A comprehensive review on power quality issues and disturbances mitigation through shunt active power filters

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ABSTRACT

In contemporary power systems, power quality (PQ) has become a matter of paramount concern. The challenges associated with PQ extend beyond conventional three-phase systems, encompassing the integration of various distributed generation (DG) sources like renewable energy installations, storage systems, and diverse power generation technologies such as diesel generators and fuel cells. The prevalent adoption of rapid-switching devices within the utility infrastructure has resulted in a surge of harmonics and reactive power disturbances. The increased use of harmonics-producing loads has led to several power quality issues, particularly harmonics. The distortions caused by these power quality issues must adhere to the limits established by international standards. Mitigation of these concerns is critical, and active power filters are a realistic option. However, passive filters have problems such as bulkiness, and resonance with either/both load and utility impedance, and the source impedance affects filtering properties. As a result, active power filters (APF) are designed to address the shortcomings of passive filters. Active power filters (APF) offer several advantages over passive filters, including compact size, enhanced filtering characteristics, dynamic performance, and flexible operation. The control strategy of APF strongly influences the APF performance, efficiency, and reliability. This paper presents a detailed assessment of current active filter control systems, highlighting their key features. The characteristics, performance, applicability, and implementation of various control techniques are explored and investigated.

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1. INTRODUCTION

Enhancing power quality has evolved into an imperative undertaking for researchers and engineers involved in utility networks. Advances in power electronics technology have streamlined the process of aligning power quality with IEEE standards [1], [2]. Insufficient power quality can give rise to numerous issues, such as undesirable device operation, increased power losses, a diminished power factor, compromised performance efficiency, and interference with communication networks [3]-[6].

Custom power devices (CPD) are widely employed to overcome these undesired disturbances. CPD performance at variable voltage stages appears to be becoming more common in the electricity (utility) and industrial sectors [7]-[10]. Initially, passive filters (PF) in the electricity industry were primarily employed for harmonic reduction and rectification. However, issues like fixed compensation, unwieldy size, and resonance constraints limited their application. Subsequently, a modified configuration of active power filters (APF) emerged to address and rectify distorted voltage and current in dynamic nonlinear loads. Nevertheless, these filters still exhibit drawbacks in terms of their ratings, particularly in close proximity to the load, sometimes reaching higher percentages in crucial scenarios, and pose a costly alternative for enhancing power quality. This review article aims to delve into the evolutionary progression of APF systems, widely utilized for harmonics reduction in utility systems. The aspiration is that this exploration will inspire more power engineering enthusiasts to pursue careers in this evolving field.

In this paper initially, the issues of power quality are highlighted, followed with the mention of role of APFs in mitigating these issues. Then after, a comprehensive evaluation of APF papers showcasing various APF methodologies has been presented [11]-[15]. With the issue of current harmonic injection being graver compared to voltage harmonics, a detailed analysis of shunt active power filters along with various control strategies is presented. Furthermore, the advantages, disadvantages, and comparative evaluation of each offered strategy are explored. This paper thereby focuses on analyzing different reference current generation schemes and current controller behavior. Overall, this analysis provides a wide understanding of many APF management mechanisms for power quality (PQ) augmentation.

2. POWER QUALITY ISSUES AND THEIR MITIGATIONS

Power quality is essentially the interaction between electrical power and electrical equipment. It is deemed satisfactory when electrical equipment operates correctly and reliably without sustaining damage. Conversely, if electrical equipment experiences failures or proves to be unreliable, it raises concerns about the adequacy of power quality [16]. The remedy to the power quality problem can come from either the customer or the utility. Power quality and reliability cost the sector a lot of money because of sags and short-term outages. Voltage waveforms are distorted and undesirable and the biggest issue for electricity customers is supply reliability. The challenges associated with distribution lines are categorized into two primary groups, as depicted in Figure 1. The initial group pertains to power quality, encompassing issues such as harmonic distortions, impulses, and swells [17]-[20]. The second group focuses on power reliability, involving concerns like voltage sags and outages. Voltage sags, in particular, pose a greater risk and can result in substantial damage. Processes controlled by motors, robotics, servo drives, and machine tools face difficulties in maintaining control if the cycle count exceeds a few instances.

The dependability and quality of supply are both critical. For example, a consumer supplied from the same bus as a heavy motor load may experience a significant drop in supply voltage whenever the motor load is turned on. In some extreme instances, we must tolerate blackouts, which are unacceptable to consumers. There are other sensitive loads that demand clean and uninterrupted power, such as hospitals, air traffic control, and financial institutions [21], [22]. Thus, in this environment, where consumers are increasingly demanding high-quality power, the word power quality (PQ) becomes of greater significance. Voltage dips are the frequently encountered power quality issues nowadays. A voltage dip is a brief (10 ms to 1 minute) interval event in which the root mean square (rms) value of voltage decreases. It is frequently determined by two parameters: duration and magnitude. The size of the voltage dip ranges from 10% to 90% of the nominal voltage (corresponding to 90% to 10% remaining voltage) and has a duration of half a cycle to 1 minute [23]-[25]. A voltage dip has effect on both the phase-to-phase and phase-to-ground voltages in a three-phase system. Table 1 shows power quality problems and its effects.

As harmonics play a dominating role in power quality deterioration, active power filters are dominantly used for mitigating harmonics. Three types of active power filters include shunt APF, series APF, and hybrid APF [26]. As shown in Figure 2, shunt APF is connected in parallel to the load as well as utility and helps in mitigating current harmonics. As depicted in Figure 3, the series APF is connected in series with the utility voltage to address and rectify voltage harmonics within the system. A hybrid APF combines a series and shunt APF or an APF and a passive filter as shown in Figure 4. The combination of an APF and a passive filter reduces the rating (as well as the cost of compensating) of the APF while simultaneously improves the APF dynamic performance. Because current harmonic removal is a current concern, the suggested research study focuses on shunt APF [27], [28].

Table 1. Power quality issues and effects

Sr. No.	Issues	Effects	Sr. No.	Issues	Effects
1	Excessive voltage	Overstressed insulation	5	Interruption	Complete shutdown
2	Insufficient voltage	Excessive motor current	6	Sag	Variable speed drive and computer trip-out
3	Voltage unbalance	Motor heating	7	Swell	Overstressed insulation
4	Neutral-ground voltage	Malfunction of digital devices, interruption	8	Fluctuations	Light flicker

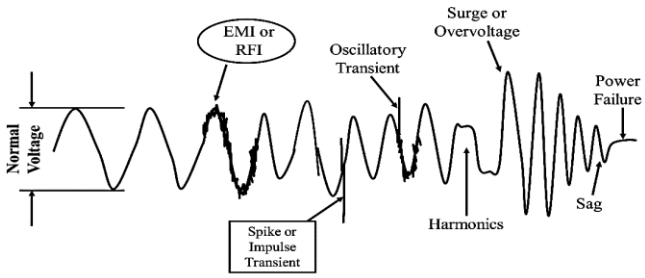

Figure 1. Power quality issues

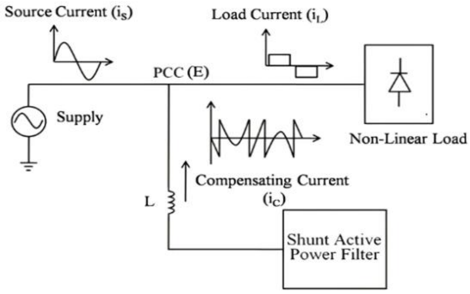

Figure 2. Shunt active power filter

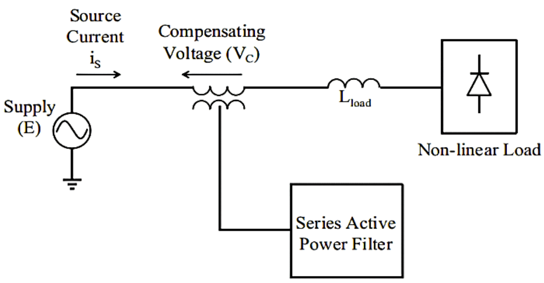

Figure 3. Series active power filter

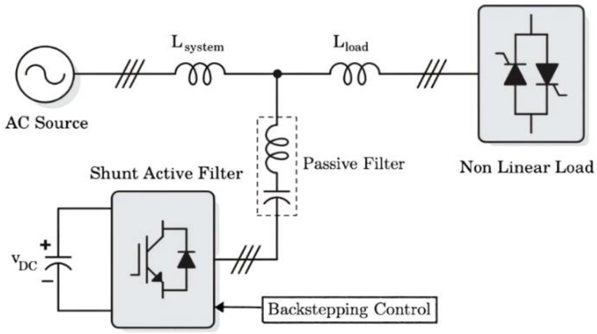

Figure 4. Hybrid active power filter

3. SHUNT ACTIVE POWER FILTERS

Figure 5 depicts operation of a shunt active power filter (SAPF). It is essentially a voltage source inverter linked in parallel with the load via a coupling inductor at the point of common coupling (PCC). The SAPF requires the utility to give only sinusoidal current while maintaining unity power factor on the utility side by injecting harmonic current and hence compensating for the reactive power into the system [29], [30].

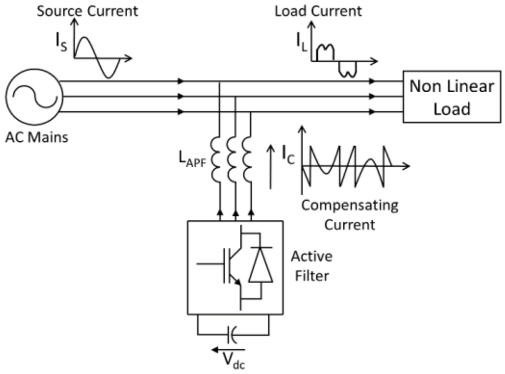

Figure 5. Operation of SAPF

4. CONTROL STRATEGIES USED FOR SHUNT ACTIVE FILTER

SAPFs are used to remove harmonic currents introduced into the system by nonlinear loads. The SAPF functions as a current source, injecting compensatory current to negate the harmonic currents. Since the implementation of APF technology, numerous control mechanisms have been introduced or current ones have been enhanced [31]. SAPF control primarily consists of balancing the DC link capacitor voltage, generation of gate pulses for SAPF devices, and a system for generating reference current.

SAPF control can be accomplished in three simple steps. To begin, requirement of current and voltage sensors such as CTs/PTs or hall sensors sense the requisite current and voltage magnitude. Second, reference current is calculated using the measured current and voltage amount, as well as by regulation of SAPF DC-link voltage. Finally, gate pulses are created for the APF devices. Superior dynamic response, correct reference signal extraction, balancing of DC-link voltage, and fast accurate sensing of electrical parameters are critical features in the compensating device's efficient operation [32], [33]. To meet these objectives, researchers have used a variety of control approaches for reference current generation like DC-link voltage balancing, P-Q theory and controllers with good dynamic response for effective SAPF switching state generation. Various control strategies are employed to ensure effective operation of SAPF.

Numerous researchers have devised and documented innovative and efficient methods for generating reference compensation current [34]-[35]. These techniques encompass the instantaneous reactive power theory, synchronous reference frame method, DC-link voltage control method, Fryze current computation technique, notch filter technique, sliding mode control, predictive scheme, state feedback scheme, fast Fourier transform method, and non-linear least-squares approach.

Akagi, Nabe, and Kanazawa [1], [6], [29], [30] proposed instantaneous reactive power (IRP) theory, often known as P-Q theory. This theory proposes to develop an IRP compensator using switching devices with no energy storage components which reduces fundamental reactive power as well as harmonic currents. Appropriate design of the DC-link capacitor, SAPF inductor, and DC-link voltage are critical for proper SAPF performance. The major consideration in SAPF inductor design is to allow harmonics (to be compensated) to flow through it and prevent high frequency switching harmonics from being injected at PCC (in the supply mains). While the DC-link capacitor and DC-link voltage should be chosen so that the SAPF provides adequate compensation. Many studies have attempted to address the design considerations for SAPF component selection.

4.1. Reference current extraction schemes

As show in in Figure 5 depicts SAPF extracts load current harmonics by using reference compensating current generation strategies and generates reference compensating currents. The obtained reference compensating currents are fed into the current controller, which generates gate signals for the SAPF such that the APF compensating (real) current tracks the reference compensating current [36]. These schemes generate the reference currents used by the SAPF to adjust for harmonic currents and reactive power in the power system. The following methods for generating reference compensating currents are used: theory of instantaneous reactive power, synchronous reference frame method, method of regulating DC-link voltage and Fryze current computation method.

4.1.1. Theory of Instantaneous reactive power

Figure 6 depicts the principle of instantaneous reactive power which utilizes a set of time-domain instantaneous powers. This hypothesis is also termed as the p-q theory [37], [38]. The theory applies to any three-phase system, neutral or not. This theory applies to both steady-state and transient system operation. Voltages and currents are translated from abc to α-β coordinates first, and then the instantaneous power is defined on these coordinates. As a result, under this theory, the complete three-phase system is converted to equivalent single unit.

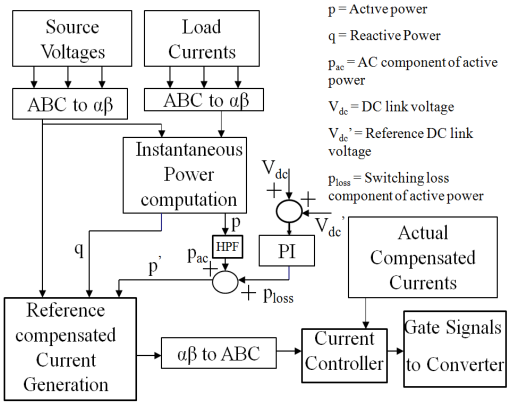

Figure 6. Instantaneous reactive power theory

4.1.2. Synchronous reference frame method

Three phase load currents (i_{la}, i_{lb}, and i_{lc}) are converted here into rotational d-q axis (i_{ld} and i_{lq}). The d-q transformation converts quantities in of three-phase system into components along the direct (d) and quadrature (q) axes [39], [40]. All components having angular frequency become DC quantities in a revolving D-Q axis frame, whereas the rest are non-DC (AC). A high pass filter is used to remove the DC offset for compensating reactive power and current harmonic mitigation. As a result, the fundamental component is eliminated, and what remains is the harmonic current which needs to be compensated. Then, as shown in Figure 7, the D-Q to A-B-C transformation is carried out to obtain three phase reference compensating currents.

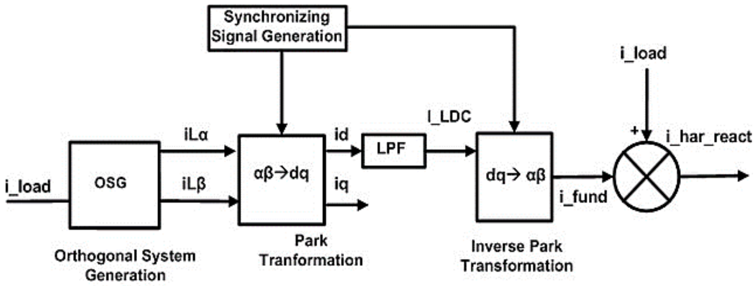

Figure 7. Synchronous reference frame method

4.1.3. Method of regulating DC-link voltage

Figure 8 depicts the basic functionality of this approach. Supply currents not only provide active power to the load but also helps in maintaining the SAPF DC-link voltage. The main principle behind the APF's PI controller-based functioning is utilization of measured DC-link voltage for the estimation of reference currents [41]. To keep the stored energy in the capacitor constant, the actual DC-link capacitor voltage V_{dc} is compared to its reference value V_{dc}*. The PI controller is used to control the difference in voltage between the DC-link capacitor and its reference. The PI controller output (I_{smax})* provides the size of the peak component of supply current that mitigates the imbalance of DC-link capacitor voltage and SAPF switching losses.

In order to generate the instantaneous supply reference currents i_{sa}*, i_{sb}*, and i_{sc}*, i_{smax}* is multiplied with sinusoidal signals of magnitude equal to unity and phase locked with each of the supply phase voltages. These supply reference currents are compared with i_{la}*, i_{lb}*, and i_{lc}* (nonlinear load currents), which in turn yields reference compensating currents i_{ca}*, i_{cb}*, and i_{cc} *.

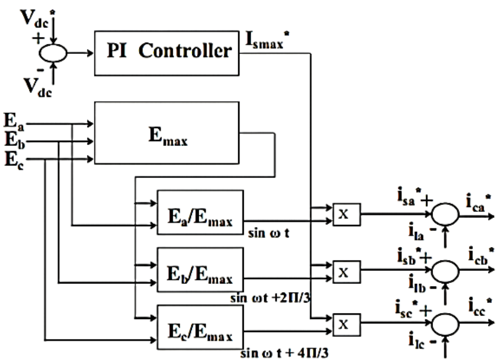

Figure 8. Control scheme for reference current generation by regulating the DC-link voltage

4.1.4. Fryze current computation method

The generalized Fryze current computation method is utilized for achieving linearity between voltage and current while doing power compensation, even for distorted and/or unbalanced supply voltages. Figure 9 depicts the approach for implementing the Fryze current computation algorithm. The primary strategy in this case is to calculate the minimized currents (generalized Fryze currents) using the three-phase instantaneous active power average value [42], [43]. Admittance G_e is expressed by an average value to provide linearity between current and voltage. The average value of G_e is obtained with low-pass filter. The generalized Fryze currents are denoted by the symbols i_{wa}, i_{wb}, and i_{wc}, and are defined as $i_{wk}= G_eE_k$, where k = a, b, and c.

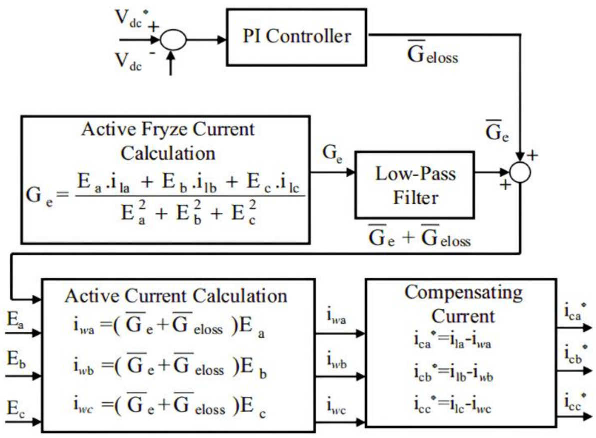

Figure 9. Fryze current computation technique

4.2. Current controllers for shunt APF

The goal of current control in SAPFs is to achieve effective compensation of load harmonics by enabling actual compensating currents to be in line with generated reference compensating currents. This task of making actual currents track reference currents is carried out by current controller and hence its selection becomes crucial for achieving effective compensation characteristics of SAPF. Commonly used controller approaches are:

4.2.1. PI controller

In a proportional-integral control scheme aimed at preserving DC-link voltage and estimating source current, an error signal is initially created by comparing the reference voltage (V_{ref}) with the actual DC-link voltage (V_{dc}) [44]. Subsequently, a proportional-integral (PI) controller is employed to handle this steady-state error. Drawbacks of the PI controller include the challenges of intricate and challenging linear mathematical modeling, as well as its susceptibility to fluctuations and imbalances in parameters.

4.2.2. Fuzzy controller

Fuzzification, interface mechanism, and defuzzification units comprise a fuzzy controller. Figure 10 depicts the basic structure of a fuzzy controller. The generated voltage error signal is provided to the fuzzy controller, the input error signal is mapped into fuzzy sets by the fuzzification unit, fuzzy control action to the fuzzy sets is applied with the interface mechanism, and the defuzzification unit converts the fuzzy output from the interface mechanism to the required control signals [45]-[47]. According to the performance investigation of SAPFs, the TS fuzzy controller produces a better response in less computational time and requires fewer fuzzy sets and rules.

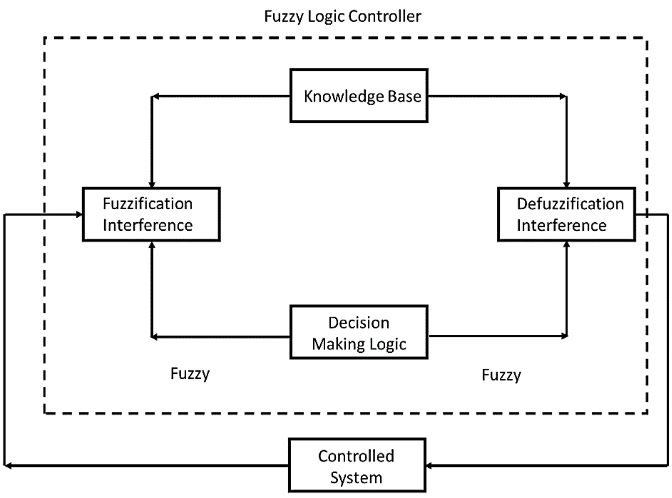

Figure 10. Fuzzy controller

4.2.3. ANN controller

Adaptive controllers can be used to control SAPF compensating current. For the current control mechanism, a three-layer ANN structure has been developed, and the Levenberg Marquardt method is utilized to minimize errors by modifying the network's adaptive weights. ANN-based current controllers outperform predictive and hysteresis controllers in terms of percentage THD [48]-[50]. To improve SAPF performance during transient conditions, the DC-link voltage is managed by ANN, and the ANN is trained using PI data. Table 2 presents comparative analysis of various SAPF controllers.

Table 2. Performance comparison of SAPF controllers

PI	Fuzzy	ANN
Accurate mathematical model of SAPF system is required to calculate PI parameters	Rule based operation and hence precise mathematical modelling of the SAPF system is not required	Biological neural network learning based operation and hence precise mathematical modelling of the SAPF system is not required
Tuning is required for supply or load changes.	Self-learning capability with supply or load changes	Self-learning capability with supply or load changes
Slow dynamic response	Fast dynamic response	Fast dynamic response
Simple in implementation	complex in implementation	Moderate complexity in implementation
Moderate compensation of harmonics especially for fluctuating load conditions	Effective compensation of harmonics especially for fluctuating load conditions	Effective compensation of harmonics especially for fluctuating load conditions
Less processing time required	More processing time required	Moderate processing time required

5. CONCLUSION

The paper is focused to provide an in depth understanding of various control strategies employed in SAPFs. This includes the generation of current references and controllers, crucial aspects for ensuring the effective operation of SAPFs. The major power quality problems highlighted in the paper are current harmonics and reactive power. These issues can lead to inefficiencies and disturbances in power distribution systems, affecting the overall performance of electrical networks. SAPFs are known for their ability to mitigate current harmonics, compensate reactive power, and improve overall power quality in electrical systems. The paper suggests that SAPFs are identified as an effective solution to address power quality problems. Both selection of reference current generation schemes as well as controller affect the compensation capabilities of the SAPF. Hence, their selection should be done so as to get appropriate compensation in steady-state as well as dynamic conditions of operation. Researchers and practitioners in the field of power electronics and power quality would find such studies valuable for understanding and implementing advanced control strategies in practical applications.

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