A Novel Active Power Filter for High-Voltage Power Distribution Systems Application

Changzheng Zhang, Qiaofu Chen, Youbin Zhao, Dayi Li, and Yali Xiong

***Abstract*—In this paper, a novel principle of an active power filter based on the harmonic impedance control of a transformer is proposed for high-voltage power distribution systems application. A linear transformer with multiple secondary windings is adopted. The primary winding is shunted with harmonic-producing loads, while the secondary windings are connected with inverters. The primary harmonic current is detected and then tracked by the inverters with fixed compensation coefficient. When the harmonic current compensation condition is satisfied, the transformer can really exhibit nearly zero impedance to harmonic current and primary self-impedance to fundamental current. As a result, the harmonic currents in power systems can be led to flow into the transformer branch. The operation principle, the control scheme, and the harmonic current detection method are discussed in detail. Finally, simulated waveforms and experimental results are presented to verify the effectiveness of the active power filter.**

***Index Terms*—Active power filter, harmonic impedance, high power, high voltage, linear, multiple windings, power distribution systems, pulsewidth-modulated (PWM) inverter, transformer.**

I. Introduction

HARMONIC propagation in power distribution systems has become a serious problem in recent years. In order to keep the harmonic contamination within acceptable limits, as well as compensate reactive power, passive LC filters have been used conventionally. However, in practical applications, passive LC filters present many disadvantages [1]. As a result, attention has been focused on active power filters. Various active power filter configurations with their respective control strategies have been proposed during the last decade [2], [3]. Most of the researches are restrained in low-voltage utilities due to the constraint of power semiconductor switches. So far, there is still no generally accepted scheme for the high-voltage grid.

Currently, studies on high-voltage active power filters are mainly focused on two ways. One attempt consists of various hybrid active power filters that combine passive and active techniques [4]–[7]. These configurations make use of the passive LC filters to reduce the voltage rating of the active power filters. Nevertheless, when accident occurs, such as the possible direct short of lines or loads, the instantaneous voltages of the active power filters will be very high, which reduces the reliability of the active power filters. The other attempt consists of various hybrid multilevel inverters and cascaded multicell converters, which seem to be the standard solution to high-voltage active power filters [8]–[12]. However, their configurations and control schemes are rather complex and system dynamic responses are relatively slow.

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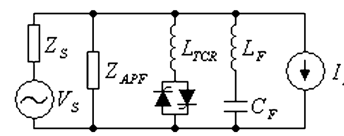

Fig. 1. Simplified compensation system.

A novel principle of magnetic flux compensation (MFC) is proposed in [13], which has been implemented in an arc suppression coil and a series hybrid active power filter. In the arc suppression coil, the linear transformer in natural behaves as a controllable reactor. The series hybrid active power filter is presented in [14]. In this scheme, the series transformer exhibits primary leakage impedance to fundamental and magnetizing impedance to harmonics under the control of power electronic inverter. To manufacture a high-power active filtering device, a novel transformer structure with one primary and multiple secondary windings is proposed in [15].

On the basis of [13]–[15], a novel shunt active power filter applied to high-voltage power distribution systems is presented in this paper, which is based on the transformer's harmonic impedance control. A specially designed linear transformer with air gap and multiple secondary windings is used. Under the control of power electronic inverters, the transformer can exhibit nearly zero impedance to harmonic current and primary self-impedance to fundamental current. Thus, the harmonic currents in power systems can be led to flow into the transformer branch. The configuration and current control are relatively simple. The filtering characteristics are satisfactory. With a step-down transformer, the reliability of the active power filter is very high. The simulated waveforms and experimental results show the validity of the novel principle.

II. Principle of Harmonic Suppression

High voltage nonlinear loads usually produce reactive currents and harmonic currents. Thyristor-controlled reactors (TCRs) together with capacitor banks, which are designed as shunt passive LC filters to reduce the harmonic currents, are commonly used in high-voltage distribution lines to provide a controlled reactive power to the mains. The residual harmonic currents that produced by TCRs and loads are suppressed by the active power filter. The simplified configuration of this compensation system is shown in Fig. 1. This paper primarily

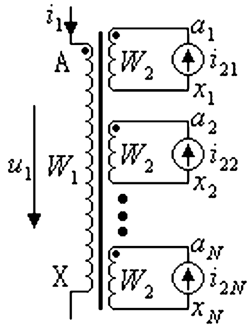

Fig. 2. Configuration of the linear transformer.

considers the realization of an active power filter that can exhibit very low impedance to harmonic current and very high impedance to fundamental current.

Fig. 2 shows the configuration of the linear transformer with air gap and multiple secondary windings. The turns of the primary winding and each secondary winding of the transformer are W_1 and W_2, respectively. The turns ratio is represented by $k = W_1/W_2$. Assume that the primary winding AX is shunted with harmonic-producing loads. Then the transformer's primary current consists of no-load current $i_1^{(1)}$ and harmonic current $\sum i_1^{(n)}$, i.e., $i_1 = i_1^{(1)} + \sum i_1^{(n)}$. The harmonic component $\sum i_1^{(n)}$ is detected, and then multiplied by a harmonic current compensation coefficient to get a reference current. The reference current is tracked by pulsewidth-modulated (PWM) voltage-source inverters to produce multiple harmonic compensation currents, which are respectively injected into the corresponding multiple secondary windings.

The nth-order harmonic voltage equation of the transformer's primary winding can be obtained in phasor form

$$U_1^{(n)} = (r_1 + j\omega_n L_{11})I_1^{(n)} + j\omega_n M_{11} I_{21}^{(n)} + \cdots + j\omega_n M_{1N} I_{2N}^{(n)} \quad (1)$$

where ω is the angular frequency; r_1 is the resistance of primary winding; L_{11} is the self-inductance of the primary winding; and M_{1P} is the mutual inductance between the primary and Pth secondary winding. Here, $\mathrm{P} = 1, 2 \ldots \mathrm{N}$.

Assume that the transformer's secondary windings are designed with identical structures. Then, the mutual inductances are almost the same

$$M_{11} = M_{12} = \cdots = M_{1N} = M. \quad (2)$$

The secondary harmonic compensation currents are also the same, which can be expressed as

$$i_{21} = i_{22} = \cdots = i_{2N} = -\alpha \cdot \sum i_1^{(n)} \quad (3)$$

where α is the harmonic current compensation coefficient.

Then, (1) can be reformulated to

$$U_1^{(n)} = r_1 \cdot I_1^{(n)} + (j\omega_n L_{11} - j\omega_n \alpha N M)I_1^{(n)}. \quad (4)$$

If the harmonic current compensation coefficient α satisfies

$$\alpha = L_{11}/N \cdot M. \quad (5)$$

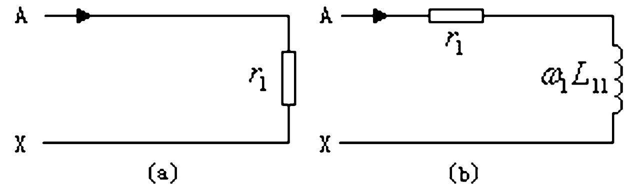

Fig. 3. Equivalent circuits of the linear transformer. (a) Harmonic equivalent circuit. (b) Fundamental equivalent circuit.

Then, from terminals AX, the equivalent impedance of the transformer at the nth-order harmonic frequency is derived

$$Z_{\mathrm{AX}}^{(n)} = U_1^{(n)} \Big/ I_1^{(n)} = r_1. \quad (6)$$

The fundamental voltage equation of the transformer's primary winding can be obtained in phasor form

$$U_1^{(1)} = (r_1 + j\omega_1 L_{11})I_1^{(1)}. \quad (7)$$

Then, from terminals AX, the equivalent impedance of the transformer at fundamental frequency is derived

$$Z_{\mathrm{AX}}^{(1)} = U_1^{(1)} \Big/ I_1^{(1)} = r_1 + j\omega_1 L_{11}. \quad (8)$$

Note that (5) is the harmonic current compensation condition.

The equivalent circuits of the transformer to the fundamental and the harmonics are shown in Fig. 3.

The resistance of the transformer's primary winding is nearly zero. Therefore, when the harmonic current compensation condition is satisfied, the transformer exhibits nearly zero impedance to harmonic current and primary self-impedance to fundamental current. The PWM voltage-source inverters in nature behave as harmonic current controlled harmonic current sources. Before compensation, the primary harmonic current is very weak. When the compensation system starts to work, positive feedback occurs, which results in sharp increasing of the primary harmonic current. The harmonic currents in power systems are led to flow into the transformer branch.

A specially designed linear transformer with multiple secondary windings is adopted to increase the capacity of the active power filter and ensure that the power semiconductor switches work in relatively low voltage. Saturation must be avoided in the transformer in order to obtain excellent filtering performance. To make sure that the transformer works in linear range (i.e., to reduce the magnetic flux density), the air gap is necessary in the core.

In order to reduce the reactive power produced by the transformer (i.e., to reduce the no-load current $i_1^{(1)}$), the only approach is to increase the primary self-inductance. However, too large primary self-inductance brings two disadvantages: 1) higher precise control system is needed and 2) the bandwidth of the positive feedback loop is increased, which may cause the invalidation of the positive feedback in view of the error of harmonic current detection and compensation. Therefore, the primary self-inductance should be moderate.

The transformer's secondary windings are identical in turns, lead cross section, parallel wound lead number, and structural dimension including inner diameter, outer diameter and height. Therefore, the mutual inductances between the primary winding

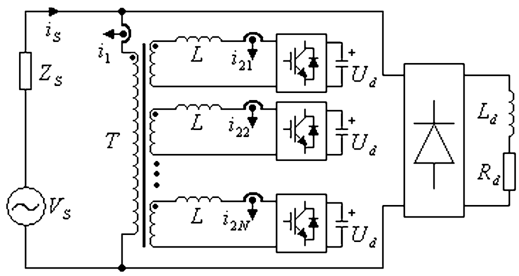

Fig. 4. Configuration of the proposed active power filter.

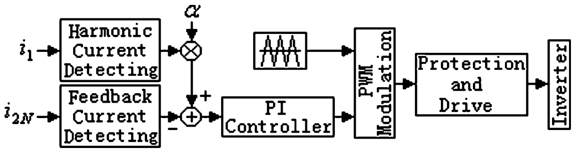

Fig. 5. Block diagram of the current control scheme.

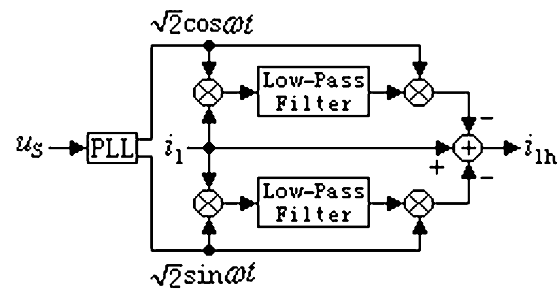

Fig. 6. Block diagram of the harmonic current detection method.

and each of the secondary windings are almost the same. The self-inductances of the multiple secondary windings have small discrepancy due to the difference of their distributing position in the core (i.e., the leakage inductances of the multiple secondary windings are different). The discrepancy has a negligible influence on filtering performance since each secondary winding is connected with a harmonic current source, which is formed by a PWM voltage-source inverter.

III. System Configuration and Control Strategy

A. System Configuration

Fig. 4 shows the system configuration of the proposed active power filter. With a step-down transformer, the PWM inverters actually work in relatively low voltage, so that the 1200-V insulated-gate bipolar transistors (IGBTs) that are easily available on the market at low cost can be used. The capacity of each inverter is not too large, so the switching frequency can be higher than those of the existing standard active power filters that are designed for high-voltage high-power applications. With multiple secondary windings, high-power active filtering devices can easily be manufactured. Since the PWM inverters are the same, modular design scheme can be adopted for the proposed active power filter.

In practical application, to reduce the switching loss, the order of main system harmonic currents and the capacity of active power filter should be reduced, and then the proposed active power filter should combine with the passive LC filters. In this paper, to confirm the effectiveness of the novel principle, passive LC filters are not included.

In Fig. 4, V_S and Z_S represent the source voltage and the system impedance, respectively. The transformer's primary winding is shunted with a harmonic-producing load, while the secondary windings are connected with PWM voltage-source inverters. L represents the output inductance of each inverter, which is negligible on condition that the corresponding secondary leakage impedance is relatively large. U_d represents the voltage of the dc side of each inverter. A typical diode full-bridge rectifier with resistive and inductive (RL) load is used as the current-type harmonic-producing load.

B. Current Control Scheme

The current control scheme can be arbitrarily selected since different control methods can be applied to the proposed active power filter. The control strategy used for this harmonic current compensation system is based on triangle comparison current controller due to its excellent characteristic of fixed switching frequency, as shown in Fig. 5.

The control scheme of the proposed active power filter includes a harmonic reference current generator and a harmonic compensation current controller. The harmonic reference current generator first detects the primary harmonic current of the transformer. Then, the primary harmonic current is multiplied by the harmonic current compensation coefficient, the result of which is the reference current. The harmonic compensation current controller compares the reference current with the feedback current of the transformer's secondary winding, the error of which is regulated by a proportional and integral (PI) regulator. Compared with the triangular waveform, the output of the PI regulator is modulated to get PWM driving pulses, which drive the power semiconductor switches. The multiple secondary windings use one controller to get PWM driving pulses since the required harmonic compensation currents are the same.

C. Harmonic Current Detection Method

Two methods are available for detecting the transformer's primary harmonic current. One is the offline harmonic current detection method since the no-load current is almost constant. Considering the small change of the source voltage and frequency, another more accurate harmonic current detection method is adopted, which is based on the single-phase *d–q* transformation. The harmonic current detection method is shown in Fig. 6.

In the proposed block diagram, $\cos\omega t$ is synchronized with the phase-to-neutral source voltage by implementing the phase-locked loop (PLL). Low-pass filters (LPFs) are used to achieve the rms value of the fundamental active current and reactive current. Assume that

$$i_1(t) = \sqrt{2}\sum_{n=1}^{\infty} I_n \cos(n\omega t + \varphi_n). \tag{9}$$

Multiplying $i_1(t)$ by $\sqrt{2}\cos\omega t$, the following expressions can be obtained:

$$\sqrt{2}\cos\omega t \cdot i_1(t) = \sum_{n=1}^{\infty} I_n\{\cos[(n+1)\omega t + \varphi_n] + \cos[(n-1)\omega t + \varphi_n]\}. \tag{10}$$

The rms value of the fundamental active current can be achieved by a low-pass filter

$$I_{1p} = I_1 \cos\varphi_1. \quad (11)$$

Multiplying $i_1(t)$ by $\sqrt{2}\sin\omega t$, the following expressions can be obtained:

$$\sqrt{2}\sin\omega t \cdot i_1(t) = \sum_{n=1}^{\infty} I_n\{\sin[(n+1)\omega t + \varphi_n] - \sin[(n-1)\omega t + \varphi_n]\}. \quad (12)$$

The rms value of the fundamental reactive current can be achieved by a low-pass filter

$$I_{1q} = -I_1 \sin\varphi_1. \quad (13)$$

Then, the fundamental current can be obtained

$$I_{1p} \cdot \sqrt{2}\cos\omega t + I_{1q} \cdot \sqrt{2}\sin\omega t = \sqrt{2} I_1 \cos(\omega t + \varphi_1). \quad (14)$$

The harmonic current can be obtained by subtracting the fundamental current from $i_1(t)$.

IV. Simulated Results

The operation of the proposed active power filter applied to high-voltage power distribution systems is evaluated by simulation, which is to verify the effectiveness of the novel principle. The simulation is based on the system configuration shown in Fig. 4. The rms value of the source voltage V_S is 27.5 kV; the source frequency f_S is 50 Hz; the system impedance Z_S is 3.768 Ω. A linear transformer with air gap and eight secondary windings is adopted. The primary self-inductance L_{11} is 1200 mH; the mutual inductance between the primary winding and each secondary winding M is 145 mH; the turns ratio k is 8. The harmonic current compensation coefficient α is 1.034. IGBTs that can operate at a high switching frequency are selected for each PWM inverter. The switching frequency is 20 kHz, which ensures the real-time trace to the reference current and, thus, excellent characteristics in harmonic suppression can be obtained.

A. Steady-State Operation

Fig. 7 shows the simulated current waveforms of the source and the load in steady state. In order to verify the filtering effect, the simulated source currents without filter [Fig. 7(a)] and with filter [Fig. 7(b)] are analyzed into Fourier series and the results are shown in Table I. From the analysis, we can draw a conclusion that the equivalent harmonic impedance of the linear transformer is less than one tenth of the system impedance at each harmonic frequency. The total harmonic distortion (THD) is reduced from 36.72% to 1.44%, which shows the effectiveness of the novel principle.

Fig. 8 shows the simulated current waveforms of the linear transformer in steady state. The primary current [Fig. 8(a)] is composed of harmonic current and no-load current. The rms value of the no-load current is very small since the linear transformer can exhibit very high primary self-impedance at fundamental frequency. The reference current [Fig. 8(b)] is tracked by PWM voltage-source inverters to produce multiple harmonic compensation currents [Fig. 8(c)]. In this case, the harmonic current compensation condition is satisfied and thus the harmonic current in power system is led to flow into the linear transformer branch.

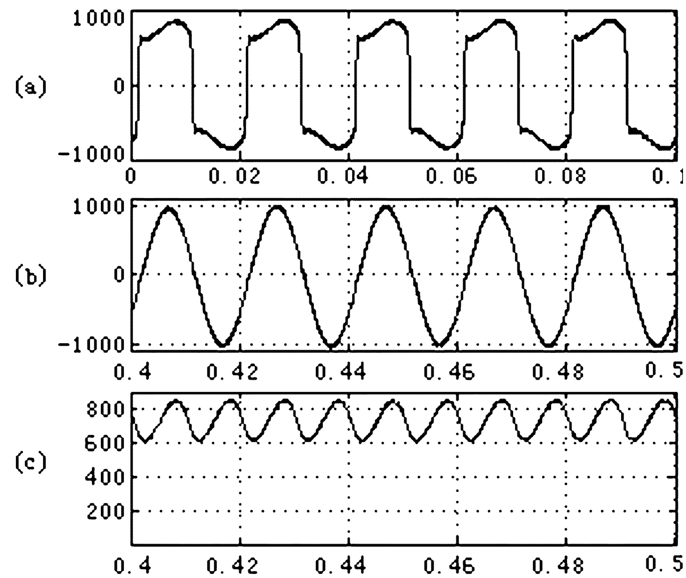

Fig. 7. Simulated current waveforms of source and load in steady state. (a) Source current waveform without filter (1000 A/div and 20 ms/div). (b) Source current waveform with active power filter (1000 A/div and 20 ms/div). (c) Load current waveform (200 A/div and 20 ms/div).

TABLE I
MAIN HARMONIC CONTENTS OF SIMULATED SOURCE CURRENT

	Without filter	With filter
Fundamental	1	1
3rd	28.0%	0.27%
5th	16.2%	0.59%
7th	11.1%	0.54%
9th	8.22%	0.49%
11th	6.4%	0.47%
13th	5.02%	0.43%
15th	3.92%	0.35%
17th	3.09%	0.29%
19th	2.47%	0.24%
21st	1.97%	0.16%
THD	36.72%	1.44%

B. Transient State Operation

The transient state performance of the proposed active power filter is also tested by simulation, as shown in Fig. 9. The active power filter starts to work when t = 0.2 s. Before compensation, the primary current as well as the primary harmonic current is very small. Once the active power filter is under operation, positive feedback in the compensation system occurs, which result in sharp increasing of the primary harmonic current. The source current waveform [Fig. 9(a)] demonstrates that the dynamic response of the proposed active power filer is extremely fast. The primary current waveform [Fig. 9(b)] indicates that the rms value of the no-load current is very small (i.e., the reactive power produced by the linear transformer is relatively

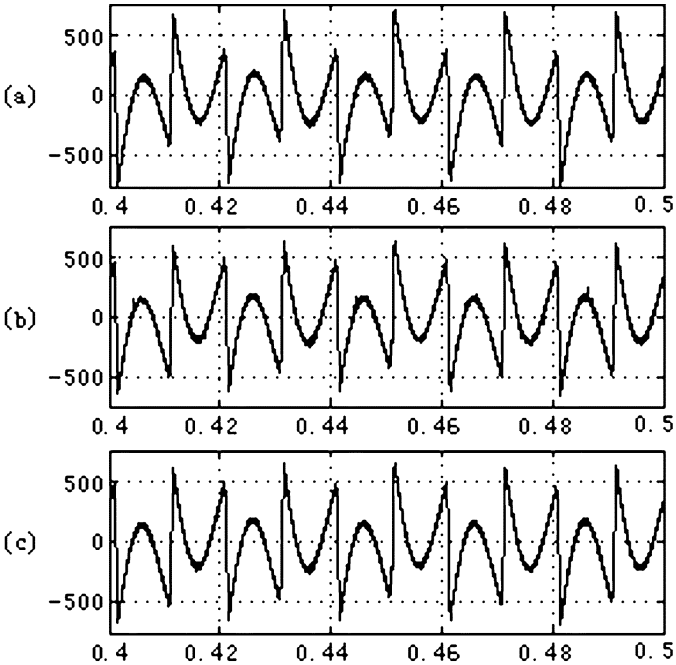

Fig. 8. Simulated current waveforms of linear transformer in steady state. (a) Primary current waveform (500 A/div and 20 ms/div). (b) Reference current waveform (500 A/div and 20 ms/div). (c) Compensation current waveform of each secondary winding (500 A/div and 20 ms/div).

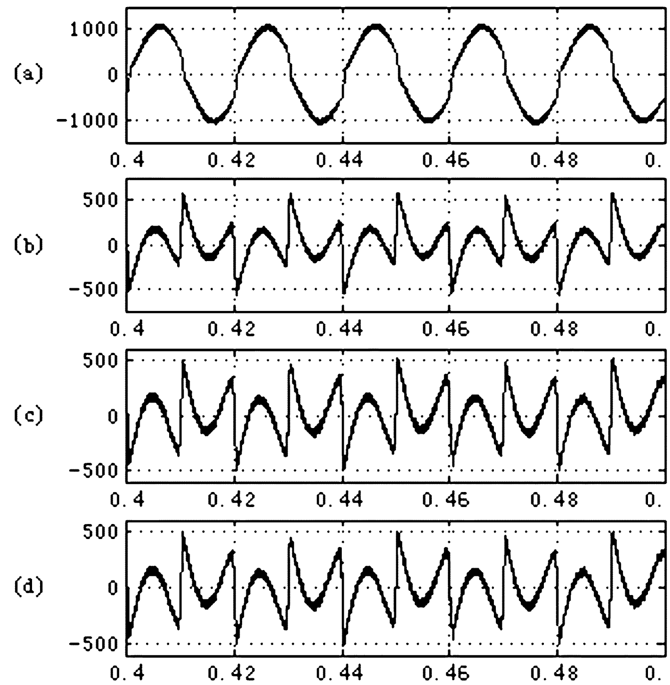

Fig. 10. Simulated results for testing saturation influence. (a) Source current waveform with active power filter (1000 A/div and 20 ms/div). (b) Primary current waveform (500 A/div and 20 ms/div). (c) Reference current waveform (500 A/div and 20 ms/div). (d) Compensation current waveform of each secondary winding (500 A/div and 20 ms/div).

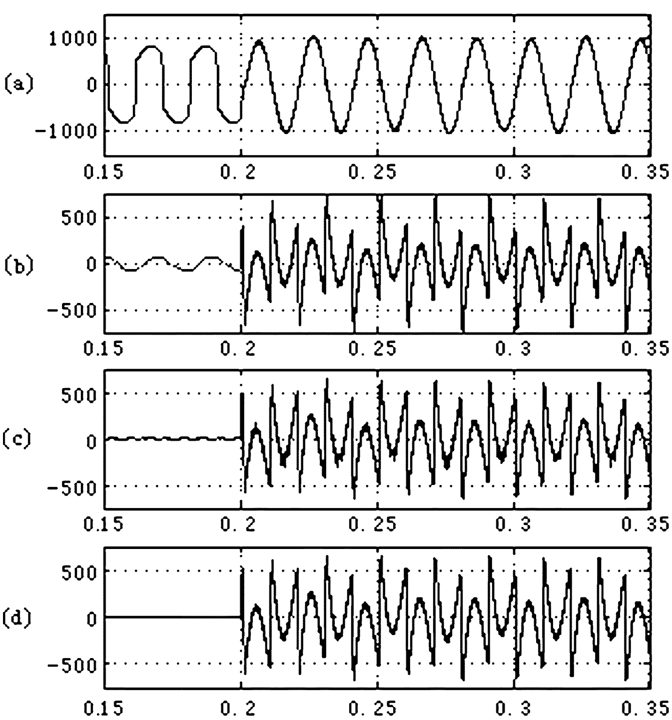

Fig. 9. Simulated current waveforms of source and linear transformer in transient state. (a) Source current waveform (1000 A/div and 50 ms/div). (b) Primary current waveform (500 A/div and 50 ms/div). (c) Reference current waveform (500 A/div and 50 ms/div). (d) Compensation current waveform of each secondary winding (500 A/div and 50 ms/div).

small). The reference current waveform [Fig. 9(c)] shows the effectiveness and the fast dynamic response of the harmonic current detection method. The compensation current waveform of each secondary winding [Fig. 9(d)] shows that the current control scheme with the triangle intersection technique based PWM is practical and effective. The harmonic compensation currents that injected into the corresponding secondary windings are almost the same as the reference current when the active power filter is under operation.

C. Influence on Filtering Performance

Saturation should be avoided in the transformer in order to obtain excellent filtering performance. On condition that the transformer is linear, the self-inductance of the primary winding, the self-inductance of each secondary winding and the mutual inductance between the primary winding and each secondary winding are all constant. Therefore, the harmonic current compensation coefficient is also constant according to (5). It is quite easy to satisfy the harmonic current compensation condition under the control of power electronic inverters. In this case, the transformer can exhibit nearly zero impedance to harmonic current and thus satisfactory filtering performance can be obtained.

If the transformer exhibits some degree of saturation, the self-inductance of the primary winding, the self-inductance of each secondary winding and the mutual inductance between the primary winding and each secondary winding are all vary with the current magnitude. So is the harmonic current compensation coefficient. In this case, it's very difficult to satisfy the harmonic current compensation condition under the control of power electronic inverters. As a result, the transformer exhibits relatively higher impedance to harmonic current, which affects the filtering performance. The simulated results shown in Fig. 10 indi-

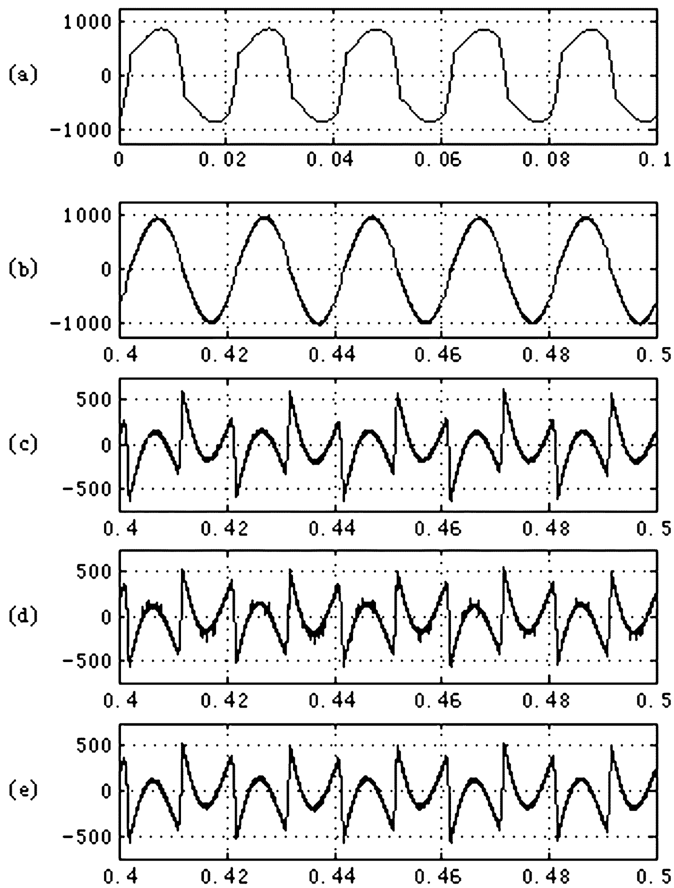

Fig. 11. Simulated results for testing system impedance influence. (a) Source current waveform without filter (1000 A/div and 20 ms/div). (b) Source current waveform with active power filter (1000 A/div and 20 ms/div). (c) Primary current waveform (500 A/div and 20 ms/div). (d) Reference current waveform (500 A/div and 20 ms/div). (e) Compensation current waveform of each secondary winding (500 A/div and 20 ms/div).

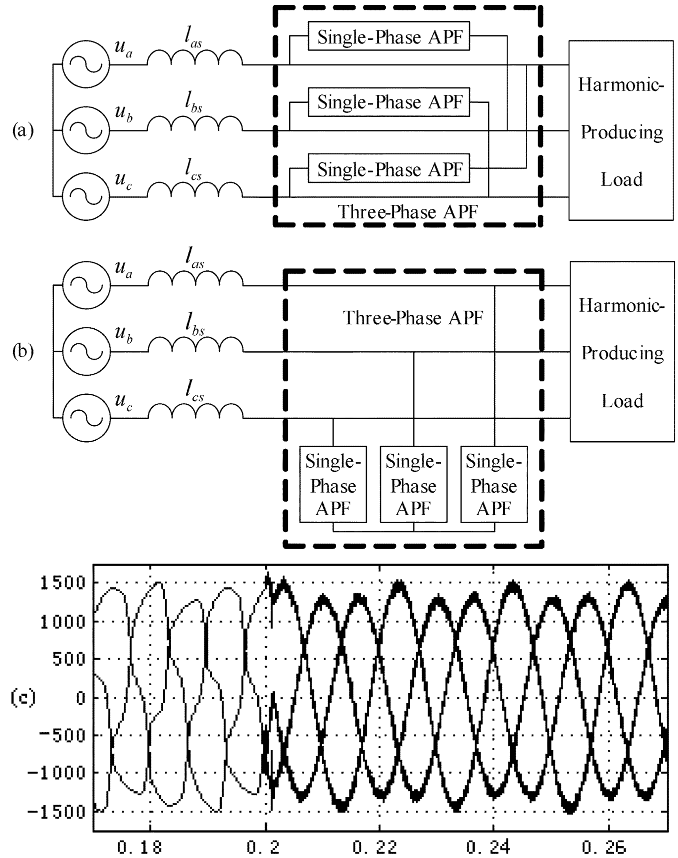

Fig. 12. Three-phase application of the novel principle. (a) Configuration I of three-phase active power filter. (b) Configuration II of three-phase active power filter. (c) Simulated source current waveforms (500 A/div and 20 ms/div).

cate the saturation influence on filtering performance. The THD of the source current is only reduced from 36.72% to 9.89%.

To harmonic current, the equivalent harmonic impedance of the transformer is shunted with the system impedance. Theoretically, if the harmonic current compensation condition is satisfied, the transformer can exhibit nearly zero impedance to harmonic current. However, in reality the equivalent harmonic impedance of the transformer is higher more or less, considering the error and the saturation of the core. The higher the system impedance is and the lower the equivalent harmonic impedance of the transformer is, the more satisfactory the filtering performance will be. The simulated results shown in Fig. 11 indicate the system impedance influence on filtering performance, in which the same degree of saturated transformer as in Fig. 10 is used and the system impedance Z_S is increased from 3.768 Ω to 9.425 Ω. The THD of the source current is reduced from 20.89% to 3.95%. The proposed active power filter is especially adapted to the high-voltage grid, due to its high system impedance.

D. Three-Phase Application

A three-phase active power filter can also be implemented in terms of the same principle. To deal with unbalanced harmonic-producing loads, the topology consisting of three independent single-phase transformers and single-phase inverters is adopted, as shown in Fig. 12(a) and (b). Each single-phase transformer can respectively exhibit nearly zero impedance to harmonic current and primary self-impedance to fundamental current under the control of corresponding single-phase inverters. Thus, the harmonic currents in three-phase power systems can be led to flow into the transformer branches.

Whether Δ network or Υ network is adopted, the simulated source current waveforms are shown in Fig. 12(c). The parameters of power system and each single-phase active power filter in the simulation are the same as those in Fig. 9 and that the three-phase harmonic-producing loads are unbalanced. From simulation analysis, we can draw a conclusion that the imbalance of three-phase harmonic-producing loads will not affect the filtering performance.

V. Experimental Verification

To demonstrate the validity of the novel principle of the proposed active power filter, a 5-kVA prototype on the basis of the system configuration shown in Fig. 4 is built. The rms value of the source voltage V_S is 220 V; the source frequency f_S is 50 Hz. A linear transformer with air gap and two secondary windings is adopted. The primary self-inductance L_{11} is 150 mH; the mutual inductance between the primary winding and each secondary winding M is 74.88 mH; the turns ratio k is 2. The harmonic current compensation coefficient α is 1. SEMIKRON's

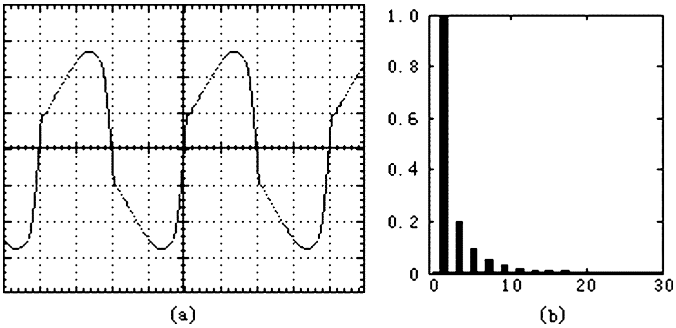

Fig. 13. Experimental source current waveform and its frequency spectrum without filter. (a) Source current waveform (10 A/div and 5 ms/div). (b) Frequency spectrum of source current.

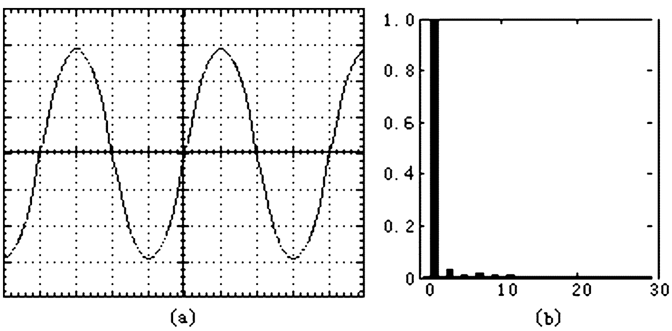

Fig. 14. Experimental source current waveform and its frequency spectrum with active power filter. (a) Source current waveform (10 A/div and 5 ms/div). (b) Frequency spectrum of source current.

TABLE II
MAIN HARMONIC CONTENTS OF EXPERIMENTAL SOURCE CURRENT

	Without filter	With filter
Fundamental	1	1
3rd	20.15%	2.99%
5th	9.30%	1.35%
7th	5.36%	1.49%
9th	3.04%	0.92%
11th	1.63%	0.56%
13th	1.08%	0.41%
15th	0.88%	0.30%
17th	0.72%	0.25%
19th	0.65%	0.18%
21st	0.50%	0.15%
THD	23.17%	3.82%

NPT-type IGBT SKM300GB123D is used to be the switching device; the switching frequency is 20 kHz. The output inductance of each inverter L is 0.6 mH. The dc voltage of each inverter U_d is 180 V.

Experimental waveforms are recorded by the Tek2002 digital oscilloscope. Fig. 13 shows the experimental source current waveform and its frequency spectrum without filter. Fig. 14 shows the experimental source current waveform and its frequency spectrum after the active power filter is under operation. The experimental source currents in two cases are analyzed into Fourier series. The contrast of the main harmonic contents is shown in Table II. The THD is 23.17% before compensation and 3.82% after the active power filter is used. Fig. 15 shows the experimental current waveforms of the linear transformer.

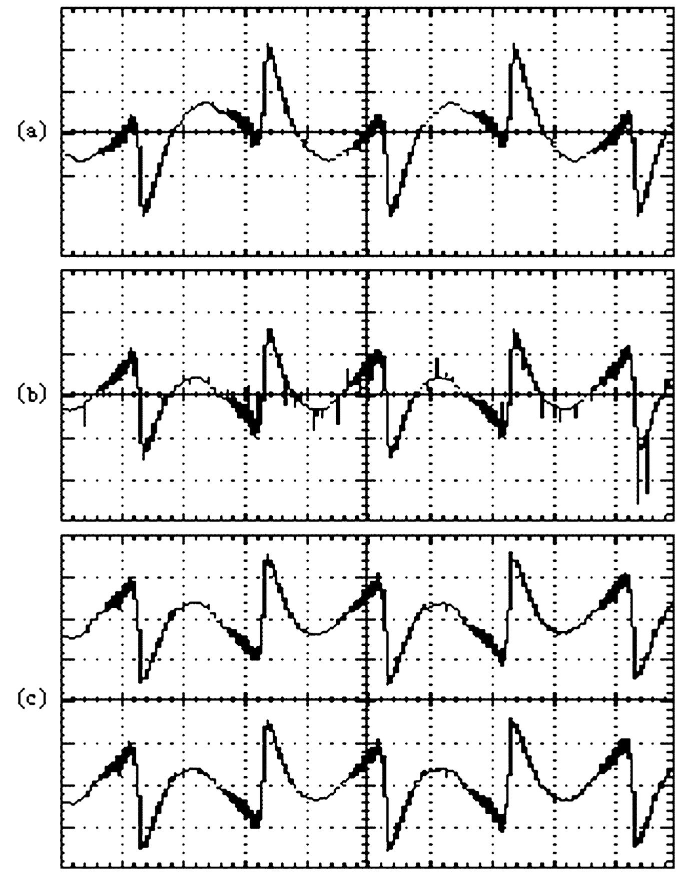

Fig. 15. Experimental current waveforms of linear transformer. (a) Primary current waveform (10 A/div and 5 ms/div). (b) Reference current waveform (10 A/div and 5 ms/div). (c) Compensation current waveforms of two secondary windings (10 A/div and 5 ms/div).

VI. CONCLUSION

This paper presents a novel principle of active power filter for high-voltage power distribution systems application. The active power filter in nature provides a low impedance path for harmonic currents in power systems. A linear transformer with air gap and multiple secondary windings is used to realize the low impedance path under the control of PWM voltage-source inverters. In terms of the characteristics of the linear transformer and the law of superposition, when the harmonic current compensation condition is satisfied, the transformer can exhibit nearly zero impedance at each harmonic frequency and primary self-impedance at fundamental frequency. Thus, the harmonic currents in power distribution systems can be led to flow into the linear transformer branch. The validity of the novel principle is verified by computer simulations and experimental results.

In the active power filter, the primary harmonic current of the linear transformer needs to be detected and tracked. Since the no-load current of the linear transformer is almost constant, the primary harmonic current can easily be detected. A harmonic current detection method based on the single-phase d–q transformation is adopted. Excellent filtering performance can easily be obtained by a simple current control scheme. With a step-down transformer, the reliability of the active power filter is very high and 1200-V IGBTs that are easily available on the market at low cost can be used, which can operate at high switching frequency. With the multiple winding structure of the transformer's secondary, high-power active filtering devices can easily be manufactured. Since the PWM voltage-source inverters that connected with the multiple secondary windings are the same, modular design scheme can be adopted for the active power filter.

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