

# Advanced Control Strategies and Intelligent Optimization Techniques for Shunt Active Power Filters: A Comprehensive Review

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**Abstract:** *The rapid expansion of renewable energy systems, distributed generation, electric vehicle (EV) charging infrastructure, and nonlinear power electronic loads has intensified power quality challenges in modern electrical distribution networks. Harmonic distortion, reactive power demand, voltage fluctuations, current imbalance, and poor power factor have become major concerns affecting system reliability, efficiency, and compliance with international power quality standards. Among various compensation technologies, Shunt Active Power Filters (SAPFs) have emerged as one of the most effective solutions for mitigating current harmonics and improving power quality under dynamic operating conditions. Recent research has focused on developing advanced control strategies, intelligent optimization algorithms, adaptive controllers, and improved converter topologies to enhance SAPF performance. This review presents a comprehensive analysis of recent developments in SAPF technologies, including synchronous reference frame (SRF) control, instantaneous reactive power (p-q) theory, Direct-Quadrature (d-q) control, fuzzy logic control (FLC), adaptive neuro-fuzzy inference systems (ANFIS), particle swarm optimization (PSO), modified complex coefficient filters (MCCF), Adaline-based control (ABC), and nonlinear PID (NPID) controllers. Additionally, renewable-energy-integrated SAPFs, modular converter architectures, unified power quality conditioners (UPQCs), and real-time hardware validation techniques are critically reviewed. The comparative analysis indicates that intelligent and optimization-based control techniques provide superior harmonic mitigation, faster transient response, enhanced DC-link voltage regulation, and improved compliance with IEEE-519 standards. Finally, current research gaps and future opportunities involving artificial intelligence, digital twins, adaptive optimization, and next-generation semiconductor technologies are discussed.*

**Keywords:** Shunt Active Power Filter (SAPF); Power Quality; Intelligent Control; Harmonic Mitigation; Artificial Intelligence; Total Harmonic Distortion (THD)

## I. INTRODUCTION

The widespread deployment of renewable energy sources, distributed generation, electric vehicle charging systems, and nonlinear power electronic devices has significantly transformed modern electrical distribution systems. Although these technologies contribute to sustainable energy development and improved energy efficiency, they also introduce several power quality issues, including harmonic distortion, reactive power imbalance, voltage fluctuations, poor power factor, and current unbalance. These disturbances negatively impact electrical equipment, increase system losses, reduce operational efficiency, and create challenges in meeting international power quality standards such as IEEE-519.

Shunt Active Power Filters (SAPFs) have become one of the most effective solutions for mitigating harmonics and improving power quality. Unlike conventional passive filters, SAPFs dynamically inject compensating currents at the Point of Common Coupling (PCC), enabling real-time harmonic cancellation, reactive power compensation, and load



balancing under varying operating conditions. Their fast response, adaptability, and ability to compensate multiple power quality disturbances simultaneously have made them essential components of modern smart grids, renewable energy systems, and electric vehicle charging infrastructure.

Recent advancements in SAPF research have shifted from conventional proportional-integral (PI) controllers toward intelligent and adaptive control techniques. Advanced methods including synchronous reference frame (SRF) control, instantaneous reactive power (p-q) theory, Direct-Quadrature (d-q) control, fuzzy logic control (FLC), adaptive neuro-fuzzy inference systems (ANFIS), particle swarm optimization (PSO), nonlinear PID (NPID), and machine learning-assisted optimization have demonstrated superior harmonic compensation, enhanced transient performance, and robust operation under uncertain load conditions. Furthermore, modular converter topologies, renewable-energy-assisted DC-link regulation, and real-time hardware validation have expanded the practical applicability of SAPFs in modern electrical systems.

This review paper provides a comprehensive overview of recent developments in advanced SAPF control strategies, intelligent optimization techniques, renewable energy integration, converter topologies, and experimental validation methods. The paper critically compares existing approaches, identifies current research gaps, and discusses emerging technologies that can enable the next generation of intelligent power quality compensation systems.

## **II. LITERATURE REVIEW**

Sunitha P; M. Gengaraj; Lourdhu Jone Avila A; Snowin Rubiha J [1] This paper presents the modeling, control, and performance analysis of a grid-tied solar photovoltaic (PV) system integrated with a shunt active power filter (SAPF) using a d-q reference frame control strategy. This kind of system typically consists of a PV array, a DC-DC boost converter (allowing harvesting maximum energy available), and a three-phase voltage-source inverter connected to the utility grid. To control the inverter's current and sustain both the DC-link voltage and reactive power/harmonic compensation, a synchronous-reference-frame-based Direct-Quadrant (d-q) control scheme is developed in connection with a phase-locked-loop. Using MATLAB/Simulink for modelling and simulating the entire system, simulations of the proposed design showed that by combining PV sources and SAPF operation, the harmonic distortion level was significantly reduced, thus allowing both the improved quality of energy and compliance with the IEEE 519 standard(s) concerning harmonics for both current and voltage. This method provides a simple, low-cost, and effective option for small and medium-scale PV systems connected to the grid.

Amjad Ali Khan Surque; Mohd Ilyas; Sheeraz Kirmani [2] The increasing of nonlinear loads, distributed generation, and renewable energy sources connection brought many challenges to power quality in electrical networks. This review paper summarizes recent advances in Active Power Filters (APF), which are used to improve power quality in electrical networks. The paper covers advances in APF topologies, including modular and reduced-switch designs, and control algorithms, such as Model Predictive Control, Repetitive and Resonant Controllers, and Adaptive Observer-Based Methods. It also explores the application of artificial intelligence for adaptive tuning and optimization. The paper also shows cases of hybrid APFs, they coordinated with grid-tied converters in microgrids, and the use of wide-bandgap devices (SiC/GaN) for improved efficiency. It identifies challenges like achieving cost-effective and reliable solutions that meet grid standards, outlines future research directions, including scalable modular topologies, robust adaptive control, and standardized performance evaluation methods. This survey serves as comprehensive reference for recent advancements in APFs practical application.

Bandar Alshehri; Turki Omar Al-Shehri; Mohanna Usama Mohanna; Abdulwahab Ateeq [3] Power quality degradation in low-voltage commercial and industrial electrical systems has intensified due to the increasing penetration of nonlinear and electronically controlled loads, resulting in excessive harmonic distortion, poor power factor, and voltage profile deviations. These disturbances lead to higher power losses, accelerated equipment aging, and challenges in complying with international power quality standards. This paper proposes a modular power quality enhancement system for large commercial buildings and industrial facilities, combining a shunt active power filter (SAPF) with a detuned reactor/capacitor compensation unit to simultaneously mitigate current harmonics and compensate reactive



power. The proposed architecture is modeled and evaluated in MATLAB/Simulink, with real-time validation conducted using an OPAL-RT-based simulation platform. Performance assessment is carried out under multiple nonlinear load scenarios representative of commercial and industrial operating conditions, focusing on key power quality indices including total harmonic distortion (THD), power factor, and voltage profile regulation. Simulation results demonstrate a significant reduction in current THD and an improvement in power factor to near-unity operation, confirming the effectiveness, scalability, and suitability of the proposed modular solution for enhancing power quality in modern commercial and industrial low-voltage power distribution systems, thereby improving energy efficiency, reducing grid losses, and supporting climate-sustainable next-generation power grids.

Soundarrajan A; Balachander K; Nagamani Prabu A; Jayanthi G [4] Power quality (PQ) has become a significant concern in modern electrical networks due to the increasing use of nonlinear loads and renewable energy systems, which introduce current and voltage harmonics. To address these issues, this study presents a Shunt Active Power Filter (SAPF) controlled by a Fuzzy Logic Controller (FLC) for effective PQ improvement. The system integrates both conventional PI and FLC schemes to regulate the DC-link voltage of the Voltage Source Inverter (VSI). Using instantaneous reactive power ( $p-q$ ) theory, reference currents are generated, and a hysteresis current controller provides fast and accurate switching for the VSI. The MATLAB/Simulink-based model is tested under varying load and harmonic conditions. Results show that the FLC-based SAPF achieves better transient performance, reduced Total Harmonic Distortion (THD), and improved voltage stability compared to the PI-controlled system. Additionally, power quality analysis of a single-phase AC-DC converter feeding a DC motor demonstrates the controller's capability to maintain stable operation under different load and firing conditions.

Sakib Ahmad Dar; Ragavan K [5] Numerous control strategies have been developed for Shunt Active Power Filter (SAPF). Among them, the recently introduced Modified Complex Coefficient Filter (MCCF) and Adaline-Based Control (ABC) are compared in this study. A comprehensive simulation and experimental validation of the ABC technique under distorted voltage and the MCCF-based technique under unbalanced and distorted voltage conditions has been carried out—an aspect that has not been previously explored in the literature. These techniques differ in their approach to reference current calculation, computational complexity, and adaptability to different operating conditions. This article thoroughly examines these control techniques, focusing on their accuracy, response time, dynamic performance, and robustness in maintaining power quality at the Point of Common Coupling (PCC). The findings contribute to a better understanding of SAPF control strategies, aiding in the selection of optimal techniques for power quality improvement.

Mohammed Aslam A. K.; Samina T. [6] Power quality issues have become increasingly significant due to the widespread use of nonlinear power electronic converter loads, which lead to voltage and current distortions in power distribution systems. To address these challenges, the Unified Power Quality Conditioner (UPQC) has emerged as a comprehensive solution, incorporating series and shunt active filters connected through a common DC-link capacitor. A crucial aspect of UPQC performance lies in the regulation of the DC-link voltage, typically managed by a conventional Proportional-Integral (PI) controller. However, PI controllers often fall short in dynamic conditions due to fixed gain values, resulting in inadequate voltage regulation and reduced system reliability. To overcome these limitations, this study proposes an intelligent control strategy using an Adaptive Neuro-Fuzzy Inference System (ANFIS) for DC-link voltage regulation in a customized UPQC. The ANFIS controller enhances performance by combining adaptive learning and fuzzy reasoning, enabling more accurate and robust control. The proposed system is modeled and simulated using MATLAB/Simulink, where its effectiveness in improving power quality and addressing the shortcomings of classical controllers is demonstrated through comprehensive performance analysis.

Jotirmoy Samanta; Ralli Sangno; Rajen Pudur [7] Power quality issues in a single-phase system are equally important as in the case of a three-phase system, especially in rural areas where single-phase applications are prominent. Shunt Active Power Filter (SAPF) is a compelling device for power quality improvement. This paper proposes a modified Synchronous Reference Theory (SRF) for solving multiple power quality issues in single-phase systems. Harmonics, Power Factor (PF), and DC link capacitor voltage regulation are addressed simultaneously. The model is designed in



MATLAB and tested with various loading configurations. A nonlinear PID (NPID) controller reduces the system's peaks and settling time. A good performance of the proposed modified SRF scheme is observed and presented. The proposed control scheme has been validated in real time using OPAL-RT (OP4510).

Syahr Azalia Ab Shukor; Wahidah Abd Halim; Atikah Razi [8] This paper presents an optimal tuning of a Proportional-Integral (PI) controller for a shunt active power filter (SAPF) using the Particle Swarm Optimization (PSO) approach for nonlinear load applications. The widespread use of power electronics in home, commercial, and industrial sectors introduces significant harmonic distortion, which degrades power quality and causes inefficiencies in electrical systems. Conventional PI controllers are commonly used for harmonic mitigation in SAPFs but suffer from suboptimal performance under varying load conditions due to difficulty in parameter tuning. This research is motivated by the need to enhance the performance of SAPFs and improve power quality by reducing harmonic distortion. By leveraging the PSO algorithm, the PI controller parameters are optimally tuned to improve SAPF performance. The proposed PI-PSO approach is evaluated through MATLAB/Simulink simulations, demonstrating a significant reduction in Total Harmonic Distortion (THD) from 22.06% without a filter to 3.66%, compared to 4.87% using conventional methods. These results highlight the effectiveness of the PI-PSO technique in achieving superior power quality, making it a promising solution for mitigating harmonics in systems with nonlinear loads.

Vikas Kumar Sharma; Vineet Sharma; Vishal Rohela [9] In distribution systems, the load has been an unexpected increase or decreases and it is like as nonlinear loads so the load draw non-sinusoidal currents from the utility mains and causes the reactive power load, harmonics and high neutral currents that occurs the power quality problem in electrical distribution systems. Most power quality problem created in distribution systems are due to the nonlinear load and fast switching of power electronic devices. Shunt active filter based on current controlled PWM converters are seen as a most viable solution. In this paper, a shunt active power filter (SAPF) with PI controller is used. Current controlled voltage source converter topology is used in this SAPF. The quality and performance of SAPF depend on design of power converter, DC voltage control strategy, the method implemented to generate reference command and generation of switching pulses. For reference command generation Unit Active Power Component Theory (APCT) is used and for DC voltage control PI controller is used. A hysteresis current controller is used to generate the switching pulses. The detailed simulation study of work has been carried out in MATLAB/Simulink environment. Keywords—Power Quality, SAPF, Distribution System, APCT.

Mohammed Nadeem Iqbal; Asini Kumar Baliarsingh; Pratap Sekhar Puan [10] Power Quality (PQ) in distribution system can be refer to voltage quality at the point of common coupling (PCC) and hence it is important to maintain the voltage at PCC. In this work, a Shunt Active Power Filter (SAPF) is designed to inject an accurate filtering signal to maintain the voltage ideal and a novel controller implementation is required for the said purpose. The controller algorithm combines Instantaneous Reactive Power Theory (IPRT) and D-Q Transformation methodology to provide accurate reference signal which is one of the important parameter for filtration process of SAPF, error signal between references and actual is fed to hysteresis band to deliver the required switching pulses using hysteresis current control (HCC) technique. The effectiveness of the proposed SAPF with the developed controller is verified with the distribution system by connecting a nonlinear load in it. The performance is verified with three conditions such as balanced ideal source, unbalanced source and finally distorted signal with MATLAB/SIMULINK platform.

### III. RESEARCH GAPS AND FUTURE RESEARCH DIRECTIONS

Although substantial progress has been made in SAPF control technologies, several important challenges remain:

Conventional PI-based controllers exhibit limited adaptability under rapidly changing operating conditions.

Artificial intelligence techniques are still not widely adopted for real-time harmonic prediction and adaptive control.

Large-scale experimental validation using practical distribution systems remains limited.

Most studies optimize only harmonic compensation, while simultaneous optimization of voltage stability, reactive power, energy efficiency, and converter losses is rarely addressed.

Cybersecurity and communication reliability of digitally controlled SAPFs in smart grids require further investigation.



Digital twin technology for predictive monitoring and condition-based maintenance has received limited attention. Coordination among multiple SAPFs operating within interconnected microgrids remains largely unexplored. Wide-bandgap semiconductor devices (SiC and GaN) require additional research for high-frequency, high-efficiency SAPF applications. Future research should focus on reinforcement learning-based adaptive control, explainable artificial intelligence, digital twin-assisted monitoring, federated learning, coordinated multi-SAPF control, edge computing, predictive maintenance, and hardware-in-the-loop validation for next-generation intelligent power quality compensation systems.

#### IV. CONCLUSION

Shunt Active Power Filters have become indispensable components for improving power quality in modern electrical distribution systems containing renewable energy sources, nonlinear loads, and electric vehicle charging infrastructure. This review critically examined recent developments in advanced SAPF control algorithms, intelligent optimization techniques, modular converter topologies, renewable energy integration, and experimental validation methods. The reviewed studies demonstrate that intelligent controllers such as Fuzzy Logic Control, ANFIS, Particle Swarm Optimization, nonlinear PID, Modified Complex Coefficient Filter, and Adaline-Based Control significantly outperform conventional PI controllers by providing superior harmonic mitigation, faster transient response, improved DC-link voltage regulation, and enhanced system stability. Despite these advances, challenges associated with adaptive intelligence, coordinated multi-filter operation, cybersecurity, digitalization, and large-scale implementation remain active research areas. Future SAPF systems are expected to leverage artificial intelligence, digital twins, advanced semiconductor technologies, and real-time optimization to achieve autonomous, highly efficient, and reliable power quality management for next-generation smart power systems.

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