A New Hybrid Power Conditioner for Suppressing Harmonics and Neutral-Line Current in Three-Phase Four-Wire Distribution Power Systems

Jinn-Chang Wu, *Member, IEEE*, Hurng-Liahng Jou, *Member, IEEE*, Hsin-Hsing Hsaio, and Shun-Tian Xiao

***Abstract*—In this paper, a new hybrid power conditioner is proposed for suppressing harmonic currents and neutral-line current in three-phase four-wire distribution power systems. The proposed hybrid power conditioner is composed of a neutral-line current attenuator and a hybrid power filter. The hybrid power filter, configured by a three-phase power converter and a three-phase tuned power filter, is utilized to filter the nonzero-sequence harmonic currents in the three-phase four-wire distribution power system. The three-phase power converter is connected to the inductors of the three-phase tuned power filter in parallel, and its power rating can thus be reduced effectively. The tuned frequency of the three-phase tuned power filter is set at the fifth harmonic frequency. The neutral-line current suppressor is connected between the power capacitors of the three-phase tuned power filter and the neutral line to suppress the neutral-line current in the three-phase four-wire distribution power system. With the major fundamental voltage of the utility dropping across the power capacitors of the three-phase tuned power filter, the power rating of the neutral-line current suppressor can thus be reduced. Hence, the proposed hybrid power conditioner can effectively reduce the power rating of passive and active elements. A hardware prototype is developed to verify the performance of the proposed hybrid power conditioner. Experimental results show that the proposed hybrid power conditioner achieves expected performance.**

***Index Terms*—Harmonic, neutral-line current, power converter.**

I. Introduction

THREE-PHASE four-wire distribution power systems have been widely applied in office buildings and manufacturing-office buildings to supply single-phase or three-phase loads. The third harmonic is very serious in single-phase nonlinear loads. The third-order harmonic current of each phase is synchronous and regarded as the zero-sequence current. Therefore, the zero-sequence currents of each phase are summed up and flow into the neutral line of three-phase four-wire distribution power systems. Furthermore, single-phase loads may result in serious load unbalance, and the unbalanced load current also flows into the neutral line of the three-phase four-wire distribution power systems. In many applications, the neutral-line current will exceed the phase currents. Excessive neutral-line current may cause accidents due to overload of the neutral line. Moreover, it will lead to fluctuation in ground voltage of the load, which may influence the operation of precision equipment. Hence, the major problems of three-phase four-wire distribution power systems are harmonic currents and neutral-line current [1], [2].

The zig-zag transformer, connected to the load in parallel, has been employed to attenuate the neutral-line current [1], [3], [4]. However, the attenuation of neutral-line current is dependent on the ratio between the impedance of the utility system and the zig-zag transformer. Furthermore, the zig-zag transformer also has a low impedance path for zero-sequence voltage of the unbalanced utility, which will further cause a significant neutral-line current [4]. A single-phase power converter can be combined with the zig-zag transformer to advance the performance of the neutral-line current suppression [5], [6]. The single-phase power converter is inserted at the neutral line between the load and the utility, thus causing fluctuation in the ground voltage of the load. A neutral-current suppression scheme, configured by a Δ-Y transformer and a single-phase power converter connected in series, is connected to the load in parallel to suppress the neutral-line current [7]. The neutral line of the load is directly connected to that of the utility, and the fluctuation in ground voltage of the load can thus be avoided. A series of active power filters connected to the neutral line between the utility and the load can suppress the neutral-line current, thus eliminating the need of the transformer for a zero current path [8]. However, there is fluctuation in ground voltage of the load because the neutral lines of the load and utility are separated.

Conventionally, passive power filters have been employed to solve the problems of harmonic currents and neutral-line current in three-phase four-wire distribution power systems. Although passive power filters have the advantage of low hardware cost, their performance is often significantly affected by the system impedance. Furthermore, salient problems, including large volume, parallel resonance, and series resonance may further offset the benefits of this method [9], [10]. With advances in power semiconductor technology, power-electronic-based active power equipment is gradually replacing or sharing the role of passive power equipment. Active power filters have been proposed for suppressing the harmonic currents in single-phase and three-phase three-wire distribution

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power systems [11]–[13]. The three-phase four-wire active power filter can further suppress the neutral-line current in three-phase four-wire distribution power systems [13], [14]. Although active power filters can solve the majority of problems of three-phase four-wire distribution power systems, the capacity of the power converter must be larger than the product of the utility voltage and the current including the fundamental reactive current and the harmonic current of the load. Therefore, the capacity and manufacturing cost of this type of power converter is very high, thus limiting wide application of active power filters. Moreover, the switching power loss of the power converter due to high voltage and high current switching is significant.

Hybrid power conditioners have been developed to solve the problems of passive and active power conditioners. A hybrid power filter consists of a passive power filter and a power converter [15]–[23]. In operation, the passive power filter can reduce the capacity of the power converter while the power converter is employed to improve the filter characteristics of the passive power filter. Hybrid power filters can be divided into series-linked type [15]–[17] and shunt type [18]–[24]. In hybrid power filters of the series-linked type, the power converter is connected between the utility and the load through a linked transformer, and the passive power filter is parallel to the load [15]–[17]. The voltage drop on the power converter is low in order to reduce the dc bus voltage. However, the current of the power converter, including the fundamental current of the load and the fundamental reactive current of the passive power filter, is still large. In hybrid power filters of the shunt type, the power converter is connected to the passive power filter in series and then connected to the load in parallel [18]–[21]. The major part of the utility voltage will drop on the passive power filter. In this way, the dc bus voltage and voltage rating of the power converter can be significantly reduced. However, the current of the power converter, including the harmonic currents of the load and the fundamental reactive current of the passive power filter, is not diminished. Although the shunt-type hybrid power filter can be applied to improve problems of the neutral-line current in three-phase four-line distribution power systems [21], it cannot attenuate the fundamental component of neutral-line current caused by the unbalanced load. In addition, the current of the power converter is not diminished yet.

A new hybrid power conditioner for solving the problems of harmonic currents and neutral-line current in three-phase four-wire distribution power systems is proposed in this paper. This hybrid power conditioner is configured by a neutral-line current attenuator and a hybrid power filter. The hybrid power filter, configured by a three-phase power converter and a three-phase tuned power filter, is utilized to filter the nonzero-sequence harmonic currents in the three-phase four-wire distribution power system. The neutral-line current suppressor is connected between the power capacitors of the three-phase tuned power filter and the neutral line to attenuate the neutral-line current in the three-phase four-wire distribution power system. The proposed hybrid power conditioner can effectively reduce the power rating of passive and active elements. A hardware prototype is developed to verify the performance of the proposed hybrid power conditioner.

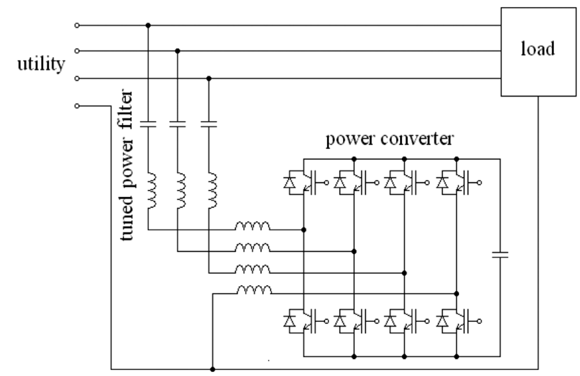

Fig. 1. Configuration of the conventional shunt-type hybrid power filter.

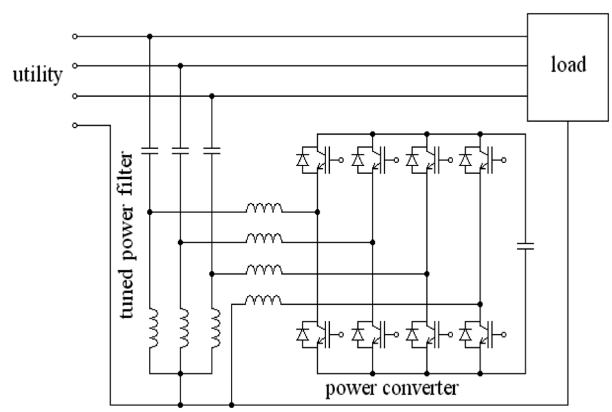

Fig. 2. Configuration of the advanced hybrid power filter.

II. THREE-PHASE FOUR-WIRE HYBRID POWER FILTER

Fig. 1 shows the configuration of a conventional shunt-type hybrid power filter applied to the three-phase four-wire distribution power system. In the conventional shunt-type hybrid power filter, the power converter is connected to the passive power filter in series and then connected to the load in parallel [18]–[21]. The power converter can be configured by a four-arm bridge structure or a three-arm bridge structure with a split-capacitor arm. The passive power filter is configured by three-phase tuned power filters with an inductor and a capacitor connected in series in each phase, and their tuned frequency is the dominant harmonic frequency of the load. The tuned frequency of the tuned power filters is designed at the third harmonic frequency in the application of three-phase four-wire distribution power systems. As seen in Fig. 1, the major part of the utility voltage will drop on the passive power filter. In this way, the dc bus voltage and voltage rating of the power converter can be significantly reduced. However, the current of the power converter, including the harmonic currents of the load and the fundamental reactive current of the passive power filter, is not diminished. An advanced hybrid power filter, shown in Fig. 2, is proposed to further reduce the power rating of the power converter [22]–[25]. As seen in Fig. 2, the power converter is connected to the inductors of the three-phase tuned power filter in parallel. Since the power converter is parallel to the inductors of the tuned power filters, the major fundamental reactive current of the three-phase tuned power filter and the dominant harmonic current of the load will flow through the inductors

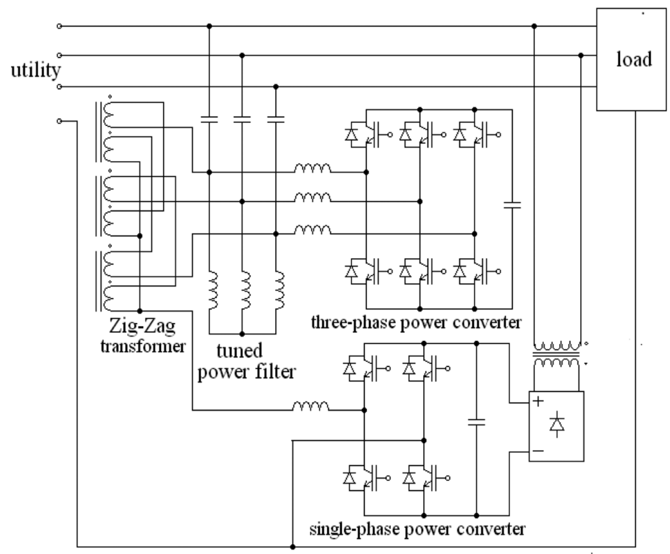

Fig. 3. System configuration of the proposed hybrid power conditioner.

of the three-phase tuned power filter by proper control of the power converter, thus decreasing the current flowing through the power converter.

The major role of the conventional shunt-type hybrid power filter applied to the three-phase four-wire distribution power system is to filter harmonic currents of the load. If the three-phase loads are unbalanced, the neutral-line current of the load contains a fundamental component. The conventional shunt-type hybrid power filter cannot respond to this fundamental component of the neutral-line current. Therefore, it cannot effectively suppress the neutral-line current under the unbalanced load.

III. System Configuration of the New Hybrid Power Conditioner

Fig. 3 shows the system configuration of the proposed hybrid power conditioner. In comparison with the conventional hybrid power filter, a neutral-line current attenuator is integrated into the hybrid power filter in the proposed hybrid power conditioner. The integrated neutral-line current attenuator can advance the filter performance of the hybrid power filter under the unbalanced load. Hence, the proposed hybrid power conditioner can simultaneously and effectively solve the problems of harmonic currents and neutral-line current in three-phase four-wire distribution power systems.

To further reduce the power rating of the power converter, the advanced hybrid power filter is used with the three-phase power converter connected to the inductors of the three-phase tuned power filter in parallel. By incorporating the neutral-line current attenuator, the hybrid power filter is utilized to suppress only the nonzero-sequence harmonic currents in three-phase four-wire distribution power systems. Hence, the three-phase power converter is configured by a three-arm bridge structure and the tuned frequency of three-phase tuned power filter is set at the fifth harmonic frequency. With an increase in tuned frequency of the tuned power filters, the inductance of inductors can be reduced. Consequently, the volume and weight of the three-phase tuned power filter are reduced. The neutral-line current attenuator of the hybrid power conditioner is employed to suppress the neutral-line current. Conventionally, the neutral-line current attenuator is connected between three-phase lines and the neutral line of the three-phase four-wire utility [6]. Hence, the voltage rating of the zig-zag transformer used in the conventional neutral-line current attenuator is the phase voltage of the three-phase four-wire utility, thus enlarging the volume and weight of the zig-zag transformer. As can be seen in Fig. 3, the neutral-line current attenuator is connected to the capacitors of tuned power filters in series, and the fundamental component of phase voltage will drop on these capacitors. The voltage rating of the zig-zag transformer is almost equal to the voltage of inductors in the tuned power filters, and its voltage is very small compared with the zig-zag transformer used in the conventional neutral-line current attenuator. Hence, the volume and weight of the zig-zag transformer used in the proposed neutral-line current attenuator are reduced. The single-phase power converter is connected to the zig-zag transformer in series to advance the performance of the zig-zag transformer. As seen in Fig. 3, the neutral line of the load is directly connected to that of the utility, and the fluctuation in ground voltage of the load can thus be avoided. Owing to power loss caused by the operation of the single-phase power converter, the dc bus voltage of the power converter is decreased. However, the power loss is low because the dc bus voltage of the single-phase power converter is low. A simple single-phase diode rectifier is employed to supply power to the dc bus of the single-phase power converter to sustain the dc bus voltage at an acceptable range. A transformer is employed to step down the line-to-line voltage. The input current of the single-phase diode rectifier is small.

IV. Control Principle

Current-mode control is adopted to control the three-phase power converter of the hybrid power filter. The output currents of the three-phase power converter are controlled to be

$$\mathrm{I_{ca}} = \mathrm{k_1 I_{sah}} + \mathrm{k_2 V_{sa1}} \tag{1}$$

$$\mathrm{I_{cb}} = \mathrm{k_1 I_{sbh}} + \mathrm{k_2 V_{sb1}} \tag{2}$$

$$\mathrm{I_{cc}} = \mathrm{k_1 I_{sch}} + \mathrm{k_2 V_{sc1}} \tag{3}$$

where $\mathrm{I_{sah}}$, $\mathrm{I_{sbh}}$, and $\mathrm{I_{sch}}$ are the harmonic components of the three-phase utility currents; $\mathrm{V_{sa1}}$, $\mathrm{V_{sb1}}$, and $\mathrm{V_{sc1}}$ are the three-phase fundamental voltages of the utility. As seen in (1)–(3), the first term is for suppressing the nonzero-sequence harmonics, and the second term is for regulating the dc bus voltage of three-phase power converter. Since the three-phase power converter is parallel to the inductors of the three-phase tuned power filter and its output currents are controlled as (1)–(3), the major fundamental reactive currents of the tuned power filters and the dominant harmonic currents of the load will flow through the inductors of the tuned power filters. Therefore, the currents flowing through the three-phase power converter can be effectively decreased.

The single-phase power converter of the neutral-line current attenuator is controlled by the general pulsewidth modulation (PWM), and its output voltage can be represented as

$$\mathrm{V_{con}} = \mathrm{k_{con}} \mathrm{V_m} \tag{4}$$

where $\mathrm{k_{con}}$ is the gain of the single-phase power converter, and $\mathrm{V_m}$ is the modulation signal of the PWM circuit. The gain of the single-phase power converter can be represented as

$$\mathrm{k_{con}} = \frac{\mathrm{V_{dc}}}{\hat{\mathrm{V}}_{\mathrm{tri}}} \tag{5}$$

where $\mathrm{V_{dc}}$ is the dc bus voltage of the single-phase power converter, and $\hat{V}_{tri}$ is the amplitude of the carrier of the PWM circuit. The single-phase power converter adopts the simple feedforward control. The neutral-line current of the utility is detected, amplified, and sent to the PWM circuit as the modulation signal, and the output voltage of the power converter can be derived as

$$\mathrm{V_{con}} = \mathrm{k_{con}} \mathrm{k_3} \mathrm{I_{sn}} \tag{6}$$

where $\mathrm{k_3}$ is the feedforward gain.

V. Analysis of Hybrid Power Conditioner

To analyze the proposed active power conditioner, the sequence networks are used. Besides the fundamental frequency, the positive- and negative-sequence networks are similar under the harmonic frequency. Hence, the positive- and negative-sequence networks under the harmonic frequency can be integrated as a nonzero-sequence network. Fig. 4 shows the nonzero-sequence network of the three-phase four-wire distribution power system with the proposed active power conditioner under a specified harmonic frequency. The three-phase currents of the neutral-line current attenuator are the same; hence, it will not appear in the nonzero sequence network. The nonzero-sequence network contains two harmonic sources. One is the nonzero-sequence harmonic voltage source $(\mathrm{V_{sh}^{nz}})$ which reveals the distorted utility voltage and the other is the nonzero-sequence harmonic current source $(\mathrm{I_{Lh}^{nz}})$ generated by the nonlinear load. In Fig. 4, $\mathrm{Z_{sh}}$, $\mathrm{Z_{ch}}$, and $\mathrm{Z_{Lh}}$ are the system impedance of the utility, the impedance of the capacitors, and the inductors in the tuned power filters under the specified harmonic frequency, respectively. Since the current-mode control is adopted to control the three-phase power converter, the three-phase power converter can be regarded as a dependent current source. As seen in Fig. 4, the harmonic components $(\mathrm{I_{sh}^{nz}})$ of the nonzero-sequence utility current can be derived as

$$\mathrm{I_{sh}^{nz}} = \frac{\mathrm{Z_{ch}} + \mathrm{Z_{Lh}}}{\mathrm{Z_{sh}} + \mathrm{Z_{ch}} + \mathrm{Z_{Lh}}(1+\mathrm{k_1})} \mathrm{I_{Lh}^{nz}} + \frac{1}{\mathrm{Z_{sh}} + \mathrm{Z_{ch}} + \mathrm{Z_{Lh}}(1+\mathrm{k_1})} \mathrm{V_{sh}^{nz}}. \tag{7}$$

As seen in (7), the first term of (1)–(3) can operate the three-phase power converter to enlarge the denominator, thus decreasing the nonzero-sequence harmonic current of the utility.

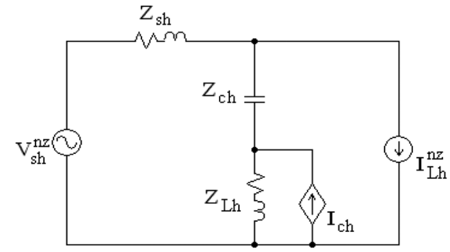

Fig. 4. Nonzero-sequence network under a specified harmonic frequency.

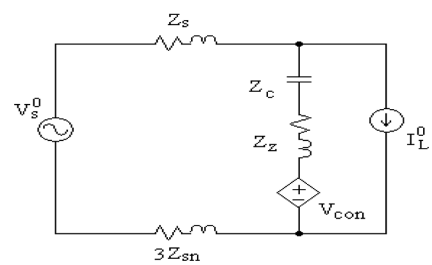

Fig. 5. Zero-sequence network.

Fig. 5 shows the zero-sequence network of the three-phase four-wire distribution power system with the proposed active power conditioner under all frequencies. Since the three-phase power converter adopts a three-arm bridge structure, it will not appear in the zero-sequence network. Moreover, the inductors of tuned power filters are not connected to the neutral line, and they will not appear in the zero-sequence network either. As seen in (6), the output voltage of the single-phase power converter in the neutral-line current attenuator is dependent on the neutral-line current of the utility, and it can thus be considered as a dependent voltage source. In Fig. 5, $\mathrm{Z_s}$ and $\mathrm{Z_{sn}}$ are the phase-line impedance and neutral-line impedance of the utility, respectively; $\mathrm{Z_c}$ and $\mathrm{Z_z}$ are the impedance of the capacitors of tuned power filters and zig-zag transformer; and $\mathrm{V_{con}}$ is the dependent voltage source of the single-phase power converter. Since the neutral-line current of the utility is three times its zero-sequence current, $\mathrm{Z_{sn}}$ must be multiplied by 3 in the zero-sequence network. This zero-sequence equivalent circuit is configured by two zero-sequence sources $\mathrm{V_s^0}$ and $\mathrm{I_L^0}$. $\mathrm{V_s^0}$ is a zero-sequence voltage source caused by the unbalanced utility voltage. Assuming that the three-phase voltages $(\mathrm{V_{an}}, \mathrm{V_{bn}}, \mathrm{V_{cn}})$ are unbalanced, the zero-sequence voltage can be expressed as

$$\mathrm{V_s^0} = \frac{1}{3}(\mathrm{V_{an}} + \mathrm{V_{bn}} + \mathrm{V_{cn}}). \tag{8}$$

$\mathrm{I_L^0}$ is the zero-sequence current source caused by the load, and it can be derived as

$$\mathrm{I_L^0} = \frac{1}{3}(\mathrm{I_{La}} + \mathrm{I_{Lb}} + \mathrm{I_{Lc}}) \tag{9}$$

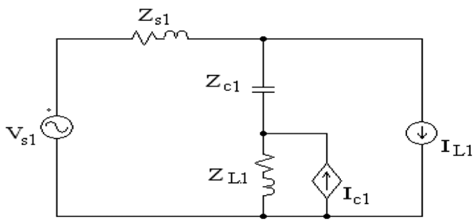

Fig. 6. Positive-sequence equivalent circuit under the fundamental frequency.

where I_{La}, I_{Lb}, and I_{Lc} are three-phase load currents. As seen in Fig. 5, the zero-sequence current I_s^0 of the utility can be derived as

$$I_s^0 = \frac{Z_c + Z_z}{(Z_{sp} + 3Z_{sn}) + Z_z + 3k_{con}k_3} I_L^0 + \frac{1}{(Z_{sp} + 3Z_{sn}) + Z_z + 3k_{con}k_3} V_s^0. \quad (10)$$

The neutral-line current of the utility can be represented as

$$I_{sn} = 3I_{s0}. \quad (11)$$

As seen in (10), the term $3k_{con}k_3$ is added to the denominator due to the single-phase power converter being used. Hence, operation of the single-phase power converter is equivalent to inserting a resistor into the neutral line between the utility and zig-zag transformer. Hence, the neutral-line current of the utility can be suppressed. Although the single-phase power converter acts as a resister inserted into the neutral line between the utility and zig-zag transformer, the neutral line of the load is practically connected to that of the utility. Hence, the fluctuation in ground voltage of the load can be avoided.

If the fundamental component of the utility voltage is balanced, the three-phase four-wire distribution power system with the hybrid power conditioner contains only the positive-sequence equivalent circuit under the fundamental frequency. Fig. 6 shows the positive-sequence equivalent circuit of this system under the fundamental frequency. The utility and load are equivalent to a voltage source and a current source, respectively. The three-phase power converter is regarded as a dependent current source whose current is the second term of (1)–(3). The neutral-line current attenuator is opened. If the voltage across the system impedance can be neglected, the voltage of the hybrid power filter is equal to the utility voltage.

The fundamental voltage of the inductor in the tuned power filter can be derived as

$$V_{L1} = \frac{Z_{L1}}{Z_{L1} + Z_{c1}} V_{s1} = \frac{\omega_1 L}{\omega_1 L - 1/\omega_1 C} V_{s1} \quad (12)$$

where V_{s1} and ω_1 are the fundamental voltage and frequency of the utility, respectively. If the tuned frequency of the tuned power filter is $n\omega_1$, the fundamental voltage of the inductor in the tuned power filter can be rewritten as

$$V_{L1} = \frac{1}{1 - n^2} V_{s1}. \quad (13)$$

As seen in (13), the fundamental voltage of the inductor in the tuned power filter is out of phase with the fundamental voltage of the utility. As seen in Fig. 6, real power will be injected into the three-power converter because the current of the dependent current source is in phase with the fundamental voltage of the inductor. The injected real power of the three-phase power converter is dependent on k_2 of (1)–(3), and k_2 may be positive or negative according to the direction of the injected real power of the three-phase power converter. In the proposed hybrid power conditioner, the tuned power filter is tuned at the fifth harmonic frequency, and the fundamental voltage of the inductor in the tuned power filter is 1/24th of the utility voltage. Hence, the voltage rating of the three-phase power converter is further reduced compared with that of the advanced three-phase four-wire hybrid power filter, shown in Fig. 2, where the tuned frequency is set at the third harmonic frequency. In addition, the voltage rating of the neutral-line current attenuator is also low. Since the neutral-line current attenuator does not appear in the positive-sequence equivalent circuit of the fundamental frequency, it cannot inject real power from the utility into the single-phase power converter. Therefore, a simple single-phase diode rectifier is employed to supply power to the single-phase power converter to overcome its power loss.

VI. Control Block Diagram

Fig. 7 shows the control block diagram of three-phase and single-phase power converters. The three-phase power converter adopts the current-mode control. The current references should be calculated first. The current references should be equal to (1)–(3), and they contain a fundamental signal and a harmonic signal. The detected three-phase utility currents are sent to the bandstop filters to extract their harmonic components. The outputs of the bandstop filters are sent to the amplifier with gain k_1, and the harmonic signals of the current references are then obtained. The detected dc bus voltage of the three-phase power converter is compared with the setting voltage, and the compared result is sent to a proportional-integral (PI) controller. The output of the PI controller is k_2. Both the outputs of the PI controller and the detected three-phase utility voltages are sent to the multipliers so that the fundamental signals of the current references are obtained. The current references are obtained by summing up the harmonic signals and the fundamental signals. The detected output currents of the three-phase power converter are compared with the current references, and the compared results are then sent to the controllers. The outputs of the controllers are sent to the PWM circuits to generate the driver signals of the power-electronic switches for the three-phase power converter.

The feedforward control is employed to control the single-phase power converter. The neutral-line current of the utility can be obtained by summing up the detected three-phase utility currents and is then sent to an amplifier of gain k_3. The output of the amplifier is sent to the PWM circuit to serve as the modulation signal. The PWM circuit adopts unipolar PWM to generate four PWM signals for the power-electronic switches of the single-phase power converter. The control blocks of three-phase

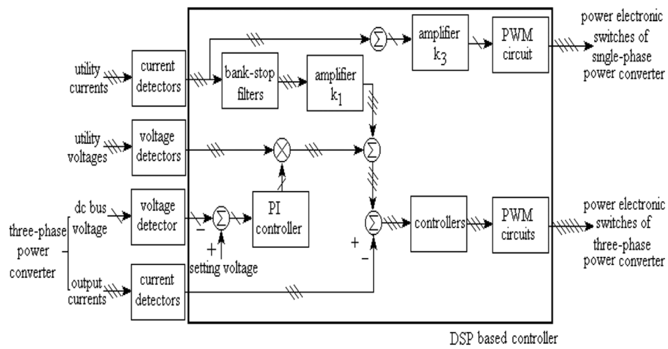

Fig. 7. Control block diagram of the three-phase and single-phase power converters.

TABLE I
MAIN PARAMETERS OF THE PROTOTYPE

tuned power filter			
Inductor	2.5mH	capacitor	130uF
Three-phase power converter			
switching frequency	20kHz	filter inductor	2mH
DC bus voltage	80V	DC capacitor	2200uF
single-phase power converter			
switching frequency	20kHz	filter inductor	2mH
DC bus voltage	80V	DC capacitor	2200uF

and single-phase power converters can be integrated into a digital-signal-processor (DSP) chip.

VII. Experimental Results

To verify the performance of the proposed three-phase four-wire hybrid power conditioner, a prototype is developed and tested. The line voltage and frequency of the utility are 220 V and 60 Hz in the experimental system. The main parameters of the prototype are shown in Table I.

Figs. 8 and 9 show the experimental results of the three-phase four-wire hybrid power conditioner under the balanced load. Fig. 8 shows the three-phase four-wire load which is composed of three single-phase rectifiers. The total harmonic distortion (THD%) of the load currents is 47%. The neutral-line current of the load is 11.2 A. Fig. 9 shows the experimental results of the utility currents after being compensated by the proposed hybrid power conditioner. As seen in Fig. 9, the three-phase utility currents are nearly sinusoidal where the THD% of the utility currents is 3.9%, and the neutral-line current of the utility is 0.81 A. In this case, the output currents of three-phase and single-phase power converters are 1.325 A and 11 A, respectively, showing expected performance of the proposed hybrid power conditioner. It can be found that the output current of three-phase power converter is much smaller than that of the conventional hybrid power filter [21]. Hence, the power rating of the three-power converter is reduced. The zig-zag transformer is configured by three single-phase transformers with a turn ratio of 1:1. In this case, the voltage and current of the single-phase transformer are 25 V and 3.67 A. The power rating of the zig-zag transformer is small compared with that in the conventional neutral-line current attenuator where the zig-zag transformer is connected to the utility directly [6]. Fig. 10 shows the experimental results of the three-phase four-wire hybrid power conditioner under the transient of applying the neutral-line current attenuator. As seen in this figure, the utility current is still distorted due to the existence of the third harmonic, and the neutral-line current is large before applying the neutral-line current attenuator. However, the utility current is sinusoidal and the neutral-line current disappears after applying the neutral-line current attenuator. This phenomenon verifies that the hybrid power filter suppresses the positive-sequence and negative-sequence harmonic components while the neutral-line current attenuator suppresses the zero-sequence components, which is in agreement with the aforementioned analysis. Figs. 11 and 12 show the experimental results of the three-phase four-wire hybrid power conditioner under the unbalanced load. Fig. 11 shows the experimental results of the unbalanced three-phase load currents and the neutral load current. As can be seen, only a single-phase rectifier is applied between the phase a and neutral line of three-phase four-wire distribution power system. It is the worst case for the unbalanced load. Fig. 12 shows the experimental results of the utility currents after being compen-

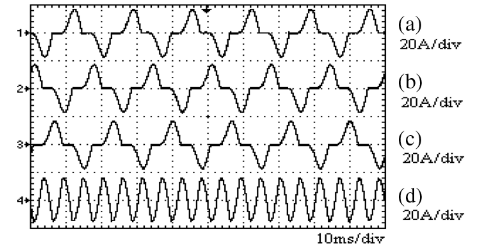

Fig. 8. Experimental results of the balanced three-phase load: (a) phase a load current, (b) phase b load current, (c) phase c load current, and (d) neutral line current of load.

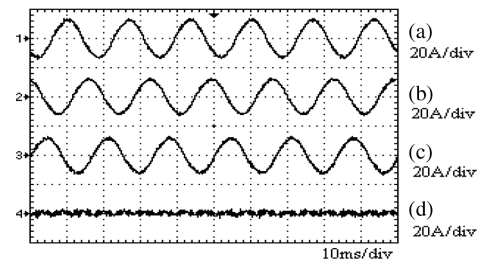

Fig. 9. Experimental results of the hybrid power conditioner under the balanced three-phase load: (a) phase a utility current, (b) phase b utility current, (c) phase c utility current, and (d) neutral line current of the utility.

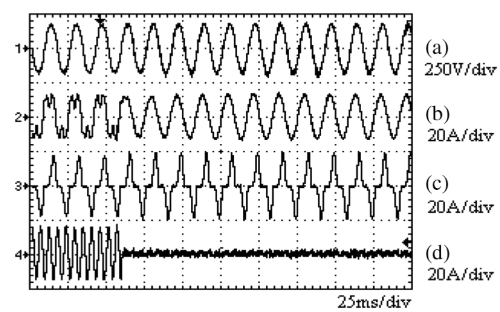

Fig. 10. Experimental results of the three-phase four-wire hybrid power conditioner under the transient of applying the neutral-line current attenuator: (a) phase a utility voltage, (b) phase a utility current, (c) phase a load current, and (d) neutral line current of the utility.

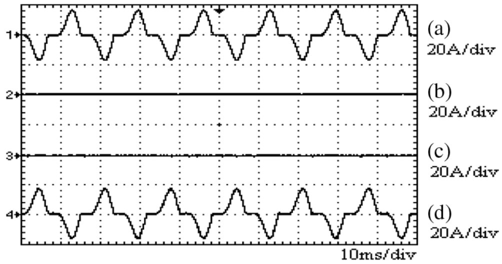

Fig. 11. Experimental results of the unbalanced three-phase load, (a) phase a load current, (b) phase b load current, (c) phase c load current, and (d) neutral line current of the load.

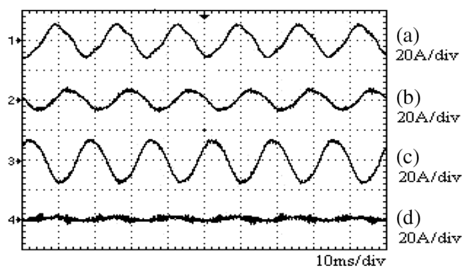

Fig. 12. Experimental results of the hybrid power conditioner under the unbalanced three-phase load: (a) phase a utility current, (b) phase b utility current, (c) phase c utility current, and (d) neutral line current of the utility.

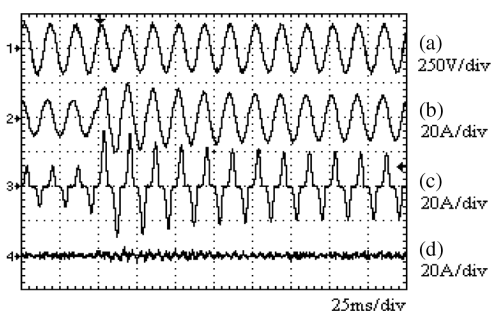

Fig. 13. Experimental results of the hybrid power conditioner under the transient of increasing load: (a) phase a utility voltage, (b) phase a utility current, (c) phase a load current, and (d) neutral line current of the utility.

sated by the proposed hybrid power conditioner. As can be seen, the three-phase utility currents are nearly sinusoidal where the THD% are 7.35%, 4.71% and 3.23%, respectively, and the neutral-line current is 0.96 A. Moreover, the three-phase utility currents are more balanced. Hence, it verifies that the proposed hybrid power conditioner can suppress the harmonic currents and attenuate the neutral-line current effectively even when the load is seriously unbalanced. The THD% of three-phase utility currents can be further improved by increasing the dc bus voltage of the three-phase converter. Fig. 13 shows the experimental results of the three-phase four-wire hybrid power conditioner under the transient of increasing load. As can be seen, the utility current can follow the change of load, and the transient performance of the proposed hybrid power conditioner is good.

VIII. Conclusion

Three-phase four-wire distribution power systems have been widely applied to low-voltage applications; however, they encounter serious problems of harmonic current pollution and large neutral-line current. In this paper, a new hybrid power conditioner, composed of a hybrid power filter and a neutral-line current attenuator, is proposed. In the proposed hybrid power conditioner, the power capacity of power converters in the hybrid power filter and neutral-line current attenuator can be effectively reduced, thus increasing its use in high-power applications and enhancing the operation efficiency. A prototype is developed and tested. Experimental results verify that the proposed hybrid power conditioner can suppress the harmonic currents and attenuate the neutral-line current effectively whether the loads are balanced or not. Hence, the proposed hybrid power conditioner is an effective solution to the problems of harmonic currents and neutral-line current in three-phase four-wire distribution power systems. Besides, the output current of the three-phase power converter is much smaller than the conventional hybrid power filter, and the power rating of the zig-zag transformer is smaller than the rating of the conventional neutral-line current attenuator.

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