Parallel Power Quality Compensation in Modern Buildings

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Abstract –Power quality monitoring results of a modern building is presented and evaluated in this paper. Excessive current quality problems are detected, which is caused by large numbers of nonlinear loads, such as PCs, printers and TVs, in the building. In order to suppress the current harmonics and the neutral current, parallel power quality compensators should be applied. The two voltage source inverter topologies for 3-phase 4-wire compensators are compared in this paper. Results indicate that the four-leg inverter can double the neutral current compensation capability. But its phase current harmonics compensation capability is the same as three-leg center-split inverter. The initial cost and control complexity of the two kinds of inverter are compared both in 2-level and in 3-level system. And a 3-phase 4-wire parallel power quality compensator prototype is implemented. Experimental results are given to show that the current harmonics and neutral current can be compensated simultaneously.

Keywords: Power Quality, Parallel power quality compensator, 3-phase 4-wire system

I. INTRODUCTION

Power quality has become an issue that is of increasingly importance to electricity consumers at all levels of usage. In the past, concentrations of the current quality problem were mainly focused on the large rating industrial loads. Due to the proliferation of non-linear electronic equipments, such as personal computers, printers, TVs etc., there has been a growing concern for power system distortions in modern buildings [1]-[4].

Recently, power qualities for several modern buildings are monitored by our research group. Both voltage and current quality are recorded and evaluated. The recorded data at one of the monitored sites are presented in this paper. At this site, which is the input of a computer center, the voltage quality is good. But large current harmonics and excessive neutral current exist.

In order to compensate the current harmonics and neutral current, parallel power quality compensators should be applied in the distribution system. Both 2-level three-leg center-split inverter and 2-level four-leg inverter can be used to implement a parallel power quality compensator for a three-phase four-wire system. And a comparison study between the two inverters is given in Section III.

When the 2-level inverter is applied to medium and large capacity compensators, the voltage stress across each switch is so high that the corresponding dv/dt causes large electromagnetic interference (EMI). The 3-level VSI topologies are good substitutes, since it can reduce voltage stress and improves output harmonic contents. The existing 3-level neutral point clamped (NPC) inverter in three-phase three-wire systems can be directly used in three-phase four-wire systems, because the split d.c. capacitors provide a neutral connection. And comparisons between the 3-level four-leg NPC inverter and conventional 3-level NPC inverter are also given in Section III.

Corresponding to the adoption of the inverter structure, the 3-Dimensional (3D) Pulse Width Modulation (PWM) techniques have been proposed. The 3D space vector allocation of a 3-level NPC inverter is introduced. And a three-phase four-wire parallel power quality compensator prototype is implemented, in which a 3-level NPC inverter is used. The 3-dimensional Space Vector Modulation (3DSVM) control strategy is used to control the compensator. Experimental results are given to show the validity of the current quality compensation.

II. POWER QUALITY MONITORING IN MODERN BUILDINGS

Recently, power quality of some modern buildings has been monitored by our group. And some recorded data are presented hereinafter, which is obtained at the input line of a computer center.

The recorded voltage waveform is shown in Fig.1. According to the recorded data, the Total Harmonic Distortion (THD) of the phase voltage is always smaller than 1.5%. The threshold of voltage sag is set to 90% of the normal voltage (230V). And there is no voltage sag being recorded during the duration of monitoring. Hence, the voltage quality of the monitored site is good according to IEEE standard 519:1992[5] and IEEE standard 1159:1995[6].

When the current quality is monitored, at least a complete work cycle (five businesses days and a weekend) is needed. Fig.2 shows the variation of the Root Mean Square (RMS) values of the three-phase and neutral current for one week. The working days and weekends can be easily distinguished in the Fig.2 according to the variation of the load current. The recorded minimum and maximum RMS values are listed in Table 1. The variations of THD values of the phase current are shown in Fig.3, which is recorded at the same time duration as that in Fig.2. And a one-period-long current waveform is shown in Fig.4. It can be seen from the given results that all the three phase currents contain large harmonics. The THD of each phase current exceeds the accepted tolerance in IEEE standard [5]. And a large neutral current exists at the monitored site. The harmonic spectrum of the neutral current is shown in Fig.5, in which the third harmonics is about twenties times larger than the fundamental components. Although, only up to 11th harmonics are shown in Fig.5, it is explicit that the neutral current is mainly generated by the triple harmonics of the phase current.

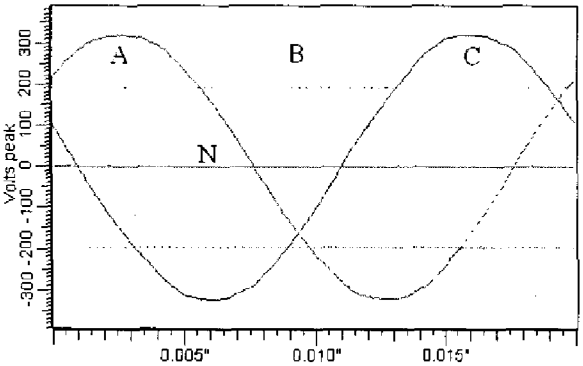


Fig.1: Main input voltage waveforms

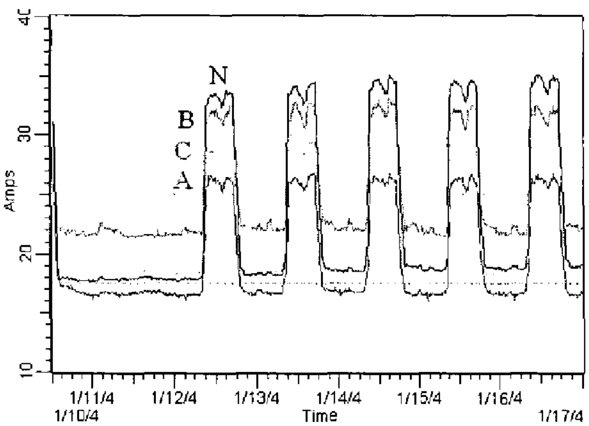


Fig.2: Current RMS variation in one week

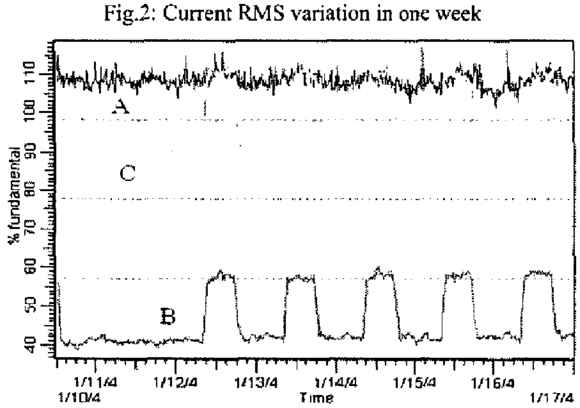


Fig.3: Current THD variation in one week

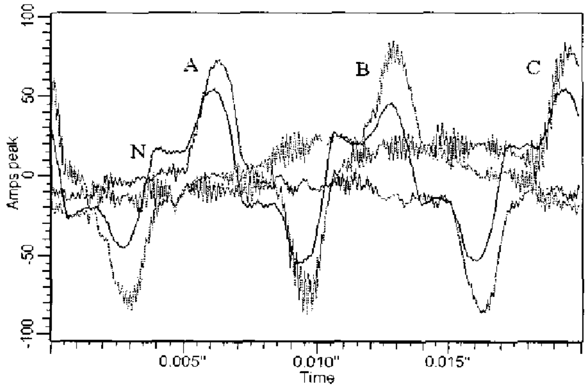


Fig.4: Current waveform for one period

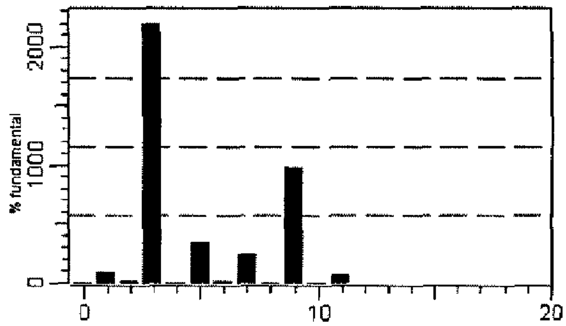


Fig. 5: Harmonic spectrum of Neutral Current

Table 1: RMS values of the recorded current

	Minimum RMS values	Maximum RMS values
A	15.97A	26.93A
B	21.36A	33.19A
C	18.07A	30.40A
N	17.70A	35.12A

Most of the loads at this site are nonlinear loads, such as PCs, laser printers. According to the harmonic performance test results in [7] , the triple harmonic component is usually the dominating one in the current of these loads. Hence, large current harmonics and excessive neutral currents are generated, when large numbers of these loads run simultaneously. The main detrimental effects of harmonics are [1]:

- mal-operation of control devices, mains signaling systems and protective relays,
- extra losses in capacitors, transformers and rotating machines,
- additional noise from motor and other apparatus,
- telephone interference.

And excessive neutral currents in a system contribute to the following:

- Neutral to earth voltages that create common-mode noise problems;
- Circulating currents flowing in transformers and it may cause transformer overheating;
- High voltage drop at loads;
- Overheating and failure of the neutral conductor.

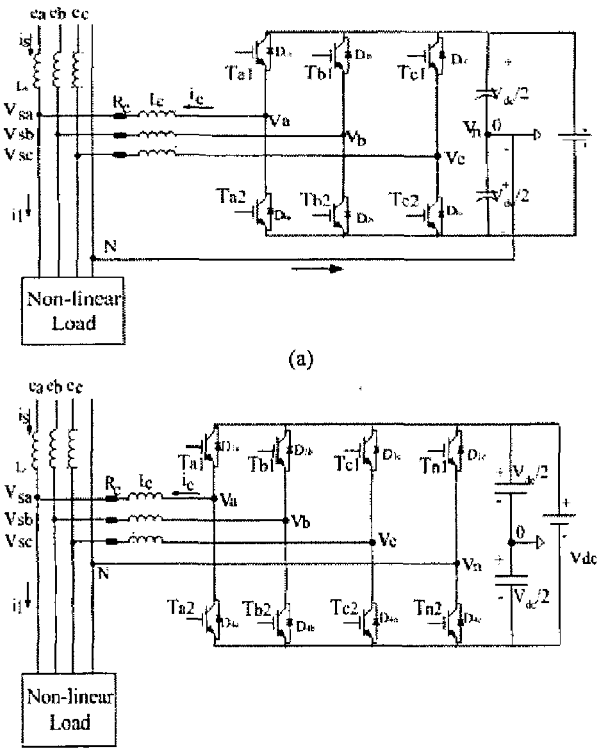
By the way the overheating caused by excessive neutral current have a potential dangerous of catching fire. The power quality issues at the other sites of the monitored modern buildings have almost the same character as the presented site. Hence, the current quality must be controlled and active power filters can be used to compensate harmonics and neutral current in a modern building.

III. Three-Phase Four-Wire Active Power Filters

In the past research, most active power filters are designed for three-phase three-wire systems. In order to compensate the current harmonics and neutral current simultaneously, three-phase four-wire active power filters should be developed. There are mainly two ways to provide neutral current compensation in a voltage source inverter [8]. 1) using split dc link capacitors and tying the neutral point to the mid-point of the dc linked capacitors ; 2) using a four-leg inverter topology and tying the neutral point to the mid-point of the fourth neutral leg. Comparison studies between these two inverter structures are given hereinafter.

A.Comparison of 2-level four-leg and three-leg center-split inverter

The structure of the 2-level three-leg center-split inverter and the 2-level four-leg inverter are shown in Fig.6 (a) and (b) respectively. The numbers of the main components of the two inverters are listed in Table 2. The four-leg inverter needs two more IGBT switches. But it only needs one d.c. capacitor. The d.c. capacitor of the four-leg inverter in Fig. 6(b) is split to two, so that a virtual ground can be defined. Actually only one capacitor is enough. This is different from the three-leg center-split inverter, in which the two split capacitors are necessary. Both of the two inverters can be used as a parallel power quality compensator for a three-phase four-wire system, as shown in Fig.6.



(a)

(b)

Fig.6: Inverter for three-phase four-wire system (a) three-leg center-split inverter (b) four-leg inverter

Table 2: Comparison of numbers of components

	IGBT	capacitors
2-level center-split VSI	6	2
2-level 4-Leg VSI	8	1

In order to compare the compensation performance of the two inverters, the output space vector should be analyzed. And the switching function of each leg of the inverter is defined as:

$$S_j = \begin{cases} 1, & when\ \ T_{j1}\ \ is\ \ closed \\ -1, & when\ \ T_{j2}\ \ is\ \ closed \end{cases} \quad j=a,b,c,n \qquad (1)$$

It is assumed that the d.c. voltages of the two capacitors both equal to $V_{dc}/2$. If the ground is defined at the midpoint of the two capacitors, the output voltage of each leg can be expressed as:

$$v_j = V_{dc}/2 * S_j \quad j=a,\ b,\ c,\ n \qquad (2)$$

v_j represents the output voltage of each leg with respect to the defined ground. However, when the inverter is connected to a three-phase four-wire system as a parallel power quality compensator, it is the phase to neutral voltage, which determines the output of the inverter. And the phase to neutral voltage is defined as:

$$v_{jn} = v_j - v_n, \quad j=a,b,c \qquad (3)$$

The output voltage vector of the inverter is expressed as:

$$\vec{v} = \sqrt{\frac{2}{3}}\left(v_{an} + \alpha \cdot v_{bn} + \alpha^2 \cdot v_{cn}\right) \qquad (4)$$

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

According to the α-β-0 transformation as shown in (5), the instantaneous voltage vector in α-β-0 frame is given as (6).

$$\begin{bmatrix} v_\alpha \\ v_\beta \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} \qquad (5)$$

$$\vec{v} = (v_\alpha \cdot \vec{n}_\alpha + v_\beta \cdot \vec{n}_\beta + v_0 \cdot \vec{n}_0) \qquad (6)$$

where
$$\begin{cases} v_\alpha = \sqrt{\frac{2}{3}}(v_{an} - \frac{1}{2}v_{bn} - \frac{1}{2}v_{cn}) \\ v_\beta = \frac{1}{\sqrt{2}}(v_{bn} - v_{cn}) \\ v_0 = \frac{1}{\sqrt{3}}(v_{an} + v_{bn} + v_{cn}) \end{cases} \qquad (7)$$

If (3) is substituted to (7), the following results can be obtained:

$$\begin{cases} v_\alpha = \sqrt{\frac{2}{3}}(v_a - v_n - \frac{1}{2}(v_b - v_n) - \frac{1}{2}(v_c - v_n)) = \sqrt{\frac{2}{3}}(v_a - \frac{1}{2}v_b - \frac{1}{2}v_c) \\ v_\beta = \frac{1}{\sqrt{2}}(v_b - v_n - (v_c - v_n)) = \frac{1}{\sqrt{2}}(v_b - v_c) \\ v_0 = \frac{1}{\sqrt{3}}(v_a - v_n + v_b - v_n + v_c - v_n) = \frac{1}{\sqrt{3}}((v_a + v_b + v_c) - 3v_n) \end{cases} \qquad (8)$$

For a three-leg center-split inverter, the v_n is always equal to *0*, because the neutral wire is connected to the defined ground. If (2) is substituted to (8), (9) can be obtained.

$$\begin{cases} v_\alpha = \frac{V_{dc}}{\sqrt{6}}(S_a - \frac{1}{2}S_b - \frac{1}{2}S_c) \\ v_\beta = \frac{V_{dc}}{2\sqrt{2}}(S_b - S_c) \\ v_0 = \frac{V_{dc}}{2\sqrt{3}}(S_a + S_b + S_c) \end{cases} \qquad (9)$$

For a 2-level four-leg inverter, the value of v_n equals to $S_n \cdot V_{dc/2}$ and is determined by the switching state of the fourth leg. In this case, (8) is simplified to:

$$\begin{cases} v_\alpha = \frac{V_{dc}}{\sqrt{6}}(S_a - \frac{1}{2}S_b - \frac{1}{2}S_c) \\ v_\beta = \frac{V_{dc}}{2\sqrt{2}}(S_b - S_c) \\ v_0 = \frac{V_{dc}}{2\sqrt{3}}((S_a + S_b + S_c) - 3S_n) \end{cases} \qquad (10)$$

It can be seen from (9) and (10) that the α- and β-axis components of the output voltage vector are only determined by the switching state of leg A, B and C. If S_a, S_b and S_c of the two inverters are the same, the α- and β-axis output of the four-leg and three-leg center-split inverter are the same. There are 8 vectors corresponding to the different switching state combination of leg A, B and C. And the space vector allocation on α-β plane for four-leg inverter and three-leg center-split inverter are the same, as shown in Fig.7.

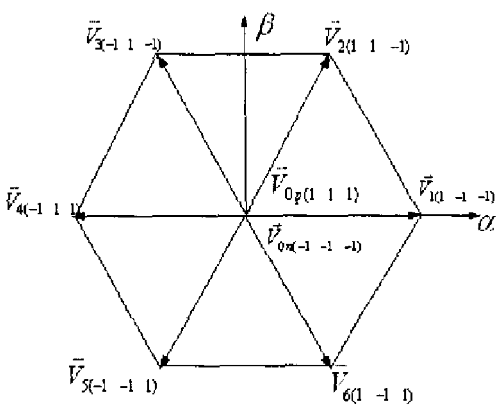


Fig.7: The 2-level space vector allocation on α-β plane

The difference of output voltage vector between four-leg inverter and three-leg center-split inverter exists in the zero-axis output v_0. The zero-axis output of the 2-level center-split inverter has four possible values: $-\sqrt{3}V_{dc}/2$, $-V_{dc}/(2\sqrt{3})$, $V_{dc}/(2\sqrt{3})$ and $\sqrt{3}V_{dc}/2$. And there are totally eight space vectors for a three-leg center-split inverter. However, the zero-axis output of a 2-level four-leg inverter has seven possible values: $-\sqrt{3}V_{dc}$, $-2V_{dc}/\sqrt{3}$, $-V_{dc}/\sqrt{3}$, 0, $V_{dc}/\sqrt{3}$, $2V_{dc}/\sqrt{3}$, $\sqrt{3}V_{dc}$. And there are totally sixteen space vectors of a 2-level four-leg inverter.

The compensation performance is determined by the output space vector of the inverter. Following results can be obtained based on the previous analyses:

- Four-leg inverter and the three-leg center-split inverter have the same compensation capability on α- and β-axis. That is to say, when they are used to compensator harmonics in phase current, their d.c. voltage utility ratio is the same.
- Compared with the center-split inverter, the 2-level four-leg inverter doubles the maximum output on zero-axis. So, the neutral current compensation capability of four-leg inverter is higher. And the four-leg inverter has higher flexibility on zero-sequence compensation, since it has more possible zero-sequence output values.

Compared with the four-leg inverter, three-leg center-split inverter uses fewer switching devices, but is needs one more capacitor. Some researches prefer four-leg inverter since it has higher neutral current compensation capability. And the control strategy of the 2-level four-leg inverter is simpler because the control strategy for 2-level center-split inverter must include the d.c. voltage unbalance control.

B. Comparison of 3-level four-leg and three-leg NPC inverter

For the medium and large capacity power quality compensators, the multi-level VSI topologies are good alternatives, among which the 3-level inverter is the most promising one. The 3-level structure not only reduces voltage stress across the switches but also provides more available vectors, which can improve harmonic contents of the VSI by selecting appropriate switching vectors [9,10]. And the voltage stress decrease leads to corresponding decrease of dv/dt, which can lower the electromagnetic interference (EMI).

The 3-level NPC inverter, widely used in applications for a three-phase three-wire system, originally has the structure of split d.c. capacitors. So the existing d.c. neutral point can be directly utilized as the ground return. Actually the 3-level NPC inverter can be used in applications for a three-phase three-wire system and for a three-phase four-wire system. A fourth leg can also be added to provide the neutral wire connection in the 3-level NPC inverter. The structures of 3-level NPC inverter and 3-level four-leg NPC inverters are shown in Fig.8 (a) and (b) respectively. The numbers of the components in each inverter are listed in Table 3.

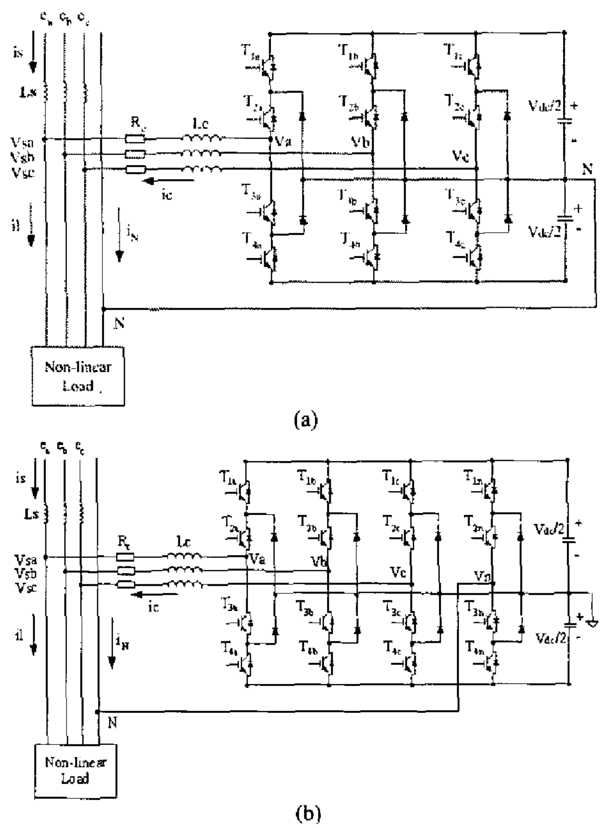


Fig. 8: 3-level NPC inverter for a three-phase four-wire system (a) three-leg structure (b) four-leg structure

Table 3: Comparison of numbers of components

	IGBT	Clamped diodes	capacitors
3-level NPC VSI	12	6	2
3-level 4-Leg NPC VSI	16	8	2

The space vector allocations on α-β plane for 3-level four-leg inverter and 3-level NPC inverter are the same, which can be proved similarly to the analyses for 2-level inverters. And there are totally 27 vectors corresponding to the different switching state combinations of leg A, B and C in a 3-level inverter, as shown in Fig.9.

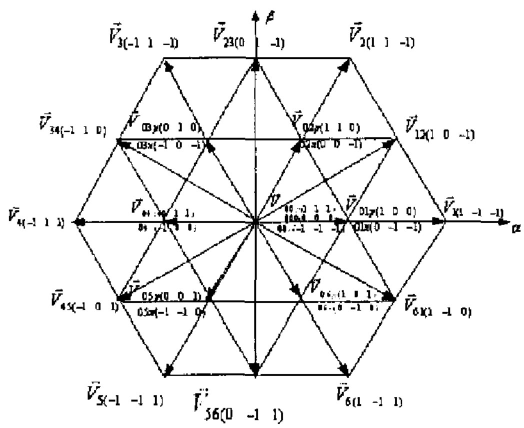


Fig.9: 3-level inverter space vector allocation on α-β plane

The difference of output space vector allocation between the two 3-level inverter also exists in the zero-axis component, which is determined by the output voltage of leg A, B, C and the neutral voltage V_n according to (8). There are totally seven different possible values for the zero-axis output of a three-leg inverter. And the maximum value is $\pm\sqrt{3}V_{dc}/2$. However, there are 21 possible zero-axis output values for a four-leg inverter. But many zero-axis outputs are overlapped. So the zero-axis output of a four-leg inverter has thirteen different possible values and the maximum value is $\pm\sqrt{3}V_{dc}$.

Except the two conclusions obtained in the 2-level system, which is also true for the comparison of 3-level inverters, following results can be obtained:

- The 3-level four-leg inverter has 3^4=81 different switching states. Although the total number of output voltage vector increases a lot compared with 27 vectors of a three-leg inverter, the number of different space vectors on α-β plane doesn't increase. Even in α-β-0 3D coordinates, some vectors of 3-level four-leg inverter are overlapped although their corresponding switching states are different. And the increasing of overlapped vectors increases the complexity of PWM control.
- As shown in Fig.8, both of the two inverters use the split d.c. capacitor. So, the d.c. voltage variation control strategy need to be implemented both for 3-level four-leg inverter and 3-level NPC inverter.

In addition, the initial cost of the 3-level four-leg inverter increases a lot because more switching components, pulse triggered terminals, drives and even controllers are needed. For example, if TI TMS320F2407 DSP Controller is chosen to generate the PWM trigger signal, only one DSP chip is enough for controlling 3-level three-leg inverter. But a second DSP chip is needed for controlling a 3-level four-leg inverter. The coordination and synchronization between the two DSP controllers increase the complexity of the control too.

In a word, both the 3-level four-leg NPC inverter and 3-level NPC inverter can be used to compensate the neutral current in a three-phase four-wire system. But, the 3-level NPC inverter is cheaper and easier to control. Hence, for medium and large capacitor 3-phase 4-wire active power filters, 3-level NPC inverter is more preferable.

C. 3DPWM Control Strategy

In 3-phase 3-wire system, there are many research focusing on the Pulse-Width Modulation techniques such as the Sinusoidal PWM, Hysteresis Control PWM and Space Vector PWM etc. However, all of them are only investigated in 2-dimensional aspect. Only 2-D PWM cannot be utilized to solve the issues in a 3-Phase 4-Wired System.

Corresponding to the adoption of the inverter structure with neutral-wire, 3-Dimensional (3D) PWM techniques should be developed for applications in a three-phase four-wire system. The 3D space vector allocation of a 3-level NPC inverter is shown in Fig.10. In the novel 3D PWM control strategies, the zero-sequence component of each vector needs to be considered, so that the neutral current compensation can be implemented. Two 3D Hysteresis Control [11][12] strategies are proposed for controlling 3-level NPC inverter in a parallel power quality compensators. Because the space vector modulation can reduce commutation losses and the harmonic content of output voltage, a 3-Dimensional Space Vector Modulation (3DSVM) for 3-level NPC inverter is proposed by the authors in 2003 [13].

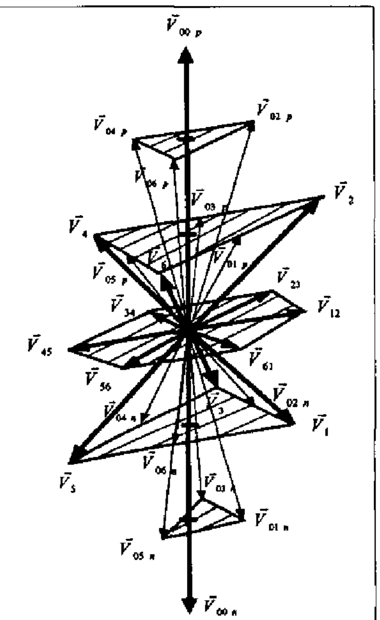


Fig. 10: 3-Level Voltage Vector's Allocation in 3D aspect

IV. Experimental Results

A 3-phase 4-wire parallel power quality compensator prototype is implemented, in which a 3-level NPC inverter is used. The 3DSVM control strategy for 3-level NPC inverter is achieved with 5kHz switching frequency by TMS320F2407 DSP Controller. The value of d.c. side capacitor is 10mF. The system configuration is as shown in Fig.11.The load current before compensation is shown in Fig.12. Fig. 13 shows the source current after compensation. It can be seen from Fig.13 that current harmonics and neutral current are compensated simultaneously. The phase current THD value before and after compensation are listed in Table 4 respectively. And the validity of the current compensation is proved in the experiment.

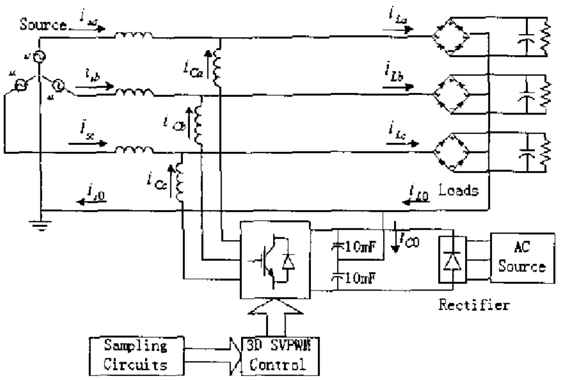


Fig. 11: Experimental System Configuration

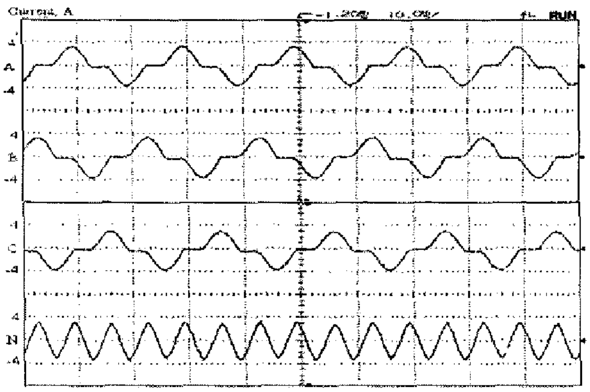


Fig. 12: Source Current before Compensation

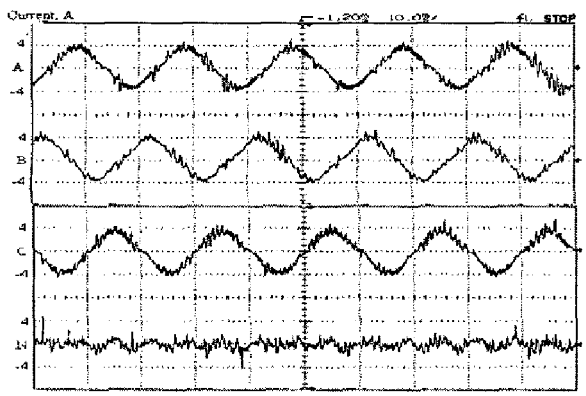


Fig. 13: Source Current after Compensation by 5KHz 3DSVM

Table 4: Current THD value

	THDA	THDB	THDC
Before Compensation	39.68%	38.53%	39.14%
After Compensation	10.15%	8.925%	8.859%

V. CONCLUSION

This paper focuses on the current quality problems and parallel power quality compensation in a three-phase four-wire distribution system. Firstly, power quality in some modern buildings are monitored and evaluated. The load current varies according to the office hour in a commercial building. Hence, when the current quality is monitored, a cycle of one week, including working days and weekend, is needed. The recorded data at an input line of a computer centre is presented in this paper, in which large harmonic and excessive neutral current are detected. And the other sites of the modern buildings should have the same problems according to the recorded data.

In order to control the current quality in modern buildings, parallel power quality compensator, which can be used in a three-phase four-wire system, should be developed. Comparison studies for 3-phase 4-wire voltage source inverters are given both in 2-level and in 3-level system. The four-leg inverter has more advantages when it is applied in a 2-level system, since the neutral current compensation capability can be doubled without greatly increasing the initial cost. And the control strategy for 2-level four-leg inverter is simpler than 2-level centre-split inverter. However, when the 3-level inverter is applied to a medium or large capacity parallel power quality compensator, the conventional 3-level NPC inverter is more preferable, because the 3-level four-leg inverter greatly increases the initial cost and the complexity of the control strategy.

A parallel power quality compensator prototype is implemented in our lab. And experimental results are given to show that current harmonics and neutral current can be compensated simultaneously by using the 3-level 3-phase 4-wire parallel power quality compensator.

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