frac{1}{\sqrt{2}}S_\beta\right)^2}$$

and

$$V_0 = \frac{1}{\sqrt{3}}S_0$$

Ideally, the large vector will pay more action in α-β frame, but it gives less action in zero direction than small vector. The error amplitude of $\sqrt{(\Delta i_\alpha)^2 + (\Delta i_\beta)^2}$ is compared with Δi_0, the largest one will be chosen so that it can be decided to activate which vector from those pair-vectors to reduce error. Moreover, according to the characteristics of the five-level system, the vectors with the same direction and the same amplitude in α-β frame will be selected by the amplitude of the zero direction.

For example, assume that the vector is located at the first frame which can be shown in the 3 dimensions and 2 dimensions respectively as Fig.5 (b). And at least one phase is 2 which means one phase error current is greater than the second limitation. The selection can be shown in the Table III.

TABLE III
VOLTAGE SELECTION RULE TABLE

α	β	0	Selected Voltage Vector	
			$V_{\alpha\beta} \geq V_0$	$V_{\alpha\beta} < V_0$
2	2	Select from $\vec{V}_3, \vec{V}_4, \vec{V}_5, \vec{V}_8, \vec{V}_{11}$		
2	2	2	$\vec{V}_3$	$\vec{V}_{8p}$
2	2	1	$\vec{V}_4$	$\vec{V}_4$
2	2	0	$\vec{V}_5$	$\vec{V}_{8n}$
2	2	-1	$\vec{V}_5$	$\vec{V}_{11n}$
2	2	-2	$\vec{V}_{11n}$	
2	1	Select from $\vec{V}_5, \vec{V}_6, \vec{V}_{11}, \vec{V}_{12}$		
2	1	2	$\vec{V}_{11p}$	
2	1	1	$\vec{V}_{12p}$	
2	1	0	$\vec{V}_5$	
2	1	-1	$\vec{V}_6$	$\vec{V}_{11n}$
2	1	-2	$\vec{V}_{12n}$	
2	0	Select from $\vec{V}_6, \vec{V}_7, \vec{V}_9, \vec{V}_{12}$		
2	0	2	$\vec{V}_{12p}$	$\vec{V}_{9p}$
2	0	1	$\vec{V}_{12p}$	$\vec{V}_{9p}$
2	0	0	$\vec{V}_{9n}$	
2	0	-1	$\vec{V}_7$	$\vec{V}_6$

2	0	-2	$\vec{V}_7$	$\vec{V}_{12n}$
1	2	Select from $\vec{V}_2,\vec{V}_3,\vec{V}_8,\vec{V}_{10}$		
1	2	2	$\vec{V}_2$	$\vec{V}_{8p}$
1	2	1	$\vec{V}_2$	$\vec{V}_{10p}$
1	2	0	$\vec{V}_{8n}$	
1	2	-1	$\vec{V}_{8n}$	$\vec{V}_{10n}$
1	2	-2	$\vec{V}_{10n}$	
0	2	Select from $\vec{V}_1,\vec{V}_2,\vec{V}_{10}$		
0	2	2	$\vec{V}_2$	$\vec{V}_{10p}$
0	2	1	$\vec{V}_2$	$\vec{V}_1$
0	2	0	$\vec{V}_1$	
0	2	-1	$\vec{V}_1$	$\vec{V}_{10n}$
0	2	-2	$\vec{V}_{10n}$	

IV. SIMULATION RESULTS

The simulation is performed as an active filter for non-linear load and the results are shown in the following figures. The system switching frequency is 20kHz. Fig. 6 and Fig. 7 show the current waveforms before compensation in time-domain and 3-dimensional aspect. Fig. 8 shows this current locus in $\alpha-\beta-0$ frame. The performance of this five-level 3-dimensional double-band controller is quite acceptable with the results shown in Fig. 8 and Fig. 9.

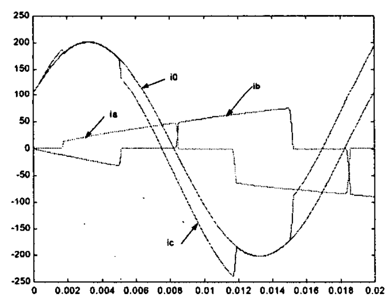


Fig. 6 Load Current before Compensation

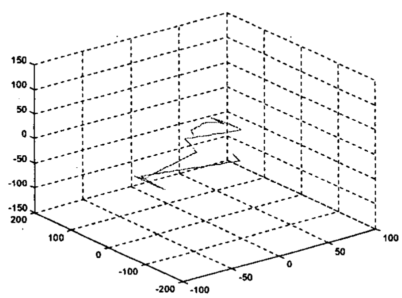


Fig. 7 Load Current in 3D before Compensation

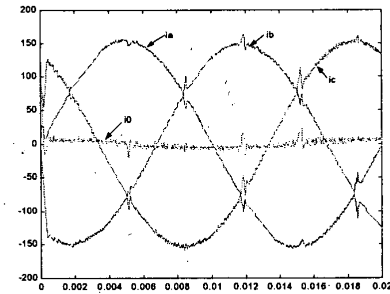


Fig. 8 Source Current by Five-Level Inverter Compensation, 20K Hz

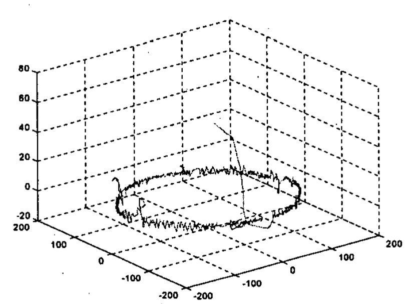


Fig. 9 Source Current 3D by Five-Level Inverter Compensation, 20 KHz

V. CONCLUSION

The Shunt-Connected Five-Level Converter in 3-phase 4-wired systems is studied with the 3-dimensional PWM technique. The report describes the novel 3-dimensional double-level Hysteresis current control method as well as the mathematical model of 5-level Inverter. It shows that the validity of this 3-dimensional PWM theory can be applied to compensate power quality problems in 3-phase 4-wired 5-level Inverter system. It simplified the control algorithm of 5-level Inverter system and conventional 3-arms inverter can be employed to solve the harmonics, unbalance and reactive power issues as well as the neutral line current.

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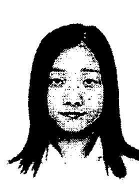
VI. BIOGRAPHIES



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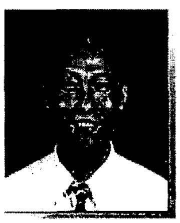

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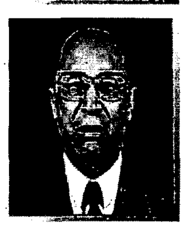

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