Three-phase hybrid active power filter: an overview

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ABSTRACT

Hybrid active power filter (HAPF) is considered an effective solution for filtering harmonics and compensating reactive power in power systems. It is a combination of passive power filters and an active power filter to form many different structures depending on the system voltage and load characteristics. This paper aims to introduce an overall picture of the results of research on three-phase HAPF systems, such as: HAPF models, advantages, disadvantages, and scope of application of each model; methods for determining parameters of passive power filters; structure, response time, resonance, power loss and cost of types of output filters; inverter structure and commonly used pulse width modulation methods in HAPF; control strategies and used controllers are also listed and compared; the DC Link voltage stabilization is also summarized and analyzed. Finally, the existing problems and the development trends of HAPF.

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1. INTRODUCTION

Currently, the majority of industrial loads are electric motors. The speed of those electric motors is controlled by power electronics. To ensure the desired speed, power electronic devices are required to turn ON and OFF at very high frequencies, resulting in the generation of harmonics in the electrical system. The existence of harmonic components in the electrical system will cause very serious consequences, such as: reducing the life of electrical equipment, causing the protection system to operate incorrectly, overheating electrical equipment, and causing interference in the information systems. Therefore, the issue of handling harmonics in the power system is of urgent significance, contributing to improving the power quality in the power system.

To eliminate harmonics generated from loads, hybrid active power filter (HAPF) is one of the most effective solutions. HAPF is constructed from a hybrid of passive power filters (PPFs) and active power filter (APF) [1]–[30]. Therefore, it has all the advantages of both PPF and APF. HAPF has two forms: parallel [1]–[13] and series [14]–[16]. PPFs are typically designed to suppress the high harmonics of the load and compensate for reactive power, while APF is designed to suppress the remaining low harmonics. The advantage of PPF is that it has a simple structure and is easy to use. However, it also has disadvantages, such as: being sensitive to the environment, susceptible to resonance with the system impedance, and less flexible when the load changes. To overcome the disadvantages of PPFs, the APF is added. The structure of APF is a power electronic system. The working principle of APF is that it compensates into the grid at the point of common coupling with a harmonic current equal to the load harmonic current, resulting in the supply current having no harmonic components of the load. Because PPFs are designed to suppress high order harmonics. Therefore, the APF only has to compensate for the lower harmonics. This means reducing the switching frequency of the inverter because it only has to switch with low-order harmonics. The result is a reduction of unwanted harmonics generated by the switching of the inverter's semiconductor switches.

Research on HAPF has focused on the following contents: harmonic detection method, passive power filter design, inverter structure, output filter, pulse width modulation method, APF control and DC link voltage stabilization. However, because HAPF has many different structures, the above research contents are also different. Passive power filters are sometimes designed with resonance components of order 11th, 13th, and sometimes with harmonics of order 2nd, 3rd, 5th, and 7th. The inverter structure usually uses a two-level voltage source inverter or three-level neutral point clamped (NPC) inverter. The output filter uses many forms such as *L*, *L-C*, *L-C-L* and *L-C-L-C*. Pulse width modulation methods include sinusoidal pulse width modulation, space vector, hysteresis. Control for HAPF is very rich and diverse from the method to the controller used. Finally, the DC link voltage stabilization. Depending on each model, the DC link stabilization method is also different such as the method with and without power supply from the system through a three-phase bridge rectifier connected to the DC link. Therefore, to provide readers with an overview of HAPF, this paper presents a comprehensive analysis of the structure, design, and control of HAPF in three-phase three-wire system.

The structure of the paper includes five sections: section 1 presents the urgency of harmonic filtering, the inevitability of the birth of HAPF and researches on HAPF. Models of HAPF are presented in section 2. The design and control of HAPF are given in section 3. Results and discussion are introduced in section 4 and section 5 is the conclusion.

2. HAPF MODELS

Because HAPF is a hybrid between APF and PPFs as shown in Figure 1. Therefore, it has the following typical model types, the first model is shown in Figure 1(a). The structure of this model includes PPFs and an APF connected in parallel with the load, so this model is also called a shunt hybrid active power filter [1]–[3]. PPFs are designed to suppress high-order harmonics generated from nonlinear loads. Meanwhile, APF is used to eliminate the remaining low-order harmonic components, such as the 3rd, 5th, and 7th. The advantage of this model is that it overcomes the resonance phenomenon between the impedance of the PPF and the system impedance, reducing switching losses because the inverter circuit only operates to compensate for low-order harmonics. However, it also has the disadvantage that the system voltage is applied directly to the APF inverter, leading to an increase in initial investment costs. It is only capable of eliminating current harmonics generated by the load. From the above characteristics, this model can only be applied to filter current harmonics for nonlinear loads in low voltage grids and the source is ideal.

The second model has the structure shown in Figure 1(b). In which the APF is connected in series with the PPF and all are connected in parallel with the load [4], [5]. PPFs are designed to eliminate harmonic components that account for a large proportion (5th, 7th) of the load. Meanwhile, APF only plays the role of improving the efficiency of PPF and overcoming the resonance problem between the impedance of the source and the impedance of the PPF. The advantage of this model is that it reduces the voltage applied to the inverter, the APF's capacity can be reduced many times compared to the capacity of load. From there, this model can be used for high power loads. The disadvantage is that it can only eliminate a few selected harmonic components of the load, and it is unable to eliminate harmonics generated from the source.

The third model is structured as shown in Figure 1(c). This model uses a fundamental frequency resonant circuit. L_1 and C_1 resonate at the fundamental frequency and couple to C_F. The APF is connected in parallel with the resonant circuit L_1-C_1 and is connected directly to the transformer. C_F is directly connected to grid voltage and has the ability to compensate for reactive power [6]–[8]. Meanwhile, the fundamental frequency resonant circuit only stands for harmonic voltage. This significantly reduces the capacity of the APF and minimizes the rated voltage applied to the power electronic switches of the inverter. Therefore, this model can be used effectively in medium voltage power grids of 6 kV, 15 kV, and 35 kV. Harmonics generated from the source cannot be handled.

The fourth model has the structure shown in Figure 1(d). Similar to the model in Figure 1(c). PPFs are designed to suppress higher harmonics (11th, 13th) [9]–[13]. This model also cannot handle voltage harmonics from the source. Because it uses a fundamental frequency resonant circuit, it receives fundamental frequency power from the grid. Therefore, the models in Figures 1(c) and 1(d) are difficult to stabilize the DC link voltage, whenever the source voltage sags or distorts, the DC link voltage will increase or decrease suddenly. Therefore, this model at the DC link is usually supplied by a three-phase uncontrolled bridge rectifier.

The fifth model has the structure shown in Figure 1(e). This model includes PPFs connected in parallel with the load. The APF is connected in series with the load through a transformer [14]–[16]. The PPFs are designed to resonate at current harmonic frequencies. APF has the function of eliminating voltage harmonics from the source, it acts like a large impedance to block harmonic components from the source but pass through the fundamental components. As a result, the voltage applied to the load is an ideal sinusoidal. Thus, this model is capable of handling current harmonics from nonlinear loads and voltage harmonics emitted from the source. The disadvantage of this model is the iron loss due to the use of a transformer. When the source has many harmonic components, the inverter must switch at high frequency, leading to switching losses. Therefore, this circuit is rarely used in practice.

The sixth model has the structure shown in Figure 1(f). This model is a combination of the first model and the fifth model. This model uses two voltage source inverters sharing the same DC link. Therefore, it is capable of eliminating the current harmonics generated from the load and the voltage harmonics generated from the source. In addition, it also has all the advantages and disadvantages of the first model and the fifth model.

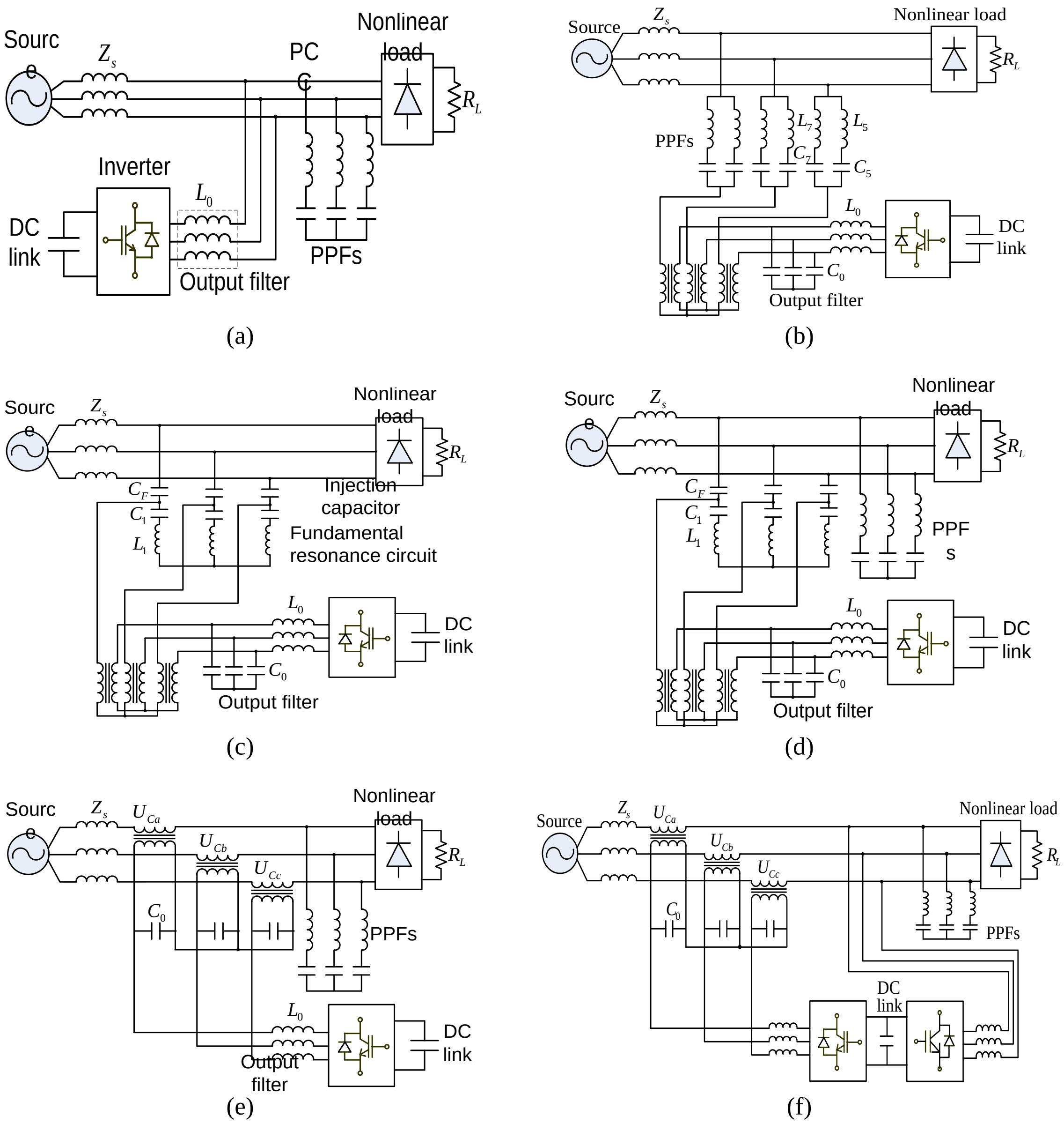

Figure 1. HAPF models: (a) PPFs and an APF connected in parallel with the load (b) APF is connected in series with the PPF and all are connected in parallel with the load (c) APF is connected in parallel with the resonant circuit L_1-C_1 (d) APF is connected in parallel with the resonant circuit and PPFs (e) PPFs are connected in parallel with the load, APF is connected in series with the load and (f) PPFs are connected in parallel with load and APF to compensate both voltage and current harmonics

3. DESIGN AND CONTROL FOR HAPF

3.1. Calculate the parameters of PPF

PPFs are designed to cancel high-order harmonics generated by nonlinear loads and to compensate for reactive power. The types of PPFs are listed in Figure 2. Among them, the PPF in Figure 2(a) is the most used [9]–[13] because of its simplicity. Types of passive filter circuits in Figures 2(b) to 2(f) are rarely used. There are two ways to calculate PPFs parameters: based on load characteristics and using multi-objective optimization algorithms.

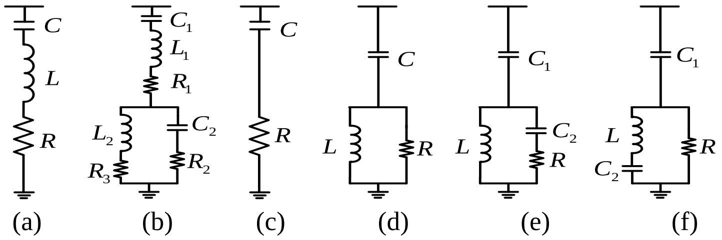

Figure 2. Types of passive filter circuits: (a) single-tuned filter (b) double-tuned filter (c) 1st order high-pass filter (d) 2nd order high-pass filter (e) 3rd order high-pass filter and (f) type C filter

a. Based on the characteristics of the load:

First the value of C_n is calculated based on the reactive power requirement Q_c of the load

$$C_n = \frac{Q_c}{n\omega U_s^2} \tag{1}$$

In which U_s is the phase voltage applied to capacitor C_n and ω is the fundamental angular frequency of the source. To eliminate the n^{th} harmonic component, L_n and C_n must resonate at the n^{th} frequency.

$$L_n = \frac{1}{n^2\omega^2 C_n} \tag{2}$$

The series resistance for the inductor of the n^{th} order is

$$R_n = \frac{n\omega L_n}{Q_n} \tag{3}$$

where Q_n is the quality factor of the inductor, which is normally considered as $10 < Q_n < 100$

b. Using multi-objective optimization algorithms:

the parameters of the PPF are also determined by applying multi-objective optimization algorithms such as genetic algorithm [17]–[19], particle swarm optimization (PSO) [20]–[22], Cuckoo search algorithm [23], Fortran feasible sequential quadratic programming [19]. There are also a few studies using multi-objective optimization algorithms to find all the parameters of PPF, APF and control circuit [25]–[28]. PSO with system stability constraints [25], Social Spider algorithm [26], Vortex algorithm [27], Jaya [28] with constraints: $Ri_{imax_{imin}}$, $Li_{imax_{imin}}$, $Ci_{imax_{imin}}$ and an objective function such as minimizing total harmonic distortion of the voltage applied to the load ($min\,THD_U$) or minimize the total harmonic distortion of the supply current ($min\,THD_I$).

3.2. Design the output filter

The output filter (OF) is designed to filter unwanted harmonic components at the inverter output. It affects the compensation effect of HAPF. The requirements when designing the OF for HAPF are: simple structure, fast response time, avoiding resonance problems, reducing DC link voltage, attenuation with high order harmonics, low initial investment costs and power loss. The types of OF commonly used in HAPF are shown in Figure 3.

Figure 3(a) [15], [31], and Figure 3(b) [4], [6], [7], [9]–[13], [26]–[28] have a simple structure. However, with this structure, the capacity requirement of the APF must be large, leading to increased initial investment costs and large losses, making it difficult to reduce high-order harmonics. Figure 3(c) has the ability to reduce high-order harmonics, but the response time is not fast and requires the DC link voltage to be large enough, investment costs and power loss are also large [29], [30]. Figure 3(d) is the most effective form [32]. It has a relatively complex structure, moderate investment costs, and average dynamic response time. However, its biggest advantage is small power loss and DC link voltage value is lower than other structures.

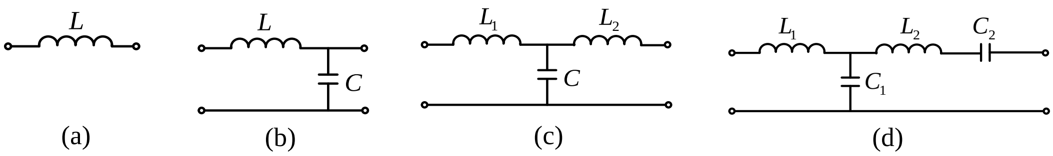

Figure 3. Types of output filter (a) L type (b) LC type (c) LCL type and (d) LCLC type

3.3. Inverter structure and pulse width modulation method

The inverters used in HAPF are three-phase two-level voltage source inverters [4], [6], [7], [9]–[13], [33], [34] and use the sinusoidal pulse width modulation method. Because the structure of HAPF in the second, third, fourth and sixth models uses PPFs to filter high-order harmonic components and uses injection circuits. Therefore, the voltage applied to the inverter is significantly reduced, and the inverter is only controlled to compensate for low-order harmonics. Therefore, the switching loss in the inverter is also significantly reduced. However, in the first and fifth models, a multi-level inverter can be used if the load has a large harmonic capacity or the source has a high voltage. The most common here is to use a three-level NPC inverter [35]–[38] and a nine-level voltage source inverter and using space vector modulation method [39].

3.4. Control strategies and methods

The general control block diagram of HAPF is shown in Figure 4. The reference current here can be the supply harmonic current or the load harmonic current [40]–[42]. It depends on the structure of the HAPF and the chosen control strategy. The reference current is normally determined using the synchronous reference frame method [43] as shown in Figure 5. Where i_{La}, i_{Lb}, i_{Lc} are the load currents and i_{Lah}, i_{Lbh}, i_{Lch} are the harmonic components of the load current.

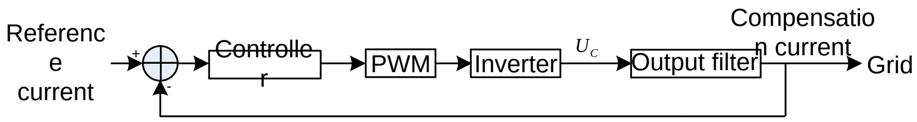

Figure 4. Control block diagram of HAPF

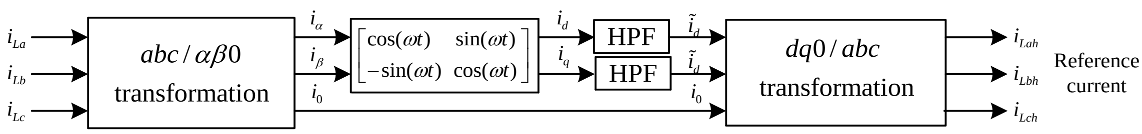

Figure 5. Harmonic detection method using the synchronous reference frame

The harmonic detection method using the synchronous reference frame has the advantage of being simple. However, it has the disadvantage of depending on high-pass filter (HPF) or low-pass filter (LPF). When the LPF has a high cut-off frequency, its dynamic response will be fast, but in the steady-state is poor. On the contrary, when the cut-off frequency is low, the dynamic response time will be large, but at steady state, the harmonic content in the fundamental current will be very low. Furthermore, when using LPF, the overshoot during the transition period will be very large. To reduce the dependence on LPF. Studies have used neural network to determine the harmonic current [31], [44]. The load current will be analyzed into separate components and each component is assigned a weight. During the working process, the neural network will update and adjust the weights so that the error is zero. This method has the advantage of determining the exact harmonic components at steady-state. However, it also has the disadvantage of a slow dynamic response time. A few studies have improved the p-q harmonic detection method, such as changing the cut off frequency using 1st, 2nd, 3rd low-pass or high-pass filters [43], [45]–[47] use a regulator fuzzy to improve the LPF in the p-q harmonic determination method to reduce dynamic response time. References [48] and [49] use an improved least mean square (LMS) algorithm that makes the dynamic response time faster and independent of LPF. Moradi and Pichan [50] used the wavelet transform to identify harmonics. This method does not use LPF, but collecting sample data is complicated, especially when the load changes. Boussaid *et al.* [51] used multivariable filters (MVF) to increase the harmonic filtering efficiency and reduce the harmonic content in the fundamental harmonic current. Tao *et al.* [52] determines harmonics based on an improved Gray Wolt algorithm with optimized variational mode decomposition. The reference current signal can be based on the supply harmonic current or the load harmonic current, depending on the chosen control strategy. The error between the reference signal and the compensation signal will be passed through the controller, pulse width modulation (PWM), inverter, output filter and applied to the grid at the point of common coupling (PCC). Most research focuses on controllers that minimize errors and respond to load changes. The simplest is to use single controllers such as: proportional integral (PI) [53]–[57], deadbeat [58], fuzzy [59], neural [60]. The above single controllers have the disadvantage of slow response and constant parameters during control, so they are not suitable for changing load systems and have large errors. Since then, hybrid controllers have been proposed, such as: PI-fuzzy [61], PI-neural [62], [63] and fuzzy-neural [64]–[67]. Several recent studies used proportional resonant (PR) controller [68], [69]. The advantage of PR controller is that it gives error at steady state equal to zero. However, it often has a long transient time. Therefore, PR controller is often combined with fuzzy controllers [70] to reduce transient time. There are also a few studies using self-adaptive control [71], predictive control [72], [73] and sliding control [74]. These controls are modern and highly efficient and are suitable for variable load situations.

3.5. DC Link voltage stabilization

Stabilizing the DC link voltage of the inverter is one of the most important jobs in the HAPF system. Depending on the structure of each system, the method of stabilizing the DC link voltage is also different. Normally, the DC link voltage is adjusted as in Figure 6. The actual voltage on the DC link is compared with the reference DC voltage value, will be passed through the PI controller, and the result will be added to the reactive current component in the synchronous reference frame [75], [76]. However, this method is often suitable for systems with small DC link voltage fluctuations. Luo *et al.* [77] proposed two methods to stabilize the DC link voltage for the fourth model: the first method is to use a circuit to discharge energy through a resistor, whereby when the voltage on the DC link increases, it will be discharged through a resistor by an insulated-gate bipolar transistor (IGBT) key. The second method is to use a controlled rectifier connected to the inverter via the DC link, whereby when the DC link voltage increases, it will be discharged into the grid and vice versa. Lam *et al.* [78] proposes an adaptive DC link voltage control method according to load changes. This study is different from previous studies in that it allows the DC link voltage to change according to the load, each load will correspond to an optimal DC voltage value. In the case of a fixed DC link voltage, the switching loss will be directly proportional to the DC link voltage, the system will obtain a large loss if the DC link value is large, and vice versa. Therefore, if the DC link voltage is adaptively adjusted according to the different power situations of the load, the system can achieve better and more flexible results. Bao and Thuyen [79] proposed a method to stabilize the DC link voltage using an uncontrolled bridge rectifier combined with a Boost DC/DC converter. Gong *et al.* [80] used a nonlinear PID controller based on robust exact differentiation to improve the dynamic response time on the DC link voltage.

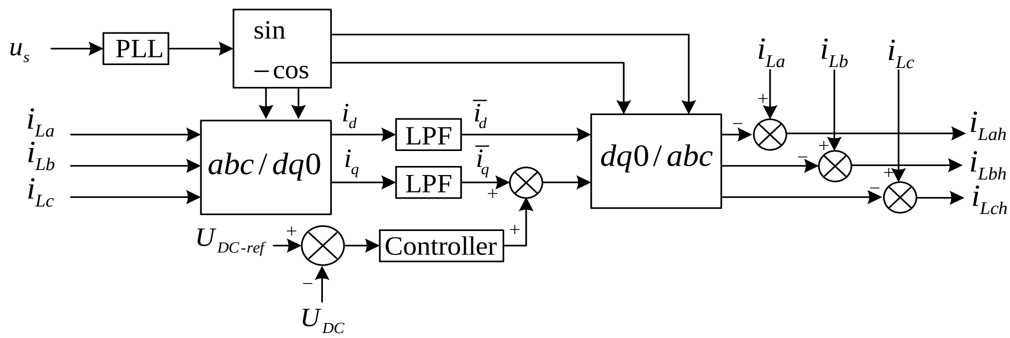

Figure 6. DC link voltage stabilization diagram

4. RESULTS AND DISCUSSION

From the above analysis results, we can see that which model to use depends on the purpose and function of each model, the function of each model can be summarized as in Table 1. The most commonly used structure of PPF is the form in Figure 2(a). Calculate the parameters of PPFs in Figure 2(a) can be based on the characteristics of the load to find the values of L and C so that it resonates at a certain harmonic frequency or use multi-objective optimization algorithms. Some studies have used multi-objective optimization algorithms to determine the parameters for both PPF and control. In the case of changing load, determining the control circuit parameters is not necessary. Moreover, in online control, the control parameters must be continuously updated.

Designing the OF plays a decisive role in the accuracy of the compensation signal to the grid. Output filters also come in many forms. Therefore, when deciding which type to use, we should consider factors such as structure, response time, resonance, DC link voltage value, high harmonic attenuation, power loss and investment cost. Below is a comparison of the characteristics of the output filters summarized in Table 2.

Table 1. Functional comparison of HAPF models

Compensation for specific application	Hybrid active power filters models					
	1st model	2nd model	3rd model	4th model	5th model	6th model
Current harmonics	*	*	*	*		*
Voltage harmonics					**	*
Reactive power	*	**	**	**	*	*
Voltage imbalance and distortion					**	*
Voltage regulation					**	*

Higher number of '*' is more preferred

Table 2. Comparison of characteristics of output filters

Output filters	Structure	Response time	Resonance	Voltage DC-link	High-order harmonics attenuation	Power loss	Cost
L [15], [31]	Simple	Fast	No	High	Large	Large	Medium
LC [9]–[13]	Simple	Fast	No	High	Large	Medium	Medium
LCL [29], [30]	Complex	Medium	No	High	Small	Large	High
LCLC [32]	Complex	Medium	No	Low	Small	Small	Medium

Inverter structure and pulse width modulation method: In the HAPF structures, it is only necessary to use three-phase two-level voltage source inverter (VSI) without using multi-level inverters. The most popular modulation method here is the sine pulse width modulation method because of its simplicity and ease of experimental implementation, but the output power of the inverter is not large. The Hysteresis method has the advantage of fast response, but the disadvantage is that the steady-state error is poor. The space vector modulation method can give an output power of the inverter larger than the sinusoidal pulse width modulation method, but it is complicated. This method is often used for model 1, accompanied by the use of a three-level NPC inverter.

Control strategies and methods: The choice of control strategy based on the load harmonic current or the supply harmonic current (models 1 to 4) or based on the load harmonic voltage or the supply harmonic current (models 5 and 6) is depends on system characteristics. Next is the selection of the controller. The selected controller must ensure accuracy, fast response, small error and has the ability to update online with changes in load and easy to implement in practice. Single controllers are simple and easy to implement in practice although they have the disadvantage of poor steady-state performance. Therefore, they are often combined with fuzzy, neural, adaptive controllers. However, the above combined controllers are complex and difficult to minimize the steady-state error. Therefore, a new trend is to use PR controller combined with fuzzy and neural controllers to control online with load changes and can reduce the compensation error to zero at steady-state.

DC link voltage stabilization: From the above summaries, we can see that there are two main methods of DC link voltage stabilization as follows: for models without fundamental frequency resonance circuit (models 1, 2, 5, 6), we can use the method in Figure 6. For models 3, 4, there is a fundamental frequency resonance circuit, so the voltage applied to the inverter is mainly harmonic, so once the voltage at the common connection point is sagged or distorted, the voltage on the DC link will fluctuate greatly, causing danger to the system. Therefore, DC link voltage stabilization of these models must be powered from a three-phase source through a three-phase PWM or uncontrolled rectifier [77] as in Figure 7. The existing problems and the future development directions:

a. The circuit that determines the reference harmonic current depends on phase-locked loop (PLL) and LPF. Therefore, during the transient period, the reference current signal generated is not accurate and the transient time is long. As a result, the supply current during the transient period or when the load changes suddenly will be very large, which can easily cause system instability. Therefore, it is necessary to study a method to determine harmonic currents without using PLL and LPF.
b. HAPFs have a rather large DC-link voltage and high switching frequency. This results in a large voltage applied to the IGBT and large switching loss. Therefore, research to improve the structure of the traditional two-level voltage source inverter is necessary.
c. In practical applications, the IGBTs in the inverter may have a conduct together phenomenon that causes short circuits and open circuits in the inverter. This is very dangerous. Therefore, research to improve the VSI structure and control method so that it can overcome the conduct together, short circuit, open circuit phenomena in the inverter. It contributes to improving the safety during the operation of HAPF.
d. Because the structure of HAPF includes many *R*, *L*, *C* elements connected together. Therefore, the compensation signal to the grid at the PCC will be phase shifted compared to the reference signal. As a result, there is always a deviation between the reference signal and the compensation signal. So, it is very important to study a control method has fast response, small error and phase shift compensation capability.
e. In applications that require dynamic compensation of a large amount of reactive power, HAPF is often not satisfy. Therefore, research on HAPF models with connections between static var compensator and active power filter is necessary.
f. Harmonic filtering for smart grids. Smart grids are large systems with many interconnections and many harmonic generating devices such as inverters and converters connected to renewable energy sources. Therefore, research on harmonic filtering for smart grids also needs to be interested.

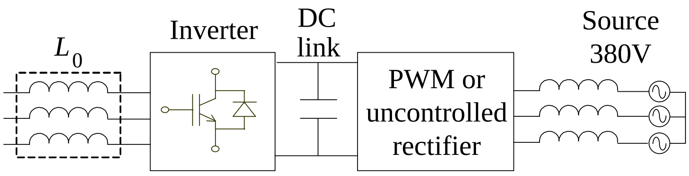

Figure 7. DC link voltage stability with the third model and fourth model

5. CONCLUSION

This paper has given an overview of the three-phase three-wire HAPF systems, including: structures of HAPF, calculation of passive power filters, output filter design, inverter structure and pulse width modulation methods, control strategies, and DC link voltage stabilization and control methods. This study also serves as a basis for researchers to research, apply, and develop HAPF in practice. Studies have proven that: HAPF has many advantages in harmonic filtering and reactive power compensation. However, it also has many shortcomings that need to be addressed in the future, such as: adaptive control according to changes in load, stabilizing the DC link voltage in case the load has large harmonic capacity and sudden changes, large reactive power to be compensated, large investment costs as well as losses during the switching process, short circuit or open circuit of the semiconductor switches of the inverter.

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