KEY TECHNOLOGIES OF ACTIVE POWER FILTER FOR AIRCRAFT: A REVIEW

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Abstract:

Active Power Filter (APF) is not only an advanced technology to improve power quality and purify power system pollution but also a good approach to solve electrical problems of an advanced aircraft such as harmonic, reactive power and unbalanced load. However, there are still some specific problems for the application of aeronautic APF in practice. Based on current research on aeronautic APF, this paper reviews three key technologies where APF can be used in aircraft AC power supply system, including the acquisition method of reference current, the strategy of APF current control and the main circuit topology. Consecutively, the features of current aeronautic APF research are summarized, and the future research directions are also suggested.

1 Introduction

With the development of aviation technology, the development of electric aircraft has become the mainstream direction of advanced aircrafts. Considering the requirements of more electricity in aircrafts, the capacity of aircraft power needs to be increased to a certain level. At present, power electronic devices using power switching devices such as SCR, MOSFET and IGBT, have been widely used in aircrafts, which can effectively reduce the system weight and improve its performance [1]. Meanwhile, due to the nonlinear characteristics of power electronic devices, there are some intractable problems such as harmonics, unbalanced components and reactive power to aircraft power grid, which greatly reduce the power supply quality of aircraft power system and even endanger the safe operation of entire aircraft power system [2].

In order to prevent the harm and influence of harmonic in aircraft grid, there are many international standards for aircraft electrical power quality, such as MIL-STD-704F, RTCA DO-160F and ISO 1540-200, etc. The aircraft manufacturing enterprises also have their own standards, such as Boeing D6-44588 and Airbus ABD-0100. All the standards above put forward demands for aircraft power and harmonic content, and typically require the harmonic distortion rate below 3%. But the standards only dictate the total voltage or current harmonic contents demands and some single harmonics demands. When all power electronic devices work together, because of their comprehensive properties they may still have larger influence on the quality of power supply system, and even beyond the steady state requirements of aircraft power supply features. Therefore, the aircraft grid harmonic governance should be solved as a system problem.

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Active Power Filter (APF) is a device designed to realize dynamic harmonic suppression and reactive power compensation. It can achieve centralized compensation of harmonic, reactive power and unbalanced load [3]. The compensation of APF is not subjected to the power grid impedance so that there are no overload problems and the reliability is high. Related studies indicate that the application of APF to aircraft power harmonic is one of the best ways to improve the power supply quality for airborne equipments [4]. However, because of the particularity of aircraft power grid, there are still many difficulties in practical implementation of APF.

2 Current research status of aeronautic APF

In 1969, B. M. Bird and J. K. Marsh proposed a method as the sprout of APF, in which a third harmonic current was injected into the grid in order to reduce the power grid harmonic current [5]. Before long, in 1976, L. Gyugyi and E. C. Strycula presented an APF using PWM (Pulse Width Modulation) control inverter, and established the concept of APF and the main circuit topology [6]. Since then, APF had been in the stage of theoretical exploration due to the restriction of power electronic devices until 1983 when H.Akagi et al. proposed the three-phase instantaneous reactive power theory [7]. Based on that theory, the instantaneous detection method of harmonics and reactive power was proposed, thus laying theoretical foundation for the application of APF. On the other hand, with the development of GTO, IGBT and other new high-power electronic devices as well as the mature of PWM technology, the practical foundation for the application of APF also gradually formed [8]. As a result, it is now feasible and widely used to control harmonic by APF in industrial field [9].

Current studies of research and applications of APF are mainly aimed at industrial power systems of 50Hz and 60Hz, whereas studies on APF in independent power supply with high fundamental frequency (such as aeronautic APF) are relatively few. With the development of electric aircraft and other advanced aircrafts, the demand for aircraft power capacity is increasing, and the corresponding harmonic components also become more and more complex due to the increase of airborne equipments. Consequently, the quality control of aircraft power system has recently attracted more and more attention around the world. Depending on the types of access to power system, APF can be divided into shunt and series APFs. Shunt APF is mainly applied to compensate for the harmonic of inductive current source load independently, and it is the focus of current aeronautic APF research. By contrast, series APF is seldom used alone, and it is generally studied as a part of a shunt-series APF.

In 2006, Milijana Odavic et al. reported a five-level shunt APF in aircraft AC power system, and proposed a high-bandwidth predictive current control method to analyze the feasibility of aeronautic APF [10]. Further, Milijana Odavic et al. studied the current control method of aeronautic APF, and endowed APF a good current traceability. In order to reduce power tube switching frequency, they adopted the H-bridge cascade and multi-level structure shunt APF to ensure its filter characteristics, thus improving the reliability of system [11].

In order to suppress harmonic caused by the operation of flight control surface actuators, D. Ganthony and C. M. Bingham proposed a design of series APF integrating 6-pulse diode rectifier [12]. However, there was only a setup diagram and a few simulation waveforms in their work, whereas the topology and the control methods were not clear.

In the following two years, Elisabetta Lavopa et al. proposed a real-time detection method of fundamental frequency and harmonic based on the real-time algorithm of discrete Fourier transform, which could quickly and accurately detect the harmonic amplitude and phase parameters from the detected signal [13], thus providing the real-time information of fundamental frequency and harmonic for harmonic detection.

From 2009 to 2010, Ahmad Eid et al. studied the filter control circuit based on the perfect harmonic cancellation method [14], and set up a kind of aircraft equivalent model of variable speed constant frequency AC power system. Their simulation results showed that the model could suppress the current and voltage harmonic of aircraft constant frequency and variable frequency power system, correct power factor and reduce the effects of unbalanced nonlinear loads [15-16].

In 2010, V. Biagini and Milijana Odavic improved a deadbeat control method and successfully applied it to aeronautic APF. Then, they proposed a simple way to compensate for the inherent delay caused by digital control [17]. In the same year, in order to reduce the computing time and improve the accuracy and speed of harmonic detection, Haibing Hu et al. proposed a multi-resolution control strategy, and applied it to the aircraft shunt APF by DSP control [18].

From 2011 to 2012, Zhong Chen and Yingpeng Luo et al. proposed a method through pre-load current feedforward compensation circuit to improve the dynamic performance of APF, and studied the corresponding H-bridge cascaded inverter topology control strategy. On this basis, they designed a 7.2 KVA experimental device, which was proved to have good dynamic and static performance [19-20].

In 2013, S. Khalid and B. Dwivedi compared three forms of APF reference signal acquisition methods by simulation. In their study, sinusoidal current control strategy was proved to have better adaptability, and synchronous reference frame strategy was proved to have faster speed. However, their comparison was only under ideal conditions, but they ignored the impact of load changes on the algorithm of the voltage [21]. Furthermore, Saifullah Khalid, Anurag Tripathi and V. M. Mishra et al. compared and analyzed the constant instantaneous power control and synchronous rotating frame strategy, but they did not take a variety of actual situations into account, either [22]. Around the same time, Saifullah Khalid and Bharti Dwivedi proposed a new algorithm to obtain the reference current by a novel ANN control, and improved APF parameters through genetic algorithm and fuzzy logic. The simulation results confirmed the effectiveness of this method in the application of aeronautic APF, but there were no specific practical cases to support the conclusion [23].

The above references mainly studied the constant frequency power system. Variable frequency power system is one of the developing directions of more electric aircraft. Some advanced and more commercial electric aircrafts, such as the Airbus A380 and Boeing 787, have adopted the variable frequency AC power system [24]. In order to meet the requirements of non-linear electric equipments and ensure the good properties of power source, both of them adopted aeronautical active power filter based on the theory of instantaneous reactive power. Due to the limitation of compensation performance, the two aircrafts also used the power factor correction circuit and passive filter circuit. Obviously, the aeronautical active power filters used in A380 and B787 were imperfect. They could not solve all the power quality problems, there were still passive filter and power factor correction devices on the aircraft which increased the weight. At present, there are relatively few theories in view of harmonic detection for variable frequency power system. Paolo Tenti and Helmo K. Morales Paredes et al. studied the accountability of using Conservative Power Theory in smart microgrids to control the power quality [25]. This method can also be used for aircraft variable frequency power system.

Currently, the focus of aeronautic APF mainly concentrates in three aspects: the acquisition method of reference current, the APF current control strategy and the main circuit topology, which are also the three key technologies to realize the practical application of aeronautic APF. Unlike civil power grid, aircraft power system has its own special characteristics as follows:

- Aircraft AC power system is an independent three-phase four-wire system with small capacity, and there will be a load imbalance phenomenon due to the existence of midline. Since there is a certain lack of power theory in three-phase four-wire system, relevant detection and compensation algorithms for independent three-phase four-wire power system should be further explored.
- Aircraft AC power system has a small capacity and a large resistance, and the power is easily affected by the load. Because of the diversity of aircraft electrical equipments, there are a large number of non-linear power conversion equipments which bring complex harmonic contents.
- The frequency of aircraft AC power system is 400 Hz, which is much higher than that of civilian grid (50-60 Hz). Thus, APF in the concrete hardware will be restricted by the arithmetic capability of digital signal processors and switching devices, which increases the difficulty of using APF to compensate the harmonic in aircraft AC power system.
- At present, the more electric aircraft with variable frequency power system, such as A380 and B787, has already been commercialized. The harmonic problems in variable frequency power system are more complex. Therefore, its governance is a quite a big challenge.

- Finally, in order to adapt to the harsh environment of high-altitude operations, safety guarantee must be a precondition for aeronautic APF so that the requirements of its comprehensive compensation performance, life and reliability should be much higher than those of ordinary industrial APF. Meanwhile, the connection of aeronautic APF should not change the existing mature aviation AC power transmission lines.

3 Acquisition methods of reference current

In order to obtain the APF compensation reference current signal, the harmonic and reactive current component should be detected quickly and accurately, which is the precondition to ensure the compensation performance of APF. In general, harmonic detection methods can be divided into two categories, namely the frequency domain method and the time domain one, of which the latter is commonly used in practical applications of aeronautic APF. For some APF, the PLL system is very important, mainly in the variable frequency generation system [26].

3.1 Harmonic current detection algorithm based on instantaneous reactive power theory

In 1983, H. Akagi, Y. Kanazawa and A. Nabae proposed the instantaneous reactive power theory, which greatly promoted the development of APF. Since the theory was based on the definition of instantaneous real power "*p*" and instantaneous imaginary power "*q*", it was also called *p-q* theory [27]. The instantaneous reactive power theory did not require the waveform of voltage and current so that it was mainly used in a symmetrical three-phase three-wire system in the early stage. As research continues, the instantaneous reactive power theory is more and more widely used in harmonic detection, and can now be used in a three-phase four-wire system of both steady state and transient state.

Define the instantaneous values of three-phase voltage and current in circuit as u_a, u_b, u_c and i_a, i_b, i_c, respectively. Then, the three-phase voltage and current can be converted into an *α-β-0* coordinates system.

$$\begin{bmatrix} u_\alpha \\ u_\beta \\ u_0 \end{bmatrix} = C_{abc/\alpha\beta 0} \begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix}, \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = C_{abc/\alpha\beta 0} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

$$C_{abc/\alpha\beta 0} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \tag{2}$$

$$C_{\alpha\beta 0/abc} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & 1/\sqrt{2} \\ -1/2 & \sqrt{3}/2 & 1/\sqrt{2} \\ -1/2 & -\sqrt{3}/2 & 1/\sqrt{2} \end{bmatrix} \tag{3}$$

Thus, the instantaneous active component *p*, the instantaneous reactive component *q* and the instantaneous zero-sequence component p_0 in the system are respectively:

$$\begin{bmatrix} p \\ q \\ p_0 \end{bmatrix} = \begin{bmatrix} u_\alpha & u_\beta & 0 \\ -u_\beta & u_\alpha & 0 \\ 0 & 0 & u_0 \end{bmatrix} \bullet \begin{bmatrix} i_\alpha \\ i_\beta \\ i_0 \end{bmatrix} = \begin{bmatrix} \bar{p} + \tilde{p} \\ \bar{q} + \tilde{q} \\ p_0 \end{bmatrix} \tag{4}$$

$$\begin{gathered} p = u_\alpha i_\alpha + u_\beta i_\beta = u_a i_a + u_b i_b + u_c i_c \\ q = u_\alpha i_\beta - u_\beta i_\alpha \\ = -\frac{1}{\sqrt{3}}[(u_a - u_b) i_c + (u_b - u_c) i_a + (u_c - u_a) i_b] \\ p_0 = u_0 i_0 = \frac{1}{3}(u_a + u_b + u_c)(i_a + i_b + i_c) \end{gathered} \tag{5}$$

Figure 1 shows the principle block diagram of harmonic detection algorithm based on the instantaneous reactive power. According to i_α and i_β through the low-pass filter (LPF), we can get the DC component of the instantaneous active and reactive power, as well as the compensation reference current of APF through $C_{abc/\alpha\beta 0}$ transformation. The reference current can be injected into the grid to compensate the harmonic, unbalance and reactive component.

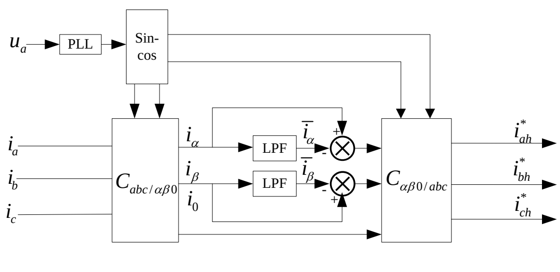

Figure 1. Harmonic detection algorithm based on the instantaneous reactive power.

It is noticed that the harmonic detection algorithm is based on a three-phase sinusoidal and symmetrical system, so that there are some deficiencies when this algorithm is used in three-phase four-wire system. Particularly, when the supply voltage is non-sinusoidal and asymmetrical, the compensation effect will be greatly affected.

3.2 Synchronous rotating frame strategy and its improved algorithm

Synchronous rotating frame strategy (*d-q* method) comes from the *d-q* transformation in electromechanics [28]. Define the three-phase load current as i_a, i_b and i_c. Then we can decompose the n-th positive sequence current into positive, negative and zero sequence component as i_n^+, i_n^-, i_n^0, where n represents the number of harmonic, and +, - and 0 represent positive, negative and zero sequences, respectively. Thus, we can get:

$$\begin{bmatrix} i_n^+ \\ i_n^- \\ i_n^0 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix} \bullet \begin{bmatrix} i_{an} \\ i_{bn} \\ i_{cn} \end{bmatrix} \tag{6}$$

where $a = -\frac{1}{2} + \frac{\sqrt{3}}{2} i, n = 1, 2, 3\ldots$.

Then,

$$\begin{gathered} i_m^+ = \sum_{n=1}^{\infty} I_n^+ \cos[n\omega t - (m-1)\frac{2\pi}{3} + \varphi_n^+] \\ i_m^- = \sum_{n=1}^{\infty} I_n^- \cos[n\omega t - (1-m)\frac{2\pi}{3} + \varphi_n^-] \\ i^0 = \frac{1}{3}(i_a + i_b + i_c) = I_0 \end{gathered} \tag{7}$$

where m=1, 2, 3 represents a, b, c phase, respectively. Through *d-q* synchronous rotating transformation, the *d* and *q* axis current components can be represented by the positive and negative sequence current components of each phase as follows:

$$\begin{bmatrix} i_d^+ \\ i_q^+ \end{bmatrix} = \sqrt{\frac{3}{2}} \sum_{n=1}^{\infty} I_n^+ \begin{bmatrix} \cos[(n-1)\omega t + \varphi_n^+] \\ \sin[(n-1)\omega t + \varphi_n^+ \end{bmatrix} \tag{8}$$

$$\begin{bmatrix} i_d^- \\ i_q^- \end{bmatrix} = \sqrt{\frac{3}{2}} \sum_{n=1}^{\infty} I_n^- \begin{bmatrix} \cos[(n+1)\omega t + \varphi_n^-] \\ \sin[(n+1)\omega t + \varphi_n^- \end{bmatrix} \tag{9}$$

Obviously, the fundamental positive sequence component is the DC component in *d-q* coordinates, while other components correspond to the harmonic components. Thus, the low-pass filter can separate the DC component and AC component. Finally, we can get the negative sequence and harmonic current through the inverse transformation to compensation and offset through APF [29-30].

For the conventional *d-q* method, the power source provides not only the power of fundamental positive sequence voltage and current but also the power of each harmonic voltage and current in positive and negative sequence. Hence, the current generated by the power supply will be larger [31]. In addition, the load current contains zero-sequence component and its distortion often leads to the distortion of power supply voltage. If the compensation current is symmetrically sinusoidal, it cannot guarantee the balance of power before and after compensation.

In order to solve these problems, Donghua Chen et al. proposed a reference frame strategy based on the power supply voltage vector [32]. Firstly, the voltage signal and three-phase load current signal is processed by *α-β* transformation:

$$\begin{aligned} u_{\alpha\beta} &= C_{abc/\alpha\beta} \bullet u_{abc} \\ i_{\alpha\beta} &= C_{abc/\alpha\beta} \bullet i_{abc} \end{aligned} \tag{10}$$

The voltage and current vectors in the synchronous reference frame are illustrated in Fig. 2.

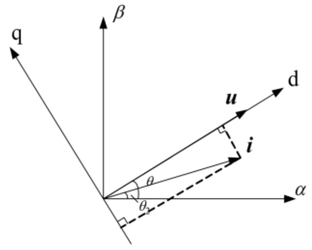

Figure 2. Voltage and current vectors in the synchronous reference frame.

As can be seen, in *α-β* coordinates, the projection of current vector i above the voltage vector u is:

$$i_U = \begin{bmatrix} \dfrac{i_\alpha u_\alpha + i_\beta u_\beta}{u_\alpha^2 + u_\beta^2} \bullet u_\alpha \\ \dfrac{i_\alpha u_\alpha + i_\beta u_\beta}{u_\alpha^2 + u_\beta^2} \bullet u_\beta \end{bmatrix} \tag{11}$$

In the transformation process from α-β coordinates to d-q coordinates

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \bullet \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}, \tag{12}$$

synchronous rotation angle θ does not satisfy $\frac{d\theta}{dt}$=constant under the conditions of power supply voltage imbalance and distortion. In order to represent the information of three-phase power supply voltage in the d-q coordinates, the voltage vector can be directly used to represent the synchronous rotation angle θ. Thus, we can get the synchronizing current, namely the projection of the current vector above the voltage vector.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \frac{u_\alpha}{\sqrt{u_\alpha^2 + u_\beta^2}} & \frac{u_\beta}{\sqrt{u_\alpha^2 + u_\beta^2}} \\ -\frac{u_\beta}{\sqrt{u_\alpha^2 + u_\beta^2}} & \frac{u_\alpha}{\sqrt{u_\alpha^2 + u_\beta^2}} \end{bmatrix} \bullet \begin{bmatrix} \frac{i_\alpha u_\alpha + i_\beta u_\beta}{u_\alpha^2 + u_\beta^2} \bullet u_\alpha \\ \frac{i_\alpha u_\alpha + i_\beta u_\beta}{u_\alpha^2 + u_\beta^2} \bullet u_\beta \end{bmatrix} = \begin{bmatrix} \frac{i_\alpha u_\alpha + i_\beta u_\beta}{\sqrt{u_\alpha^2 + u_\beta^2}} \\ 0 \end{bmatrix} = \begin{bmatrix} \bar{i}_d + \hat{i}_d \\ 0 \end{bmatrix} \tag{13}$$

According to i_d through a low pass filter, we can obtain the DC component of the synchronous current, which has a synchronous speed of the power supply voltage vector. Then, the harmonic and reactive reference current signal can be obtained through the inverse transformation.

$$\left[i^*_{habc} \right] = \left[i_{labc} \right] - \begin{bmatrix} \bar{i}_d \\ 0 \end{bmatrix} \bullet \left[C_{dq/\alpha\beta} \right] \bullet \left[C_{\alpha\beta/abc} \right] \tag{14}$$

Figure 3 shows the principle of the reference current detection method. Compared with traditional methods, the method proposed in this paper omits PLL and trigonometric calculations, and only needs to go through a coordinate transformation and an inverse transformation. For DSP implementation, the computational complexity is significantly reduced, while the influence of PLL error on the calculation results is effectively avoided.

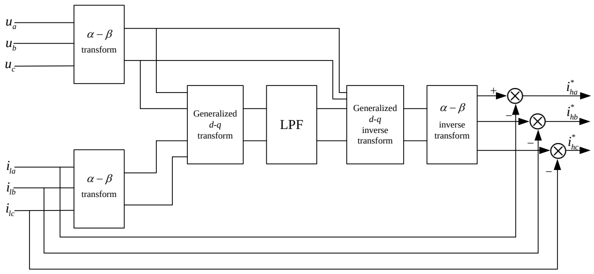

Figure 3. Improved synchronous rotating frame strategy.

3.3 Adaptive detection method and its improved algorithm

This method is based on the adaptive interference cancellation principle in signal processing techniques. The adaptive noise cancellation is a variant of the optimal filter, and its basic principle is to counteract the noisy signal with a reference signal, thereby eliminating the noise in the signal [33]. Harmonics can be considered as noise so that this method is applicable to harmonic detection. Its advantage is that the reference current can be detected when the network voltage waveform is distorted, while the deficiency lies in its slow dynamic response [34].

With the development of artificial neural network (ANN), a harmonic current adaptive detection method based on ANN is proposed. ANN is an adaptive system in which neurons connect to each other following certain rules, and can be applied to automatic control, signal processing, artificial intelligence and so on by virtue of its learning ability. In view of this, we can constitute adaptive harmonic current detection method based on ANN instead of the adaptive filter [35].

The key of adaptive harmonic detection method is the selection of adaptive filtering algorithm. Currently, the most commonly used algorithm is the least mean square (LMS) algorithm [36] based on the principle of adaptive algorithm. Its iteration formulas are:

$$c(n) = d(n) - y(n) = X^T(n)W^*(n) - X^T(n)W(n) \tag{15}$$

$$e(n) = d(n) + \xi(n) - y(n) = c(n) + \xi(n) \tag{16}$$

$$W(n+1) = W(n) + 2\mu e(n)X(n) \tag{17}$$

in which $X(n)$ is the reference input information in time n; $W(n)$ is the weight coefficient of adaptive filter; $W^*(n)$ is the weight coefficient of the unknown system; $d(n)$ is the desired signal; $y(n)$ is the filter output signal; $e(n)$ is the error signal, composed by $c(n)$ and $\xi(n)$; $\xi(n)$ is the interfering signal; $c(n)$ is the tracking error signal; and μ is the step factor.

The purpose of the LMS algorithm is to constantly adjust $W(n)$ based on the feedback error so as to gradually approach $W^*(n)$, and to track the change of $d(n)$ by $y(n)$. The harmonic component is regarded as interference signal $\xi(n)$, the fundamental component is regarded as the desired signal $d(n)$, and the system voltage signal is regarded as the reference input. Once the reference input has gone through an adaptive filter, the output signal can track the change of the desired signal, and we can get the current compensation signal of APF from the difference.

Conventional fixed step-size LMS algorithm has an inherent contradiction between convergence rate and steady-state error, and many improved adaptive algorithms have been proposed to overcome this tough problem [37-38], of which the most important one is the variable step-size LMS algorithm [39]. The principle of variable step-size LMS algorithm can be summarized as follows: when weight coefficient is far from the optimal weight coefficient $W^*(n)$, the step is larger, thereby strengthening the dynamic response speed and the ability of tracking time-varying systems [40]; when weight coefficient is close to the optimal weight coefficient, the step is smaller in order to obtain a small steady-state error. During the adaptive process, variable step-size LMS adaptive algorithm generally uses the error signal as the provided feedback value to adjust the step, and presents good detection performance in the simulation. However, its updating standard is derived from the instantaneous error $e(n)$ polluted by noise $\xi(n)$ instead of the actual tracking error $c(n)$ so that the detection performance of this method is very susceptible to environmental noise [41].

3.4 No harmonic detection control strategy

Approaches based on the instantaneous reactive power theory generally need a large amount of calculation. In order to solve this problem, J.C. Wu proposed a simple harmonic detection method without harmonic calculation [42], and demonstrated its effectiveness for single-phase system. The basic principle of its detection algorithm is illustrated as Fig. 4. The purpose of this algorithm is to get the power system reference current only through detecting APF DC side capacitor voltage and network voltage phase. The amplitude of the network reference current signal can be obtained using the voltage loop, and then the network voltage phase information can be extracted using phase-locked loop, thus getting the sine wave unit. Finally, the power system reference current i_s^* can be obtained through multiplying the amplitude signal by the sine wave unit.

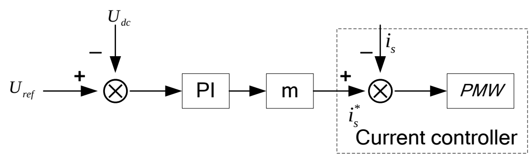

Figure 4. No harmonic detection control strategy.

In 1999, le Roux A D published a paper in IEEE Trans. P. e [43], which can be regarded as the popularization and application of this control strategy in the type of three-phase shunt APF. In three-phase four-wire system, the reference current phase information can be obtained through the network voltage, since each phase has the same current amplitude, which means the network power output for three-phase follows an equilibrium distribution. Thus, unbalanced load will not have much impact on the control process. At present, typical control strategies without harmonic detection include one-cycle control theory [44-45], power system current control based on the DC side capacitor voltage control, etc. [42-43]

3.5 Conservative power theory

In 2003, Paolo Tenti and Paolo Mattavelli published a paper which put forward the Conservative Power Theory (CPT); they defined the instantaneous power in non-sinusoidal conditions, then decomposed the current of single-phase system into active, reactive and distortion terms, and the single-phase approach was extended to poly-phase systems [46]. H.K.M. Paredes and Fernando Marafao et al. verified conservative power theory by means of virtual instrument. They decomposed the current of single-phase, three-phase three-wire and three-phase four-wire systems, the results show that conservative power theory can accurately detect the harmonic current in three-phase four-wire system [47]. H. K. M. Paredes and D. I. Brandao et al. used conservative power theory in the application of three-phase four-leg APF. The results show that it can accurately detect the harmonic current and effectively compensation [48]. The harmonic detection method based on conservative power theory can not only accurately detect the harmonic current but also can be decomposed as each harmonic component. So, the compensation can be more flexible and the physical concept of decomposed current component is more clear. However, this method has no practical application cases and the unbalanced situation also needs further study.

3.6 Comparative analysis

The detection effect of *p*-*q* method is fairly good for symmetrical and sinusoidal system, but it cannot be used in three-phase asymmetrical and non-sinusoidal system. *d*-*q* algorithm can calculate the system harmonic, reactive power and unbalanced component through coordinate rotating transformation, but when the supply voltage is asymmetrical and non-sinusoidal, the active power before and after compensation may not always keep the same due to the power voltage distortion. In contrast, the improved synchronous rotating frame strategy fully considers the power supply voltage distortion, and can detect the harmonic and reactive component on the premise of the constant power before and after compensation.

Adaptive harmonic detection algorithm is equivalent to an ideal second-order notch filter, and has an excellent fundamental wave filtering characteristic owing to the infinite attenuation of fundamental frequency signal. Its detection accuracy is relatively high, and has a good performance in the MATLAB simulation. However, its detection performance is susceptible to environmental noise for actual applications.

No harmonic detection method requires only detecting the network voltage, network current and APF DC side voltage; it avoids complex harmonic and reactive power calculations. Its control process is simple and easy for hardware implementation. Meanwhile, it has high stability and reliability, and exerts little interference on the control under the influences of network voltage distortion and unbalanced load. However, no harmonic detection method fails to separate the active power and harmonic of the fundamental wave, and its dynamic response is limited compared with instantaneous reactive power algorithm. In addition, its tracking accuracy is inferior to that of adaptive closed-loop detection algorithm.

Conservative power theory is applied widely in micro smart grid harmonic detection. This method solves quite well the problems of three-phase four-wire, distorted and unbalanced grids, independently of the frequency.

From the aspects of whether to consider the information of power supply voltage or not, whether to compensate for asymmetrical current, and whether to need coordinate transformation and other aspects, we can compare those harmonic current detection methods with three-phase four-wire system.

Table 1 shows the comparison of harmonic current detection methods with three-phase four-wire system. Aircraft AC power system is an independent three-phase four-wire power system with small capacity. Due to relatively large non-linear load and unbalanced load in the power system, the load current contains not only harmonic and reactive current but also seriously imbalanced current. Moreover, its power source internal resistance is relatively large so that the power supply voltage will be greatly influenced by loads. As a result, the reference current detection of APF should take full account of the power supply voltage.

4 Current control strategy

As an important technology of active power filter control, the current control technology determines the compensation performance of active power filter [49]. In order to meet the compensation requirements, current control should adopt the instantaneous value control strategy. Current APF current control technologies mainly include hysteresis current control [50], triangular wave intersection pulse width modulation (PWM) technology [51], space vector modulation technology [52], and deadbeat control [53]. Meanwhile, some new control methods such as predictive current control, adaptive control, sliding mode variable structure control, fuzzy control and neural network control, are gradually applied to power electronic field [54].

4.1 Hysteresis current control

Hysteresis current control is a common instantaneous current control technology. Through the hysteresis comparator, the error of APF command current signal and the compensation current feedback signal can be restricted to less than a ring width [55]. Figure 5 shows the diagram of hysteresis current control, in which i_c^* is the APF reference current signal, h is the ring width, and i_c is the compensation current. By switching control,

Table 1. Comparison of harmonic current detection methods for three-phase four-wire system

Algorithm	Whether to consider the power supply voltage	Whether to compensate for asymmetrical current	Whether to transform coordinates
p-q method	Yes	No	Yes
d-q method	No	Yes	Yes
Improved *d-q* method	No	Yes	Yes
Adaptive algorithm	No	Yes	No
No harmonic detection control strategy	No	Yes	No
Conservative power theory	No	Yes	No

i_c can be maintained between $i_c^* - h$ and $i_c^* + h$. As can be seen from the diagram, hysteresis current control has a strong real time performance.

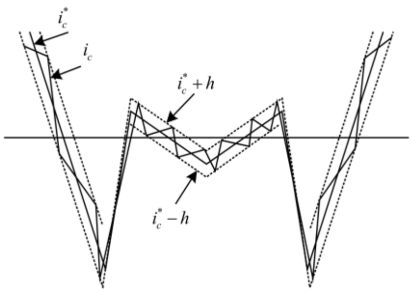

Figure 5. Diagram of hysteresis current control.

Figure 6 shows the principle of hysteresis current control. As can be seen, hysteresis current control method is relatively simple, and the PWM drive signals can be obtained from the error between the reference current signal i_c^* and the compensation current feedback signal i_c through the hysteresis comparator to control the power switch on and off, thus ensuring the real-time tracking of compensation current to the reference current signal. When the modulation frequency of current control is high, the hysteresis current controller can be viewed as a current follower [56].

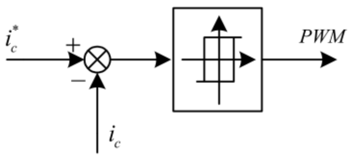

Figure 6. Principle of hysteresis current control.

Hysteresis current control has the characteristics of simple control and easy implementation, fast dynamic response, real-time monitoring, high stability and so on. Besides, it also owns the function of automatically limiting current. However, the width of the hysteresis h is usually fixed, so that the switching frequency of switching devices is not fixed, especially when the variation of i_c is large. Obviously, the variable switching frequency increases the difficulty of filter circuit design [57].

4.2 Triangular wave intersection pulse width modulation technology

Triangular wave intersection pulse width modulation technology is to generate a PWM signal through comparing modulated wave with a high frequency triangular wave. In the APF current control, the modulated wave is an error amplification signal between the reference current and the compensation current. The modulated wave intersects with the triangular wave, and the compensation current tracks the reference current signal in real time with pulse width modulation technology, thus realizing the control of APF compensation current. Figure 7 shows the principle of triangular wave intersection pulse width modulation control, in which i_c^* is the reference current, and i_c is the feedback signal of actual compensation current. The error between i_c^* and i_c passes through PI regulator, and intersects with the high frequency triangular wave to generate a PWM signal to control the power switch. Thus, the APF can track the reference current signal.

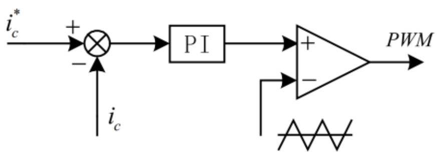

Figure 7. Principle of triangular wave intersection pulse width modulation control.

The triangular wave intersection pulse width modulation method has the characteristics of simple control and fixed switching frequency (the frequency of the triangular wave is the switching frequency). However, when the triangular wave slope is relatively small, it is prone to error intersection. Consequently, the current tracking speed is restricted by the triangular wave. Although the compensation performance can be improved by increasing the triangular carrier wave frequency, the frequency of triangular carrier wave is limited due to the limited switching frequency.

In order to improve the current tracking performance of APF, triangular carrier wave phase shifting based on triangular wave intersection PWM can be adopted to control the multilevel APF power circuit. Thus, a higher equivalent switching frequency can be achieved [58], and the performance of APF compensation current is improved. There are mainly two kinds of phase shifting angle, i.e., 90° and 180°, and the latter is generally superior to the former.

4.3 Space vector modulation technology

Space vector modulation (SVM) originates from AC speed control, and has now become an important three-phase circuit control technology. SVM is very suitable for digital control and its switching frequency is fixed [59]. For three-phase four-leg structure, high-performance control can be achieved through three-dimensional SVM so that most three-phase four-leg inverters adopt 3D SVM for efficient control [60]. Since there is a cube relationship between the number of electrical level and the voltage space vector, multi-level SVM technology is greatly limited for the higher level number. At present, the research on the SVM technology is generally limited to five levels.

To the neutral circuit formed by split capacitors and three-phase four-leg circuit, the SVM modulation schemes are different. Generally, classical control algorithm in the circuit topology can be used to handle the neutral circuit formed by split capacitors. First, the zero-sequence component is removed. Then, each current and voltage component is transformed to α-β coordinate system. Finally, switching signals can be calculated out via SVM algorithm. For three-phase four-leg circuit, due to the presence of neutral current, 3D SVM control should be used to modulate voltage integrated vector in α-β-γ coordinates or *a*-*b*-*c* coordinates. The space vector control algorithm based on α-β-γ coordinates is very complex since it requires complicated coordinate transformation, which enlarges the calculation work and prolongs the computation time. Consequently, the computing speed of this algorithm can hardly meet the high real-time demand of aeronautic APF [61]. In order to reduce the current control time, the space vector modulation control algorithm is executed directly in *a*-*b*-*c* coordinates. As shown in Fig. 8, the dodecahedron can be divided into 24 tetrahedra in space, and each tetrahedron is composed of three non-zero vectors and two zero vectors. Once the tetrahedron whose reference vector falls on has been ascertained, the corresponding space vector can be used to synthesize the switching vector.

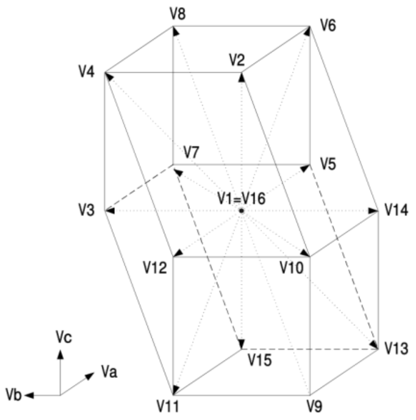

Figure 8. Switch vectors in a-b-c coordinates.

4.4 Dead-beat control

Dead-beat control (DBC) is essentially a predictive control [62]. Its working principle can be summarized as follows. Firstly, according to the actual output value of the compensation current and load side current at a certain moment, the reference current signal at next moment and the predicted value of compensation current under various possible switch working conditions can be calculated. Then, the accumulative error function of reference and predicted compensation current is calculated. Finally, the switching condition under which the objective function is minimal can be selected as N+1 time switch action basis. From the principle, it can be seen that the DBC control has fast dynamic response, but is readily influenced by the parameter variations. The larger the transient response overshoot, the poorer the robustness, and the higher the hardware requirements.

4.5 Comparative analysis

Four current control schemes of hysteresis current control, including triangular wave intersection PWM, SVM and DBC, are compared, and Table 2 shows the results in terms of stability, real-time tracking performance, control complexity and modulation frequency.

Compared with other methods, hysteresis current control has better current tracking performance. As the aircraft power system frequency is relatively high, the current control scheme for aeronautic APF needs high real-time capability. Hysteresis current control is very simple, and has strong stability and good performance in real-time current tracking. In addition, hysteresis current control has itself current limiting function so that it is very suitable as a current control scheme for the aeronautic APF.

5 Circuit topology structure

There are two kinds of three-phase four-wire shunt APF circuit topology, i.e., neutral circuit formed by split capacitors and three-phase four-leg circuit. In recent years, some new three-phase four-wire topologies, such as adding a two-way switch or split inductors in the neutral circuit have been proposed [63-65], but their advantages and features are not very obvious.

5.1 Three-phase four-wire APF of split capacitors

Figure 9 shows the diagram of three-phase four-wire APF of split capacitors. Six switches Q1~Q6 construct a three-phase bridge circuit, and the output of each leg through the filter inductor L connects with the three-phase power system. DC side through the voltage-dividing capacitors C1 and C2 can form a neutral midpoint that connects to the centerline of power system. Due to the large capacitance of the two capacitors, the voltage can be considered as constant in a switching cycle, namely the two capacitors are equivalent.

As can be seen from the circuit topology, the APF output voltage of each phase is $u_{AO} = \pm V_d / 2$ through the switch, and the voltage stress of each switch tube is V_d. By controlling the switch tube, the output current of APF i_c can trace the APF compensation reference current i_c^*.

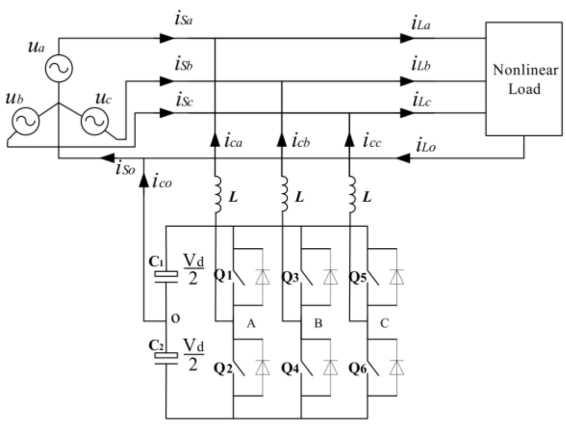

Figure 9. Diagram of three-phase four-wire APF of split capacitors.

Table 2. Comparison of current control schemes

Current control schemes	Stability	Real-time performance	Control complexity	Modulation frequency
Hysteresis current control	Very good	Very quick	Simple	Flexible
Triangular wave intersection PWM	Medium	Quick	A little complex	Fixed
SVM	Good	Medium	Complex	Fixed
DBC	Medium	Very quick	Complex	Fixed

Three-phase four-wire shunt APF of split capacitors has only six power switches so that the control process is relatively simple. Moreover, the current control technology is relatively mature, and there are various current control technologies such as current hysteresis control, triangular intersection current control and SVM that can be adopted to control the APF current. Therefore, it is the main circuit topology for shunt APF used in industrial field.

5.2 Three-phase four-leg APF

Figure 10 shows the diagram of three-phase four-leg APF main circuit structure. The APF has four bridges and eight switches Q1~Q8. Q1~Q6 constitute a three-phase bridge, which connects with the three-phase power system through the filter inductor L. Q7~Q8 constitute the fourth leg to construct a midpoint. Thus, we can use the switch on the fourth leg to control the neutral current. As can be seen from Fig. 10, through controlling Q7~Q8, the electric potential of O can be p or n. In this way, the APF phase output voltage value is $u_{AO} = \pm V_d$, and the voltage stress of the switching tube is V_d.

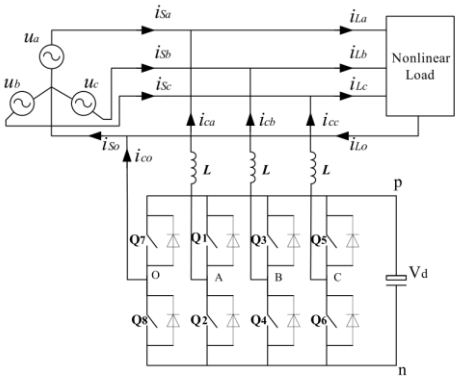

Figure 10. Diagram of three-phase four-leg APF main circuit.

Each phase output voltage value for the midpoint of three-phase four-leg circuit topology APF has three states of V_d, $-V_d$ and 0. Compared with the three-phase four-wire shunt APF topology where the neutral circuit is formed by split capacitors, in unit time, the current change rate of three-phase four-leg circuit topology APF is faster under the same filter inductor and DC voltage, so that its current tracking speed is faster. However, due to the existence of the fourth leg, SVM technology is generally used to control the system, and the control process is more complex.

5.3 Three-level circuit structure of three-phase four-wire

Multi-level circuit structure is mainly used in large-capacity transformer to effectively reduce the switch voltage stress. Because the level number and output waveform equivalent switching frequency of multi-level circuit are both relatively high, its harmonic content is relatively small. The application of multi-level circuit structure to aeronautic APF can effectively improve the equivalent switching frequency and reduce the switch tube voltage stress. Figure 11 shows the diagram of diode clamping three-level three-phase four-wire APF circuit structure. Each phase leg output of the three-level inverter connects with the three-phase power system through the filter inductor L. The DC side through the voltage-dividing capacitors C1 and C2 forms a neutral midpoint that connects to the centerline of power system.

Due to the large capacitance of the two voltage-dividing capacitors, the voltage on the capacitor can be considered as constant ($V_d/2$) in a switching cycle. Each phase bridge of the inverter has four switching devices, and each switch antiparallel freewheeling diode can provide feedback energy to DC side reactive pathway for perceptual load current. In addition, the midpoint clamp diode can provide the current channel and prevent capacitance short circuit when the switch tube is turned on. Three-level circuit clamping diode can restrict the voltage of switch device within $V_d/2$ so that the DC voltage can be doubled relative to the switch tubes of the same rated voltage applied to three-level APF. Thus, the DC side voltage of APF control can be high enough to get a better compensation effect.

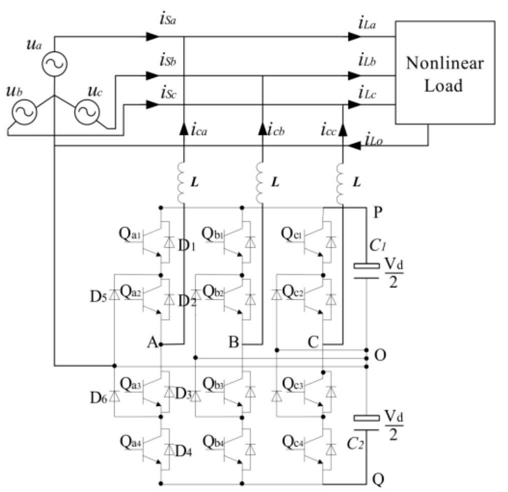

Figure 11. Diagram of diode clamping three level three-phase four-wire APF circuit.

5.4 Comparative analysis

The above three methods can achieve desirable harmonic suppression effect and compensate the reactive power and unbalance for three-phase four-wire power system. However, there are some differences among them in terms of power tube number, switch tube voltage stress and control complexity, as shown in Table 3.

It can be seen that the above three circuit topologies have their own characteristics. Due to the high real-time requirements of aeronautic APF, the control cannot be too complicated. In addition, less switch tube number can improve the system reliability. As a result, the APF circuit topology where neutral circuit is formed by split capacitors can be selected as the aeronautic APF circuit topology.

6 Conclusions

In summary, current research on aircraft active filtering system has the following characteristics:

- For three-phase four-wire system, the focuses mainly concentrate on the main circuit topology and corresponding current control strategy that can improve the equivalent switching frequency. Most studies on the main circuit of APF are aimed at three-phase three-wire or single-phase system, but the algorithms for three-phase three-wire system are not always suitable for three-phase four-wire system.
- Almost all shunt APFs are based on traditional control strategies, which detect the load current and then control the compensation current. As the frequency of aircraft power system is 400Hz, the current controller is restricted by the reference current accuracy and switching frequency, thus generating some higher harmonics and some current mutation. For high-frequency characteristics of aircraft power system, the existing strategies are extensively improved, and some new current control strategies are proposed.
- Most studies simulate the aircraft power system and verify the APF feasibility in aviation application, but just give small power experiments instead of convincing experimental waveforms. There is still a long distance for the practical application of APF.

For further study, some promising directions can be recommended as follows:

- Since a higher switching frequency is required in order to obtain better compensation effect, further studies should consider new power circuit topologies. For example, the multilevel inverter structure [66], such as cascade structure, can be adopted to reduce the switching frequency of the power tube or achieve a better compensation effect under the same switching frequency.
- APF can be combined with passive filters for harmonic suppression of aircraft power system. Thus, APF can restrain the larger amplitude and the lower harmonics, while passive filters mainly filter the smaller amplitude and the higher harmonic components.
- Variable-frequency power source is widely used in large capacity power aircraft. Considering the wide frequency range of power source within 360~800 Hz, the APF technology for variable-frequency power source should be developed to ensure the quality of aircraft power supply system.
- Application of APF in aircraft power system is a new concept, and it requires vigorous technology promotion and wide support from the civil

Table 3. Comparison of the circuit topology for three-phase four-wire shunt APF

Circuit topology	Switch tube number	Switch tube voltage stress	Control complexity	Current tracking speed
Split capacitors	6	V_d	Simple	Medium
Three-phase four-leg	8	V_d	Complex	Faster
Three-level	12	$V_d / 2$	Complex	Faster

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