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A Comprehensive Review of Shunt Active Power Filter Technologies for Power Quality Improvement in Renewable Energy Systems and Electric Vehicle Charging Applications

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ABSTRACT

The rapid integration of renewable energy sources (RES), electric vehicle (EV) charging infrastructure, and nonlinear power electronic loads has introduced significant power quality challenges in modern electrical distribution systems. These challenges include harmonic distortion, reactive power imbalance, voltage fluctuations, poor power factor, and current unbalance, which adversely affect system efficiency, reliability, and equipment lifespan. Shunt Active Power Filters (SAPFs) have emerged as one of the most effective solutions for mitigating harmonic currents and improving overall power quality by injecting compensating currents at the point of common coupling (PCC). This review presents a comprehensive analysis of recent developments in SAPF technologies with emphasis on control strategies, converter topologies, renewable energy integration, EV charging applications, damping techniques, and intelligent control algorithms. Various control approaches, including Proportional-Integral (PI), Hysteresis Current Control (HCC), Sinusoidal Pulse Width Modulation (SPWM), Synchronous Reference Frame (SRF), instantaneous power theory (p-q theory), and nonlinear PID controllers, are critically examined. Furthermore, recent advancements involving photovoltaic (PV)-supported SAPFs, wind-energy-assisted DC-link regulation, battery-integrated filters, and real-time experimental validation are reviewed. The analysis indicates that modern SAPF configurations substantially reduce Total Harmonic Distortion (THD), improve power factor, enhance system stability, and ensure compliance with IEEE-519 power quality standards. Finally, current research gaps and future research opportunities involving artificial intelligence, adaptive control, digital twins, and predictive power quality management are discussed.

KEYWORDS: *Shunt Active Power Filter (SAPF); Power Quality; Harmonic Mitigation; Electric Vehicle Charging; Renewable Energy Systems; Total Harmonic Distortion (THD).*

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I. INTRODUCTION

The increasing penetration of renewable energy sources, electric vehicle (EV) charging systems, and power electronic converters has fundamentally transformed modern electrical distribution networks. Although these technologies contribute significantly to sustainable energy development and carbon emission reduction, they also introduce considerable power quality challenges. Nonlinear loads associated with photovoltaic inverters, battery chargers, variable-speed drives, and EV charging stations generate harmonic currents, reactive power demand, voltage distortion, and current imbalance, which degrade overall system performance and reduce equipment lifespan. Maintaining acceptable power quality has therefore become a critical requirement for reliable and efficient operation of smart power systems.

Traditionally, passive filters were employed to mitigate harmonic distortion. However, passive filters

suffer from several limitations, including resonance problems, fixed compensation characteristics, bulky design, and poor adaptability to varying load conditions. These drawbacks have accelerated the development of Active Power Filters (APFs), particularly Shunt Active Power Filters (SAPFs), which dynamically inject compensating currents to eliminate harmonics, improve power factor, balance load currents, and enhance voltage stability.

Recent research has focused on improving SAPF performance through advanced control algorithms, intelligent optimization techniques, renewable-energy-assisted DC-link regulation, battery energy storage integration, and modern converter topologies. Various control techniques such as Proportional-Integral (PI) control, Hysteresis Current Control (HCC), Sinusoidal Pulse Width Modulation (SPWM), Synchronous Reference Frame (SRF), instantaneous power theory (p-q theory), nonlinear PID control, and adaptive damping methods have been proposed to improve harmonic compensation under dynamic operating conditions. Furthermore, the integration of photovoltaic systems, wind energy systems, and battery storage with SAPFs has enhanced both energy efficiency and power quality while reducing dependency on external power sources.

This review paper presents a comprehensive analysis of recent developments in SAPF technology for power quality improvement. It critically examines various control methods, converter configurations, renewable energy integration strategies, EV charging applications, and experimental validation techniques. In addition, the review identifies current research challenges and discusses future research directions aimed at developing intelligent, adaptive, and highly efficient power quality compensation systems for next-generation smart grids.

II. LITERATURE REVIEW

Leslie Odartei Lamptey [1] The increasing penetration of power-electronic loads in modern power systems has intensified current harmonic distortion and degraded power quality at the point of common coupling (PCC). This paper investigates harmonic mitigation in a balanced three-phase system using a shunt active power filter (SAPF) implemented in MATLAB/Simulink. The nonlinear load is represented by a synthesized three-phase harmonic-current model to provide controlled and repeatable distortion conditions, while the SAPF is realized as a practical voltage source inverter (VSI) with a DC-link capacitor, pulse-width modulation (PWM), and coupling inductors. A current-reference generation method based on harmonic extraction from the load current is used to drive the compensating current injected by the filter. In addition to steady-state evaluation, a dynamic test is introduced through a step increase in harmonic content at 0.15 s to assess the transient response. Simulation results show that the source current total harmonic distortion (THD) is reduced from 34.57% before compensation to 1.31% after compensation, corresponding to a 96.21% reduction. The results confirm that the proposed VSI-based SAPF effectively suppresses harmonic distortion and significantly improves source-current quality under nonlinear loading conditions.

Sejal Puri; Namra Joshi; Sejal Patil; Hemangi Thakare [2] The increment in integration of renewable energy sources & nonlinear loads in micro grids give rise to power quality issues like harmonic distortion, reactive power imbalance & poor power factor. These problems have a significant impact on reliability & performance of power system. In micro grids, nonlinear loads produce large-scale current harmonics, voltage distortion, and also have poor power factor, which in turn affects system reliability and performance. To put forth solutions to these issues, a MATLAB/Simulink model that included a three-phase AC source, a nonlinear load, a PV-supported DC link, and a SAPF, which was controlled via PI and hysteresis current strategies. This paper explains how SAPF works. The SAPF cancels out the unwanted currents at the Point of Common Coupling and enhances the waveform quality by injecting compensating currents. In the simulations, state-of-the-art performance was demonstrated through the considerably lower THD, along with improvements in the power factor and in the sinusoidal shape of the source currents. As a result, the source currents were in compliance with the IEEE-519 standard of performance. Therefore, concludes that the SAPF shapes power quality and solidifies the micro grid's stability with hybrid renewable energies. In addition, power factor improves and reduces harmonic as well.

Pradosh Kumar Mishra; Sarita Samal; Chitralekha Jena; Prasanta Kumar Barik [3] Power quality (PQ) refers to any irregularity in the voltage or current of an electrical system that disrupts or interferes with the proper functioning of electrical or electronic devices. Traditional methods involved using passive filters (PFs) to address harmonic problems. However, several issues with PFs led to the creation of active filtering methods. This study examines the system's PQ and investigates the usage of a shunt active power filter (SAPF) to diminish harmonics. Three control methods are used by the SAPF: one to generate reference current, another to produce switching pulses, and a third to regulate the DC-link voltage (VDC). The efficiency of the SAPF in producing

sufficient compensating current is influenced by these regulatory loops. The VDC has a direct effect on the performance of SAPFs. In light-load conditions, the VDC might become high, causing switching noise and losses. Thus, in this article, as a solution to the aforesaid problem, a well-managed wind energy system (WES) is incorporated across the DC-link side of the SAPF, which will maintain the VDC under any loading situations. This study uses the MATLAB Simulink platform, and simulation results obtained confirm the effectiveness of the WES-based SAPF system.

Priyashree S; Madhu S; Shruti V Joshi [4] This paper investigates the improvement of power quality in Electric Vehicles (EV) charging systems through the implementation of a Shunt Active Power Filter (SAPF). The SAPF is regulated using a Proportional-Integral (PI) controller combined with Sinusoidal Pulse Width Modulation (SPWM) and Hysteresis Current Control strategies. EV chargers operate as non-linear loads because of their power electronic interfaces, which introduce harmonic distortion and adversely affect the performance of the distribution network. The proposed SAPF system is modeled and analyzed using MATLAB/Simulink to mitigate current harmonics and enhance power factor performance. A comparative evaluation of SPWM and Hysteresis control techniques is conducted with respect to Total Harmonic Distortion (THD) and transient response characteristics. During the analysis, the implementation of SPWM method current THD provided 49% reduction, while HCC method an approximate reduction of 85%. Simulation outcomes indicate that both control approaches significantly improve current waveform quality: however, Hysteresis control offers a quicker dynamic response, while SPWM ensures smoother switching behavior with lower current ripple. The study confirms that the SAPF is an effective solution for maintaining improved power quality in EV charging applications.

Weiqin Zhang; Han Cai; Hongce Hu; Weiqin Zhang; Ke Dai; Xinyan Yu [5] This article focuses on the resonance suppression problem of LCL-type SAPF under different grid impedance, and analyzes the principles and performances of passive and active damping. First, transfer function of the LCL filter is derived, and the resonance characteristics are analyzed according to the Bode diagram. The performance of the passive damping strategy, including system stability, steady-state error, and dynamic response, is studied with emphasis on different grid impedances. The root locus about Lg is used to intuitively display the variation trend of system stability. On this basis, an active damping strategy based on grid current feedback is introduced. Through the equivalent transformation of the control block diagram, its equivalent virtual impedance characteristics are analyzed, and a low-pass filter is adopted to artificially introduce phase lag at the resonance frequency, thereby suppressing the LCL resonance and improving the tracking capability of the SAPF harmonic current reference.

Mohammed Zaid Khan; Seema Agrawal [6] Power quality issues have become a significant concern in solar photovoltaic (PV) systems due to the intermittent nature of solar irradiance. In this study, a novel approach for optimizing power quality in PV systems using a Pulse Width Controlled Shunt Active Power Filter (PWC-SAP F) is proposed. The PWC-SAPF is equipped with a Perturbed and Observed Maximum Power Point Tracking (MPPT) algorithm to ensure efficient power extraction from the PV array. The effectiveness of the proposed system is demonstrated through simulation studies on PSIM software under various operating conditions. The results show that the PWC-SAPF with the Perturbed and Observed MPPT algorithm significantly improves the power quality by mitigating harmonics and reactive power fluctuations, thereby enhancing the overall performance of the PV system. Overall, the proposed approach offers a promising solution for optimizing power quality in solar PV systems.

Aléssio Trajano Sousa Soares Santos; Cursino Brandão Jacobina; Jean Torelli Cardoso [7] This paper proposes a modified configuration of a three-phase shunt active power filter (SAPF), employing halfbridge cells per phase combined with a three-phase converter, designed for four-wire electrical systems. The converter topology reduces the number of semiconductor devices by eliminating legs through clamping techniques, while also mitigating harmonic distortion and compensating reactive and harmonic power in four-wire systems. A scalar PWM modulation technique is applied for switching control. Simulation and closed-loop experimental results under unbalanced load conditions demonstrate the effectiveness of the proposed solution in maintaining unity power factor and balancing the DC link voltages.

Darcy d'Apresentacao; Ricardo Luis; Paulo Gamboa [8] This work presents the study and implementation of a three-phase four-wire shunt active power filter applied to electrical network, aiming to reduce the power quality problems associated with current harmonic distortion, power factor and unbalance. The determination of the compensation currents reference is performed using the instantaneous powers theory (p-q theory). The results obtained with the

methodology employed are proven through numerical simulations and validated by experimental data using a 10kVA prototype implemented in the ISEL Electrical Machines Laboratory. The use of the shunt active power filter provided the reduction of the harmonic content of the non-linear loads employed in the tests, as well as the power factor improvement to practically unity values, reduced current in the neutral wire, and unbalance of the currents. This simulation analysis shows that this system complies with energy quality standards.

Jotirmoy Samanta; Ralli Sangno; Rajen Pudur [9] 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).

Aboubakr Brahimi; Djallel Kerdoun; Abderraouf Boumassata [10] This paper addresses the design and control of a PV and battery integrated shunt active power filter, The perturb and observe algorithm was used to extract the maximum power from the PV system in changing environmental conditions, and a battery was used as an energy storage device for a stable and reliable source of energy, the control of the shunt active power filter was designed in the synchronous reference frame using a cascade control schema and simulated using MATLAB Simulink software, and the obtained results show the effectiveness of the proposed system in mitigating the power quality issues with an excellent performance.

III. RESEARCH GAPS AND FUTURE RESEARCH DIRECTIONS

Although significant progress has been achieved in SAPF technology, several research challenges remain:

- Most studies evaluate SAPF performance only under simulation environments, while large-scale experimental validation remains limited.
- Adaptive and self-learning control strategies for highly dynamic operating conditions are still insufficient.
- Artificial intelligence and machine learning techniques have not been widely integrated into SAPF control for predictive harmonic compensation.
- Cybersecurity aspects of digitally controlled SAPFs in smart grids remain largely unexplored.
- Coordination between SAPFs, distributed energy resources, and electric vehicle charging infrastructure requires further investigation.
- Real-time optimization of multiple power quality indices, including harmonic distortion, voltage stability, reactive power, and frequency regulation, has received limited attention.
- Digital twin technology for predictive maintenance and online monitoring of SAPFs is still in its infancy.
- Few studies investigate coordinated operation of multiple SAPFs in interconnected microgrids and smart distribution networks.

Future research should focus on AI-assisted adaptive control, reinforcement learning-based harmonic compensation, digital twin-enabled monitoring, edge computing, coordinated multi-SAPF control, hardware-in-the-loop testing, and integration with Industry 4.0 technologies to develop intelligent and autonomous power quality management systems.

IV. CONCLUSION

Shunt Active Power Filters have become one of the most effective technologies for mitigating harmonic distortion and improving power quality in modern electrical systems integrating renewable energy sources, electric vehicle charging stations, and nonlinear loads. This review critically analyzed recent developments in SAPF control strategies, converter topologies, renewable energy-assisted compensation, damping techniques, and real-time implementation. The reviewed studies demonstrate that advanced control methods such as PI, Hysteresis Current Control, Synchronous Reference Frame control, instantaneous power theory, nonlinear PID controllers, and renewable-energy-supported DC-link regulation significantly improve harmonic suppression, power factor correction, voltage stability, and compliance with IEEE-519 standards. Despite these advances, challenges related to adaptive intelligence, cybersecurity, experimental validation, coordinated multi-device control, and predictive maintenance remain open research areas. Future SAPF systems are expected to integrate artificial intelligence, digital twins, advanced optimization algorithms, and real-time monitoring technologies to achieve autonomous, reliable, and highly efficient

power quality enhancement for next-generation smart grids.

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