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A comprehensive review of improving power quality using active power filters

Jie Gong, Dayi Li, Tingkang Wang [*], Wenhao Pan, Xinzhi Ding

State Key Laboratory of Advanced Electromagnetic Engineering and Technology, School of Electrical and Electronic Engineering, Huazhong University of Science and Technology, Wuhan, 430074, China

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ABSTRACT

Power system is gradually developed into a power electronic based power system and exists various power quality problems, which promotes the development of active power filter (APF). APF has developed into a comprehensive power quality conditioner. From the perspective of circuit topology, this paper has a more comprehensive classification of existing APFs, which are divided into parallel type, series type, hybrid type and others. Then, based on the fundamental four types, each APF is reviewed from the perspectives of topology, operating principle, application scenarios, and advantages and disadvantages, which provides a reference for researchers. Finally, the problems of the current industrialized APF have been analyzed by simulation, and other existing problems also have been summarized simply, such as supra-harmonics, background harmonics, multi-function power quality Controller. Moreover, this paper also briefly summarizes the further development trend of APF.

1. Introduction

The urgent demands for energy conservation, environmental protection and clean energy have promoted the rapid development of global energy internet, AC/DC long-distance transmission, distributed generation, and smart distribution network. To achieve new energy consumption, efficient utilization and flexible control of electric energy, power electronics technology has been widely used in power system generation, transmission, distribution, storage and other fields, which makes the power system be a power electronic based power system [1, 2]. Power electronic devices are non-linear so that the pollution of harmonic is unavoidable, causing pollution and public hazard to power system. Not only it can threaten the safe and stable operation of power system itself and its economy, but also can bring great influence and harm to the surrounding electrical environment. In recent years, the use of non-linear loads in distribution network, such as rectifiers, frequency control devices and electric arc furnaces, has been increasing, resulting in non-linear impact and unbalanced electrical characteristics [3, 4]. Therefore, the transient impact, reactive power, harmonic pollution, voltage flicker and three-phase unbalance in the power grid are becoming more and more serious [4, 5]. These problems seriously pollute the power quality of the power grid and typical hazards [6-9] include:

1) Harmonics may cause parallel or series resonance between passive filters or reactive compensation capacitors and power system, causing harmonic amplification and burning of capacitors and reactors.
2) Harmonics make the equipment, such as rotating motor and transformer, produce additional harmonic loss and voltage drop, which causes the power quality to decline and reduces the efficiency of power generation and transmission.
3) Harmonics may interfere with the relay protection and the automatic control device, and make the electric measuring equipment inaccurate.
4) Affect the operation of sensitive equipment in power system (such as PLC and computer), causing interference or even damage to electronic equipment.
5) Adjacent communication systems may be interfered by electromagnetic induction coupling, electrostatic induction coupling and conduction coupling.
6) Multiple harmonics are superimposed on each other while multiple inverters are connected to the grid, resulting in over-current, over-voltage and oscillation in the power system.

Additionally, the harmonic propagation speed is fast, and the harmonic coverage is wide. For example, the rapid development of

* Corresponding author.

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electrified railways (including subways) has caused serious harmonic pollution to the power grid [10]. Therefore, harmonic suppression and reactive power compensation in power system have become an important research topic in power grid construction.

The traditional harmonic suppression and reactive compensation scheme is passive power filter (PPF). Although the PPF has the advantages of mature technology, simple structure, low cost, large capacity, etc. However, it also has the following drawbacks [11-14]:

1) The filtering performance depends on the impedance of power system greatly as the impedance of power transmission line would affect the current flow in each branch according to Kirchhoff current law. In low-voltage power system, the internal impedance is very small, so the filtering performance is greatly reduced.
2) It needs to install too many filtering branches because one LC branch can only compensate a specific frequency harmonic. Besides, it has the risk of series or parallel resonance which increases the design difficulty.
3) There exists resonance between the internal impendence of power system and the PPFs, causing harmonic amplification.
4) PPF cannot attenuate harmonic and compensate reactive power dynamically.
5) Larger weight and volume.

Compared with PPF, the active power filter (APF) is the effective equipment of enhancing power quality by eliminating harmonic, compensating reactive power, correcting power factor, solving problems of voltage sag and swell and the three-phase unbalance in some cases. The application advantages of APF are as follows [15-24]:

1) Fast dynamic response performance.
2) Suppress the propagation of harmonic and compensate the reactive power dynamically without being influenced by grid's parameters.
3) Smaller volume and lighter weight.

With the increasing development of power electronics and semiconductor device, APF has been popularized and developed, which could bring the economic and social benefits. Many researchers have carried out a large number of researches on the operating principle, topology structure, harmonics detection, current tracking control strategies and main circuit parameter selection of APF, and gained lots of research achievements and monographs [25], [26-29].

According to power circuit configurations and connection, this paper presents a comprehensive literature survey to classify and summary the existing APFs, analyze the application range, advantages, and disadvantages of various APFs, as well as the development prospects and trends of APF. To be specific, the paper is divided into eight parts. In Section 2, it presents the classification of APF based on circuit configuration and the state of art of APF. According to the classification of APF, in the following Section 3, 4, 5, 6, shunt APFs, series APFs, hybrid APFs and other types of filters are analyzed in detail, respectively. The comprehensive review of improving power quality using APFs are presented and gives a good reference for understanding the characteristics of various filters. In Section 7, the existing problems and the development trends of APFs are also presented and described.

2. Classification and state of art of active power filters

The thought of APFs has been firstly put forward by B. M. Bird, J. F. Marsh in 1969, and they presented the method of harmonic reduction in multiplex convertors by triple-frequency current injection [30]. In 1971, H. Sasaki and T. Machida presented a new method of eliminating AC harmonic current based on the principle of the magnetic flux compensation (MFC) in a transformer core [31], which explained the basic principle of APF comprehensively. In 1976, APF composed of PWM converter was proposed by L. Gyugyi et al. in [32], which established the basic concept, topology and control strategy of main circuit. The instantaneous reactive power theory of three-phase circuits [3, 33] proposed by H. Akagi in 1983 in Japan solved the key issue of harmonic current detection. After 1980s, with the great development of power electronic devices and control technologies, especially PWM technology, many approaches of APF were proposed and could be applied to high-voltage and high-power situations [34-38]. Hence, APF has become the most promising and effective way to suppress the harmonic propagation in power system or microgrid.

Fig. 1 shows the classification of APF according to power circuit configurations and connection. APFs can be divided into four categories, i.e., shunt APF, series APF, hybrid APF and the other APFs. Among them, the traditional shunt APF has been widely used because of its application advantages such as simple configuration and mature technology. By extracting the harmonic signal from the load current, the voltage-source inverter (VSI) generates the compensate current to inject into the point of common coupling to reduce the total harmonic distortion (THD) as shown in Fig. 2. Additionally, the other types of filter have the potential to be generalized. Objective analysis of APF will be conducted according to comprehensive literature survey in this paper.

3. Passive power filter and shunt active power filters

3.1. Passive power filter

Common PPF composed of inductors and capacitors can be classified into single-tuned, double-tuned and triple-tuned filter as shown in Fig. 3.

PPFs are connected in parallel with nonlinear loads, such as electric traction locomotive, semiconductor rectifier, frequency converter, arc furnace, induction furnace, etc., so as to provide a low impedance path for harmonic current. For example, the nth-harmonic impedance and the number of resonances of single tuned LC filter branch are given by

$$Z_{fn} = R + \mathrm{j}\left(n\omega_s L - \frac{1}{n\omega_s C}\right) \tag{1}$$

$$n = \frac{1}{\omega_s \sqrt{LC}} \tag{2}$$

For the tuning points, the impedance of the single tuned LC filter is R, which is very small, so that the nth-harmonic current can be shunted to attenuate harmonic.

In Fig. 4, there are the four types of high-pass damped filters, i.e., first order, second order, third order and C-type filters. For the second order high-pass filter in Fig. 4(b), the impedance can be derived as follow:

$$Z_n = \frac{1}{\mathrm{j}n\omega_s C} + \left(\frac{1}{R} + \frac{1}{\mathrm{j}n\omega_s L}\right)^{-1} \tag{3}$$

The high-pass filter exhibits low impedance over a wide frequency band, providing a low-impedance path to higher harmonics, so the higher harmonics flow into the filter.

Usually, the combination of the 5th-, 7th-, 11th- and 13th-harmonic frequencies and the second order passive high-pass filter have been used in a high-power three-phase circuit to eliminate AC harmonic and even have a value-added function of correcting power-factor.

However, the most obvious defect is that PPFs can only suppress harmonics of a certain frequency. Also, interaction between PPFs and the power system impedance may cause harmonic parallel and/or series resonances. The parameter of a passive filter may varies with the temperature around and other operating conditions [5, 15], which might cause the resonance point to shift. And they has greater weight and volume to increase the difficulty of installation.

3.2. Traditional shunt active power filter

Fig. 5 shows the configuration of traditional shunt APF for the

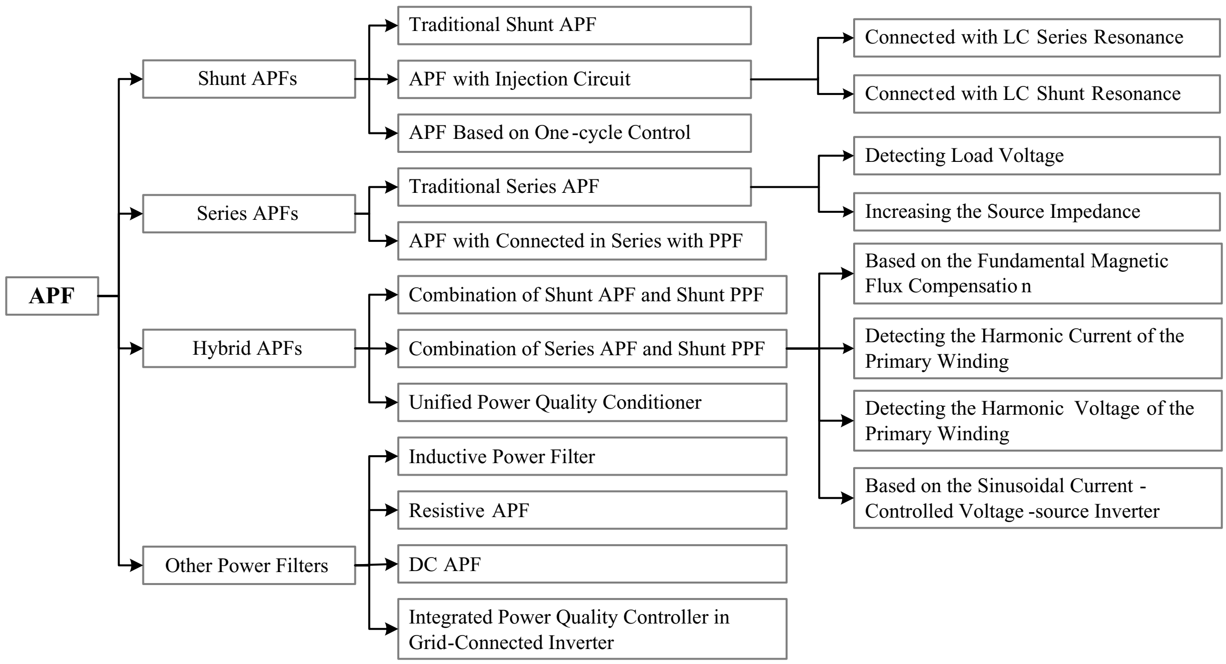


Fig. 1. Classification of active power filter according to power circuit configurations and connection.

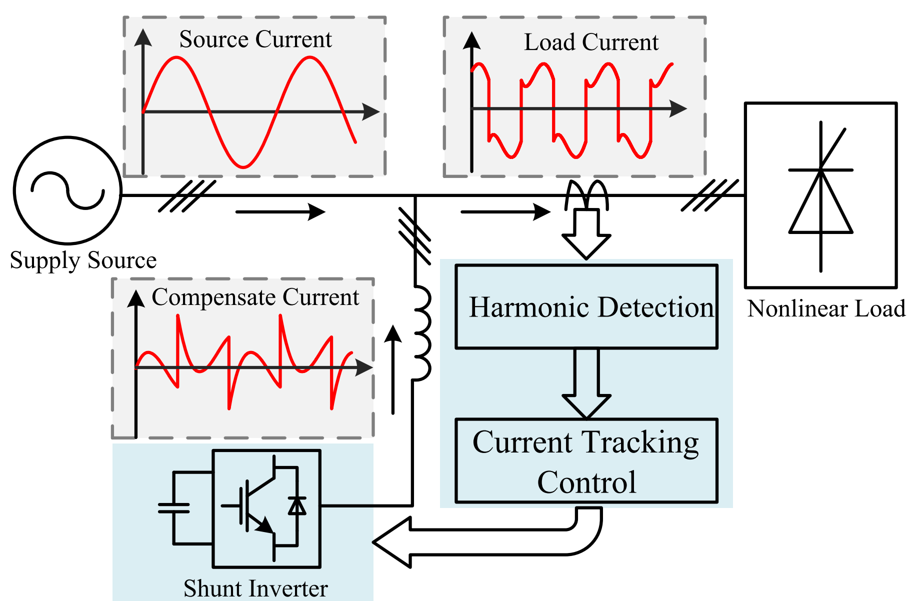


Fig. 2. The principle block diagram of APF.

harmonic current suppression of single-phase or three-phase nonlinear loads, which consists of shunt VSI, DC capacitor, and the inductor for ripple elimination. The traditional shunt APF is the fundamental and conventional topology of other types of hybrid APF, which has been widely used and industrialized [39-43].

The equivalent circuit of traditional shunt APF connected with the current-source harmonic loads, like the rectifier with large filtering inductance in DC side, is shown in Fig. 6. The hth-harmonic current i_{Sh} flowing into power utility can be derived as

$$i_{Sh} = \frac{u_{Sh}}{Z_{Lh} + Z_{Sh}} + \frac{Z_{Lh}}{Z_{Lh} + Z_{Sh}}(I_{Lh} - I_{Ch}) = \frac{u_{Sh}/Z_{Lh} + I_{Lh} - I_{Ch}}{1 + Z_{Sh}/Z_{Lh}} \tag{4}$$

Generally speaking, in (4), if the power utility background harmonic voltage $u_{Sh} \approx 0$, the traditional shunt APF can attenuate nth-harmonic when $I_{Ch} = I_{Lh}$ in term of (4). Thus, while the controller detects the instantaneous load current i_{Lh} and extracts the harmonic or reactive power current signal I_{Ch} from i_{Lh} by means of the calculation of digital signal processor, the traditional shunt APF is able to achieve the harmonic suppression or reactive power compensation when the shunt VSI generates control current I_{Ch}.

However, the application scenarios of traditional shunt APF is not suitable for the voltage-source harmonic loads, like the rectifier with filtering capacitor in DC side, because the compensation current I_{Ch} would be very high if the filtering capacitor is quite large. Moreover, the harmonic compensation range of this type APF can only be limited to 3th, 5th, 7th and other low order harmonics. Due to the limitation of control system bandwidth and switching frequency, it is difficult to effectively compensate supra-harmonics.

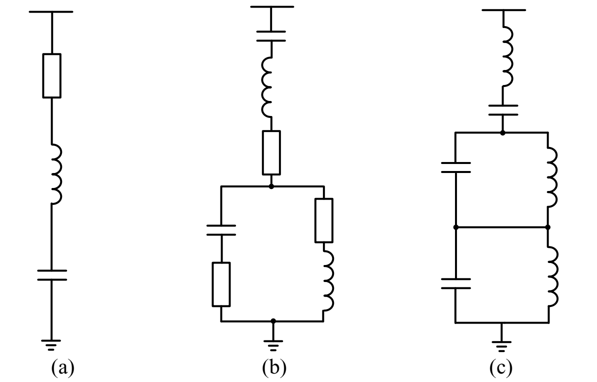


Fig. 3. Common PPFs. (a) Single-tuned fitter. (b) double-tuned filter. (c) triple-tuned filter.

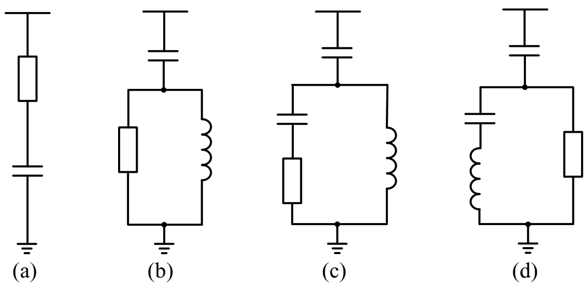


Fig. 4. High pass PPFs. (a) First order filter. (b) second order filters. (c) third order filters. (d) C-type damped filters.

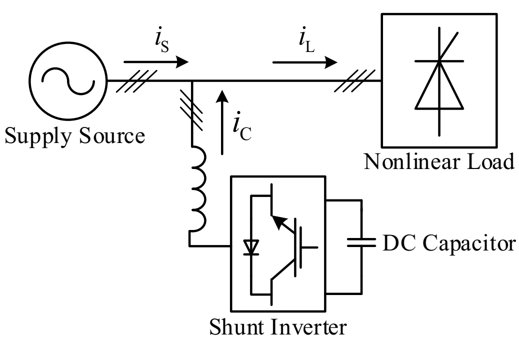


Fig. 5. The configuration of traditional shunt APF.

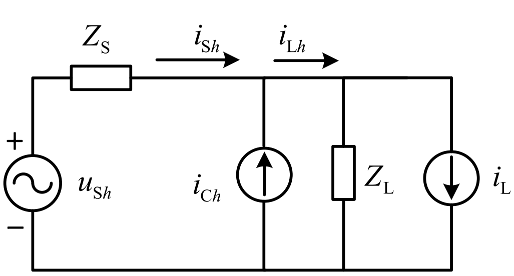


Fig. 6. The equivalent circuit of traditional shunt APF.

3.3. Active power filters with injection circuit

Case A: Based on parallel resonant of LC filter

Fig. 7 shows the configuration of shunt APF with injection circuit based on shunt resonant of L_1—C filter [9]. L_1—C filter resonating at the fundamental frequency is connected between the APF and the power grid. The fundamental voltage is mostly loaded on the resonant circuit. Both APF and L_2 only bear the rest of the fundamental voltage. Another advantage of this shunt APF is that only a small fundamental current flow through L_1—C filter and inductance L_2. However, it can't compensate the reactive power because the fundamental impedance of parallel resonant circuit L_1—C is so large that it's difficult to generate fundamental reactive current to inject into main circuit.

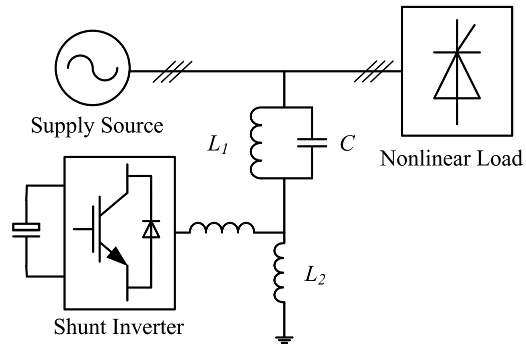


Fig. 7. The configuration of shunt APF with injection circuit based on shunt resonant of LC filter.

Case B: Based on Series Resonant of LC filter

Fig. 8 shows the topology configuration of shunt APF with injection circuit based on series resonance of LC filter, and the filter system is composed of a three-phase VSI, an output filter, coupling transformers, and injection branches [27, 37, 44]. The capacitor C_1 and inductor L_1 form the fundamental resonance circuit, i.e., fundamental impedance is approximately 0, and another capacitor C is mainly used to compensate fundamental reactive power as shown in Fig. 8.

As the series resonance of LC filter occurs at the fundamental frequency, the fundamental current flowing through the injection branch mostly flows into the network and very few flows into coupling transformers and inverters. Therefore, this type shunt APF with injection circuit based on series resonance of LC filter combines the advantages of larger capacity reactive compensation and smaller inverter capacity [36-38, 45-47]. Meanwhile, the APF can suppress series or parallel resonance between PPF and power utility internal impedance, which can make up for the drawbacks of only using PPF. It should be noted that it is difficult for this type APF to obtain better harmonic compensation performance and smaller device capacity at the same time, and the capacitance C volume will be large.

Fig. 9 shows the configuration of APF based on double resonance injection branch. The active part is connected in parallel with series fundamental resonant branch composed of L_2—C_2 filter through the coupling transformer, and then connected in series with the parallel fundamental resonant injection branch composed of L_1—C_1 filter.

In this structure, the parallel branch and the series branch constitute a double protection. When the parallel branch is fully resonant, the

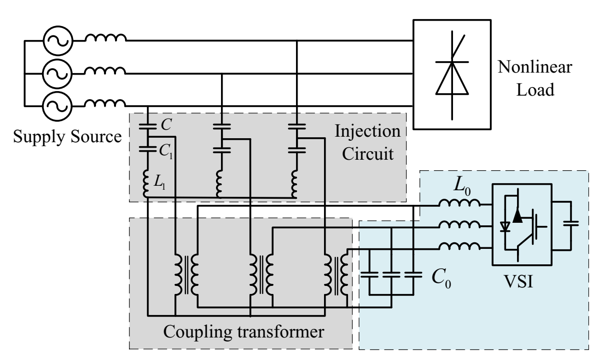


Fig. 8. The configuration of shunt APF with injection circuit based on series resonant of LC filter.

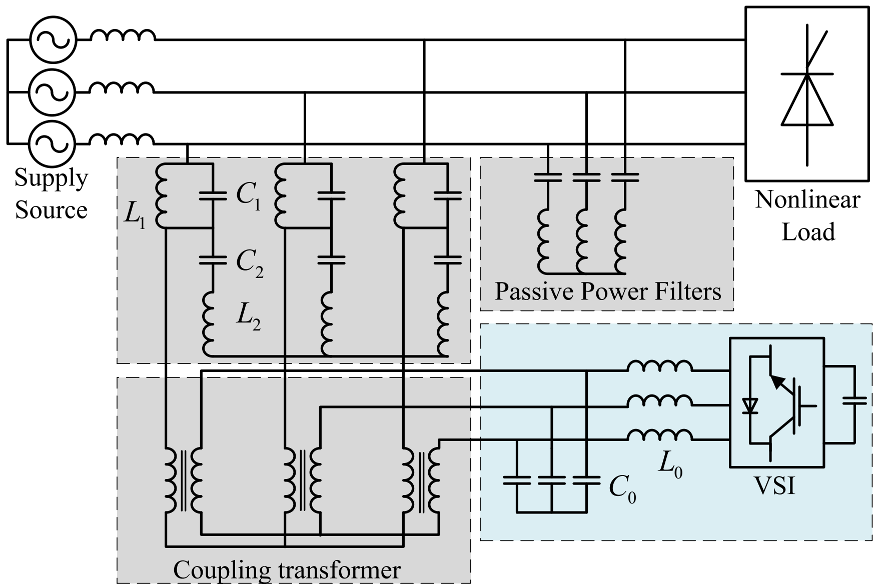


Fig. 9. The configuration of APF based on double resonance injection branch.

parallel resonance branch bears all the fundamental voltage. Although the parallel branch cannot resonance at the fundamental frequency, almost the fundamental current can still flow into the series resonant branch, so as to ensure that the active part shares a small part of the fundamental voltage. Therefore, it can reduce the rating of the active part effectively and solve the fundamental circulation suppression in traditional injected circuit configuration. However, the injection branch cannot compensate the reactive power because of the parallel resonance of the L_1—C_1 filter, which could be remedied by applying PPFs.

Therefore, the structure can effectively solve the problem of great reactive power compensation and harmonic suppression in high voltage system, as well as fundamental circulation suppression in traditional injected circuit structure. So, the safety and reliability are greatly improved in this case.

3.4. Active power filters based on one-cycle control

Due to the different characteristics from other conventional control methods, such as unnecessity of harmonic detection in one-cycle control method [48-49], it is necessary to be classified as another type of shunt APF.

One-cycle control method was firstly proposed by American scholars Keyue Ma Smedley and Slobodan Cuk [49]. One-cycle control is very general and directly applicable to switching converters in either PWM or quasi-resonant modes, like power factor correction, uninterruptible power supply (UPS), DC/DC converter, APF and so on.

As shown in Fig. 10, there is the basic circuit of one-cycle control method, where the circuit is composed of the one reset integrator along with a few comparators, flip-flops, and a clock [70]. The basic idea is to control the duty-ratio d of the switch in real time such that in each cycle the average value of the chopped waveform at the output diode of the switch rectifier is exactly equal to the control reference. Thus, based on the one-cycle control circuit, the RMS value of the output signal in a switching cycle [71, 72] can be derived as follow

$$\overline{u}_{\rm out} = \frac{1}{T_s}\int_0^{T_s} s(t)\mathrm{d}t = \frac{1}{T_s}\int_0^{dT_s} u_i(t)\mathrm{d}t \tag{5}$$

The APF with unified constant-frequency integration (UCI) control was proposed based on one-cycle control [50-53]. Fig. 11 shows the circuit of double-direction compensating control scheme, which improves the system stability and can be used in single phase shunt APF.

To sum up, the one-cycle control method has the following characteristics [54-59] compared with the other conventional control strategies:

1) There is no need to detect the harmonic current caused by nonlinear loads.
2) There are no multipliers or sensors for the load current and the APF inductor current so that the complicated digital computation of generating harmonic and reactive current reference can be eliminated.
3) Switching-frequency is constant when operating.
4) It is simpler, and has better effect of harmonic or reactive power current compensation, robustness and stability.
5) Currently, it is only available for low-power applications.

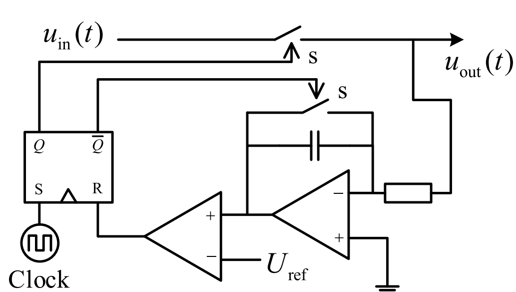


Fig. 10. The basic circuit of one-cycle control method.

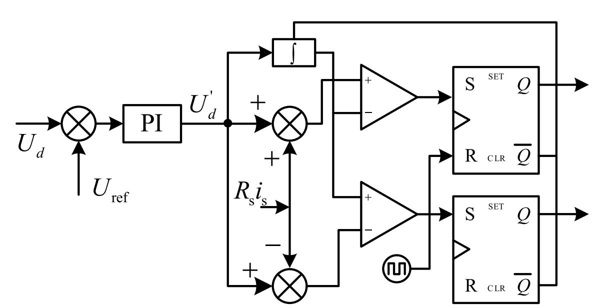


Fig. 11. Circuit of double-direction compensating control scheme.

The classic one-cycle control applied in APF is really dependent on accuracy of circuit parameters. When the integral parameters of control circuit deviate or float, the incoming current of main circuit will introduce DC component, which seriously hinders its popularization and application.

4. Series active power filters

4.1. Traditional series active power filters

Fig. 12 shows the configuration of traditional series APF, which consists of the series transformer, filtering branches and inverter [60-63]. The traditional series APF is in duality relation with traditional shunt APF as shown in Fig. 4. According to the filtering principle of traditional series APF, it is divided into the following cases.

In terms of traditional series APF, Fig. 13 shows the system equivalent circuit with the control approach of detecting source current. U_{Sh}, U_{Lh}, i_{Sh} and Z_S are the background harmonic voltage of power utility, harmonic voltage of nonlinear load, harmonic current of power utility, internal impedance of power utility, respectively. U_{Lf}, i_{Sf}, U_{Sf} are the fundamental components of load voltage, current of power utility and voltage of power utility.

$$i_{Shn} = \frac{U_{Shn} - U_{Lhn}}{k + Z_{Sn}} \tag{6}$$

When the control parameter $k >> Z_{Sn}$, the nth harmonic current i_{Shn} is reduced obviously, and $i_{Shn} \approx 0$ if k is large enough. Therefore, by controlling the APF to make k large enough, the power supply current can be turned into sinusoidal current with very few harmonic components, when the controller makes the traditional series APF generate the voltage which is equal to the load harmonic voltage but opposite in phase, i.e., $u_C = -U_{Lh}$ by extracting load harmonic voltage [54, 81, 84, 85]. So, without background harmonic voltage, the nth harmonic current can be achieved according to the system equivalent circuit in Fig. 13.

$$i_S = \frac{(U_{Lf} + U_{Lh}) + (-U_{Lh})}{Z_S} = \frac{U_{Lf}}{Z_S} \tag{7}$$

Therefore, the source current i_S is sinusoidal and the method can effectively eliminate load harmonics voltage if this type APF can make $u_C = -U_{Lh}$.

The APF has the same impedance to all harmonics, which is control parameter k, so it just has limited ability to suppress supra-harmonics. If the value of k is too large, the stability margin of the control system will become small or even unstable.

4.2. Series active power filter connected in series with passive power filters

This series APF is connected in series with PPFs which is parallel with power utility as shown in Fig. 14. It's a combined system of PPF and a

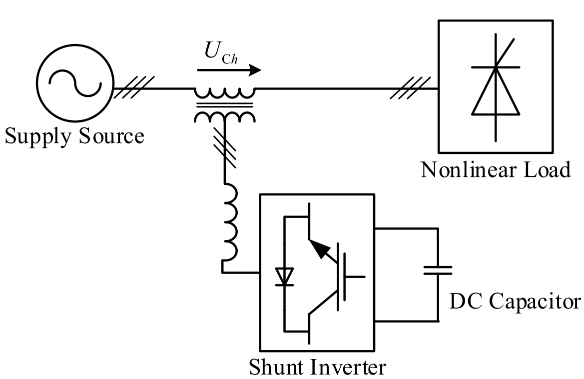


Fig. 12. The configuration of traditional series active power filters.

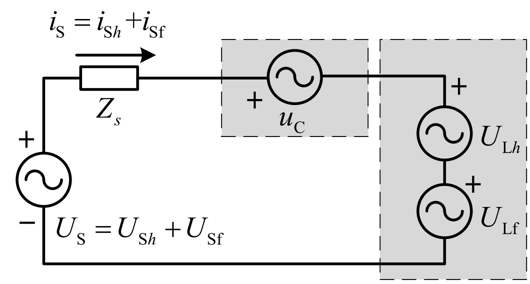


Fig. 13. System equivalent circuit (control approach of detecting source current).

small-rated APF [13, 45]. The features of this series APF has been summarized as follows.

1) The characteristics of this APF are not affected by the parameters of power utility because the APF can improve the filtering characteristics of PPF.
2) There is less possibility of parallel resonance or series resonance caused by LC filter.
3) The required rating of APF is greatly reduced compared with a conventional APF used alone, which can form a practical and economical system.

This type APF is very sensitive to the harmonic voltage in power grid; moreover, fundamental impedance of this APF is much smaller than that of PPF in order to reduce the fundamental voltage and current of APF, and the filter branch cannot produce large reactive current, so it is not suitable for large capacity reactive power compensation. In addition, as the tuning frequency of LC filter should be designed according to the characteristic harmonics generated by nonlinear loads, it cannot dynamically compensate these harmonics of other frequencies.

5. Hybrid active power filters

5.1. Combination system of shunt active power filters and shunt passive power filter

Fig. 15 shows the configuration combination of shunt APF and shunt PPF, which has two types of this filtering scheme [9, 64, 65]. The shunt APF compensates lower order harmonics while the shunt PPF that consists of the high-pass filter is used to eliminate higher order harmonics, so this method can reduce switching frequency of devices in APF main circuit. However, when using this device, there are harmonic channels between the power grid and APF, and between APF and PPF, especially the latter, which may make the harmonics injected by APF flow into PPF or power grid. At the same time, although the capacity of APF is reduced, the APF still bears all the fundamental voltage, and withstand voltage level of switching device cannot be not reduced.

In the other scheme, the PPF consists of the multi group single-tuned filters and high-pass filter. For the harmonic source of three-phase bridge rectifier, the PPF includes 5th, 7th tuned filter and high-pass filter, even 11th, 13th tuned filter. More proportion of harmonics have been filtered by PPFs. The APF only needs to eliminate the harmonics that LC filters fail to compensate. Therefore, in this scheme, APF just needs to provide a small compensating current, so the rating is much than the rating of shunt APF used alone. But there are harmonic channels between the grid and APF, and APF and PPF, which exists the same problem with the above scheme.

Fig. 16 shows the basic configuration of the combination of series APF and shunt PPF, i.e., the series hybrid APF (SHAPF). The PPFs consisting of 3th- and 5th-tuned LC filters, which play the main role of filtering, are shunted with a harmonic-producing load. If necessary, a

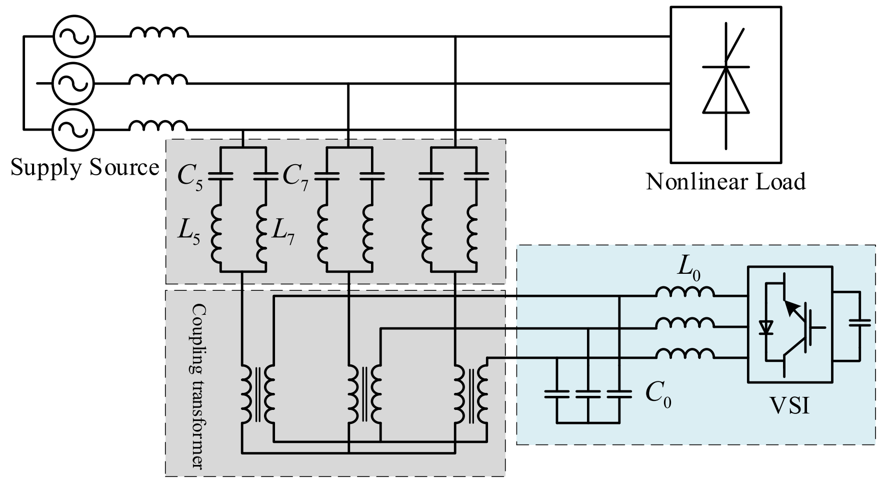


Fig. 14. The configuration of series APF connected in series with PPFs.

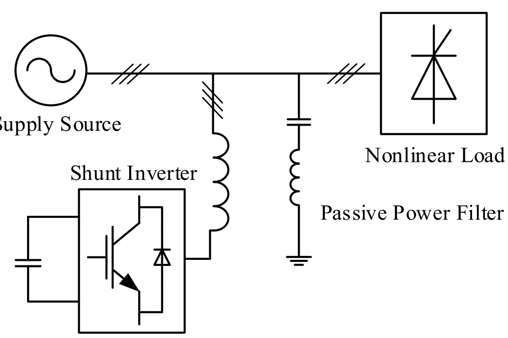


Fig. 15. The combination configuration of shunt APF and shunt PPF.

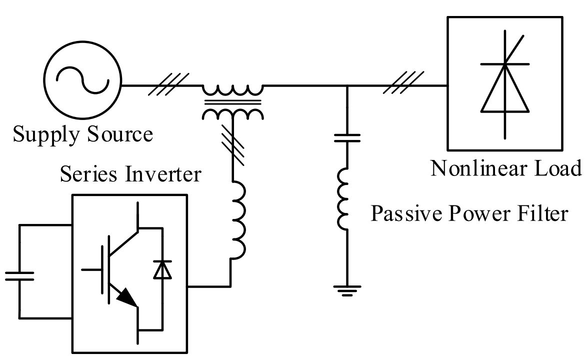


Fig. 16. The combination configuration of series APF and shunt PPF.

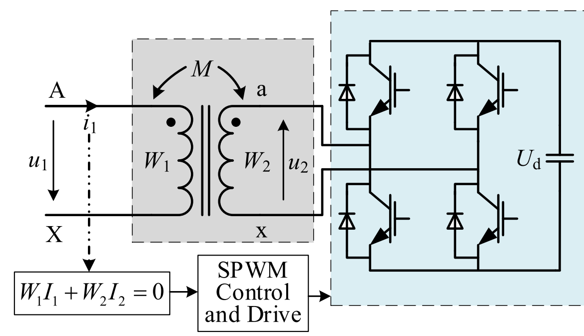


Fig. 17. The circuit of the series APF based on FMFC.

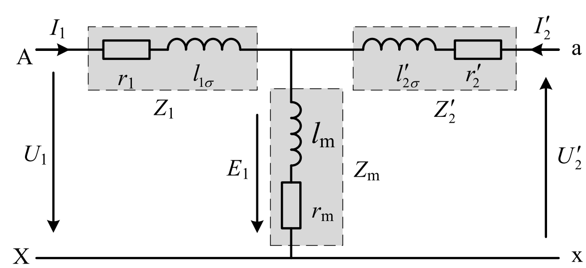


Fig. 18. The Equivalent-T circuit of series transformer.

high-pass filter branch can be added. The voltage-source PWM inverter is parallel with the secondary winding of the series transformer inserted in series between the power utility and the nonlinear load, which constitutes the series APF. In terms of the operation principle, the most typical SHAPF can be categorized into the following four types [62].

Case A: Based on the magnetic flux compensation

Fig. 17 shows the circuit of the SHAPF based on the fundamental MFC (FMFC) [45, 88, 89]. The turns of the primary and secondary windings of the transformer are W_1 and W_2, respectively; the turns ratio is represented by $k = W_1/W_2$. The fundamental component is detected from the power utility current i_1 and followed by applying a voltage source inverter so as to produce a fundamental current $i_2^{(1)}$. $i_2^{(1)}$ is inversely in phase injected to the secondary winding axe.

Equivalent-T circuit of transformer can be derived, as shown in Fig. 18 (here, the prime denotes referred quantities of secondary winding to primary winding). Z_1, Z_2, and Z_m represent leakage impedance of the primary winding AXE, the secondary winding axe referred to primary winding and the magnetizing impedance of the transformer, respectively. For the fundamental and harmonics, there are two cases in terms of the law of superposition.

It can be assumed that the injected fundamental current satisfies

$$I_1 + I_2/k = 0 \quad \text{i.e.,}\ W_1I_1 + W_2I_2 = 0 \tag{8}$$

For the fundamental, the equivalent impedance of the transformer can be obtained

$$Z_{AX}^{(1)} = U_1/I_1 = r_1 + jx_1 = Z_1^{(1)} \tag{9}$$

For the *n*th-order harmonic, since only a fundamental current is injected to the secondary winding of the transformer, i_2 does not include any harmonic current expect the fundamental current, i.e., $i_2^n = 0$. From the terminals AXE, the equivalent impedance is

$$Z_{AX}^{(n)} = U_1^n / I_1^n = r_1 + jnx_1 + jnx_m = nZ_m^{(1)} \quad (10)$$

For the simple analysis above, if the VSI can be controlled to inject the current which satisfies the condition $W_1 I_1 + W_2 I_2 = 0$, the series transformer exhibits very low impedance (primary leakage impedance$Z_1^{(1)}$) to the fundamental component and simultaneously exhibits very high impedance (magnetizing impedance$nZ_m^{(1)}$) to the harmonic component. Besides, the high harmonic impedance is predominately inductive and in proportional to the system frequency.

Therefore, this SHAPF based on FMFC can isolate harmonic currents to suppress harmonic propagation and have little influence on the fundamental current. However, obviously, it cannot carry out reactive power compensation, has single function of harmonics elimination, is difficult to protect, and is generally only suitable for voltage type harmonic source, which is rarely used in practice.

Case B: Detecting the harmonic current of the primary winding

In this case, the harmonic current of primary winding of series transformer is detected and functions as the reference signal. A PWM inverter is applied to track the reference signal to yield a harmonic voltage, which is applied across the secondary winding of the series winding. So, the control strategy can be set to

$$U_C = KI_{Sh} \quad (11)$$

Thus, this SHAPF is equivalent to the resistance K and consume the active power which is constant and lowest. The disadvantage of the control strategy is that the filtering method needs to install many PPF branches in order to achieve better filtering performance.

Case C: Detecting the harmonic voltage of the primary winding

The harmonic voltage of primary winding is detected and used as reference signal. The reference signal is tracked by applying a VSI in order to yield a controllable harmonic voltage, which is applied across the secondary winding [62]. Voltage generated by the inverter and voltage of primary winding can be controlled to satisfy the following relationship.

$$-U_2' = -\alpha U_1 \quad (12)$$

Additionally, the equivalent impedance of the series transformer is $2nZ_m^{(1)}$, which is proportional to harmonic frequency and magnetizing impedance. Limited by the control system bandwidth or switching frequency, this APF is difficult to suppress the higher harmonic voltage when it generates the opposite harmonic voltage.

Case D: Based on the sinusoidal current-controlled voltage-source inverter / detecting the fundamental and harmonic current of the primary winding

When the hybrid filter system shown in Fig. 15 is based on the sinusoidal current-controlled VSI, the series APF works as the sinusoidal current source and is in phase with the voltage supply [60]. The series APF, working as a sinusoidal current source in phase with the line voltage supply, keeps "unity power factor", and presents very high impedance for current harmonics. The amplitude of fundamental current is controlled through the error signal between the load voltage and the reference voltage values. Similarly, the PPFs in parallel with the nonlinear load consists of some tuned filters that provide a low impedance path for harmonic current. The control strategy can be derived as follow:

$$(I_S K_{SC} - I_{ref}) A(s) G(s) \quad (13)$$

Based on this control strategy, the hybrid series APF can achieve the functions of harmonic suppression, power factor correction, voltage regulation.

However, the rating of the voltage-source inverter will be relatively large, as it is necessary to compensate the fundamental reactive power as well as isolating the harmonics. Meanwhile, the equivalent resistance for harmonic current would consume active power [62]. In order to achieve better filtering effect, many PPFs must be used.

Table 1 is given to show the comparisons among Case A, Case B, Case C and Case D. The criterions of analysis are detected signal, inverter output, control strategy, harmonic equivalent impedance, characteristic of harmonic equivalent impedance, characteristics of the APF system, respectively.

From table 1, it can be concluded that the largest harmonic equivalent impedance is from the Case C because it is in proportional to twice the frequency. It would perform best in filtering and be more cost-effective.

For the four cases mentioned above, they are the most common control strategies of series hybrid APF. The essence is to deduce the maximum impedance to harmonic component through different control strategies in order to achieve the best filtering effect. To illustrate the general situation, the equivalent impedance of harmonics and fundamental components of series transformers based on different control strategies is given in table 2 in detail. It has certain reference value for how to choose a good control strategy.

5.2. Unified power quality conditioner

In 1989, S. Moran proposed the circuit where both series APF and shunt APF were connected in parallel to DC capacitor in back to back form [66] as shown in Fig. 19. The topology was addressed as the line voltage regulator/condition. H. Fujita, and H. Akagi named the configuration as the unified power quality conditioner (UPQC) and verified the viability and effectiveness of the UPQC based on the experimental results of a laboratory 20 kV system [67, 68].

The UPQC can effectively solve various problems of power quality in power distribution or industrial system by providing parallel and series compensation simultaneously, such as the compensation of voltage/

Table. 1
Comparisons among Case A, Case B, Case C and Case D.

Comparison criterions	Case A	Case B	Case C	Case D
Detected signal	The fundamental current of the primary winding	The harmonic current of the primary winding	The harmonic voltage of primary voltage	The fundamental and harmonic current of the primary winding
Inverter output	Fundamental current	Harmonic voltage	Harmonic voltage	Modulated PWM voltage
The control strategy	$I_1 + I_2/k = 0 \quad i.e., W_1 I_1 + W_2 I_2 = 0$	$U_C = KI_{Sh}$	$-U_2' = -\alpha U_1$	$(I_S K_{SC} - I_{ref})\ A(s)G(s)$
Harmonic equivalent impedance	$nZ_m^{(1)}$	K	$2nZ_m^{(1)}$	$K_{SC}A(s)G(s)$, which is equivalent to the K in Case B.
The characteristic of harmonic equivalent impedance	Inductive; consume the reactive power, the value is middle and in proportional to the line frequency.	Resistive; consume the active power, the value is a constant and lowest.	Inductive; consume the reactive power; value is largest and in proportional to the line frequency.	Resistive; consume the active power, the value is a constant and lowest.
The characteristics of the APF system	1) More cost-effective for harmonic equivalent inductance consumes the reactive power. 2) Reduced PPF can be used easily. 3) The loss of series active power is low.	1) Harmonic equivalent resistance consumes the active power. 2) Many PPF branches added in order to achieve better filtering performance.	1) More cost-effective because the harmonic equivalent inductance consumes the reactive power. 2) Reduced PPFs can be used easily.	1) Harmonic equivalent resistance consumes the active power. 2) Many PPFs branches are added in order to achieve better filtering performance. 3) The rating is the biggest.

Table. 2
Summary and Comparisons Under Different Control Strategies.

Control strategy	Detected signal	Coefficient α value	Fundamental equivalent impedance	Harmonic equivalent impedance	Controllable impedance effect or goals
$\dot{I}_2 = -\alpha\dot{I}_1$	Fundamental current	$\dot{I}_2 = -\alpha\dot{I}_1^{(1)}$ $\alpha = -1$	$Z_1 + (1+\alpha)Z_m$	$Z_1 + Z_m$	1) For the fundamental current, the impedance approximately equal to zero; 2) For the harmonic current, the impedance is very large.
	Harmonic current	$\dot{I}_2 = -\alpha\sum\dot{I}_1^{(n)}$ $\alpha$is large	$Z_1 + Z_m$	$Z_1 + (1+\alpha)Z_m$	
$\dot{I}_2 = \alpha\dot{U}_1$	Fundamental current	$\dot{I}_2 = \alpha\dot{U}_1^{(1)}$	$\frac{Z_1 + Z_m}{1-\alpha Z_m}$	$Z_1 + Z_m$	
	Harmonic current	$\dot{I}_2 = \alpha\sum\dot{U}_1^{(n)}$	$Z_1 + Z_m$	$\frac{Z_1 + Z_m}{1-\alpha Z_m}$	
$-\dot{U}_2 = \alpha\dot{I}_1$	Fundamental current	$-\dot{U}_2 = \alpha\dot{I}_1^{(1)}$ $\alpha$is large	$Z_1 + \frac{(Z'_2-\alpha)Z_m}{Z'_2+Z_m}$	$Z_1 + \frac{(Z'_2-\alpha)Z_m}{Z'_2+Z_m}$	
	Harmonic current	$-\dot{U}_2 = \alpha\sum\dot{I}_1^{(n)}$	$Z_1 + \frac{(Z'_2-\alpha)Z_m}{Z'_2+Z_m}$	$Z_1 + \frac{(Z'_2-\alpha)Z_m}{Z'_2+Z_m}$	
$-\dot{U}_2 = \alpha\dot{U}_1$	Fundamental current	$-\dot{U}_2 = \alpha\dot{U}_1^{(1)}$	$\frac{Z_1Z'_2 + Z_1Z_m + Z'_2Z_m}{Z'_2 + (1+\alpha)Z_m}$	$\frac{Z_1Z'_2 + Z_1Z_m + Z'_2Z_m}{Z'_2 + Z_m}$	
	Harmonic current	$-\dot{U}_2 = \alpha\sum$ $\dot{U}_1^{(n)}$	$\frac{Z_1Z'_2 + Z_1Z_m + Z'_2Z_m}{Z'_2 + Z_m}$	$\frac{Z_1Z'_2 + Z_1Z_m + Z'_2Z_m}{Z'_2 + (1+\alpha)Z_m}$	

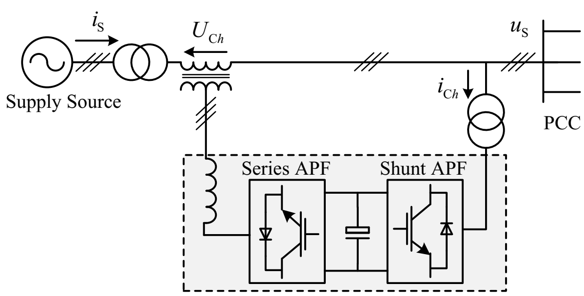


Fig. 19. The configuration of unified power quality conditioner.

current harmonic, reactive power, voltage sag/swell, voltage imbalance and negative sequence current [2, 69-76]. Due to specific controller applied to limit power level of series and parallel inverters, UPQC can only compensate a certain amount of reactive power and cannot provide enough amount when the load changes. In addition, when unbalanced load injects unbalanced current to common coupling node, the unbalanced current cannot be corrected, so power consumption of neutral line in three-phase four wire power grid cannot be neglected. Of course, initial manufacturing cost of UPQC system is also relatively high.

For the series inverter in UPQC, it is controlled as the voltage source which is equal to the set reference voltage value based on the UPQC control algorithm. It can make the nonlinear load obtain the desired sinusoidal voltage at load terminal [2]. In order to achieve this function, the operation conditions of the series APF must satisfy the following equation:

$$u_{Ch}(\omega t) = u_L^*(\omega t) - u_S(\omega t) \tag{14}$$

Where the u_{Ch}, u_L^*, u_S represent the compensated voltage of series APF, reference load voltage and supply source voltage, respectively.

For the shunt inverter in UPQC, it acts as the controlled current source to achieve the harmonic suppression and reactive power compensation. Simultaneously, it can keep the DC capacitors as the set reference value as governed by the control algorithm. The shunt APF must satisfy the following equation.

$$i_{Ch}(\omega t) = i_S^*(\omega t) - i_L(\omega t) \tag{15}$$

Where the i_{Ch}, i_S^*, i_L represent the compensated current of series APF, the reference source current and the load current, respectively.

6. Other active filters

6.1. Inductive power filter

Differing from passive and reactive filtering, the inductive filter technology displays the transformer's potential electromagnetic capability and uses the inter coupling wingding's ampere-turn balance action, which could suppress the harmonic in the secondary winding and avoid the harmonics flowing into the primary winding. Actually, inductive filter technology is an effective combination of PPF and transformers based on a reasonable impedance matching, which changes the electromagnetic induction path of harmonic in transformers [77-80]. In addition, it could effectively eliminate the bad influence of the harmonic magnetic potential. But the filtering effect of APF is worse than that of traditional APF, and it needs the coordination of impedance matching and compensation equipment.

There are three types of inductive filter technology, i.e., multifunction impedance matching and balance traction transformer, harmonic suppression single-phase traction transformer and three phase multi-pulse rectifier and converter transformer [79, 81-84] as shown in Fig. 20, Fig. 21, Fig. 22 respectively.

In Fig. 20, the harmonic suppression single-phase transformer can supple power to traction load, such as single-phase locomotive of electrified railway, single-phase rectifier, arc furnace load, etc. By connecting the secondary side of the balance transformer with the *LC* tuning branch as shown in Fig. 21, the multifunction impedance matching and balance traction transformer is constructed, which can also improve the comprehensive performance of reactive power compensation and harmonic suppression in electrified railway traction substation [85]. As

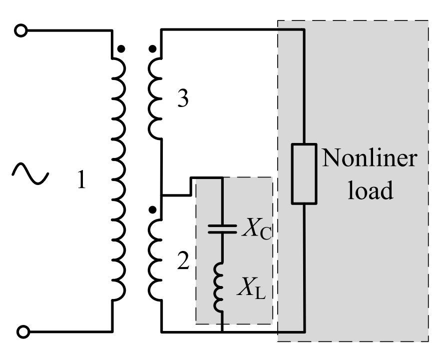


Fig. 20. Harmonic suppression single-phase traction transformer.

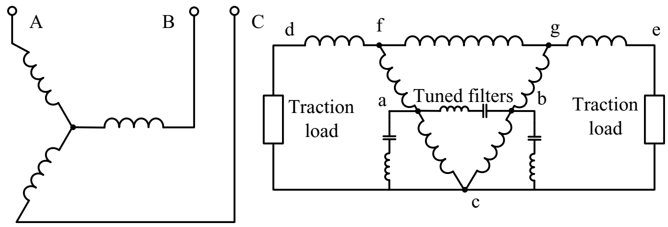


Fig. 21. Multifunction impedance matching and balance traction transformer.

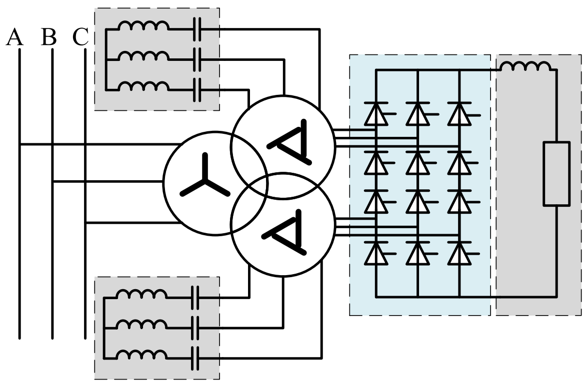


Fig. 22. Three phase multi-pulse rectifier and converter transformer.

shown in Fig. 22, three phase multi-pulse rectifier and converter transformer is used for the HVDC systems [86, 87]. It can effectively shield the main harmonics, so that most of them only flow in the secondary wingding and the total harmonic distortion in the primary winding is very low.

6.2. Resistive active power filter

When the reactive compensation capacitor is parallel with the nonlinear load, from the load side, there is a risk of parallel resonance between capacitor and inductance in the power system line. Therefore, the harmonic current injected by nonlinear load near the resonant frequency will be greatly amplified. Meanwhile, the background harmonics in the power system may be greatly amplified when there exists the series resonance between capacitors and inductance in the power system line. By establishing a distributed parameter model of power system feeder line, harmonic voltage resonance propagation caused by background harmonic voltage was analysed theoretically. Although the implementation of this scheme is more complex and the cost is higher, the resistive active power filter (RAPF) can be controlled to match characteristic impedance of power distribution systems to eliminate the harmonic amplification caused by resonance.

In reference [88], a RAPF proposed by H. Akagi, matching the characteristic impedance of the transmission line, was installed in the end terminal of the primary line on a feeder of a power distribution system, which can restrain the harmonic voltage propagation effectively. In reference [89-91], H. Akagi, et al. described a shunt APF based on voltage detection for harmonic termination of a radial or long power distribution line. The RAPF has been further developed later, such as double-RAPF system, RAPF equivalent to an infinite feeder to attenuate harmonic voltages of a radial power distribution feeder, single-frequency tuned RAPF for background harmonic voltage damping in power systems [92-95] and so on.

6.3. DC active power filter

There exists 12*n*th-order harmonics current and other non-characteristic harmonics current in the high voltage direct current (HVDC) system. In the case of overhead transmission line, these harmonic currents will cause serious interference to adjacent communication lines and increase the transmission line. In order to eliminate the harmonic currents in the HVDC system and ensure the system safety and economical operation, the active DC filter (ADF) was proposed to achieve the goal [96-98] as shown in Fig. 23.

Fig. 23 shows the structure of the ADF parallel in the HVDC system. In this structure, the PPF is the double tuned filter which is used for filtering the certain harmonics of the HVDC system, i.e., 12th and 24th harmonic. Thus, it can reduce the rating of active part. This APF is connected in series under the double tuned PPF and then they are connected in parallel with DC transmission line. This APF is applied to reduce impedance at resonance point of double tuned PPF and eliminate the remaining harmonics which PPF cannot compensate [99].

In Fig. 24, the series hybrid ADF is composed of the PPF and the series APF. The passive filter with series resonance at 12th harmonic exhibits high impedance at resonance frequency and ensure the active part does not withstand DC bus voltage. And this active filter can suppress other harmonics and improve the effect of harmonic elimination. At the same time, this structure can combine the double tuned filter which is in parallel with the series hybrid ADF or DC bus, which can further reduce the rating of active filter and decrease the harmonic components.

6.4. Integrated power quality controller in grid-connected inverter

For all we know, there has been many power electronics interfaced distributed generation (DG) units installed in micropower grid or the power distribution. Although The problems of power quality urgently need to be solved in these systems, the cost of installing special filters to improve power quality are much higher.

Alternatively, the thought of integrated power quality controller in grid-connected inverter has been put forward, which has become a hot topic. In the literature [100-105], these papers proposed some effective application methods of DG-grid interfacing converters in flexible microgrid power quality enhancement. For example, an adaptive hybrid voltage and current controlled method has been applied in the DG unit power electronics interfaces to achieve harmonic suppression [105]. Additionally, the power control can be obtained based on an improved current control method when the function of harmonic suppression works [100].

7. The existing problems and the development trends of active power filters

7.1. The existing problems

According to the characteristics of nonlinear load, harmonic sources can be divided into two types. The load with capacitive impedance

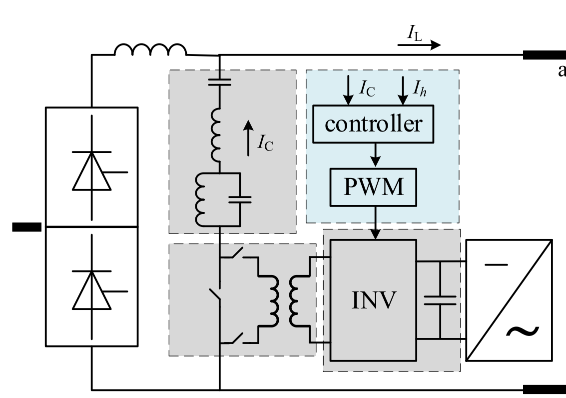


Fig. 23. The active DC filter parallel equipment of HVDC system.

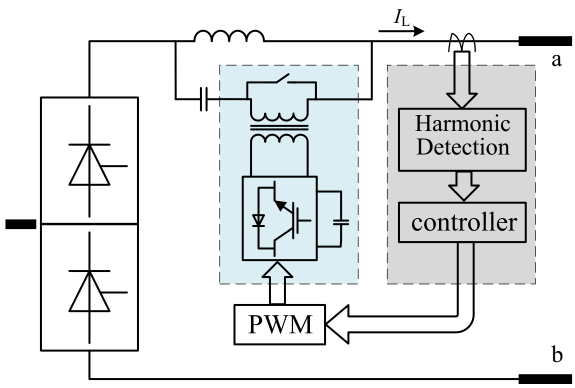


Fig. 24. the active DC filter series equipment of HVDC system.

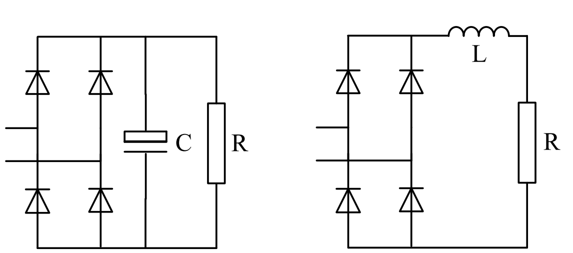
belongs to voltage type harmonic source, while the load with inductive impedance belongs to current type harmonic source, as shown in Fig. 25 (a) and Fig. 25(b). The shunt APF was suitable to suppress the current-source harmonic currents, while the series APF was suitable for the voltage-source harmonics. However, the former has been industrialized, while the latter has not. When shunt APF is applied to solve the problem of harmonic pollution caused by voltage type harmonic source load, there would exist the problem of load current being amplified, which would be analysed in detail below.

The simulation model of shunt APF shown in Fig. 5 has been built in PSIM software to eliminate harmonics caused by voltage type harmonic source nonlinear load, and table. 3 showed the detailed simulation parameters. Fig. 26 shows the waveforms of load side current I_L and system current I_S before and after harmonic suppression. Fig. 26(a) and (b) show that I_L has a single peak and two peaks respectively after harmonic suppression as result of different capacitive impedance.

Obviously, when the conventional shunt APF was put into use in the power grid at 0.51 s, the load current amplitude was magnified greatly, as shown in Fig. 26, since there is a certain relationship between harmonic amplification factor and the ratio of load impedance to equivalent impedance of power system. Specifically, there is a large capacity filter capacitor in the DC side of rectifier circuit, and its equivalent impedance is small, resulting the fact that harmonic amplification phenomenon in the AC side of the load is very serious. In terms of the equivalent circuit of traditional shunt APF shown in Fig. 6, the load side current can be derived as followed.

$$i_L = \frac{u_S}{Z_L + Z_S} + \frac{Z_S}{Z_L + Z_S}(I_L + I_C) = \frac{u_S + Z_S(I_L + I_C)}{Z_L + Z_S} \quad (16)$$

Therefore, when load impedance Z_L is small, i_L would be amplified and be really large compared with the situation before harmonic suppression. So, unfortunately, the current industrial application of shunt APF harmonic control scheme cannot be applied to eliminate the harmonic generated by voltage harmonic source load though there are more and more nonlinear loads belonging to this type in power electronic based power system.

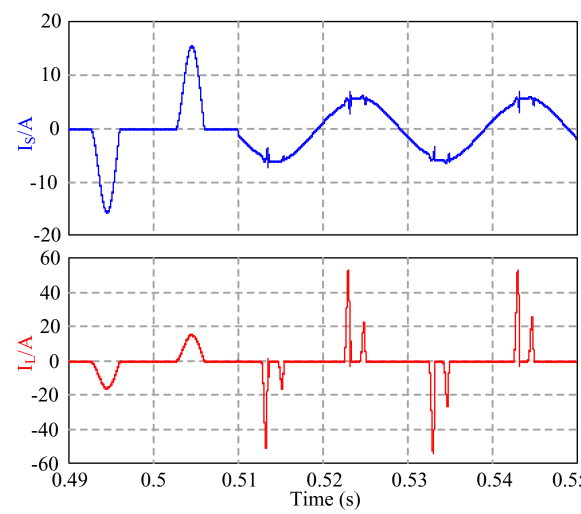


(a) Voltage type harmonic source (b) Current type harmonic source

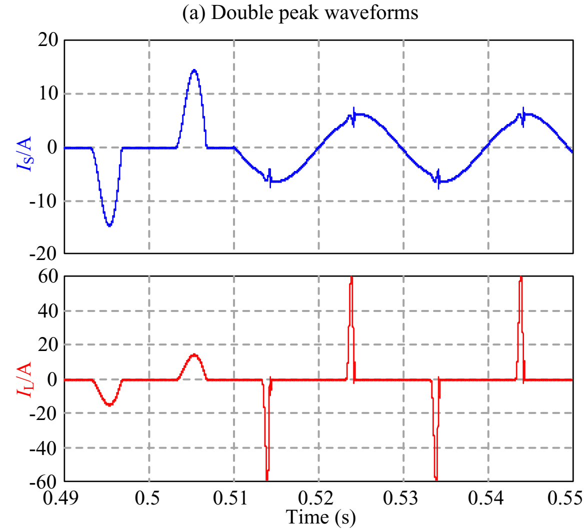
Fig. 25. Two types of harmonic source nonlinear loads.

Table. 3
Related Parameters of Shunt APF Simulation Model.

Parameters	Value
Single phase power system AC voltage u_S	50V
Frequency of u_S	50Hz
Internal impedance of system power supply	0.2Ω and 0.3mH
Load impedance in the first case of voltage type harmonic source	15Ω and 1100μF
Load impedance in the second case of voltage type harmonic source	15Ω and 2200μF
DC side voltage of VSI in shunt APF	60V
Filter inductance of VSI in shunt APF	1.0mH
Time step in PSIM simulation model	5e-6s



(a) Double peak waveforms



(b) Single peak waveforms

Fig. 26. Load side current I_L and system current I_S waveforms.

Additionally, conventional shunt APF is difficult to suppress the background harmonics of large power grids with distributed generation system. New energy sources are increasingly connected with power grids, which is the voltage-source background harmonic. The shunt APF can only eliminate the harmonic current generated by current-source harmonic loads but cannot effectively suppress the background harmonic voltage from the preceding power grids.

Besides, conventional APFs can only compensate harmonics at low frequencies. With the rapid development of power electronics technology applied in power systems, there exists the problems of supra-harmonics [106-109]. For example, the characteristic frequencies of the electric vehicle charging device, photovoltaic inverters, fan inverters, carrier communication are 2–120 kHz, 2–150 kHz, 2–20 kHz and 9–148.5 kHz [110-112], respectively. The conventional APFs are difficult to eliminate supra-harmonics because the limitation of various factors, such as harmonic detection, control strategy accuracy and so on.

7.2. Development trends

According to the latest developments, research applications of APFs as well as the current existing problems, APF would have broad application and research prospects in improving power quality of power systems and purifying grid harmonic pollution. However, with the increasingly wide application of APFs, the requirements of its capacity and voltage level are also higher and higher, and some factors that need to be considered in practical application are also different, so the topology and control strategy of APF also change.

1) With the development of power electronic based power systems, especially the application of photovoltaic inverter and various switching power supply, 2–150khz supra-harmonics has increased rapidly. It would be a hot topic to study the APF which is dedicated to suppress supra-harmonics.
2) In the implementation of various control schemes, the current use of general DSP cannot make full use of its internal resources. If we can design a special DSP chip for different control schemes, it will be able to better cooperate with the controlled object, and improve the performance price ratio of the controller. Whether in practical application or research and development, it will have a broad application prospect.
3) The trend of APFs, especially series APFs, would have multi-functions so that they can simultaneously suppress harmonics, correct the power factor, and compensate the voltage distortion, etc., through some advanced control and optimal strategies [82]. For example, APF is supposed to be developed to isolate the background harmonic except for the elimination of the harmonic current caused by nonlinear loads due to the existence of background harmonics in distributed generation system.
4) Various control strategies of APF (including space vector modulation, hysteresis current control, proportional resonance control, one-cycle control, sliding mode control, dead-beat control, repetitive control, predictive control, fuzzy control and controllers based on artificial neural network and so on) will be developed so as to deal with signal tracking and control in different harmonic suppression scenarios [113-116]. The application of advanced control algorithm to APFs has a good development prospect.
5) In recent years, some relevant research shows that the time-varying frequency of the power grid causes errors to the PLL, which reduces the detection accuracy. In addition, the delay link caused by LPF will also affect the detection accuracy, which is a problem that need to be solved based on the instantaneous reactive power detection method; the traditional fixed step size least mean square (LMS) algorithm cannot also take into account both the convergence speed and steady-state accuracy. More and more scholars begin to pay attention to the application of adaptive and other advanced algorithms in the field of harmonic and reactive current detection, which has become one of the research hotspots in the future.
6) According to the requirements of practical applications, the study of APF topology can provide a more practical and powerful theoretical basis for practical application of APF. For example, the research of shunt APF technology can focus on the improvement of output filter. In order to meet the harmonic compensation under high voltage, a variety of HAPF topologies can be studied to reduce the capacity and cost of DC side capacitor of APF, and to improve its voltage level, including transformerless or four switches dual arm APF, which can overcome the cost and volume problems, enhance reliability and reduce complexity. Therefore, reducing the number of switches in APF topology has become the main research trend of APF topology.
7) For the application of APF in high voltage and large capacity situation, multilevel structure of VSI has become effective solutions, which greatly improve the power level and stability of APF. What's more, with the increase of level, the output voltage level can be improved, and the switching frequency and harmonic content are able to be effectively reduced. Scholars have carried out in-depth research on multilevel converters, and the number of levels output in theory is unlimited, but it is only in the laboratory research stage. In practice, the two-level and three-level technology are still the main ones. The application of multilevel technology in harmonic control of medium- and high-voltage distribution network still needs to be vigorously promoted in the future. Cascade structure of VSI overcomes the circulation of currents problem and is easy to realize modularization, which has become the focus of multi-level research. However, the research mainly focuses on compensation performance and control technology of main circuit. The literature on dynamic performance is still rare, which may become one of the important directions of APF research in the future too. With regard to modular multilevel converter (MMC) topology, the unbalanced three-phase AC power grid makes the energy distribution of MMC three-phase bridge arm unbalanced, and the internal circulation is an important problem to be solved. It is an important factor to limit the development of MMC to high level in the practical application of HVDC system. MMC has a good application prospect in high voltage and large power applications. High voltage and large capacity APF will be further developed and applied.
8) Plug-and-play integrated modular series active harmonic isolator with high reliability and cost performance can be studied and applied in practice as shown in Fig. 27(a). It is based on the principle of magnetic flux compensation so as to present large impedance for harmonic components to isolate harmonics, but it adopts split-core current transformer or core through typed current transformer,

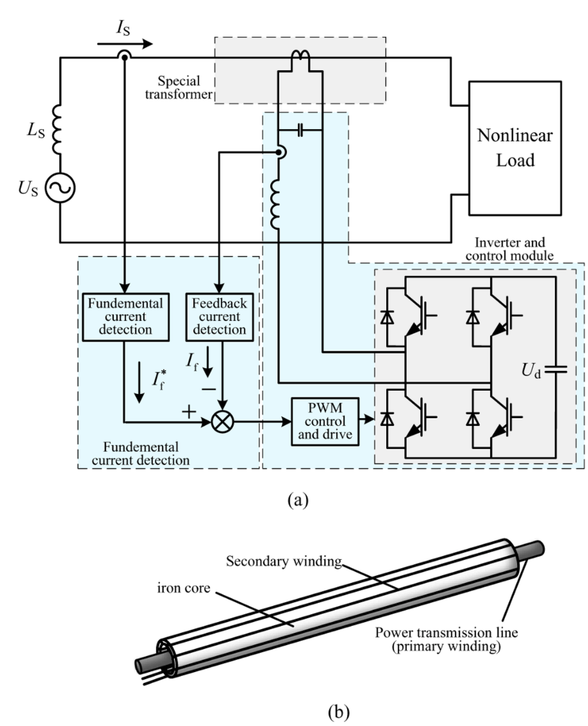


Fig. 27. The configuration of plug-and-play integrated modular series active harmonic isolator. (a) The circuit topology. (b) three-dimensional figure of special transformer.

which has no effect on the structure of power grid and can be simply connected to power grid. Fig. 27(b) is the three-dimensional figure of closed type special transformer. By using special transformer (increase the iron core length of current transformer), higher permeability material and improved control method, fundamental impedance of primary side of the current transformer would be very high, which can achieve very good harmonic isolation performance. Thus, plug-and-play integrated modular series active harmonic isolator can increase the power source impedance of harmonics to suppress harmonics caused by nonlinear loads, background harmonics caused by power source and even supra-harmonics, which provides a new way for the development of series APF.

8. Conclusion

With the development of power electronic power system, power quality problems exist in a variety of situation. Obviously, it promotes that APF would play an increasingly important role in improving power quality of power system and have a diversified development. So, this paper classifies and summarizes the APFs, and describes in detail the basic topology, working principles, advantages and disadvantages of various APFs.

Nowadays, APFs not only are limited to single function, i.e., harmonic suppression, but also develop in a multi-functional direction, such as background harmonic isolation, reactive power compensation, voltage regulation, power flow control, and fault current limiting. According to the important development trend, this paper has a detailed review of current mainstream APF. The suppression of supra-harmonics and background harmonics, the popularization and application in high- and medium-voltage power systems of APF, multi-function power quality controllers need further development and improvement, which involves filter topologies, control strategies, different advanced digital signal processors and so on. At the same time, how to balance the relationship of the better filtering performance, higher efficiency, cost reduction deserves further discussion and study.

CRediT authorship contribution statement

Jie Gong: . **Dayi Li:** Methodology, Writing – review & editing, Supervision, Funding acquisition. **Tingkang Wang:** Conceptualization, Investigation, Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing. **Wenhao Pan:** Visualization, Investigation. **Xinzhi Ding:** Conceptualization, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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