

Power Quality Enhancement in Electrical Systems Using Shunt Active Power Filter: A Literature Review

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Abstract - Increased use of nonlinear loads, power electronic converters, industrial automation systems has intensified power quality problems in modern electrical distribution networks. Problems like harmonic distortion, reactive power demand, voltage imbalance, poor power factor causes reduced system efficiency, reliability and performance of sensitive electrical equipment. Passive filters used traditionally for harmonic mitigation but their fixed compensation characteristics, resonance problems and poor adaptability under varying load conditions limit their effectiveness. This paper presents a comprehensive review of Shunt Active Power Filters (SAPFs) as a advanced solution for power quality enhancement. This study discusses the operating principles, configurations and compensation capabilities of SAPFs in the single-phase and three-phase systems both. Various reference current extraction methods including the Instantaneous Reactive Power (p-q) theory and Synchronous Reference Frame (SRF) theory are analyzed along with control techniques such as the hysteresis current control, sinusoidal PWM, fuzzy logic, neural networks, sliding mode control and optimization-based methods. Also Intelligent optimization approaches including PSO, GA and GWO are reviewed for controller tuning and DC-link voltage regulation. This review highlights significant improvements in the THD reduction, power factor correction, reactive power compensation and system stability while identifying the future research challenges in adaptive control, real-time implementation and cost-effective SAPF design.

Key Words: Power quality (PQ), shunt active power filter (SAPF), harmonic mitigation, total harmonic distortion (THD), reactive power.

1.INTRODUCTION

The increasing use of nonlinear loads, adjustable speed drives, power electronic converters, uninterruptible power supplies and industrial automation equipment has significantly affected the quality of electrical power in modern distribution systems. These nonlinear devices inject harmonic currents into the supply network resulting in voltage distortion, excessive reactive power demand, overheating of transformers, capacitor failure, increased transmission losses and poor power factor [14]. Power quality problems also reduce the efficiency and reliability of electrical systems also affect the operation of sensitive electronic equipment used in industries, commercial buildings and renewable energy applications [7]. As electrical networks continue to expand with smart grid and distributed generation technologies therefore maintaining acceptable power quality levels has become an important requirement for stable and efficient system operation. Among various power quality issues, harmonic distortion is one of the most serious concerns in electrical distribution networks. Harmonics are generated mainly due to the widespread application of nonlinear switching devices such as rectifiers, inverters, variable frequency drives and switched mode power supplies [11]. Excessive harmonic distortion leads to poor voltage regulation, malfunction of protection devices, communication interference and reduced equipment life [2]. International standards such as IEEE-519 specifies standard harmonic limits for electrical system to ensure safe and reliable operation [9]. Therefore, efficient harmonic mitigation techniques are required for modern power systems. Conventional passive filters have been widely employed for harmonic reduction because of their simple structure and low cost. These filters are designed using combinations of inductors, capacitors, and resistors tuned to specific harmonic frequencies [15]. Although passive filters provide acceptable performance under fixed

operating conditions and suffers from several limitations such as resonance problems, bulky size, fixed compensation characteristics and poor dynamic response during load variations [1]. These drawbacks reduce their effectiveness in rapidly changing industrial environments where load conditions vary continuously. To overcome the limitations of passive filtering methods Active Power Filters (APFs) have emerged as an effective solution for power quality improvement. Among different APF configurations the Shunt Active Power Filter (SAPF) has achieved attention due to its superior capability for harmonic compensation, reactive power support, load balancing and power factor correction [5]. SAPFs operate by injecting compensating currents equal in magnitude and opposite in phase to harmonic currents generated by nonlinear loads, thereby maintaining sinusoidal source currents [10]. The performance of SAPFs depends largely on accurate reference current generation and efficient controller design. Several reference current extraction techniques have been developed for SAPF applications. Instantaneous Reactive Power (p-q) theory and Synchronous Reference Frame (SRF) theory are the most commonly used approaches because of their fast response and effective harmonic compensation capability [13]. Different current control strategies such as hysteresis current control, sinusoidal pulse width modulation, fuzzy logic control, sliding mode control and artificial neural network based controllers have been investigated to improve compensation performance and DC link voltage regulation [16]. Recent researches focused on intelligent optimization techniques such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and Grey Wolf Optimization (GWO) for automatic tuning of controller parameters and enhancement of dynamic performance [6]. These optimization methods improve Total Harmonic Distortion (THD), reduce steady-state error and enhance system stability under varying load conditions. Furthermore SAPFs are increasingly integrated with renewable energy systems, microgrids and smart grid infrastructures to achieve efficient and reliable power quality management [3]. This paper presents a comprehensive review of SAPF technology for harmonic mitigation and reactive power compensation in electrical distribution systems. The review discusses operating principles, control techniques, optimization approaches and recent developments in intelligent SAPF systems. In addition, the study identifies important research gaps related to adaptive control, computational complexity, real-time implementation, and cost-effective design for future power quality applications.

2. SHUNT ACTIVE POWER FILTER

Shunt Active Power Filters (SAPFs) are widely used for power quality improvement in modern electric power distribution system. The increasing use of nonlinear loads such as variable frequency drives, rectifiers, switched-mode power supplies, and power electronic converters produces harmonic currents and reactive power demand in electrical networks. These disturbances affect the voltage quality, reduce the system efficiency, increase power losses and create overheating in transformers and electrical equipments. SAPFs provide an effective solution for harmonic mitigation and reactive power compensation under varying load conditions. A SAPF is connected in parallel with the nonlinear load at the point of common coupling (PCC). The main function of the SAPF is to inject compensating currents into the system equal in magnitude and opposite in phase to the harmonic currents generated by the load. As a result, the source current becomes nearly sinusoidal and remains in phase with the supply voltage. This process improves the power factor, reduces Total Harmonic Distortion (THD) in the supply system [14]. The basic configuration of a SAPF consists of a Voltage Source Inverter (VSI), DC link capacitor, interface inductors, switching devices, sensing circuits and a control unit. The DC link capacitor maintains a constant DC voltage which is mandatorily required for inverter operation meanwhile the VSI generates compensating currents as per the control algorithm. The interface inductors reduce current ripple therefore provides smooth current injection into the system [2]. SAPFs are classified into single phase and three phase configurations depending on the application. Single phase SAPFs are commonly used in residential and small commercial systems whereas three phase SAPFs are employed in industrial distribution networks with heavy nonlinear loads. Three-phase SAPFs offer better compensation capability for harmonic suppression, reactive power compensation, current balancing, and neutral current elimination [15]. The performance of SAPFs depends on the reference current extraction method used in the controller. The Instantaneous Reactive Power (p-q) theory and Synchronous Reference Frame (SRF) theory are the most widely adopted approaches. The d-q theory transforms three-phase quantities into d-q coordinates which gives harmonic and reactive current components for compensation. This method provides fast dynamic response under balanced operating conditions [13]. The SRF theory converts three-phase variables into rotating d-q coordinates using Park transformation. The SRF method provides accurate

compensation under distorted and unbalanced conditions and is widely used in practical SAPF systems [5]. Different current control techniques have also been developed for improving SAPF performance. Hysteresis Current Control (HCC) has simple implementation and fast response. Sinusoidal Pulse Width Modulation (SPWM) gives fixed switching frequency operation with reduced switching losses. Advanced intelligent controllers such as Fuzzy Logic Control (FLC), Artificial Neural Network (ANN) and Sliding Mode Control (SMC) improves compensation accuracy and system stability under dynamic load conditions [6]. Recent research focuses on application of optimization based control methods for tuning of PI controller parameters and regulating DC link voltage. Optimization algorithms such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and Grey Wolf Optimization (GWO) improve harmonic compensation performance and reduce steady state error [16]. Among these methods, GWO based controllers provide fast convergence, reduced computational complexity, and improved THD reduction capability. Modern SAPF systems support bidirectional power flow, distributed generation integration and adaptive compensation under changing operating conditions [3]. Due to these advantages, SAPFs have become one of the most effective technologies for harmonic mitigation and reactive power compensation in modern electrical power systems.

3. ELEMENTS OF SAPF

The control system of a Shunt Active Power Filter (SAPF) is a closed loop system to compensate harmonic currents and reactive power generated by non-linear loads in electrical distribution systems. The controller takes the source voltage, source current, load current and dc-link voltage as inputs and generates the compensating currents for harmonic suppression and power factor correction. SAPFs offer fast dynamic response and better harmonic mitigation in comparison with the conventional passive filters [14]. In a closed loop SAPF system, the load current and supply voltage are measured and processed by reference current extraction algorithms such as Instantaneous Reactive Power (p-q) theory or Synchronous Reference Frame (SRF) theory. These techniques extract the harmonic and reactive current components from the fundamental component and produce the required compensating reference current [13]. The actual filter current is compared with the reference current in the current controller. The error

signal is processed with Hysteresis Current Control (HCC), Sinusoidal Pulse Width Modulation (SPWM), Fuzzy Logic Control (FLC), Sliding Mode Control (SMC) or Artificial Neural Network (ANN) based controllers to produce inverter switching pulses [5]. The compensating currents are injected to the Point of Common Coupling (PCC) using interface inductors by the Voltage Source Inverter (VSI). The constant capacitor voltage is maintained using dc-link voltage controller and the inverter switching losses are compensated [2]. The closed loop operation significantly reduces the Total Harmonic Distortion (THD), improves power factor, balances the source currents and enhances the overall system stability under dynamic load conditions. Recent studies shows that optimization techniques like Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and Grey Wolf Optimization (GWO) improves the controller tuning accuracy and dynamic response of SAPF systems [6]. Working of SAPF consists of harmonic and reactive currents generation by non linear load, continuous measurement of system signals from Voltage and current sensors, reference current extraction, comparison with actual filter currents by current controller, inverter switching control by PWM pulses generation, injection of compensating currents into the PCC by VSI, maintain constant capacitor voltage by dc-link controller, cancellation of Harmonic currents therefore formation of sinusoidal source current. Advantages of Closed Loop SAPF are: effective harmonic mitigation, fast dynamic response, improved power factor, reduced Total Harmonic Distortion (THD), better reactive power compensation, stable DC link voltage regulation, suitable for smart grid and renewable energy integration.

4. REFERENCE CURRENT EXTRACTION TECHNIQUES

Reference current extraction is one of the most important stages in the operation of a Shunt Active Power Filter (SAPF). The performance of harmonic compensation and reactive power control mainly depends on the accuracy and speed of the reference current generation method. The objective of the reference current extraction unit is to identify harmonic and reactive current components produced by nonlinear loads and generate compensating reference currents for the Voltage Source Inverter (VSI). Accurate extraction techniques improve Total Harmonic Distortion (THD), dc-link voltage stability, and dynamic response of the SAPF system [14]. Modern electrical

distribution systems contain nonlinear devices like rectifiers, adjustable speed drives, switched mode power supplies and industrial converters. These devices introduce harmonics and reactive power into the supply system therefore causing waveform distortion and poor power factor. SAPF uses reference current extraction algorithms to separate fundamental current components from harmonic components and generate suitable compensation signals [7]. Several reference current extraction methods have been developed for SAPF applications. Among all this Instantaneous Reactive Power (pq) theory and Synchronous Reference Frame (SRF) theory are the most widely used due to their simple implementation and effective harmonic compensation capability. The Instantaneous Reactive Power theory, also called p-q theory, was developed for three-phase systems to perform harmonic and reactive power compensation. In this method, 3 phase voltages and currents are transformed into stationary coordinates using Clarke transformation. The instantaneous active power (p) and reactive power (q) components are calculated from transformed signals [5]. The harmonic and reactive components are separated using low pass filters. The compensating reference currents are then generated and supplied to the current controller. The p-q theory provides fast transient response and simple implementation. The method performs effectively under balanced sinusoidal voltage conditions. However, performance decreases under distorted or unbalanced supply voltages [13]. The Synchronous Reference Frame (SRF) theory is another widely used reference current extraction technique in SAPFs. In this method, three-phase currents are transformed into rotating d-q coordinates using Park transformation synchronized with the supply voltage vector [2]. The direct axis component represents active power whereas the quadrature axis component represents reactive power. Harmonic components are separated using filtering techniques and transformed back into three phase abc coordinates to generate compensating reference currents. The SRF method gives accurate harmonic compensation under unbalanced and distorted voltage conditions therefore offers better steady state performance compared with p-q theory [15]. The p-q theory offers simple implementation and fast response under balanced operating conditions. The SRF method provides superior performance under distorted supply conditions and dynamic load variations. Recent studies indicate that SRF based SAPF achieve lower THD and improved dc-link voltage stability in practical distribution systems [1]. Researchers have also developed advanced extraction techniques such as adaptive filtering, wavelet

transform methods, artificial neural networks, fuzzy logic systems, and optimization based algorithms. Intelligent approaches improve harmonic identification accuracy and dynamic compensation performance in renewable energy integrated systems and smart grids [6]. Optimization techniques such as Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and Grey Wolf Optimization (GWO) are increasingly used to tune controller gains and improve reference signal generation. These methods reduce steady state error, improve convergence speed and enhance harmonic compensation capability under varying load conditions [16]. The selection of a suitable reference current extraction technique depends on system complexity, computational burden, operating conditions, switching frequency, and required compensation accuracy. Recent research focuses on adaptive and intelligent extraction techniques for real-time implementation in smart grid and microgrid environments.

5. CONTROLLER DESIGN

The performance of a Shunt Active Power Filter (SAPF) mainly depends on the control strategy used for harmonic compensation and DC link voltage regulation. An effective control approach improves Total Harmonic Distortion (THD), reactive power compensation, power factor correction, transient response and overall system stability. Different control techniques have been developed to achieve accurate current tracking and fast dynamic performance under varying load conditions [14]. Conventional control methods such as Hysteresis Current Control (HCC) and Sinusoidal Pulse Width Modulation (SPWM) are widely used because of their simple structure and ease of implementation. Recently intelligent and optimization based controllers such as Fuzzy Logic Control (FLC), Artificial Neural Network (ANN), Sliding Mode Control (SMC), Particle Swarm Optimization (PSO), Genetic Algorithm (GA) and Grey Wolf Optimization (GWO) have gain attention due to their superior compensation capability and adaptive performance [7]. Hysteresis Current Control is one of the most commonly used SAPF current control techniques because of its fast response and simple implementation. In this method the actual filter current is continuously compared with the reference current within a predefined hysteresis band. The inverter switching signals are generated according to the current error [5]. When the current error exceeds the upper or lower hysteresis limit, switching action occurs to maintain the filter current within the hysteresis band. HCC provides excellent

dynamic response and accurate current tracking. However, variable switching frequency increases switching losses therefore creates electromagnetic interference problems [2]. SPWM is widely used in SAPF systems because of its fixed switching frequency operation and reduced harmonic distortion. In this technique the reference compensating signal is compared with a high frequency triangular carrier wave to generate PWM pulses for the Voltage Source Inverter (VSI) [15]. SPWM offers lower switching losses and easier filter design compared with hysteresis control. The method also improves inverter efficiency and provides stable switching operation. However, dynamic response is slower than HCC during sudden load variations [13]. Fuzzy logic control has become popular in SAPF applications due to its nonlinear control capability and robustness under transient operating conditions. FLC does not require an accurate mathematical model of the system. The controller uses linguistic rules and membership functions to process error and change in error signals [6]. Fuzzy controllers provide improved harmonic compensation, reduced steady state error, and better DC link voltage regulation compared with conventional PI controllers. The method also performs effectively under parameter variations and nonlinear load conditions [1]. Artificial neural network based controllers are widely applied in intelligent SAPF systems because of their adaptive learning capability and fast processing speed. ANN controllers are trained using system data to identify harmonic components and generate compensating signals automatically [3]. ANN based SAPF provide accurate current tracking, reduced THD and improved transient response under dynamic operating conditions. These controllers are suitable for renewable energy integrated systems and smart grid applications. Whereas training complexity and computational burden increases implementation cost [17]. Sliding Mode Control is an advanced nonlinear control technique used in SAPF applications to achieve robust performance under system uncertainties and disturbances. Sliding mode control forces system states to follow a predefined sliding surface therefore maintains stable operation during parameter variations [12]. SMC provides excellent dynamic response, fast convergence and strong disturbance rejection capability. The method also improves harmonic compensation under fluctuating load conditions. Whereas chattering effects due to high-frequency switching remain a major limitation [4]. Optimization Based Controllers Recent research focuses on optimization based control techniques for automatic tuning of SAPF controller parameters and DC link

voltage regulation. Optimization algorithms improves controller accuracy, convergence speed and harmonic compensation performance. Particle swarm optimization (PSO) is inspired by the social behavior of birds and fish schools. The algorithm optimizes controller gains by minimizing objective functions such as THD and DC link voltage error [8]. PSO based SAPF provide fast convergence and improved harmonic compensation. Genetic Algorithm is an evolutionary optimization technique based on natural selection and genetic operations. GA improves PI controller tuning and reference current extraction in SAPF system [18]. The method reduces steady state error and improves power quality performance. Grey wolf optimization (GWO) is a recent bio inspired optimization technique based on the hunting behavior of grey wolves. GWO provides fast convergence therefore reduces computational complexity and gives better optimization capability compared with conventional methods [16]. GWO based SAPF achieve lower THD, improved power factor correction and stable DC link voltage under varying load conditions. Conventional controllers such as HCC and SPWM offer simple implementation and acceptable harmonic compensation. Intelligent controllers like FLC, ANN and SMC gives improved adaptive performance and robustness under transient operating conditions. Optimization based controllers like PSO, GA and GWO further enhance controller tuning accuracy and transient response. Recent studies indicate that intelligent optimization based controllers achieve superior harmonic mitigation, lower THD, better dc-link voltage regulation and enhanced system stability in renewable energy integrated distribution systems and smart grids [11].

6. CONCLUSIONS

This paper presented a comprehensive review of Shunt active power filters (SAPFs) for harmonic mitigation and reactive power compensation in modern electrical distribution systems. The study discussed SAPF operating principles, configurations, reference current extraction methods and various control approaches including HCC, SPWM, FLC, ANN, SMC and optimization based controllers. The review showed that intelligent optimization techniques such as PSO, GA and GWO significantly decrease total harmonic distortion (THD), improves power factor, DC link voltage regulation and transient response. The application of SAPF with smart grids and microgrids was also examined. The study concluded that SAPF provide superior power quality improvement compared with

conventional passive filtering techniques. Future research should focus on adaptive intelligent control, real time implementation, reduced computational complexity and cost effective SAPF design for next generation power systems.

REFERENCES

1. Mohit Bajaj and Amit Kumar Singh. Grid integrated renewable dg systems: A review of power quality challenges and state-of-the-art mitigation techniques. *International Journal of Energy Research*, 44(1):26–69, 2020.
2. Soumya Ranjan Das, Prakash Kumar Ray, Arun Kumar Sahoo, Somula Ramasubbareddy, Thanikanti Sudhakar Babu, Nallapaneni Manoj Kumar, Rajvikram Madurai Elavarasan, and Lucian Mihet-Popa. A comprehensive survey on different control strategies and applications of active power filters for power quality improvement. *Energies*, 14(15):4589, 2021.
3. Dipak Kumar Dash and Pradip Kumar Sadhu. A review on the use of active power filter for grid-connected renewable energy conversion systems. *Processes*, 11(5):1467, 2023.
4. Juntao Fei, Shenglei Zhang, and Jian Zhou. Adaptive sliding mode control of single-phase shunt active power filter. *Mathematical Problems in Engineering*, 2012(1):809187, 2012.
5. Zineb Hekss, Abdelmajid Abouloifa, Ibtissam Lachkar, Abdelali El Aroudi, Salwa Echalih, Mohammed Al-Numay, and Fouad Giri. Advanced nonlinear controller of single-phase shunt active power filter interfacing solar photovoltaic source and electrical power grid. *International Transactions on Electrical Energy Systems*, 31(12):e13237, 2021.
6. Srilakshmi Koganti, Krishna Jyothi Koganti, and Surender Reddy Salkuti. Design of multi-objective-based artificial intelligence controller for wind/battery-connected shunt active power filter. *Algorithms*, 15(8):256, 2022.
7. P Rajesh Kumar, Chapala Shravani, M Rajitha, and Ch Lokeshwar Reddy. A review of emerging techniques for power quality improvement in renewable energy integration. In *E3S Web of Conferences*, volume 616, page 03029. EDP Sciences, 2025.
8. Ravinder Kumar, Hari Om Bansal, Aditya R Gautam, Om Prakash Mahela, and Baseem Khan. Experimental investigations on particle swarm optimization based control algorithm for shunt active power filter to enhance electric power quality. *IEEE Access*, 10:54878–54890, 2022.
9. Roberto Langella, Alfredo Testa, Et Alii, et al. Ieee recommended practice and requirements for harmonic control in electric power systems. In *IEEE recommended practice*. IEEE, 2014.
10. Xiaodong Liang. Emerging power quality challenges due to integration of renewable energy sources. *IEEE Transactions on Industry Applications*, 53(2):855–866, 2016.
11. An Luo, Qianming Xu, Fujun Ma, and Yandong Chen. Overview of power quality analysis and control technology for the smart grid. *Journal of Modern Power Systems and Clean Energy*, 4(1):1–9, 2016.
12. Majid Nayeripour and Taher Niknam. Nonlinear sliding mode control design for shunt active power filter with the minimization of load current. *World Applied Sciences Journal*, 4(1):124–132, 2008.
13. Anand Panchbhai, Nikunj Prajapati, and Shreya Parmar. Comparative study of reference current generation for shunt active power filter. In *2017 International Conference on Power and Embedded Drive Control (ICPEDC)*, pages 381–386. IEEE, 2017.
14. Mihaela Popescu, Alexandru Bitoleanu, Constantin Vlad Suru, Mihaita Linca, and Laurentiu Alboteanu. Shunt active power filters in three-phase, three-wire systems: A topical review. *Energies*, 17(12):2867 2024.
15. Pratap Sekhar Puan, Pravat Kumar Ray, and Srikanta Pottapinjara. Performance analysis of shunt active filter for harmonic compensation under various non-linear loads. *International Journal of Emerging Electric Power Systems*, 22(1):21–29, 2021.
16. Koganti Srilakshmi, Praveen Kumar Balachandran, Tangirala Murali Krishna, Harivardhini Subhadra, Subhav Singh, and Sangeetha Kannan. Design of green hydrogen-based shunt active power filter for distribution networks using a modified red-tailed hawk algorithm. *Measurement and Control*, page 00202940261434653, 2026.
17. KR Sugavanam, R Jeyabharath, P Veena, et al. Convolutional neural network-based harmonic mitigation technique for an adaptive shunt active power filter. *Automatika: časopis za automatiku, mjerenje,elektroniku, računarstvo i komunikacije*, 62(3-4):471–485, 2021.
18. Hien Phan Thanh, Huyen Dang Van, An Nguyen Duy, and Cuong Nguyen Duy. Optimizing parameters of the shunt active power filter using genetic algorithm. In *2017 9th International Conference on Knowledge and Systems Engineering (KSE)*, pages 233–238. IEEE, 2017.