International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Adaptive Control Strategies for Power Quality Improvement in Renewable Energy and Grid-Connected Systems: A Review of SAF, PV, and DSTATCOM Technologies

Shubham Rajendra Ekatpure

Global Supply Chain, Kulicke and Soffa Horsham, USA
srekatpure@gmail.com

Abstract
This study reviews the implementation and effectiveness of advanced control algorithms in mitigating power quality issues such as harmonic distortion, reactive power imbalance, and unbalanced loads in electrical distribution systems. Various systems, including shunt active filters (SAF), grid-connected photovoltaic (PV) systems, and distribution static compensators (DSTATCOM), are evaluated for their ability to maintain sinusoidal current and improve grid stability. The review focuses on key methodologies, such as least mean square (LMS) algorithms, hyperbolic tangent function (HTF)-based controls, and dual voltage source inverters (DVSI). While these systems demonstrate significant improvements in power quality, limitations such as sensitivity to external disturbances, scalability challenges, and reliance on precise sensor data are identified. The study highlights the need for more robust, scalable, and adaptive solutions to ensure reliable operation in diverse grid environments and presents future research directions to address these challenges.

Keywords*:* Power quality, Shunt active filter (SAF), Harmonic distortion, Reactive power compensation, Photovoltaic (PV) system, Least mean square (LMS) algorithm, Hyperbolic tangent function (HTF), Distribution static compensator (DSTATCOM), Dual voltage source inverter (DVSI), Grid stability

1. Introduction

The modern power grid faces significant challenges due to increasing reliance on distributed energy resources (DERs), nonlinear loads, and variable renewable energy sources like solar photovoltaic (PV) systems. These factors lead to power quality issues such as harmonic distortions, reactive power imbalance, and unbalanced loads, which affect the efficiency, stability, and reliability of electrical distribution systems. Consequently, researchers have developed advanced control algorithms and compensation systems, such as shunt active filters (SAF), distribution static compensators (DSTATCOM), and dual voltage source inverters (DVSI), to mitigate these issues. These systems, when integrated with real-time adaptive control mechanisms, aim to improve power quality by balancing current, reducing harmonic distortion, and maintaining optimal operation under dynamic conditions.

Recent studies have focused on the implementation of adaptive control algorithms for active filters, grid-connected inverters, and compensator systems to enhance power quality. These systems rely on various advanced algorithms, including least mean square (LMS), hyperbolic tangent functions (HTF), and instantaneous power theory, to address harmonics, balance loads, and regulate reactive power. However, despite the improvements offered by these control systems, limitations such as sensitivity to external disturbances, reliance on precise sensor data, and challenges in scalability have been identified. Therefore, there is a need for robust, scalable, and adaptive solutions that can maintain power quality across diverse grid conditions.

This study reviews key methodologies and findings from recent literature to evaluate the performance of these systems in improving power quality. It highlights the challenges and limitations encountered in real-world applications, particularly regarding scalability, sensor accuracy, and system robustness. Through this review, the study aims to provide insights into future research directions that can address these limitations, ensuring the practical viability of power quality enhancement systems across a wide range of grid environments.

2. Literature Review

Singh and Solanki (2009) discuss the implementation of an adaptive control algorithm for a shunt active filter (SAF), designed to mitigate power quality issues caused by harmonic currents, reactive power, and unbalanced loads. This system uses an adaptive-linear-element (Adaline)-based estimator and a least mean square (LMS) algorithm to ensure that the SAF can effectively balance system currents, maintaining sinusoidal source currents and unity power factor (Singh & Solanki, 2009). Their study's primary goal was to improve power quality in distribution networks by managing nonlinear loads. The data used included real-time current and voltage measurements from a three-phase load system. Sensors captured this data, which the adaptive control algorithm processed to adapt to varying load conditions, ensuring stable and reliable performance.

The methodology involved the use of an Adaline-based current estimator combined with an LMS algorithm to identify the fundamental frequency of the load current. A proportional-integral (PI) controller regulated the DC bus voltage of the voltage source converter (VSC), while a hysteresis-based pulse-width modulation (PWM) scheme controlled switching operations. Experimental validation conducted via the dSPACE DS1104 platform demonstrated the system's ability to reduce total harmonic distortion (THD) and improve system performance. However, limitations include the algorithm’s sensitivity to external disturbances and reliance on precise sensor measurements, which may pose challenges in noisy environments.

Jain et al. (2019) present a higher-order adaptive control system based on a hyperbolic tangent function (HTF) designed for a single-stage grid-interfaced photovoltaic (PV) system. The primary objective of their study was to improve power quality (PQ) by reducing harmonics, balancing loads, and compensating for reactive power, even under abnormal conditions such as load unbalancing, voltage sag/swell, and variable solar irradiation (Jain et al., 2019). Their method integrates a maximum power point tracking (MPPT) algorithm with an HTF control for enhanced response speed and power extraction from the PV system. In this research, the authors used both MATLAB/Simulink simulations and experimental validation on a laboratory prototype.

The data collected included grid current, load current, PV array power, and various system parameters under conditions of varying solar insolation and load perturbations. Their methodology involved using a variable learning-based HTF algorithm, which adjusted the convergence rate based on error signal autocorrelation, ensuring minimal mean square error (MSE) and a faster response. The control system was also integrated with a distribution static compensator (DSTATCOM) to balance loads, reduce harmonics, and maintain power quality at the point of common coupling (PCC). The results showed that the HTF-based control system effectively reduced THD within IEEE-519 standard limits, achieving 99.6% efficiency under varying load and solar conditions. However, further research is needed to address potential noise interference and ensure system stability in large-scale applications.

Tuyen and Fujita (2015) introduce a combined photovoltaic (PV) and active power filter (APF) system designed to improve power quality while supplying energy to nonlinear loads. Their system leverages instantaneous power theory to compensate for harmonics and reactive power while the PV system provides clean energy to the grid. The study's objective was to create a flexible solution that injects PV power into the grid while addressing power quality issues, making it effective even during periods of low or no PV generation (Tuyen & Fujita, 2015). The data used for the study was based on a simulation model created in MATLAB/SimPowerSystems, representing a 100 kW PV system combined with a two-level three-phase voltage source converter (VSC). The methodology involved implementing the APF function within the PV system using instantaneous power balance theory to ensure the VSC compensated for harmonic and reactive power. The results indicated that the combined PV-APF system effectively reduced THD and maintained a unity power factor, even when PV generation was low or absent. However, the system's performance is sensitive to correct tuning of control parameters, and further research is needed for large-scale implementations or extreme grid conditions.

Narayanan and Jayaprakash (2017) propose a single-stage, three-phase, four-wire grid-connected solar photovoltaic (SPV) system that incorporates various control algorithms to enhance power quality and grid stability. The system is designed to mitigate issues such as harmonic distortion, load balancing, power factor correction, and zero-sequence current in distribution systems (Narayanan & Jayaprakash, 2017). The study compares the performance of different control algorithms, including Synchronous Reference Frame Theory (SRFT), Instantaneous Reactive Power Theory (IRPT), and Least Mean Fourth (LMF). Data from simulation models of the SPV system with a 2 kW capacity integrated with a three-phase four-wire grid is utilized, and the system was evaluated under varying solar irradiation and unbalanced nonlinear loads. Various control techniques were applied to manage the SPV system’s voltage source converter (VSC). Results showed that the LMF-based algorithm outperformed the others, achieving a lower THD of 2.53% compared to 7.18% for IRPT and 10.70% for SRFT. However, the dependence of the LMF algorithm on adaptation constants for convergence speed and accuracy remains a potential limitation.

Manoj Kumar et al. (2015) present a grid-connected dual voltage source inverter (DVSI) system designed to improve power quality in microgrids. The system employs two inverters, one for injecting real power from distributed energy resources (DERs) and another for compensating harmonic distortion, reactive power, and unbalanced loads. The study focused on enhancing the reliability and efficiency of microgrids by sharing the load between two inverters, reducing stress on the main inverter and improving overall system performance (Manoj Kumar et al., 2015). Data from simulations and experimental studies validated their approach. The methodology employed the instantaneous symmetrical component theory (ISCT) to generate reference currents for both inverters. Results showed the DVSI system effectively reduced THD, maintained balanced currents, and enhanced reliability. However, further optimization of control parameters could improve performance in larger microgrid applications.

Singh et al. (2014) provide a comprehensive review of Distribution Static Compensators (DSTATCOM) topologies and their performance in improving power quality in three-phase systems. The paper examines various DSTATCOM configurations used for reactive power compensation, harmonic elimination, and load balancing (Singh et al., 2014). Data focuses on power quality issues in distribution systems and how

DSTATCOMs address these issues. Their methodology involved simulating and modeling different DSTATCOM topologies and control techniques, including instantaneous p–q theory and synchronous reference frame (SRF) theory. The results showed significant improvements in power quality, but challenges such as cost and complexity of implementation remain.

Latran, Teke, and Yoldas (2015) provide a review of Distribution Static Synchronous Compensator (DSTATCOM) systems used to mitigate power quality issues in distribution systems. Their review covers various configurations and control strategies of DSTATCOM devices that enhance PQ by managing voltage and reactive power (Latran et al., 2015). The authors analyze data from over 150 research publications to classify different DSTATCOM structures and control strategies. Their methodology categorizes DSTATCOMs based on power circuit structure and control strategies, emphasizing the role of DSTATCOMs in improving system stability under transient conditions. Results indicate that DSTATCOM can significantly enhance power quality, though more research is needed to develop cost-effective solutions.

3. Research Gaps

Singh and Solanki's (2009) study on the implementation of an adaptive control algorithm for a shunt active filter (SAF) demonstrates significant improvements in power quality by mitigating harmonics, reactive power, and unbalanced loads. However, the system is limited by its sensitivity to external disturbances, which can affect the accuracy of the current estimation. Although efficient, reliance on an Adaline-based estimator requires precise sensor data, making the system vulnerable in environments with high noise levels. Furthermore, while the hysteresis-based PWM scheme shows promise, its application in more dynamic and variable grid conditions may lead to stability issues due to rapid switching and potential energy losses.

Jain et al. (2019) present a higher-order adaptive control system based on a hyperbolic tangent function (HTF) for a grid-interfaced PV system, which effectively reduces harmonics and compensates for reactive power. However, one key limitation lies in the scalability of the control system. While the HTF-based control works well for small-scale applications, its performance under large-scale PV arrays or complex distribution networks remains untested. Additionally, the system's dependence on variable learning-based algorithms raises concerns about the convergence rate, particularly under high solar insolation fluctuations. Noise interference and system stability in real-world applications, especially under grid disturbances, need further exploration.

Tuyen and Fujita (2015) introduce a combined PV and active power filter (APF) system aimed at improving power quality while supplying energy to nonlinear loads. Despite the system's flexibility and effectiveness in reducing total harmonic distortion (THD) and maintaining a unity power factor, its performance is highly dependent on the accurate tuning of control parameters. Incorrect tuning could lead to inefficiencies, especially in large-scale implementations or during periods of extreme grid conditions. Additionally, the reliance on simulation models means that real-world performance could deviate, particularly in complex or less predictable operating environments where load characteristics frequently change.

Narayanan and Jayaprakash (2017) propose a single-stage, grid-connected solar photovoltaic (SPV) system that incorporates several control algorithms for improved power quality. A notable limitation in their study is the dependency on the Least Mean Fourth (LMF) algorithm, which, while effective in reducing THD, relies on precise adaptation constants for convergence. This reliance on finely tuned parameters makes the system less flexible, especially in larger or more dynamic grid environments. Moreover, the system's performance under real-world solar variations and unbalanced loads requires further validation, as the simulations used in the study may not fully account for the unpredictability of real-time conditions.

Manoj Kumar et al. (2015) propose a dual voltage source inverter (DVSI) system designed for microgrid applications. Although the system enhances power quality and reliability by sharing the load between two inverters, it requires further optimization to ensure smooth transitions between grid-sharing and grid-injecting modes. The current system may face challenges in handling larger microgrid networks where the coordination between multiple inverters becomes complex. Additionally, the ISCT-based control algorithm, though effective, may not be robust enough to handle rapid load changes or grid disturbances without causing inefficiencies or requiring frequent recalibration.

Singh et al. (2014) review various DSTATCOM topologies used to improve power quality in three-phase systems. While their study highlights significant improvements in reactive power compensation, harmonic elimination, and load balancing, the DSTATCOM systems' high implementation costs and complexity remain major limitations. The need for specialized components, such as transformers and advanced control units, makes widespread adoption difficult, particularly in smaller or less economically developed grids. Additionally, while the simulations provide positive results, real-world testing and validation are necessary to understand the full impact of these systems in diverse grid environments.

Latran, Teke, and Yoldas (2015) provide a comprehensive review of DSTATCOM configurations aimed at mitigating power quality issues in distribution systems. One of the main limitations noted in their review is the lack of studies addressing the simultaneous compensation of multiple power quality issues, such as harmonic distortion and voltage regulation, within a single system. Additionally, while the DSTATCOM systems reviewed show promise, they are often complex to implement, requiring advanced control strategies that may not be easily adaptable to every grid system. Cost-effectiveness also remains an issue, especially when deploying these systems on a large scale.

In summary, while the various studies highlight significant advances in the development of systems and control algorithms aimed at improving power quality, several limitations persist. Many of these systems, such as those employing adaptive control algorithms, require precise tuning and rely heavily on sensor accuracy, which poses challenges in noisy or unpredictable environments. The scalability of these systems, particularly those aimed at small-scale applications like the HTF-based control for PV systems, is another concern, with real-world validation in larger, more complex grids still lacking. Additionally, while control algorithms such as LMF and ISCT show effectiveness in improving power quality, their dependency on finely tuned parameters limits their flexibility and adaptability in dynamic environments.

Moreover, the studies' cost and complexity are recurrent themes, particularly with DSTATCOM systems. While these devices are effective in improving power quality, the high cost of implementation and the need for specialized components restrict their use to larger, more economically developed grids. Future research should focus on reducing the cost and complexity of these systems while improving their robustness and adaptability to diverse grid environments. Additionally, real-world validation across larger systems and different grid conditions is necessary to ensure the practical viability of these proposed solutions.

4. Methodology

Addressing the sensitivity of adaptive control algorithms in power quality improvement systems requires refining sensor technologies and enhancing noise filtering capabilities. More robust noise-cancellation techniques, such as adaptive filtering, can be integrated into the control algorithms to mitigate the reliance on precise sensor data. Incorporating advanced signal processing techniques, including wavelet transforms or Kalman filtering, could help in differentiating noise from actual power quality disturbances, allowing the system to perform efficiently in environments with high noise levels. Moreover, using machine learning models to dynamically predict and adjust for noise could further stabilize system performance under real-world conditions.

Scalability in control systems for grid-interfaced photovoltaic (PV) systems can be enhanced by developing distributed control strategies. Instead of relying on centralized algorithms, which may struggle to scale effectively across larger networks, distributed control systems could manage localized conditions independently. This would allow each grid or PV array segment to operate optimally based on local conditions without overwhelming the central system. These distributed controllers could communicate and synchronize intermittently, ensuring overall grid stability while enabling the system to scale up to larger PV arrays or more complex networks. Modular system designs that allow for gradual scaling while maintaining high performance under fluctuating conditions should also be explored.

Improving the robustness of tuning in combined photovoltaic and active power filter (APF) systems can be achieved by implementing adaptive tuning algorithms. These algorithms would adjust system parameters in real-time, depending on the current grid conditions, without requiring manual recalibration. One approach could be to use reinforcement learning, where the system continuously learns and adapts to new conditions by observing performance outcomes. Additionally, optimization techniques like genetic algorithms could be employed to find optimal tuning parameters autonomously, reducing the risk of inefficiencies during operation. Coupling these algorithms with real-time monitoring and feedback systems could further ensure optimal performance during periods of extreme grid conditions.

To reduce the reliance on finely tuned parameters in grid-connected solar photovoltaic (SPV) systems, algorithms like Least Mean Fourth (LMF) should be made more flexible by introducing multi-objective optimization frameworks. These frameworks could balance different operational goals, such as minimizing total harmonic distortion (THD) and maintaining power quality, without relying heavily on a single parameter for convergence. The control systems can dynamically adjust their tuning based on real-time conditions by incorporating metaheuristic optimization algorithms like particle swarm optimization or differential evolution. This would enhance the adaptability of the system to variations in load and solar irradiance.

Further research should focus on enhancing the coordination between multiple inverters for dual voltage source inverter (DVSI) systems in microgrids. This can be achieved through improved communication protocols and predictive control strategies. For example, implementing model predictive control (MPC) would allow the system to predict future load demands and adjust inverter operations accordingly. Integrating such predictive models with decentralized control schemes could enable each inverter to function autonomously while still maintaining overall system coordination. Additionally, improving the system's fault tolerance through advanced redundancy schemes would ensure smooth transitions between grid-sharing and grid-injecting modes.

Developing cost-effective hardware solutions is crucial to address the high implementation costs and complexity of Distribution Static Compensators (DSTATCOM) systems. One way to achieve this is by using modular hardware designs, which allow for phased implementation of the system based on the grid's immediate needs. Additionally, leveraging low-cost power electronics components that offer high efficiency can reduce the overall cost of implementation. Advances in semiconductor technology, particularly the use of wide-bandgap materials like silicon carbide (SiC) or gallium nitride (GaN), could lead to smaller, more efficient, and cheaper DSTATCOM units capable of delivering high performance in a compact form factor.

To improve the applicability of DSTATCOM systems in smaller or less economically developed grids, control strategies must be simplified. Instead of using complex and resource-intensive control algorithms, researchers could explore simplified control techniques that require fewer computational resources. For example, fuzzy logic controllers or simple proportional-integral-derivative (PID) control systems could be used for reactive power compensation and voltage regulation. These simpler control strategies would make the systems easier to implement and maintain while still achieving satisfactory power quality improvements.

Enhancing the real-world applicability of control systems for power quality improvement requires robust real-time testing environments that mimic actual grid conditions. Currently, many systems rely on simulation models, which may not capture all the complexities of real-world grids. Developing hardware-in-the-loop (HIL) testing platforms, where control algorithms are tested in real-time with actual power hardware, can help bridge this gap. Researchers can identify and address potential performance deviations by integrating more sophisticated testing methodologies before deploying these systems at scale. This approach would significantly improve the reliability of power quality improvement systems in diverse grid environments.

Another key strategy to address the limitations in power quality systems is to incorporate artificial intelligence (AI) for predictive maintenance and fault detection. AI models can analyze historical grid data and predict when system components, such as inverters or filters, may fail or require recalibration. Implementing AI-driven predictive maintenance would reduce downtime and ensure continuous operation, especially in systems highly dependent on accurate tuning. Additionally, AI-based fault detection could automatically detect and isolate issues like harmonic distortions or voltage imbalances, allowing the system to respond proactively rather than reactively.

Lastly, addressing the simultaneous compensation of multiple power quality issues within a single system requires a multi-layered control approach. Researchers should focus on integrating multiple control objectives within a hierarchical control framework, such as harmonic elimination, voltage regulation, and load balancing. This approach would enable different control layers to address specific issues while coordinating with each other to maintain overall system stability. Techniques like coordinated multi-agent systems could be used, where each agent addresses a particular power quality issue and communicates with other agents to ensure comprehensive grid performance improvement.

5. Conclusions

The study successfully demonstrated the effectiveness of various adaptive control algorithms and inverter systems in mitigating power quality issues such as harmonic distortion, reactive power imbalance, and unbalanced loads. The implementation of the adaptive-linear-element (Adaline)-based estimator combined with a least mean square (LMS) algorithm significantly improved the performance of the shunt active filter (SAF) by maintaining sinusoidal source currents and unity power factor. The experimental validation on the dSPACE DS1104 platform confirmed the system’s ability to reduce total harmonic distortion (THD) to below acceptable limits. However, the system's reliance on precise sensor data highlighted its vulnerability to noise interference and external disturbances, underscoring the need for more robust filtering techniques to ensure stability in noisy environments.

The higher-order adaptive control system based on a hyperbolic tangent function (HTF) for grid-connected PV systems effectively reduced harmonics and improved power quality under varying load and solar conditions. The integration of the maximum power point tracking (MPPT) algorithm enhanced the system's efficiency, achieving 99.6% power extraction from the PV array. Nevertheless, the study raised concerns regarding the scalability of this control system for larger PV arrays and more complex networks. Noise interference and fluctuations in solar insolation impacted the convergence rate of the variable learning-based algorithm, suggesting the need for further refinement to ensure stability in real-world applications.

In the combined photovoltaic (PV) and active power filter (APF) system, the application of instantaneous power theory proved successful in compensating for harmonic and reactive power, maintaining the unity power factor even during low or no PV generation periods. Simulation results indicated a significant reduction in THD across different load conditions. Despite the system's flexibility, its performance heavily depended on the accurate tuning of control parameters. Incorrect tuning could lead to inefficiencies, especially in large-scale implementations or extreme grid conditions, pointing to the need for adaptive tuning mechanisms to maintain consistent performance.

The single-stage, grid-connected solar photovoltaic (SPV) system integrated with various control algorithms demonstrated notable improvements in mitigating harmonic distortion, load balancing, and power factor correction. The Least Mean Fourth (LMF) algorithm outperformed the others, achieving the lowest THD of 2.53%. However, the reliance on adaptation constants for convergence speed highlighted the potential limitations of the system in more dynamic environments, requiring further testing under real-world solar and load variations to ensure its adaptability and robustness.

The dual voltage source inverter (DVSI) system designed for microgrid applications improved power quality by sharing the load between two inverters. The system effectively reduced THD and maintained balanced currents, enhancing reliability and overall performance. However, the study highlighted the need for further optimization of control parameters to ensure smooth transitions between grid-sharing and grid-injecting modes, especially in larger microgrid networks where the coordination between multiple inverters becomes complex.

The review of DSTATCOM topologies indicated that these systems can significantly improve power quality by compensating for reactive power, eliminating harmonics, and balancing loads in three-phase systems. While the simulations demonstrated positive results, the high cost and complexity of DSTATCOM systems pose significant barriers to widespread adoption, particularly in smaller or less economically developed grids. This calls for developing more cost-effective hardware solutions and simplified control strategies to make these systems more accessible.

Lastly, the comprehensive review of DSTATCOM configurations highlighted the systems' effectiveness in addressing multiple power quality issues, including voltage regulation and harmonic mitigation. However, the lack of simultaneous compensation for these issues within a single system remains a key limitation. The complexity of the control strategies and the high cost of implementation further limit the applicability of DSTATCOM systems, particularly in smaller-scale or less economically developed grid environments.

Overall, the results indicate that while the various systems and control algorithms studied offer significant improvements in power quality, further refinements are needed to address limitations related to noise interference, scalability, tuning of control parameters, and implementation costs. Future research should focus on enhancing the robustness of these systems to ensure consistent performance across diverse grid conditions and scaling them for larger and more complex networks.

References

1. Singh B, Solanki J. An implementation of an adaptive control algorithm for a three-phase shunt active filter. IEEE Transactions on Industrial Electronics. 2009;56(8):2811-2818.
2. Jain V, Hussain I, Singh B. A HTF-based higher-order adaptive control of single-stage grid-interfaced PV system. IEEE Transactions on Industry Applications. 2019;55(2):1873–1881.
3. Tuyen ND, Fujita G. PV-active power filter combination supplies power to nonlinear load and compensates utility current. IEEE Power and Energy Technology Systems Journal. 2015;2(1):32-42.
4. Narayanan V, Jayaprakash P. Performance comparison of three-phase four-wire grid integrated solar photovoltaic system with various control algorithms. 2017 International Conference on Intelligent Computing, Instrumentation and Control Technologies (ICICICT). IEEE; 2017:406-413.
5. Manoj Kumar MV, Mishra MK, Kumar C. A Grid-Connected Dual Voltage Source Inverter With Power Quality Improvement Features. IEEE Transactions on Sustainable Energy. 2015;6(2):482-490.
6. Singh B, Jayaprakash P, Kothari DP, Chandra A, Al Haddad K. Comprehensive Study of DSTATCOM Configurations. IEEE Transactions on Industrial Informatics. 2014;10(2):854-867.
7. Latran MB, Teke A, Yoldas Y. Mitigation of power quality problems using distribution static synchronous compensator: A comprehensive review. IET Power Electronics. 2015;8(7):1312-1328.