

# Power converter based method for suppressing power capacitor harmonic current

J.-C. Wu, H.-L. Jou, K.-D. Wu, Y.-T. Kuo and Y.-J. Chang

**Abstract:** The damage to power capacitors caused by harmonic pollution was very serious in recent years due to the wide spread of power electronic related, nonlinear loads. The violent failure of power capacitors may result in power interruption and even accidents in industry. In this paper, a power converter based protection method is proposed for protecting the power capacitor from harmonic damage. A power converter, serially connected to the power capacitor, is used to generate the harmonic components of utility voltage in the proposed method. Hence, the harmonic voltage across the power capacitor is cancelled. It means that the voltage dropped in the power capacitor will be maintained as sinusoidal, despite the waveform distortion of the utility voltage; the current flowing through the power capacitor is then also sinusoidal. Therefore, the power capacitor will not be damaged by the harmonic. A prototype is developed and tested to verify the performance of the proposed method. The test results show that the proposed method has the expected performance.

## 1 Introduction

The power factor is often lagging in practical industrial power systems. It results in some problems such as, decreasing the capacity and efficiency of transmission, the substation and distribution and degrading the voltage regulation. The methods for improving the power factor include the use of the power capacitor, synchronous condenser, static VAR compensator (SVC) and active power filter [1, 2]. Of all these methods the power capacitor provides the most economical solution. Research results have shown that the power capacitors used in power systems account for about half of the power generation capacity [3]. Power electronic related equipment has seen significant growth in the recent years. Unfortunately, the input current of most power electronic related equipment has the characteristics of poor power factor and rich harmonic current components [1, 2]. Hence, the harmonic pollution becomes serious in modern distribution power systems. The harmonic amplification occurs due to the existence of the power resonance between the power capacitor and system impedance of the power system polluted by harmonic [3–6]. The power resonance may destroy the power capacitor and neighbouring power equipment [7–10]. Besides this, the impedance of the power capacitor is inversely proportional to the frequency. It provides a low impedance path for harmonic current generated by neighbouring loads. Therefore, the installation of the power capacitor in the distribution power system may

induce the undesired harmonic current from the neighbouring loads. Hence, the consideration in designing the power capacitor is not only the power factor compensation but also the over-rating caused by harmonic pollution [5].

Conventionally, passive power filters are used to suppress the harmonic current. However, the passive filters have the risk of power resonance. Recently, the shunt active power filter has been developed to suppress the harmonic current and simultaneously compensate the power factor [1, 2, 11–14]. However, its cost is still too high in the application of reactive power compensation. On the other hand, the shunt active power filter can be connected in parallel with the power capacitor to suppress the harmonic current. However, most of the shunt active power filters [2] can only suppress the harmonic current of downstream load because the compensation current is calculated from the load current, and it cannot block the harmonic injected from the utility. The active power filter desired in [1] can block the harmonic injected from the utility when the power capacitor is connected in the downstream of the active power filter. However, it may induce the high frequency oscillation between the existing power capacitor and active power filter, and a large-power capacity active power filter is required. In this paper, a new method for protecting the power capacitor from harmonic damage is proposed. The proposed method uses a small-capacity power converter. This power converter is in series with the power capacitor. This power converter generates the harmonic components of the utility voltage. Hence, the harmonic voltage across the power capacitor is cancelled. Then, both the power capacitor voltage and the power capacitor current will be maintained as a sine wave, regardless of whether or not the utility waveform voltage is distorted. Therefore, the damage to the power capacitor due to the power resonance or harmonic pollution can be avoided. Since the role of the power converter in the proposed method is to protect the power capacitor from harmonic damage, it is different from the role of the active power filter, which is to suppress the harmonic current of the utility. The power rating of the power converter in the proposed method depends on the

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J.-C. Wu is with the Department of Electrical Engineering, Kuan Shan University of Technology, Tainan, Taiwan

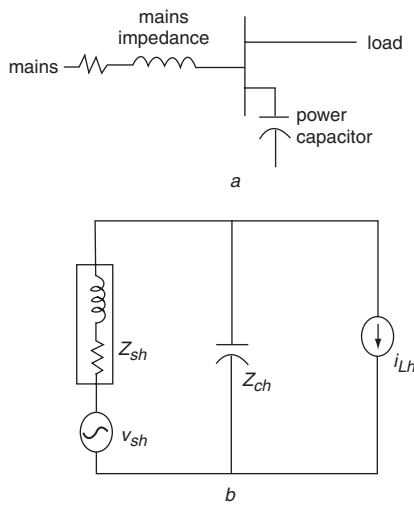
H.-L. Jou and K.-D. Wu are with the Department of Electrical Engineering, National Kaohsiung Institute of Technology, Kaohsiung 80782, Taiwan

Y.-T. Kuo and Y.-J. Chang are with the UIS Abler Electronics Corporation, Ltd. Taiwan

distortion of utility voltage. However, the total harmonic distortion (THD) of the utility voltage is limited to below 5% in most industrial power systems. Hence, the capacity of the power converter in the proposed method is much smaller than that used in the shunt active power filter. To verify the proposed method, a prototype is developed and tested.

## 2 Harmonic effect of power capacitor

An industrial distribution system using the power capacitor for compensating the reactive power can be simplified as shown in Fig. 1a. The input characteristic of the load is nonlinear. On the other hand, the utility voltage is often distorted due to the neighbouring nonlinear loads. Hence, it can be regarded as two harmonic sources in Fig. 1a, a nonlinear load and a distorted utility voltage. For simplifying the analysis, the nonlinear load is simplified as a harmonic current source, and the distorted utility voltage is regarded as a harmonic voltage source. Figure 1b shows the harmonic equivalent circuit for this system.



**Fig. 1** Simplified industrial system  
a configuration  
b equivalent circuit

### 2.1 Effect of nonlinear load

For considering the effect of nonlinear loads, the harmonic voltage source is assumed to be a short-circuit. The harmonic current injected into the power capacitor can be derived as

$$i_{ch}(t) = \frac{Z_{sh}}{Z_{ch} + Z_{sh}} i_{Lh}(t) \quad (1)$$

where  $h$  is the index for representing the harmonic components. Since the system impedance is inductive, the parallel resonance will occur when the denominator of (1) is near zero. As the power resonance occurs, it will result in a large harmonic current injected into the power capacitor. This harmonic current caused by the power resonance will be amplified, and its amplitude may be several times the amplitude of the harmonic current source. At the same time, the harmonic voltage across the power capacitor is also amplified. This means that the power quality will be degraded and the normal operation of neighbouring power equipment may be affected. In addition, the parallel resonance may damage the power capacitor due to over-voltage or over-current. In this condition, the resonant

frequency is represented as

$$\omega_r = \frac{1}{\sqrt{L_s C}} \quad (2)$$

where  $L_s$  is the inductance of system impedance.

### 2.2 Effect of distorted utility voltage

For considering the effect of distorted utility voltage, the harmonic current source is assumed to be an open circuit. The harmonic current injected into the power capacitor can be derived as

$$i_{ch}(t) = \frac{1}{Z_{ch} + Z_{sh}} v_{sh}(t) \quad (3)$$

The series resonance will occur when the denominator of (3) is near zero. The frequency of series resonance is the same as (2). From (3), it can be found that the harmonic current injected into the power capacitor will be amplified as the utility voltage contains the harmonic component near the frequency of power resonance. The utility voltage is often distorted due to the neighbouring nonlinear load in a practical industrial distribution system. It implies that the harmonic current of the neighbouring nonlinear loads will inject into the power capacitor, and it may result in harmonic resonance. Hence, the amplitude of input harmonic current may be amplified and the feeder voltage may be seriously distorted due to the existence of the power capacitor.

When preventing the power resonance, it is necessary to investigate the background harmonic before installing the power capacitor for reactive power compensation. Otherwise, the installation of the power capacitor may amplify the effect of harmonic distortion and may even damage the power capacitor itself. However, the system parameters of an industrial power system are time-varying and hard to predict, so harmonic damage of the power capacitor still frequently occurs.

## 3 Basic operation theory

The basic concept of the proposed protection method is to maintain the voltage across the power capacitor as sinusoidal. Then, its current will also be sinusoidal and hence, the harmonic damage to the power capacitor can be avoided. This can be done by inserting a harmonic voltage source in series with the power capacitor to cancel the harmonic component of the utility voltage. The inserted harmonic voltage source is the same as the harmonic voltage of the utility voltage. Therefore, this method can be called a 'harmonic voltage cancellation method'. Figure 2 shows the power circuit configuration of the proposed protection method. It contains a voltage-source power converter acting as a voltage source. Assuming the distorted utility voltage is

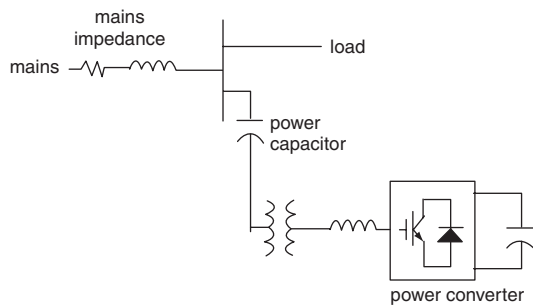
$$v_s(t) = V_1 \sin(\omega t) + \sum_{n=2}^{\infty} V_n \sin(n\omega t + \theta_n) \quad (4)$$

and if the power converter can generate a voltage as

$$v_c(t) = \sum_{n=2}^{\infty} V_n \sin(n\omega t + \theta_n) \quad (5)$$

then,  $i_c(t)$  can be represented as

$$\begin{aligned} i_c(t) &= \frac{(v_s(t) - v_c(t))}{Z_c} \\ &= \frac{V_1 \sin(\omega t)}{Z_c} \end{aligned} \quad (6)$$



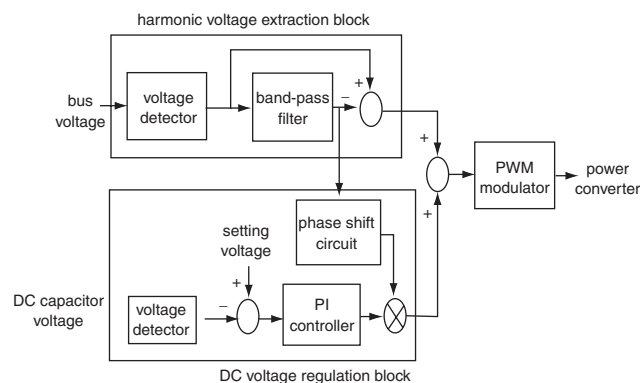
**Fig. 2** Power circuit configuration of proposed protection method

From (6), it can be found that the power capacitor current is a pure sinusoidal waveform. Thus, the harmonic damage to the power capacitor can be avoided.

The power rating of power converter is determined by its output voltage and output current. The output current of the power converter is nearly equal to the power capacitor current divided by the turns ratio of the power transformer for voltage matching. The power capacitor current depends on the amount of compensated VAR. The output voltage of the power converter depends on the distortion of the utility voltage. In Fig. 1, the harmonic current generated by the nonlinear load will result in a harmonic voltage in the utility voltage. This harmonic voltage is equal to the multiplied result of the load harmonic current and the utility impedance. In general, the THD of the utility voltage is specified to be lower than 5% in an industrial distribution system. Hence, the harmonic component of the utility voltage is very small when compared with the fundamental component, if there is no harmonic resonance. Hence, the output voltage and the capacity of the power converter are also generally very small. The power transformer in Fig. 2 is used to match the voltage rating of the power switching devices and the harmonic voltage generated by the power converter for improving the voltage utilisation ratio of power switching devices.

#### 4 Control block diagram of proposed protection method

The block diagram of the proposed protection method is shown in Fig. 3. It contains two control blocks: a harmonic voltage extraction block and a DC voltage regulation block. In ideal conditions, the output voltage of proposed power converter contains no fundamental component and its current contains only the fundamental component. Hence, no real power is consumed. However, in practice, the power loss caused by the power switching and passive devices cannot be avoided. The power loss will decrease



**Fig. 3** Block diagram of the proposed protection method

the DC capacitor voltage. The DC voltage regulation block is required to maintain a constant DC capacitor voltage.

In the harmonic voltage extraction block, the utility voltage is detected and fed to a band-pass filter to extract its fundamental component. Subtracting this fundamental component from the utility voltage leaves just its harmonic component. The power converter must absorb or generate the real power in order to regulate the DC capacitor voltage. In the proposed method, the power converter acts as a voltage source. Hence, it must generate a voltage which is either in phase or  $180^\circ$  out-of-phase with the power capacitor current to absorb or generate the real power. In the DC voltage regulation block, the DC voltage of power converter is detected and compared with its setting value. The comparative result is sent to a PI controller. Because the power capacitor current leads the utility voltage by  $90^\circ$ , the sensor for detecting the power capacitor current can be replaced by the fundamental component of the utility voltage and a  $90^\circ$  phase-shift circuit. The outputs of the PI controller and  $90^\circ$  phase-shift circuit are sent to a multiplier. Finally, the reference signal for the power converter is obtained by summing the output of the harmonic voltage extraction block and the DC voltage regulation block. The reference signal is sent to the PWM modulator to generate the driving signals of the power switching devices.

#### 5 Simulation

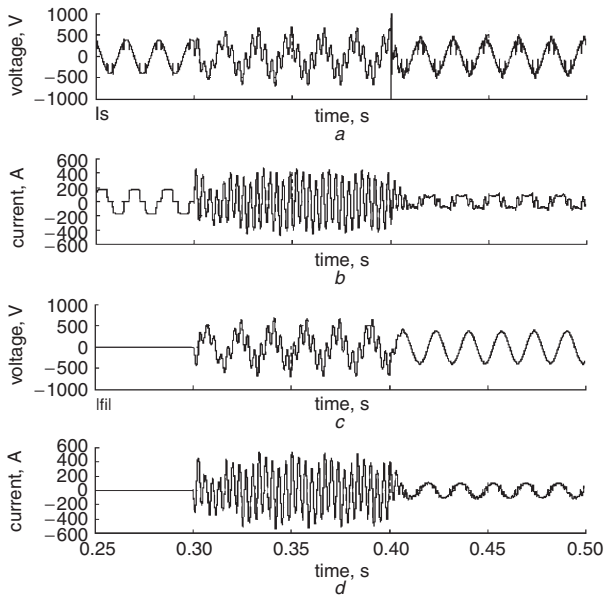
To verify the performance of the proposed protection method, a computer simulation was performed. The main parameters used in the simulation are shown in Table 1. In Table 1, the utility inductance and power capacitor are resonant near fifth-order harmonic (300 Hz). A higher power converter DC voltage is used in the simulation due to the insertion of a large utility inductor.

**Table 1: Simulation system parameters**

Power capacitor	700 $\mu$ F	Utility impedance	0.405 mH
Utility voltage	480 V	DC bus voltage	400 V
Turn ratio of transformer	4:1	Filter inductance	0.2 mH

##### 5.1 Effect of nonlinear load

For considering the effect of a nonlinear load, a rectifier load is connected in parallel with the power capacitor under the non-distorted utility voltage. Figure 4 shows the simulation result of this load condition. In Fig. 4, the power capacitor is applied at 0.3 s and the power converter at 0.4 s. Since the load is a phase-control rectifier, the load current contains rich harmonic currents of the 5th, 7th ... etc., order. The 5th harmonic load current will result in power resonance after applying the power capacitor. Hence, the 5th harmonic components of the power capacitor current and input current are amplified due to the power resonance during the 0.3 to 0.4 period. It shows that the improper installation of the power capacitor will seriously degrade the input current and means that the power capacitor becomes a new harmonic source and will degrade the power quality. Moreover, the power capacitor current contains other harmonic components. This phenomenon can be explained because the impedance of the power capacitor is inversely proportional to the frequency. The RMS value of the power capacitor current is 267 A in this period, and is more than three-times that of normal current.



**Fig. 4** Simulation result for nonlinear load condition

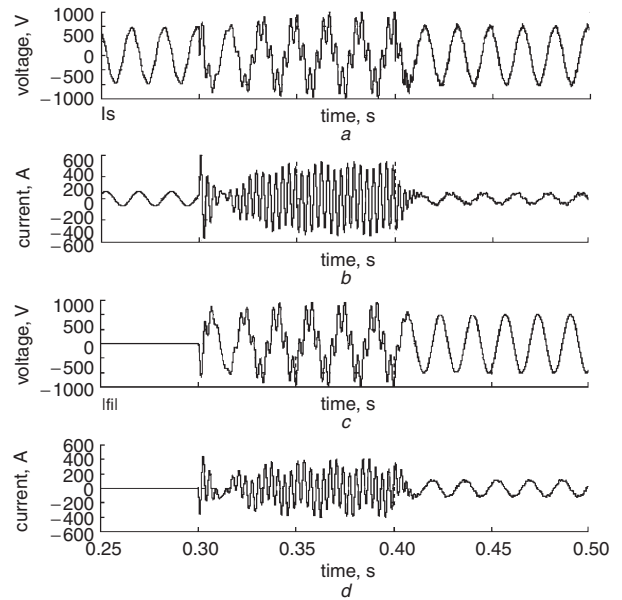
- a The utility voltage
- b The utility current
- c Power capacitor voltage
- d Power capacitor current

In IEC 871-1, the power capacitor current is specified as not being over 130% of its rating current [8–10] and therefore, the power capacitor will be destroyed due to over-current. After applying the power converter, the RMS value of the power capacitor current is reduced to 77 A which is in its safe operating range. From Fig. 4, it can be seen that the power capacitor current is nearly sinusoidal in the period 0.4 to 0.5 s, showing that the power converter can suppress the power resonance effectively.

### 5.2 Effect of distorted utility voltage

In a practical industrial power system, the utility voltage is often distorted due to the neighbouring nonlinear load. Therefore, the effect of distorted utility voltage is considered in the following simulation. The utility voltage contained 5% of the 5th order harmonic that is used in the simulation. The applied load is linear, comprising a resistor in series with an inductor. Figure 5 shows the simulation result for the distorted utility condition. In Fig. 5, the power capacitor is applied at 0.3 s and the power converter is applied at 0.4 s. From Fig. 5, it can be seen that the 5th harmonic of the utility voltage will result in resonance after applying the power capacitor. Hence, the 5th harmonic of the power capacitor current and utility current are all amplified. From Fig. 5, it can be seen that the utility current will be degraded seriously even if the applied load is a linear load when the power capacitor is used to compensate the power factor. The RMS value of the power capacitor current is 287 A, more than three-times its normal value. Hence, the installation of the power capacitor under a distorted utility voltage condition may destroy the power capacitor and neighbouring equipment. From Fig. 5, it can be seen that the power capacitor current in the period 0.4 to 0.5 s is nearly sinusoidal after applying the power converter. The RMS value of the power capacitor current is reduced to 79 A, and is in the safe operating range.

From the simulation results above, it can be seen that the proposed protection method can effectively protect the power capacitor from harmonic destruction, and can also



**Fig. 5** Simulation result for distorted utility voltage condition

- a The utility voltage
- b The utility current
- c Power capacitor voltage
- d Power capacitor current

avoid the degradation of power quality caused by the improper installation of power capacitor.

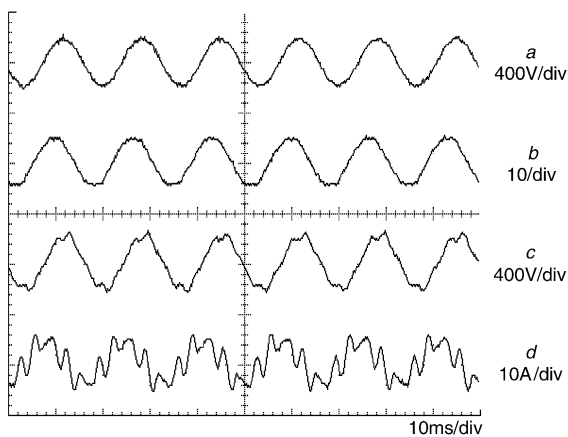
## 6 Experimental result

To verify the proposed method, a three-phase prototype was established in the laboratory. The main parameters of the prototype are shown in Table 2. Due to the limitation of power capacity in the laboratory, the prototype was scaled down. To observe the effect of the proposed protection method more clearly, a 5 mH inductor was inserted in series with the utility voltage to increase the utility impedance. A higher power converter DC voltage was used in the prototype due to the insertion of the large series inductor. A three-phase diode rectifier was used as a nonlinear load. Because it was difficult to replicate a suitable harmonic voltage source in the laboratory, only the effect of the nonlinear load was examined in the experiment results.

**Table 2: Prototype parameters**

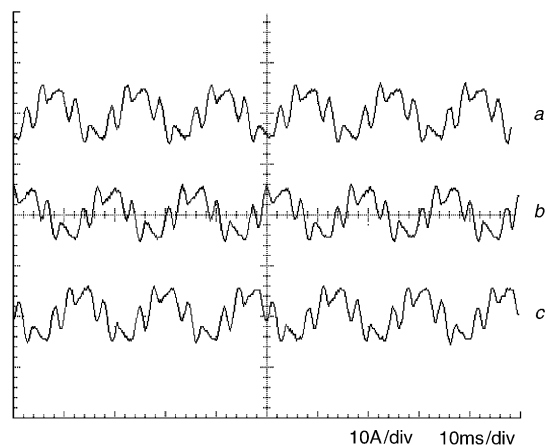
Power capacitor	100 $\mu$ F	Utility impedance	5 mH
Utility voltage	220 V	DC bus voltage	200 V
Turn ratio of transformer	4:1	Filter inductance	0.2 mH
Power MOSFET	400 V, 10 A	Switching frequency	20 kHz

Figure 6 shows the experimental result of the developed system before applying the power converter. It shows that the capacitor voltage is distorted due to the nonlinear load and the capacitor current is seriously distorted due to the distorted capacitor voltage. Figure 7 shows the experimental result of the three-phase power capacitor current before applying the power converter. It shows that the capacitor current contains rich harmonics. Figure 8 shows the experimental result of the three-phase capacitor current after applying the power converter. From Fig. 8, it can be



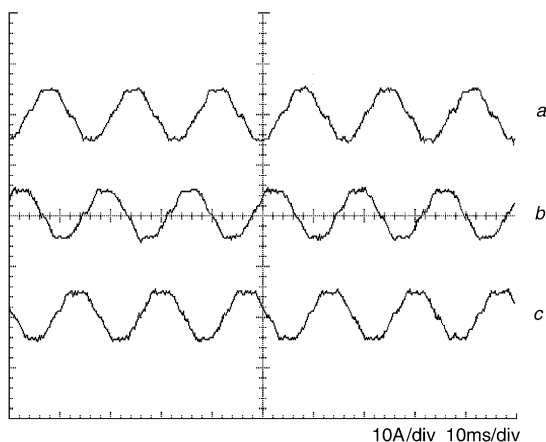
**Fig. 6** Experimental result of proposed method before applying the power converter

- a The utility voltage
- b The utility current
- c Capacitor voltage
- d Capacitor current



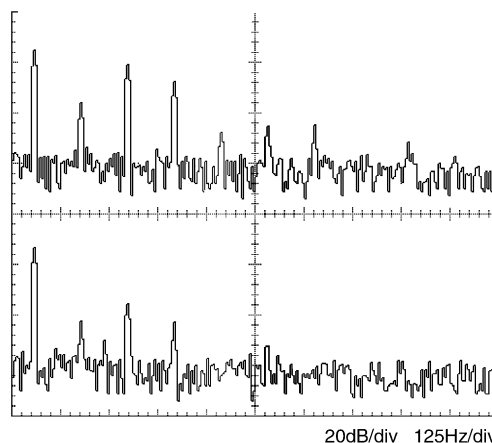
**Fig. 7** Experimental result of the three-phase capacitor current before applying the power converter

- a R-phase
- b S-phase
- c T-phase



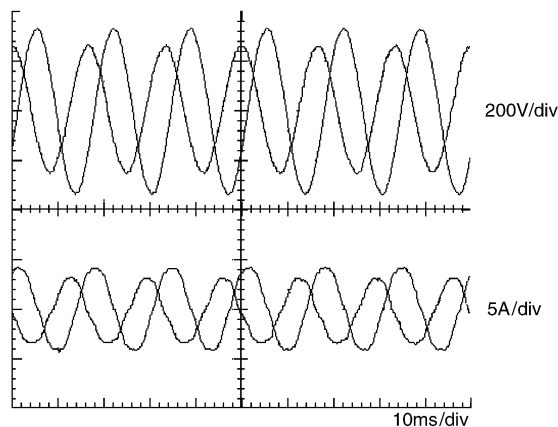
**Fig. 8** Experimental result of the three-phase capacitor current after applying the power converter

- a R-phase
- b S-phase
- c T-phase



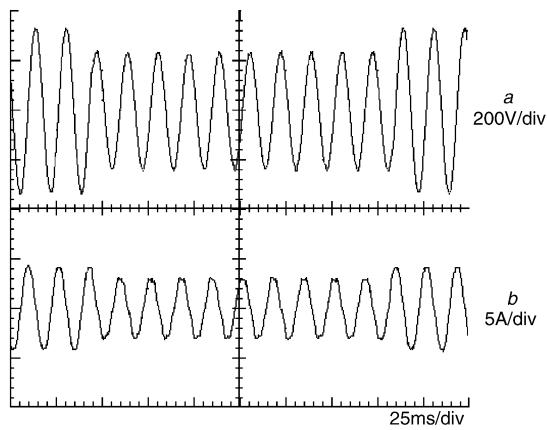
**Fig. 9** Spectrum of the capacitor current before (upper channel) and after (lower channel) applying the power converter

seen that the distortion of power capacitor current has been significantly improved. Figure 9 shows the spectrum of power capacitor current before and after applying the power converter. It shows that the THD of capacitor current is 49.1% before applying the power converter and 10.4% after applying the power converter. This indicates that the harmonic components are suppressed significantly after applying the power converter. Hence, the proposed protection method can effectively solve the harmonic amplification of the power capacitor. In practical industrial power systems, the utility voltages of three-phase industrial power systems are often unbalanced. Figure 10 shows the experimental result under the condition of the unbalanced utility voltages. Because the oscilloscope used in laboratory had only four channels, only two phases of the utility voltages and capacitor currents are shown in the test result. The voltages of two phases are 1:0.75. As seen in Fig. 10, the power capacitor currents are also unbalanced but nearly sinusoidal under the condition of unbalanced utility voltages. Since the power converter used in the proposed method only responds to the harmonic component of the utility voltage, the unbalanced utility voltages will not affect the protection performance in the proposed method. The voltage sag or the utility voltage variation occurs frequently due to the application of the heavy load or the utility fault in the distribution power system. Figure 11 shows the experimental result under the 30% voltage variation. As



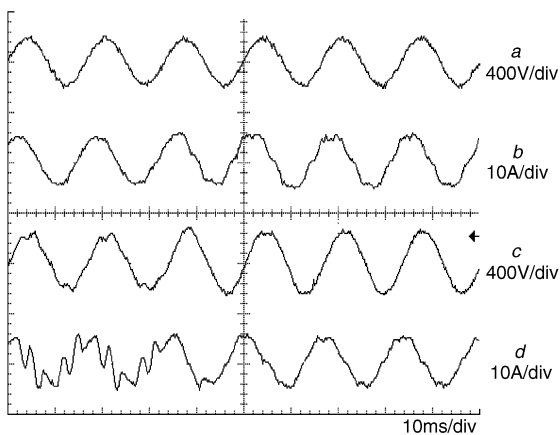
**Fig. 10** Experimental result under the condition of the unbalanced utility voltages

- a Upper channels: voltages of phases a and b,
- b Lower channels: capacitor currents of phases a and b



**Fig. 11** Experimental result under the condition of voltage sag or the utility voltage variation  
 a The utility voltage  
 b The capacitor current

seen in Fig. 11, the capacitor currents are nearly sinusoidal under this condition. This result indicates that the proposed protection method has the expected performance and no unexpected current transient during the voltage sag or the utility voltage variation. Figure 12 shows the transient performance of the proposed method before and after applying the power converter. It can be seen that the capacitor current is nearly sinusoidal after applying the power converter and that the transient performance of the proposed protection method is excellent.



**Fig. 12** Transient performance of the proposed method under applying the power converter  
 a Utility voltage  
 b Utility current  
 c Capacitor voltage  
 d Capacitor current

## 7 Conclusion

The fast growth of power electronic related nonlinear loads has resulted in serious harmonic problems. The power

capacitor is used for reactive power compensation in the distribution power system. Power capacitor damage has occurred frequently in recent years due to harmonic pollution. This problem cannot be solved effectively using the present protection method. In this paper, a novel active protection method, using a power converter, has been proposed to solve this problem. Considering the DC capacitor voltage regulation and harmonic voltage cancellation of the power capacitor, the power rating of the power converter is less than 10% of the reactive power supplied from the power capacitor under 5% distortion of the utility voltage. Hence, the power converter used in the proposed method is very small. This increases the practical application of the proposed method. Both the simulation and experimental results show that the proposed method can suppress both the harmonic voltage and harmonic current of the power capacitor. Hence, harmonic damage to the power capacitor can be avoided by using the proposed method.

## 8 Acknowledgment

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