

REVIEW OF ACTIVE POWER FILTER TECHNOLOGIES

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ABSTRACT

Active power filters (APF), are increasingly used to mitigate harmonics in utility power lines. Compared to the more established method such as the static var compensator or passive filtering, APF are relatively new in the market. However, due to its flexibility, it is envisaged to be one of the main electrical power quality equipment of the future. Since APF is quite new in this country, awareness on its concepts, merit and benefits is not widespread. Thus the focus of this paper is to review the APF operational principles and technologies. In one sense this review can also be considered as a "tutorial-type paper" as it provides a holistic coverage of the APF technologies by omitting the tedious details, but without losing the main essence of the subject matter. It is hoped that by this approach, it would be possible to lure more power engineering readers to be involved in this important and growing field.

Keywords: Active Power Filter, Harmonics Mitigation, Power Electronics, Power Quality, Voltage Source Inverter,

1.0 INTRODUCTION

The usefulness of the patented reinforced earth wall of The power quality (PQ) problems in power utility distribution systems are not new, but only recently their effects have gained public awareness. Advances in semiconductor device technology have fuelled a revolution in power electronics over the past decade, and there are indications that this trend will continue [1]. However the power electronics based equipments which include adjustable-speed motor drives, electronic power supplies, DC motor drives, battery chargers, electronic ballasts are responsible for the rise in PQ related problems [2, 3]. These nonlinear loads appear to be prime sources of harmonic distortion in a power distribution system. Harmonic currents produced by nonlinear loads are injected back into power distribution systems through the point of common coupling (PCC). As the harmonic currents pass through the line impedance of the system, harmonic voltages appear, causing distortion at the PCC.

Harmonics have a number of undesirable effects on the distribution system. They fall into two basic categories: short-term and long-term. Short-term effects are usually the most noticeable and are related to excessive voltage distortion. On the other hand, long-term effects often go undetected and are usually related to increased resistive losses or voltage stresses [4]. In addition, the harmonic currents produced by nonlinear loads can interact adversely with a wide range of power system equipment, most notably capacitors, transformers, and motors, causing additional losses, overheating, and overloading. These harmonic currents can also cause interferences with telecommunication lines and errors in metering devices [2, 3]. Because of the adverse effects that harmonics have on PQ, Standard has been developed to define a reasonable framework for harmonic control [5]. Its objective is to ensure steady-state harmonic limits that are acceptable by both electric utilities and their customers.

Harmonic distortion in power distribution systems can be suppressed using two approaches namely, passive and active powering. The passive filtering is the simplest conventional solution to mitigate the harmonic distortion [6, 8]. Although simple, the use passive elements do not always respond correctly to the dynamics of the power distribution systems [9]. Over the years, these passive filters have developed to high level of sophistication. Some even tuned to bypass specific harmonic frequencies.

Conventional passive filters consist of inductance, capacitance, and resistance elements configured and tuned to control harmonics. Figure 2.3 shows common types of passive filters and their configurations. The single-tuned "notch" filter is the most common and economical type of passive filter [8]. The notch filter is connected in shunt with the power distribution system and is series-tuned to present low impedance to a particular harmonic current. Thus, harmonic currents are diverted from their normal flow path through the filter. Another popular type of passive filter is the high-pass filter (HPF) [7]. A HPF will allow a large percentage of all harmonics above its corner frequency to pass through. HPF typically takes on one of the three forms, as shown in Figure 1. The first-order, which is characterised by large power losses at fundamental frequency, is rarely used. The second-order HPF is the simplest to apply while providing good filtering action and reduced fundamental frequency losses [9]. The filtering performance of the third-order HPF is superior to that of the second-order HPF. However, it is found that the third-order HPF is not commonly used for low-voltage or medium-voltage applications since the economic, complexity, and reliability factors do not justify them.

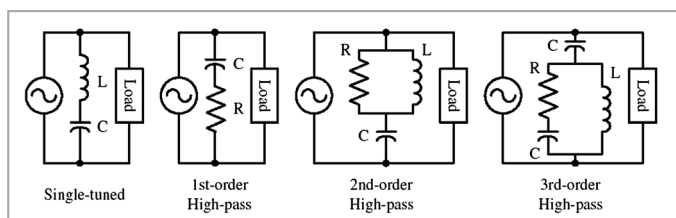


Figure 1: Common types of passive filters and their configurations

Although simple and least expensive, the passive filter inherits several shortcomings. The filter components are very bulky because the harmonics that need to be suppressed are usually of the low order [4, 9]. Furthermore the compensation characteristics of these filters are influenced by the source impedance. As such, the filter design is heavily dependent on the power system in which it is connected to [8]. Passive filters are known to cause resonance, thus affecting the stability of the power distribution systems [9]. Frequency variation of the power distribution system and tolerances in components values affect the filtering characteristics. The size of the components become impractical if the frequency variation is large [8, 9].

As the regulatory requirements become more stringent, the passive filters might not be able to meet future revisions of a particular Standard. This may require a retrofit of new filters.

2.0 ACTIVE POWER FILTERS

Remarkable progress in power electronics had spurred interest in APF for harmonic distortion mitigation. The basic principle of APF is to utilise power electronics technologies to produce specific current components that cancel the harmonic current components caused by the nonlinear load. Figure 2 shows the components of a typical APF system and their connections. The information regarding the harmonic currents and other system variables are passed to the compensation current/voltage reference signal estimator. The compensation reference signal from the estimator drives the overall system controller. This in turn provides the control for the gating signal generator. The output of the gating signal generator controls the power circuit via a suitable interface. Finally, the power circuit in the generalised block diagram can be connected in parallel, series or parallel/series configurations depending on the interfacing inductor/transformer used.

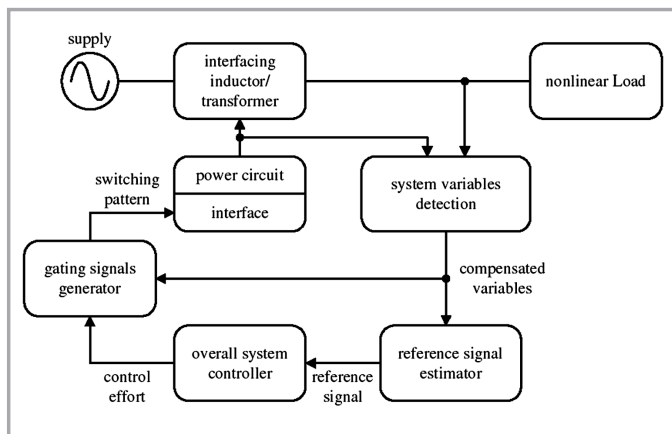


Figure 2: Generalised block diagram for APF

APFs have a number of advantages over the passive filters. First of all, they can suppress not only the supply current harmonics, but also the reactive currents. Moreover, unlike passive filters, they do not cause harmful resonances with the power distribution systems. Consequently, the APFs performances are independent on the power distribution system properties [9]. On the other hand, APFs have some drawbacks. Active filtering is a relatively new technology, practically less than four decades old. There is still a need for further research and development to make this technology well established. An unfavourable but inseparable feature of APF is the necessity of fast switching of high currents in the power circuit of the APF. This results in a high frequency noise that may cause an electromagnetic interference (EMI) in the power distribution systems [34]. APF can be connected in several power circuit configurations as illustrated in the block diagram shown in Figure 3. In general, they are divided into three main categories, namely shunt APF, series APF and hybrid APF.

2.1 Shunt Active Power Filter

This is most important configuration and widely used in active filtering applications [10]. A shunt APF consists of a controllable voltage or current source. The voltage source inverter (VSI) based shunt APF is by far the most common type used today, due to its well known topology and straight forward installation procedure. Figure 4 shows the principle configuration of a VSI based shunt APF. It consists of a DC-bus capacitor (C_f), power electronic switches and an interfacing inductors (L_f). Shunt APF acts as a current source,

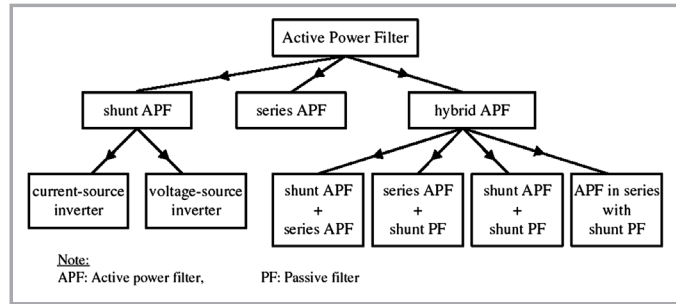


Figure 3: Subdivision of APF according to power circuit configurations

compensating the harmonic currents due to nonlinear loads. The operation of shunt APF is based on injection of compensation current which is equal to the distorted current, thus eliminating the original distorted current. This is achieved by “shaping” the compensation current waveform (i_f), using the VSI switches. The shape of compensation current is obtained by measuring the load current (i_L) and subtracting it from a sinusoidal reference. The aim of shunt APF is to obtain a sinusoidal source current (i_s) using the relationship: $i_s = i_L - i_f$.

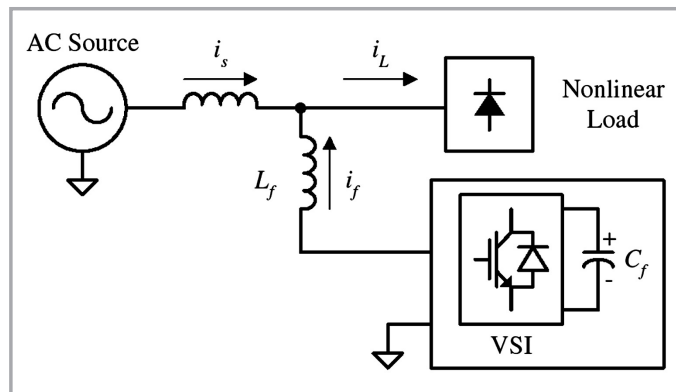


Figure 4: Principle configuration of a VSI based shunt APF

Suppose the nonlinear load current can be written as the sum of the fundamental current component ($i_{L,f}$) and the current harmonics ($i_{L,h}$) according to

$$i_L = i_{L,f} + i_{L,h} \quad (2.2)$$

then the injected compensation current by the shunt APF should be

$$i_f = i_{L,h} \quad (2.3)$$

the resulting source current is

$$i_s = i_L - i_f = i_{L,f} \quad (2.4)$$

which only contains the fundamental component of the nonlinear load current and thus free from harmonics. Figure 5 shows the ideal source current when the shunt APF performs harmonic filtering of a diode rectifier. The injected shunt APF current completely cancels the current harmonics from the nonlinear load, resulting in a harmonic free source current.

From the nonlinear load current point of view, the shunt APF can be regarded as a varying shunt impedance. The impedance is zero, or at least small, for the harmonic frequencies and infinite in terms of the fundamental frequency. As a result, reduction in the voltage distortion occurs because the harmonic currents flowing through the source impedance are reduced. Shunt APFs have the advantage of carrying only

the compensation current plus a small amount of active fundamental current supplied to compensate for system losses. It can also contribute to reactive power compensation. Moreover, it is also possible to connect several shunt APFs in parallel to cater for higher currents, which makes this type of circuit suitable for a wide range of power ratings [11].

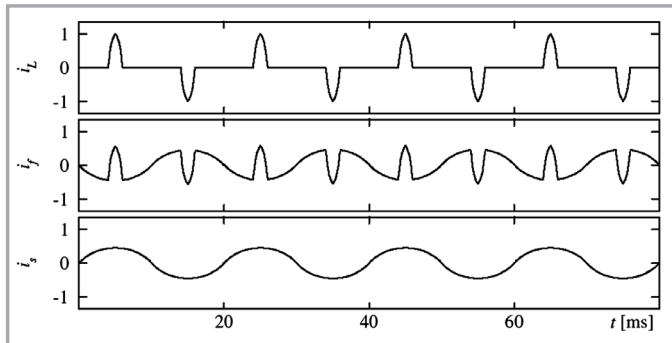


Figure 5: Shunt APF harmonic filtering operation principle

2.2 Series Active Power Filter

The series APF is shown in Figure 6. It is connected in series with the distribution line through a matching transformer. VSI is used as the controlled source, thus the principle configuration of series APF is similar to shunt APF, except that the interfacing inductor of shunt APF is replaced with the interfacing transformer.

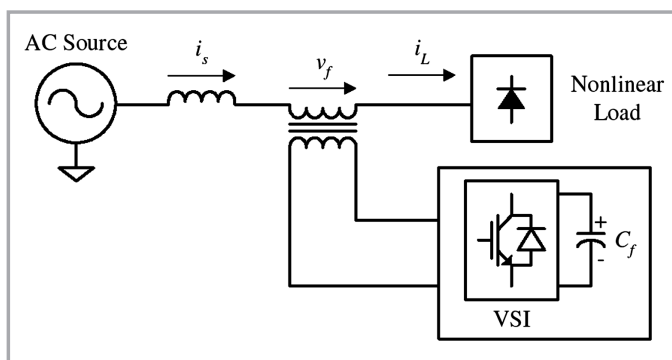


Figure 6: Principle configuration of a VSI based series APF

The operation principle of series APF is based on isolation of the harmonics in between the nonlinear load and the source. This is obtained by the injection of harmonic voltages (v_f) across the interfacing transformer. The injected harmonic voltages are added/subtracted, to/from the source voltage to maintain a pure sinusoidal voltage waveform across the nonlinear load. The series APF can be thought of as a harmonic isolator as shown in Figure 7. It is controlled in such a way that it presents zero impedance for the fundamental component, but appears as a resistor with high impedance for harmonic frequencies components. That is, no current harmonics can flow from nonlinear load to source, and vice versa.

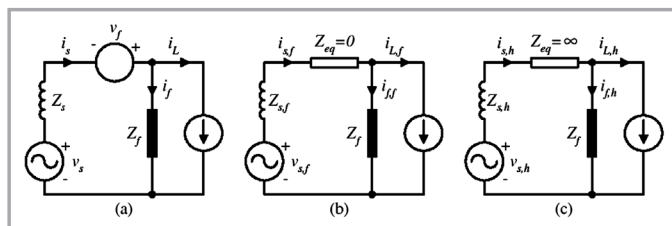


Figure 7: Operation principle of series APF: (a) single-phase equivalent of series APF, (b) fundamental equivalent circuit, and (c) harmonic equivalent circuit

Series APFs are less common than their rival, i.e. the shunt APF. This is because they have to handle high load currents. The resulting high capacity of load currents will increase their current rating considerably compared with shunt APF, especially in the secondary side of the interfacing transformer. This will increase the FR losses [10]. However, the main advantage of series APFs over shunt one is that they are ideal for voltage harmonics elimination. It provides the load with a pure sinusoidal waveform, which is important for voltage sensitive devices (such as power system protection devices). With this feature, series APF is suitable for improving the quality of the distribution source voltage.

2.3 Hybrid Active Power Filter

Previously, majority of the controllers developed for APF are based on analogue circuits [10]. As a result, the APF performance is inherently subjected to signal drift. Digital controllers using DSPs or microcontrollers are preferable, primarily due to its flexibility and immunity to noise. However it is known that using digital methods, the high-order harmonics are not filtered effectively. This is due to the hardware limitation of sampling rate in real-time application. Moreover, the utilisation of fast switching transistors (i.e. IGBT) in APF application causes switching frequency noise appears in the compensated source current. This switching frequency noise required additional filtering to prevent interference with other sensitive equipment. Technical limitations of conventional APFs mentioned above can be overcome with hybrid APF configurations [11]. They are typically the combination of basic APFs and passive filters. Hybrid APFs, inheriting the advantages of both passive filters and APFs, provide improved performance and cost-effective solutions. The idea behind this scheme is to simultaneously reduce the switching noise and electromagnetic interference.

The idea of hybrid APF has been proposed by several researchers [10]. In this scheme, a low cost passive high-pass filter (HPF) is used in addition to the conventional APF. The harmonics filtering task is divided between the two filters. The APF cancels the lower order harmonics, while the HPF filters the higher order harmonics. The main objective of hybrid APF, therefore is to improve the filtering performance of high-order harmonics while providing a cost-effective low order harmonics mitigation.

There are various hybrid APFs reported in literature [10, 11], but the two most prominent ones are shown in Figure 8. Figure 8 (a) is the system configuration of the hybrid shunt APF. Both the shunt APF and passive filter are connected in parallel with the nonlinear load. The function of the hybrid APF can thus divided into two parts: the low-order harmonics are cancelled by the shunt APF, while the higher frequency harmonics are filtered by passive HPF. This topology lends itself to retrofit applications with the existing shunt APF.

Figure 8 (b) shows the system configuration of hybrid series APF, in which the series APF is coupled to the distribution line by an interfacing transformer. The shunt passive filter consists of one or more single-tuned LC filters and/or a HPF. The hybrid series APF is controlled to act as a harmonic isolator between the source and nonlinear load by injection of a controlled harmonic voltage source. It is controlled to offer zero impedance (short circuit) at the fundamental frequency and high impedance (ideally open circuit) at all undesired harmonic frequencies. This constrains all the nonlinear load current harmonics to flow into the passive filter, decoupling the source and nonlinear load at all frequencies, except at the fundamental.

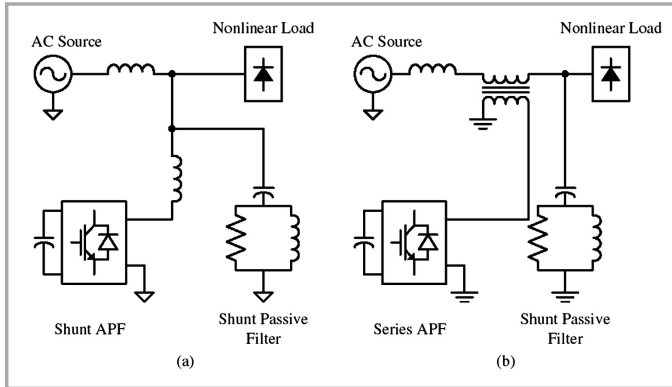


Figure 8: Hybrid APFs: (a) combination of shunt APF and shunt passive filter and (b) combination of series APF and shunt passive filter

3.0 REFERENCE SIGNAL ESTIMATION TECHNIQUES

As shown in Figure 2, the reference signal to be processed by the controller is the key component that ensures the correct operation of APF. The reference signal estimation is initiated through the detection of essential voltage/current signals to gather accurate system variables information. The voltage variables to be sensed are AC source voltage, DC-bus voltage of the APF, and voltage across interfacing transformer. Typical current variables are load current, AC source current, compensation current and DC-link current of the APF. Based on these system variables feedbacks, reference signals estimation in terms of voltage/current levels are estimated in frequency-domain or time-domain.

Figure 9 illustrates the considered reference signal estimation techniques. They cannot be considered to belong to the control loop since they perform an independent task by providing the controller with the required reference for further processing. This section presents the considered reference signal estimation techniques, providing for each of them a short description of their basic features.

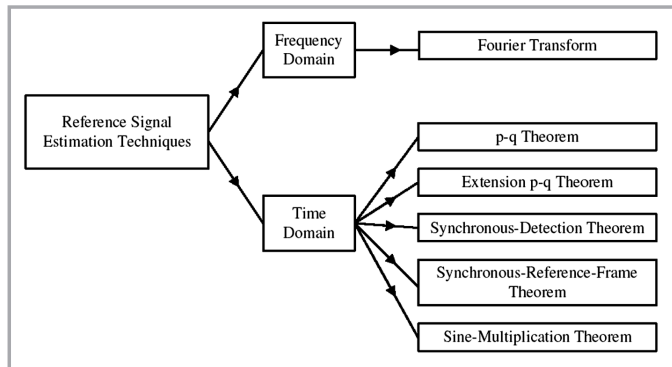


Figure 9: Subdivision of reference signal estimation techniques

3.1 Frequency Domain Approaches

Reference signal estimation in frequency-domain is suitable for both single- and three- phase systems. They mainly derived from the principle of Fourier analysis as follows.

3.1.1 Fourier Transform Techniques

In principle, Fourier Transform (either conventional or Fast Fourier Transform (FFT)) is applied to the captured voltage/current signal. The harmonic components of the captured voltage/current signal are first separated by eliminating the fundamental component. Inverse Fourier Transform is then applied to estimate the compensation reference signal in time domain [10].

The main drawback of this technique is the accompanying time delay in system variables sampling and computation of Fourier coefficients. This makes it impractical for real-time application with dynamically varying loads. Therefore, this technique is only suitable for slowly varying load conditions.

In order to make computation much faster, some modifications was proposed and practiced in [11]. In this modified Fourier-series scheme, only the fundamental component of current is calculated and this is used to separate the total harmonic signal from the sampled load-current waveform.

3.2 Time Domain Approaches

Time-domain approaches are based on instantaneous estimation of reference signal in the form of either voltage or current signal from distorted and harmonic-polluted voltage and current signals. These approaches are applicable for both single-phase and three-phase systems except for the synchronous-detection theorem and synchronous-reference-frame theorem which can only be adopted for three-phase systems.

3.2.1 Instantaneous Reactive-Power Theorem

The instantaneous reactive-power (p-q) theorem is proposed by Akagi *et al.* [1]. This theorem is based on $\alpha\beta$ transformation which transforms three-phase voltages and currents into the $\alpha\beta$ stationary reference frame. From this transformed quantities, the instantaneous active and reactive power of the nonlinear load is calculated, which consists of a DC component and an AC component. The AC component is extracted using HPF and taking inverse transformation to obtain the compensation reference signals in terms of either currents or voltages. This theorem is suitable only for three-phase system and its operation takes place under the assumption that three-phase system voltage waveforms are symmetrical and purely sinusoidal. If this technique is applied to contaminated supplies, the resulting performance is proven to be poor.

In order to make the p-q theorem applicable for single-phase system, some modifications in the original p-q theorem were proposed. Assume that the source voltage (v_s) and load current (i_L) of a single-phase system are defined as

$$v_s(t) = \sqrt{2}V_s \sin(\omega t) \quad (1)$$

$$i_L(t) = \sqrt{2}I_L \sin(\omega t + \theta) \quad (2)$$

After complementing by fictitious imaginary phase (shifted by 90°), the complemented source voltage (v'_s) and load current (i'_L) are defined as

$$v'_s(t) = \sqrt{2}V_s \sin(\omega t - 90^\circ) \quad (3)$$

$$i'_L(t) = \sqrt{2}I_L \sin(\omega t + \theta - 90^\circ) \quad (4)$$

the $\alpha\beta$ orthogonal co-ordinate system is obtained, whereas

$$v_\alpha = v_s(t) \text{ and } v_\beta = v'_s(t) \quad (5)$$

$$i_\alpha = i_L(t) \text{ and } i_\beta = i'_L(t) \quad (6)$$

Thus, the instantaneous active power of the load can be derived as

$$p = v_\alpha \cdot i_\alpha + v_\beta \cdot i_\beta = \bar{p} + \tilde{p} \quad (7)$$

The instantaneous reactive power of the load can be derived as

$$q = v_\alpha \cdot i_\beta - v_\beta \cdot i_\alpha = \bar{q} + \tilde{q} \quad (8)$$

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From the obtained instantaneous active and reactive power, the AC components (\tilde{p} and \tilde{q}) are extracted using HPF. The extracted AC components are then used for compensation reference signal estimation.

3.2.2 Extension Instantaneous Reactive-Power Theorem

The conventional p-q theorem is revised to make it applicable for three-phase unsymmetrical and distorted voltage system. In extension p-q theorem, the source voltages are shifted by 90° for instantaneous reactive power calculation. Instead of the AC components in conventional p-q theorem, the DC components are extracted using low-pass filters (LPFs) and taking inverse transformation to obtain the compensation reference signals in terms of either currents or voltages. The main advantage of this technique is that it is simpler to find three-phase instantaneous reactive power than the conventional p-q theorem.

This technique is also suitable for single-phase APF systems. In order to illustrate the difference between the extension p-q theorem with its former, the basics of extension p-q theorem for single-phase system are presented in this subsection. Assume that the source voltage (v_s) and load current (i_L) of a single-phase system are defined in equation (2.5) and (2.6) respectively. The instantaneous active power of the load can be derived as

$$p = v_s(t) \cdot i_L(t) = \bar{p} + \tilde{p} \quad (9)$$

The instantaneous reactive power of the load can be derived as

$$q = v_s'(t) \cdot i_L(t) = \bar{q} + \tilde{q} \quad (10)$$

where $v_s'(t)$ denotes the source voltage shifted by 90° .

The DC components (\bar{p} and \bar{q}) are extracted from the derived instantaneous active and reactive power using LPFs. The extracted DC components are then used for compensation reference signal estimation. It is clearly seen that the resulting equations for the instantaneous active and reactive power of the load based on extension p-q theorem are simpler compared with the p-q theorem.

3.2.3 Synchronous-Detection Theorem

Synchronous-detection theorem is very similar to p-q theorem. This technique is suitable only for three-phase system and its operation relies in the fact that the three-phase currents are balanced. It is based on the idea that the APF forces the source current to be sinusoidal and in phase with the source voltage despite the load variations. The average power is calculated and divided equally between the three-phases. The reference signal is then synchronised relative to the source voltage for each phase. Although this technique is easy to implement, it suffers from the fact that it depends to a great extent on the harmonics in the source voltage [10].

3.2.4 Synchronous-Reference-Frame Theorem

This theorem relies on the Park's Transformations to transform the three phase system voltage and current variables into a synchronous rotating frame. The active and reactive components of the three-phase system are represented by the direct and quadrature components respectively. In this theorem, the

fundamental components are transformed into DC quantities which can be separated easily through filtering.

This theorem is applicable only to three-phase system. The system is very stable since the controller deals mainly with DC quantities. The computation is instantaneous but incurs time delays in filtering the DC quantities.

3.2.5 Sine-Multiplication Theorem

This theorem is based on the process of multiplying the nonlinear load current signal by a sine wave of fundamental frequency and integrating the result to calculate the real fundamental component of nonlinear load current [11]. It is applicable for both single- and three- phase systems. The difference between the instantaneous nonlinear load current and this fundamental component is the command current for the APF. Although this technique eliminates the time delay due to low/high-pass filtering, its performance is still slow (for more than one complete mains cycle), due to integration and sampling. This technique is similar to the Fourier Technique. It is, however, differently implemented.

4.0 Control Techniques for Active Power Filter

The aim of APF control is to generate appropriate gating signals for the switching transistors based on the estimated compensation reference signals. The performance of an APF is affected significantly by the selection of control techniques [12]. Therefore, the choice and implementation of the control technique is very important for the achievement of a satisfactory APF performance.

A variety of control techniques, such as linear control, digital deadbeat control, hysteresis control etc., are implemented for the APF applications. Several publications [10]-[13] comprehensively report the theories related to APF control techniques. This section briefly describes the considered control techniques and their basic features.

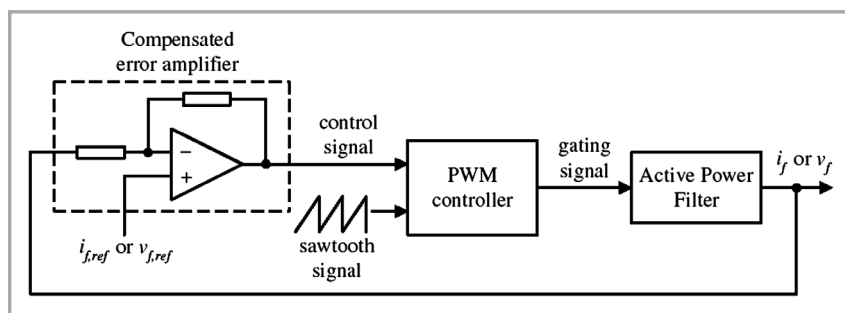


Figure 10: diagram of linear control technique

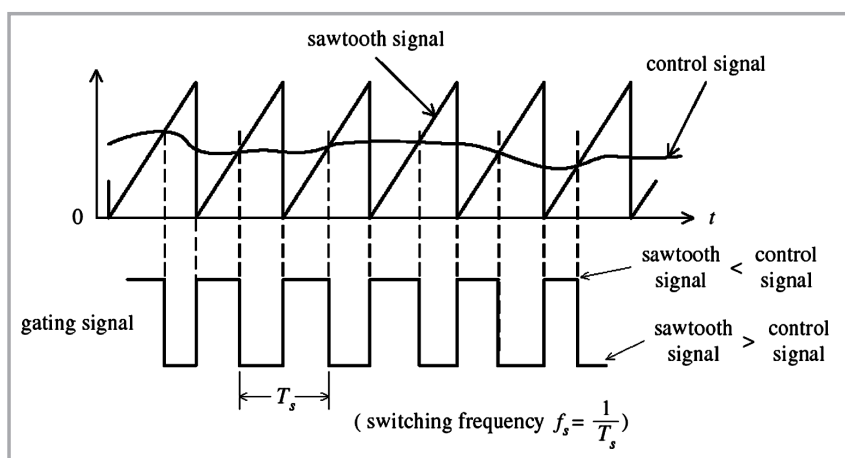


Figure 11: Gating signal generation by linear controller

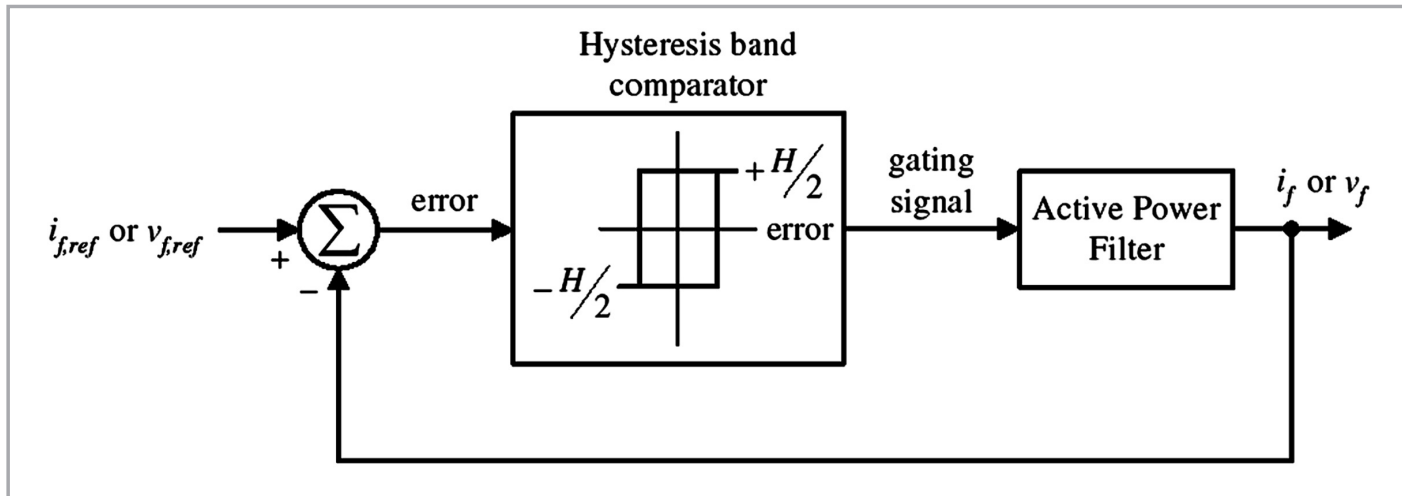


Figure 12: Block diagram of hysteresis control technique

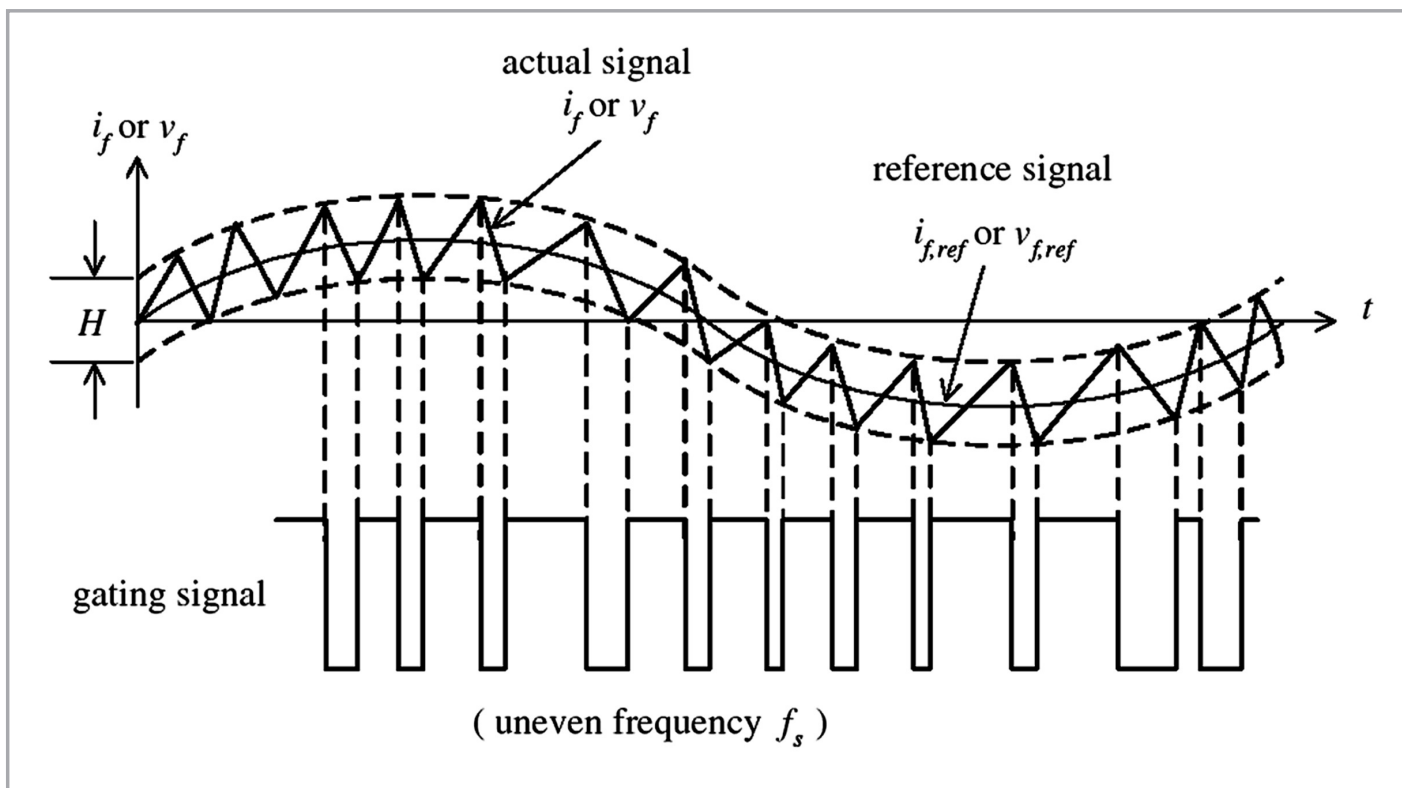


Figure 13: Gating signal generation by hysteresis controller

4.1 Linear Control Technique

The linear control of APF is accomplished by using a negative-feedback system as shown in Figure 10. In this control scheme, the compensation current (i_p) or voltage (v_p) signal is compared with its estimated reference signal ($i_{f,ref}$ or $v_{f,ref}$) through the compensated error amplifier to produce the control signal. The resulting control signal is then compared with a sawtooth signal through a pulse width modulation (PWM) controller to generate the appropriate gating signals for the switching transistors. The frequency of the repetitive sawtooth signal establishes the switching frequency. This frequency is kept constant in linear control technique. As shown in Figure 11, the gating signal is set high when the control signal has a higher numerical value than the sawtooth signal and vice versa.

Generally, the Nyquist stability criterion and the Bode plots are used to determine the appropriate compensation in the

feedback loop for the desired steady-state and transient responses. With analogue PWM circuit, the response is fast and its implementation is simple. Nevertheless, due to inherent problem of analogue circuitry, the linear control technique has an unsatisfactory harmonic compensation performance. This is mainly due to the limitation of the achievable bandwidth of the compensated error amplifier.

4.2 Hysteresis Control Technique

The control of APF can be realised by the hysteresis control technique. It imposes a bang-bang type instantaneous control that forces the APF compensation current (i_p) or voltage (v_p) signal to follow its estimated reference signal ($i_{f,ref}$ or $v_{f,ref}$) within a certain tolerance band. This control scheme is shown in a block diagram form in Figure 12. In this control scheme, a signal deviation (H) is designed and imposed on $i_{f,ref}$ or $v_{f,ref}$ to form the upper and lower limits of a hysteresis band. The i_f or

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v_f is then measured and compared with i_{fref} or v_{fref} ; the resulting error is subjected to a hysteresis controller to determine the gating signals when exceeds the upper or lower limits set by (estimated reference signal $+ H/2$) or (estimated reference signal $-H/2$). As long as the error is within the hysteresis band, no switching action is taken. Switching occurs whenever the error hits the hysteresis band. The APF is therefore switched in such a way that the peak-to-peak compensation current/voltage signal is limited to a specified band determined by H as illustrated by Figure 13.

Hysteresis current controller with a fixed H is implemented is known to be more popular. To obtain a compensation current (i_f) with switching ripples as small as possible, the value of H can be reduced. However, doing so results in higher switching frequency. Thus, increases losses on the switching transistors.

The advantages of using the hysteresis current controller are its excellent dynamic performance and controllability of the peak-to-peak current ripple within a specified hysteresis band. Furthermore, the implementation of this control scheme is simple; this is evident from the controller structure shown in Figure 12. However, this control scheme exhibits several unsatisfactory features. The main drawback is that it produces uneven switching frequency. Consequently, difficulties arise in designing the passive HPF. Furthermore, there is possibly generation of unwanted resonances on the power distribution system. Besides, the irregular switching also affects the APF efficiency and reliability.

5.0 SUMMARY

This paper covers the development of APF technologies. A brief discussion on the harmonic distortion problems and their impacts on electric PQ are given. The conventional mitigation methods using passive filters are presented first, followed by the improved mitigation methods using APFs. The main APF topologies are described, followed by reviews on different types of reference signal estimation techniques. Finally, an overview of the control strategies for APF is presented. ■

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PROFILES

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