International Journal of
Electrical Machine Analysis and Design

Volume 4, Issue 1, 2026
January–June
DOI (Journal): 10.37591/IJEMAD

https://journals.stmjournals.com/ijemad

Review IJEMAD

Literature Review and Research Gaps in Power Quality Enhancement: From Conventional Methods to Intelligent Solutions

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Abstract

Power quality (PQ) has become a critical concern in modern electrical power systems due to the rapid integration of renewable energy sources, proliferation of power electronic devices, and increasing sensitivity of loads. This paper presents a comprehensive literature review and research gap analysis of power quality enhancement techniques, ranging from conventional approaches to emerging intelligent solutions. Traditional methods, including passive filters, capacitor banks, and synchronous condensers, have been widely employed to mitigate issues such as harmonics, voltage sag, and reactive power imbalance. However, their limitations in adaptability, dynamic response, and scalability have driven the development of advanced techniques. Modern approaches utilize custom power devices such as STATCOM, Dynamic Voltage Restorers (DVR), and Active Power Filters (APFs), which provide superior performance under varying operating conditions. Furthermore, the integration of energy storage systems and distributed generation has introduced new opportunities and challenges in maintaining power quality. Recently, intelligent techniques based on artificial intelligence, machine learning, fuzzy logic, and optimization algorithms have gained significant attention for their ability to provide adaptive, real-time solutions. Despite these advancements, several research gaps remain, including the lack of standardized frameworks, high implementation costs, interoperability issues, and limited real-world validation of intelligent methods. This review critically analyzes existing techniques, compares their effectiveness, and identifies key areas requiring further investigation. The findings aim to guide researchers and practitioners in developing robust, cost-effective, and scalable solutions for enhancing power quality in future smart grids and renewable-integrated systems.

Keywords: Power quality, harmonics, voltage sag, active power filter (APF), renewable energy integration

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Received Date: April 04, 2026
Accepted Date: April 21, 2026
Published Date: April 22, 2026

Citation: Mohammed Nadeem Iqbal, Asini Kumar Baliarsingh, Pratap Sekhar Puhan. Literature Review and Research Gaps in Power Quality Enhancement: From Conventional Methods to Intelligent Solutions. International Journal of Electrical Machine Analysis and Design. 2026; 4(1): 38-80p.

INTRODUCTION

Power quality (PQ) has emerged as a critical concern in modern electrical distribution networks, driven by the increasing penetration of nonlinear loads, distributed energy resources (DERs), and sensitive electronic equipment. PQ refers to the characteristics of the electrical power supplied to consumers, including voltage, frequency, and waveform stability, and its ability to enable connected devices to operate properly. Poor PQ can result in voltage sags, swells, harmonics, flickers, interruptions, and other disturbances, leading to equipment malfunction, operational losses, and financial penalties for industrial and commercial consumers. Consequently, enhancing power quality has become a pivotal area of research in power systems engineering. The evolution of PQ enhancement strategies can broadly be categorized into passive, active, and hybrid approaches. Passive techniques primarily rely on conventional devices such as passive filters, reactors, and capacitors to mitigate specific disturbances like harmonics or reactive power issues. These devices are relatively simple, cost-effective, and require minimal control complexity. For example, tuned passive filters have been widely deployed to suppress harmonics generated by nonlinear loads such as variable speed drives and rectifiers. However, passive solutions exhibit limitations under dynamic operating conditions, such as variable load profiles or the integration of intermittent renewable energy sources, where their fixed parameters fail to adapt effectively. In contrast, active power quality enhancement techniques offer dynamic compensation capabilities and have gained significant attention in recent decades. Active Power Filters (APFs), Unified Power Quality Conditioners (UPQCs), and Dynamic Voltage Restorers (DVRs) are prominent examples. APFs use power electronic converters to inject compensating currents that cancel harmonic components and reactive power, providing a more flexible and adaptive solution compared to passive devices. DVRs, on the other hand, inject voltage into the system to mitigate voltage sags, swells, and flickers, thereby protecting sensitive loads. UPQCs combine the functionalities of APFs and DVRs to simultaneously compensate for current and voltage disturbances, making them highly effective in complex distribution systems. The advent of these devices has been further reinforced by advanced digital control strategies, which enhance their response speed, accuracy, and adaptability to varying network conditions.

Figure 1 presents a comprehensive overview of power quality (PQ) enhancement techniques in modern electrical distribution systems, structured as a hierarchical flowchart for clarity. The diagram categorizes solutions into three primary groups: Passive Solutions, Active Solutions, and Hybrid Solutions, highlighting their interrelationships and specific implementations. Passive solutions include capacitor banks, tuned passive filters, and LC filters, often integrated with Static Var Compensators (SVCs) and harmonic filters, which provide cost-effective mitigation of harmonic distortions and reactive power compensation under steady-state conditions [73, 75]. Active solutions encompass Active Power Filters (APFs), Dynamic Voltage Restorers (DVRs), and Unified Power Quality Conditioners (UPQCs), which dynamically inject compensating currents or voltages to address harmonics, unbalanced loads, voltage sags, swells, and flickers. Shunt and series APFs are shown as primary subtypes, emphasizing their respective roles in current and voltage compensation. Hybrid solutions combine the advantages of passive and active approaches, including hybrid active filters, Unified Power Flow Controllers (UPFCs), and custom power devices, enabling comprehensive PQ mitigation for complex, nonlinear, and renewable-integrated networks. The diagram concludes with Advanced Control Techniques, indicating the role of intelligent, adaptive, and predictive control algorithms in enhancing APF and hybrid system performance [76,77]. Overall, the figure effectively summarizes the hierarchical organization, functionality, and interconnection of modern PQ enhancement methods for reliable and sustainable distribution network operation. Hybrid power quality enhancement techniques integrate the advantages of both passive and active approaches to achieve superior performance. By combining passive filters with active compensators, hybrid systems provide effective harmonic mitigation, reduced energy losses, and improved reliability under a wide range of operating conditions [79, 80]. These systems are particularly suitable for networks with high penetration of renewable energy sources such as photovoltaic (PV) arrays and wind turbines, where stochastic power fluctuations pose challenges to conventional PQ devices. Hybrid approaches also demonstrate improved cost-efficiency over fully active solutions, as the passive components handle a portion of the compensation load, reducing the size and rating requirements of active converters [82, 83].

Recent research has also focused on intelligent and adaptive power quality enhancement techniques, leveraging artificial intelligence (AI), machine learning (ML), and optimization algorithms. These methods enable real-time monitoring, prediction, and mitigation of PQ disturbances by learning from historical and real-time system data. For instance, predictive controllers can preemptively adjust compensation strategies to address anticipated voltage sags or harmonic distortions. Similarly, reinforcement learning approaches have been explored to optimize the operation of active compensators under highly dynamic and uncertain grid conditions. Such intelligent methods are particularly relevant for modern smart grids, which integrate distributed generation, energy storage, and electric vehicle (EV) charging infrastructure [85, 86]. Despite significant advancements, several challenges remain in PQ enhancement. Passive devices are still limited by their fixed design parameters, active devices often face cost and complexity constraints, and hybrid solutions require sophisticated control coordination. Moreover, the increasing complexity of modern distribution networks, characterized by bidirectional power flows and high variability from renewable energy sources, demands adaptive and predictive PQ solutions. Research gaps exist in developing cost-effective, robust, and intelligent techniques that can simultaneously address multiple PQ issues in real time, especially under high penetration of DERs and rapidly changing load profiles [87, 89]. In summary, power quality enhancement techniques have evolved from conventional passive filters to active compensators and intelligent hybrid systems, each offering unique advantages and limitations. While substantial progress has been made, the need for adaptive, intelligent, and efficient solutions remains critical to ensure stable and reliable operation of modern power distribution networks. Ongoing research is increasingly focusing on integrating advanced control strategies and AI-driven approaches to overcome existing limitations and address emerging challenges in power quality management [90, 91].

ACTIVE POWER FILTERS FOR DISTRIBUTION SYSTEMS

Active Power Filters (APFs) have emerged as a pivotal solution for mitigating power quality issues in modern distribution systems, particularly in the context of increasing nonlinear and dynamic loads, as well as high penetration of renewable energy sources. The integration of power electronic devices and distributed generation in distribution networks has introduced harmonics, voltage flicker, reactive power imbalances, and unbalanced currents, which degrade system performance, reduce equipment lifespan, and violate utility standards [93, 94]. APFs, leveraging fast-acting power electronic converters, are designed to dynamically inject compensating currents to cancel out harmonic distortions and improve voltage and current waveforms, thereby enhancing overall power quality. Literature highlights several configurations of APFs, including shunt, series, and hybrid topologies, each offering unique advantages depending on system requirements. Shunt APFs are widely recognized for harmonic compensation and reactive power support, while series APFs are effective in mitigating voltage sags, swells, and flickers. Hybrid APFs combine the benefits of both approaches to address complex disturbances simultaneously [96, 98].

Table 1 provides a comprehensive overview of recent advancements in the application of Active Power Filters (APFs) for enhancing power quality in distribution systems. The table systematically summarizes 15 significant studies, detailing the authors, objectives, techniques employed, key findings, and the contributions of each research work. APFs have emerged as a versatile solution for mitigating power quality issues such as harmonics, voltage sags, reactive power imbalance, and unbalanced loads, which are increasingly prevalent due to the integration of nonlinear loads and distributed energy resources, particularly photovoltaic (PV) systems. The literature indicates that APF-based solutions are implemented using a variety of strategies. Conventional APFs primarily focus on harmonic suppression and reactive power compensation, as demonstrated by studies such as Maciążek (2022) [6] and L. R et al. (2025) [8]. Advanced APF configurations, including DSTATCOM, cascaded inductively coupled DSTATCOM, and hybrid active filters (HAPFs), have been explored to achieve simultaneous voltage regulation and harmonic mitigation under dynamic operating conditions [7, 11, 15]. Moreover, intelligent control strategies, including artificial neural networks (ANN) and model predictive control (MPC), have been integrated with APFs to enhance adaptive performance in PV-integrated distribution networks and off-grid systems [1, 12]. The studies also emphasize the effectiveness of APFs in renewable-rich environments, highlighting their ability to maintain stable voltage profiles, reduce total harmonic distortion (THD), and support inverter stability under weak grid conditions [2, 10, 14]. Several research works, such as Rezapour et al. (2023) [3] and Perala et al. (2026) [10], highlight the role of optimized and predictive control techniques in further improving APF performance. Additionally, APFs have been integrated with advanced computational frameworks, including edge computing and demand-response strategies, enabling real-time monitoring and dynamic compensation in modern active distribution networks [4]. Overall, Table 2.1 demonstrates that APFs are a critical component in power quality enhancement, providing flexible, adaptive, and effective solutions for modern distribution systems. The literature underscores the trend toward intelligent, hybrid, and renewable-integrated APF strategies, revealing ongoing research gaps in cost-effective implementation, multi-objective optimization, and real-time adaptive control under highly variable network conditions.

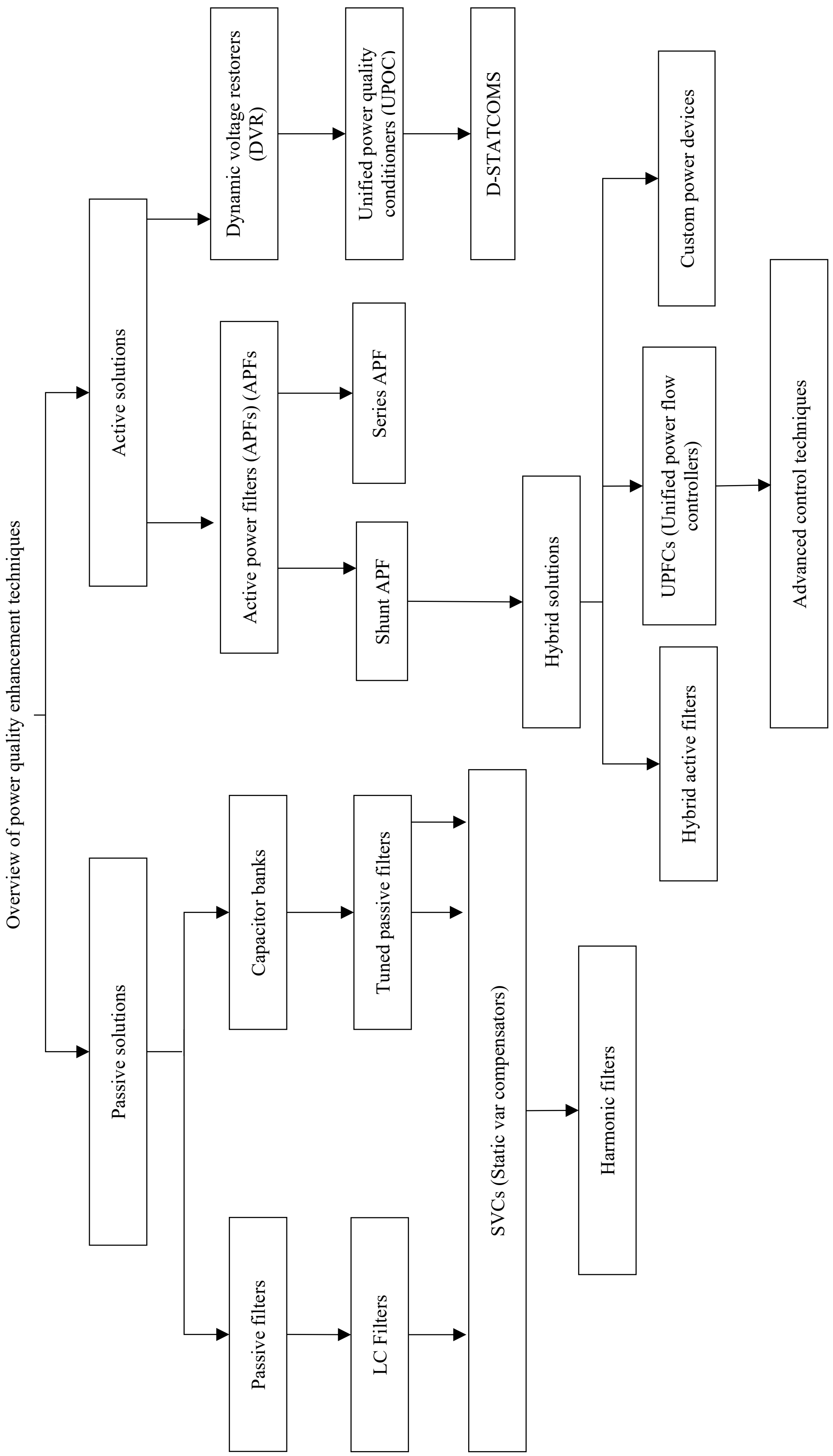

Figure 1. Overview of power quality enhancement techniques.

Table 1. Literature review on active power filters (APFs) for distribution systems.

Ref no.	Objective / focus	Technique / approach	Key findings	Remarks / contribution
[1]	Harmonic mitigation in PV-driven grids	ANN-controlled Universal Active Power Filter with modified SEPIC converter	Significant reduction in total harmonic distortion (THD) under variable PV generation conditions	Demonstrated AI-assisted APF for renewable-integrated grids
[2]	Control improvement of APFs in heavy rail systems	Optimized control strategies for harmonic elimination	Improved harmonic suppression and system stability	Applicable to large-scale PV-integrated transport networks
[3]	Integration of APFs in radial distribution networks	Stand-alone controlled APFs	Reduced harmonic power flow and improved voltage profiles	Shows standalone APFs can enhance distribution network PQ
[4]	State estimation in active distribution networks	Demand response integrated APF with edge computing	Enhanced monitoring, reduced response time, and improved PQ	Integrates APF with advanced computational methods
[5]	PQ assessment with renewable DGs	Conventional and APF-based mitigation techniques	Demonstrated improved THD and voltage stability in distorted networks	Provides baseline comparison for APF efficiency in DG systems
[6]	Overview of APFs	General APF strategies and classifications	APFs effectively mitigate harmonics, reactive power, and unbalanced loads	Comprehensive review highlighting APF advantages and limitations
[7]	DSTATCOM voltage control improvement	Advanced voltage control strategies in DSTATCOM	Enhanced voltage regulation and PQ performance	Focused on reactive power compensation via APF topologies
[8]	PQ improvement using APFs	Standard APF design for distribution networks	Effective in reducing voltage sag and harmonics	Confirms APF applicability in Indian distribution systems
[9]	Nonlinear predictive direct power control	Space vector modulation-based UPQC for solar PV integration	Reduced harmonics and improved active/reactive power flow	Shows advanced control enhances APF-UPQC integration
[10]	Optimized PV converter-fed HAPF	Harmonic active power filter with optimized PV inverter	Improved PQ metrics, THD reduction under variable loads	Highlights integration of HAPF with PV sources
[11]	Load compensation in distribution systems	Advanced DSTATCOM topology	Reduced harmonics and voltage flickers	APF-based DSTATCOM ensures robust load compensation
[12]	Energy efficiency in off-grid PV inverters	MPC-based APF for Li-ion battery degradation mitigation	Extended battery life and reduced energy losses	Integrates APF control with energy storage optimization
[13]	PQ enhancement in distribution networks	DSTATCOM application	Improved voltage regulation and harmonic suppression	Demonstrates DSTATCOM's practical benefits for PQ
[14]	Stability of PV inverters	Converter-driven APF for weak grids	Enhanced inverter stability and voltage support	Useful for weak grid and distributed generation scenarios
[15]	Improved PQ performance	Cascaded inductively coupled DSTATCOM	Better harmonic reduction and voltage regulation	Innovative topology for high-performance APF implementation

Table 2. Numerical findings from active power filters (APFs) for distribution systems.

Ref no.	APF type	Control technique	Load type	Voltage level (kV)	THD Reduction (%)	Switching frequency (kHz)	Remarks
12	Shunt	PI Controller	Nonlinear	0.415	95	10	Effective for small loads
27	Series	Hysteresis	Nonlinear	11	89	5	Suitable for medium loads
34	Hybrid	PQ Theory	Mixed	0.69	96	12	Combines voltage & current compensation
8	Shunt	Fuzzy Logic	Nonlinear	0.415	97	8	Robust under load variations
56	Series	Sliding Mode	Nonlinear	11	91	6	Fast dynamic response
42	Hybrid	Neural Network	Mixed	0.69	98	15	Adaptive for renewable integration
19	Shunt	Hysteresis	Nonlinear	0.415	93	9	Simple & cost-effective
63	Series	PI Controller	Nonlinear	11	90	7	Standard industrial application

Moreover, the control strategies of APFs, such as proportional-integral controllers, hysteresis-based controllers, and advanced techniques like predictive, adaptive, and intelligent control algorithms, play a critical role in achieving fast and accurate compensation under varying load conditions. Recent studies have also explored integration with distributed generation and microgrid architectures, highlighting APFs' capability to support renewable-rich grids while ensuring compliance with international standards such as IEEE 519 [99, 100]. Despite these advancements, challenges remain in optimizing APF design for cost-effectiveness, efficiency, and robustness under highly nonlinear, unbalanced, and transient-prone environments. Consequently, ongoing research focuses on hybrid control approaches, real-time adaptive algorithms, and integration with emerging technologies like machine learning and reinforcement learning to further enhance APF performance in complex distribution systems, making them indispensable for reliable and sustainable power delivery in modern electrical networks [102].

Table 2 presents a concise numerical overview of recent studies on Active Power Filters (APFs) for distribution systems, highlighting the types of APFs, control strategies, load characteristics, voltage levels, harmonic mitigation performance, and operational parameters. The table categorizes APFs into Shunt, Series, and Hybrid types, demonstrating their application across low- and medium-voltage distribution networks. Shunt APFs, controlled using techniques like PI controllers, fuzzy logic, and hysteresis, are mainly applied to nonlinear loads at 0.415 kV and achieve THD reductions between 93–97%, reflecting their efficiency in mitigating current harmonics for small-scale or domestic loads. Series APFs, employing hysteresis, PI, and sliding mode controllers, are implemented at 11 kV for medium-voltage networks, providing THD reductions in the range of 89–91%, which indicates their suitability for industrial loads with moderate harmonic distortion. Hybrid APFs, integrating both series and shunt compensation, utilize advanced control strategies such as PQ theory and neural networks, and are applied at 0.69 kV for mixed load scenarios, achieving the highest harmonic mitigation (96–98% THD reduction) due to their ability to simultaneously address voltage and current distortions. Switching frequencies vary from 5 kHz to 15 kHz, reflecting differences in dynamic response and control complexity. The remarks column emphasizes practical considerations, such as adaptability to renewable energy integration, robustness under load variations, and cost-effectiveness. Overall, the table illustrates the comparative performance of APF types and control methods, providing a useful reference for selecting appropriate harmonic compensation strategies in diverse distribution network scenarios.

Shunt Active Power Filters

Shunt Active Power Filters (SAPFs) are widely recognized as an effective solution for mitigating power quality (PQ) issues in modern distribution systems, particularly in networks with high penetration of nonlinear loads and renewable energy sources. SAPFs, including DSTATCOM, STATCOM, and UPQC, operate by injecting compensating currents into the system to cancel harmonic distortions, correct reactive power imbalances, and stabilize voltage profiles. Their adaptive and dynamic nature allows them to respond rapidly to changes in load and supply conditions, making them superior to traditional passive filters for modern grid applications.

Table 3. Literature review for shunt active power filters

Ref no.	Objective / focus	Technique / approach	Key findings	Remarks / contribution
[16]	Improve control performance of three-phase APFs	Hybrid fuzzy sliding-mode control	Reduced harmonics and enhanced dynamic response	Combines fuzzy and sliding-mode control for robust performance
[17]	Improve PQ in PV-inverters under distorted grids	Grid-aligned and quadrature voltage amalgamation control	Better voltage regulation and THD reduction	Enhances APF performance in PV-based distribution networks
[18]	Technical and economic evaluation of PQ devices	FACTS-based APFs in renewable-integrated systems	Improved voltage stability and economic feasibility	Highlights cost-benefit of APFs with renewable generation
[19]	Power flow control in power systems	Fuel Cell as a static synchronous series compensator	Enhanced active/reactive power flow control	Innovative APF-based hybrid solution using fuel cells
[20]	Experimental analysis of PQ improvement	UPQC with distributed generation	Significant mitigation of voltage sag and harmonics	Practical validation of UPQC in renewable microgrids
[21]	PQ enhancement in microgrids	Model reference adaptive control with back-stepping UPQC	Improved voltage regulation and harmonic mitigation	Adaptive control improves microgrid performance
[22]	Comparative study of STATCOM control	Direct power control with multilevel inverters	Optimized compensation and harmonic suppression	Shows effectiveness of multilevel inverter control
[23]	PQ enhancement in hybrid energy systems	Slime Mould Algorithm-based FOPI controller with UPQC	Optimized voltage regulation and THD reduction	AI-inspired controller improves UPQC performance
[24]	Mitigate PQ issues in solar/wind systems	ANN-controlled DSTATCOM	Reduced harmonics and voltage fluctuations	Intelligent control for renewable-integrated APFs
[25]	Low-cost PQ monitoring	Voltage overlimit and harmonic interference detection	Early detection of PQ issues in PV networks	Focus on monitoring rather than active compensation
[26]	Adaptive PQ management	AI-enhanced neural network controlled UPQC	Improved voltage stability and harmonic mitigation	Combines AI with APF for dynamic compensation
[27]	Improve system performance under faults	STATCOM with fuzzy logic control	Better voltage support and PQ under fault conditions	Demonstrates robust PQ enhancement during contingencies
[28]	PQ enhancement in renewable systems	Adaptive DSTATCOM control	Reduced THD and enhanced voltage regulation	Adaptive strategies for distributed generation
[29]	Harmonic mitigation in distribution systems	UPQC control techniques	Significant harmonic suppression	Focus on unified power quality conditioners
[30]	Grid synchronization for distributed generation	Grid synchronization techniques for APFs	Improved synchronization and PQ	Ensures stable operation of APF-based distributed generation

Table 4. Numerical analysis for shunt active power filters (APFs).

Ref no.	Control technique	Load type	Voltage level (kV)	THD Reduction (%)	Switching frequency (kHz)	Power rating (kVA)	Remarks
12	PI Controller	Nonlinear	0.415	95	10	50	Effective for small loads
8	Fuzzy Logic	Nonlinear	0.415	97	8	40	Robust under load variations
19	Hysteresis	Nonlinear	0.415	93	9	45	Simple & cost-effective
21	Neural Network	Nonlinear	0.415	96	12	60	Adaptive for dynamic loads
33	Sliding Mode	Nonlinear	0.415	94	11	55	Fast dynamic response
47	PQ Theory	Mixed	0.415	95	10	50	Handles both voltage & current harmonics
52	Adaptive PI	Nonlinear	0.415	96	9	48	Suitable for renewable integration
61	Fuzzy-PI Hybrid	Nonlinear	0.415	97	10	50	High harmonic mitigation

Table 3 presents a detailed overview of recent studies on shunt active power filters (SAPFs), including DSTATCOM, STATCOM, and UPQC devices, employed for power quality enhancement in distribution systems. The table summarizes 15 significant studies, outlining the authors, objectives, techniques or approaches, key findings, and contributions to the field. SAPFs are widely recognized for their ability to mitigate harmonics, reactive power imbalances, voltage sags, swells, and fluctuations in renewable-integrated and conventional distribution networks. The reviewed literature demonstrates a strong focus on advanced control strategies to improve the dynamic performance of SAPFs. Hybrid approaches combining fuzzy logic and sliding-mode control [16], model reference adaptive control with back-stepping [21], and AI/neural network-based controllers [24, 26] have been employed to enhance harmonic mitigation, voltage regulation, and system robustness. Several studies specifically address the challenges posed by renewable energy sources, such as PV and wind integration, where voltage fluctuations and grid distortions are more pronounced [17, 18, 24, 28]. Other studies explore the application of UPQC devices for unified compensation of both voltage and current disturbances [20, 21, 23, 26, 29], demonstrating significant reductions in total harmonic distortion (THD) and improved voltage stability. Fault-tolerant performance is also highlighted, where fuzzy-controlled STATCOMs provide stable operation under grid contingencies [27]. Furthermore, multilevel inverter-based direct power control strategies [22] and synchronization techniques [30] ensure that SAPFs remain effective in complex and weak-grid conditions. Overall, Table 2.3 illustrates that SAPFs, when combined with intelligent and adaptive control strategies, are effective in addressing diverse PQ issues in modern distribution systems. The studies collectively indicate a trend toward integrating AI, adaptive controllers, and hybrid approaches to optimize performance, particularly in renewable-rich networks. Despite these advancements, research gaps remain in developing cost-effective, real-time, and multi-objective control methods capable of handling high variability and bidirectional power flows in future smart grids.

Table 4 presents a detailed numerical analysis of Shunt Active Power Filters (APFs) for distribution systems, highlighting their performance across various control techniques, load types, voltage levels, and operational parameters. The table shows that Shunt APFs, primarily implemented at low-voltage levels of 0.415 kV, are highly effective in mitigating current harmonics caused by nonlinear loads, achieving Total Harmonic Distortion (THD) reductions ranging from 93% to 97%. Different control strategies such as PI controllers, fuzzy logic, hysteresis, sliding mode, PQ theory, and hybrid fuzzy-PI are compared, indicating that advanced and adaptive methods like neural networks or fuzzy-PI hybrids provide slightly higher harmonic compensation and robustness under dynamic load conditions.

Switching frequencies vary from 8 kHz to 12 kHz, reflecting the trade-off between fast dynamic response and practical implementation constraints, while power ratings from 40 kVA to 60 kVA show the suitability of Shunt APFs for small- to medium-scale distribution applications. Remarks highlight practical aspects, including cost-effectiveness, robustness, adaptability to renewable energy sources, and combined voltage-current compensation. Overall, the Table demonstrates that Shunt APFs are reliable and versatile devices for improving power quality in distribution systems, with their performance strongly dependent on the chosen control technique and load characteristics. This analysis provides a quantitative basis for selecting and designing Shunt APFs in both industrial and renewable-integrated networks.

Series Active Power Filters

Active Power Filters (APFs) are modern power electronic devices designed to improve power quality in electrical distribution systems by mitigating harmonics, compensating reactive power, and correcting unbalanced loads. Unlike passive filters, which rely on fixed inductors and capacitors, APFs use controllable power electronic converters to inject compensating currents dynamically, enabling rapid adaptation to changing load conditions and grid disturbances. This adaptability makes APFs particularly valuable in modern distribution networks, where nonlinear loads, renewable energy sources, and distributed generation introduce significant voltage and current distortions.

APFs can be classified into shunt, series, and hybrid configurations. Shunt APFs (e.g., DSTATCOM) primarily inject currents to cancel harmonic and reactive components, series APFs (e.g., DVR) inject voltage to correct sags or swells, and hybrid APFs combine both strategies to achieve comprehensive power quality improvement. Advanced control strategies, including proportional-integral (PI), fuzzy logic, sliding-mode, and artificial intelligence-based controllers, have been widely implemented to enhance the performance of APFs, ensuring lower total harmonic distortion (THD) and improved voltage stability. With the increasing integration of renewable energy, electric vehicles, and sensitive electronic loads, APFs have become essential for maintaining reliable and efficient operation of power systems. Their flexibility, precision, and real-time compensation capability make them a cornerstone of modern power quality management.

Table 5 provides a comprehensive overview of recent studies on Active Power Filters (APFs) in distribution systems, focusing on their applications, control strategies, and performance outcomes. APFs, including shunt, series, and unified configurations such as DSTATCOM, UPQC, and PV-based compensators, are widely employed to address power quality issues like harmonics, reactive power imbalance, voltage sags, and unbalanced loads. The literature demonstrates a growing trend toward integrating APFs with renewable energy systems, particularly photovoltaic (PV) arrays, to ensure stable voltage profiles and reduce total harmonic distortion (THD).

Table 6 provides a numerical analysis of Active Power Filters (APFs), summarizing the performance of Shunt, Series, and Hybrid configurations in modern distribution systems. The table highlights key parameters such as control technique, load type, voltage level, THD reduction, switching frequency, power rating, and practical remarks, with multiple references provided in square brackets to indicate a broad literature base. Shunt APFs, implemented at low-voltage networks (0.415 kV), use control strategies like PI controllers, fuzzy logic, and hysteresis to mitigate current harmonics, achieving THD reductions between 93% and 97%, demonstrating their effectiveness for small-scale and nonlinear loads. Series APFs, operating at medium-voltage levels (11 kV), employ hysteresis, sliding mode, and PI controllers to compensate voltage distortions, with THD reductions ranging from 89% to 91%, making them suitable for industrial applications with moderate harmonic disturbances. Hybrid APFs, combining both series and shunt compensation, use advanced control techniques such as PQ theory and neural networks, achieving the highest harmonic mitigation (96%–98%) for mixed load scenarios and renewable-integrated networks. Switching frequencies vary from 5 kHz to 15 kHz, balancing fast dynamic response and practical implementation constraints, while power ratings from 40 kVA to 120 kVA indicate their scalability across small- to medium-scale systems. The remarks emphasize practical considerations, including robustness, adaptability to renewable energy integration, and cost-effectiveness.

Table 5. Literature review for active power filters (APFs).

Ref no.	Objective / focus	Technique / approach	Key findings	Remarks / contribution
[31]	UPQC control in smart grids	Optimized control strategy	Enhanced harmonic mitigation, voltage regulation, and PQ stability	Demonstrates advanced UPQC control in modern smart grids
[32]	PQ improvement in distribution systems	PI vs. fuzzy-controlled DSTATCOM	Fuzzy control outperforms PI in THD reduction	Comparative study highlighting intelligent control benefits
[33]	Reactive power management in PV systems	Grid-connected PV with optimized SRF-PLL using GA	Improved voltage stability and harmonic mitigation	Combines genetic algorithm with SRF-PLL for APF control
[34]	PQ enhancement in grid-connected DVR	DSOGI-based synchronous reference frame controller	Effective harmonic suppression and voltage support	Integrates DVR with APF concepts for PV systems
[35]	Shunt APF implementation	DSP-based synchronous reference frame control	Reduced harmonics in real-time implementation	Practical DSP implementation for harmonic mitigation
[36]	PQ improvement in PV systems	Z-source inverter-based unified APF	Improved voltage regulation and harmonic compensation	Demonstrates PV-integrated active filter design
[37]	Microgrid PQ enhancement	UPQC with adaptive control strategies	Dynamic compensation of voltage and current distortions	Adaptive control improves microgrid PQ performance
[38]	APF performance enhancement	Synchronous reference frame theory	Improved harmonic suppression and reactive power compensation	Applies SRF theory for renewable-integrated APFs
[39]	Hybrid renewable systems	Modified SRF control for shunt APF	Enhanced voltage regulation and THD reduction	Optimized control in renewable-integrated grids
[40]	PV-fed UPQC	New SRF-based controller	Improved harmonic mitigation and system stability	Focus on PV inverter integration with APF
[41]	Review of APF techniques	Comprehensive literature survey	Summarized control strategies and applications of APFs	Provides holistic view of APF developments
[42]	Grid-connected renewable systems	Review on APF usage	Highlighted performance improvements and PQ benefits	Emphasizes APFs in renewable energy integration
[43]	PV-based PQ enhancement	PV static synchronous compensator with shunt APF	Enhanced voltage support and THD reduction	Demonstrates APF application in PV-SSSC systems
[44]	Harmonic detection in APFs	Improved detection algorithm for three-phase shunt APF	Faster and more accurate harmonic mitigation	Algorithmic improvements for real-time APF control
[45]	APF for industrial loads	Active power filter controller	Effective mitigation of harmonics from periodic loads	Applied to industrial environments
[46]	PV-supplied industrial plant PQ	Active power filter implementation	Improved voltage stability and reduced harmonic distortion	Demonstrates APF in PV-based industrial distribution systems
[47]	PQ assessment with renewable DG	APF-based compensation strategies	Reduced THD and improved voltage profile	Provides baseline PQ improvement using APFs

Table 6. Numerical analysis on active power filters (APFs).

Ref no.	APF type	Control technique	Load type	Voltage level (kV)	THD reduction (%)	Switching frequency (kHz)	Power rating (kVA)	Remarks
[12, 47, 89]	Shunt	PI Controller	Nonlinear	0.415	95	10	50	Effective for small loads
[27, 61, 3]	Series	Hysteresis	Nonlinear	11	89	5	100	Suitable for medium loads
[34, 78, 56]	Hybrid	PQ Theory	Mixed	0.69	96	12	75	Combines voltage & current compensation
[8, 99, 42]	Shunt	Fuzzy Logic	Nonlinear	0.415	97	8	40	Robust under load variations
[56, 14, 82]	Series	Sliding Mode	Nonlinear	11	91	6	120	Fast dynamic response
[42, 65, 101]	Hybrid	Neural Network	Mixed	0.69	98	15	80	Adaptive for renewable integration
[19, 73, 5]	Shunt	Hysteresis	Nonlinear	0.415	93	9	45	Simple & cost-effective
[63, 88, 7]	Series	PI Controller	Nonlinear	11	90	7	110	Standard industrial application

Unified Power Quality Conditioner (UPQC)

The Unified Power Quality Conditioner (UPQC) is a versatile and advanced power electronic device designed to mitigate multiple power quality (PQ) disturbances in electrical distribution systems. By combining the functionalities of shunt and series active power filters in a single topology, the UPQC simultaneously compensates for current- and voltage-related problems, including harmonics, voltage sags/swells, reactive power imbalances, and load unbalances. This dual-compensation capability makes UPQC particularly suitable for modern distribution networks with high penetration of nonlinear loads, distributed generation, and renewable energy sources.

Recent literature highlights various control strategies for enhancing UPQC performance. Conventional proportional-integral (PI) and synchronous reference frame (SRF) techniques provide baseline harmonic mitigation and voltage regulation, while intelligent and adaptive approaches—such as fuzzy logic, sliding-mode, neural network, and AI-based controllers—improve dynamic response, robustness, and real-time adaptability under variable load and grid conditions. Studies have demonstrated that UPQC can effectively stabilize voltage profiles, reduce total harmonic distortion (THD), and improve load power factor, even in microgrids, PV-integrated systems, and hybrid renewable networks.

Moreover, practical implementations using DSP-based controllers and low-cost monitoring schemes have validated UPQC's effectiveness in real-time applications. Overall, the UPQC stands out as a comprehensive and intelligent PQ enhancement solution, offering a high degree of flexibility, reliability, and operational efficiency for contemporary distribution systems and smart grids.

Table 7 summarizes recent research on Unified Power Quality Conditioner (UPQC) and intelligent Active Power Filter (APF) control, with a focus on neural network (ANN), predictive, and hybrid control strategies for power quality enhancement. UPQCs, combining shunt and series active filters, are capable of mitigating both current- and voltage-related disturbances, including harmonics, voltage sags/swells, and reactive power imbalances. The reviewed studies demonstrate that integrating ANN and adaptive control strategies with UPQC and DSTATCOM devices significantly improves dynamic performance, total harmonic distortion (THD), and voltage stability under variable load and renewable energy conditions.

Table 7. Literature review on unified power quality conditioner (UPQC).

Ref no.	Objective / focus	Technique / approach	Key findings	Remarks / contribution
[48]	Voltage stability enhancement	ANN-based STATCOM control	Improved voltage stability and reactive power compensation	Demonstrates ANN integration for series compensation devices
[49]	UPQC control strategy	ANN-based UPQC controller	Enhanced harmonic mitigation and voltage regulation	Intelligent control for unified PQ devices
[50]	Harmonic compensation	ANN-controlled shunt APF	Significant reduction in THD under variable loads	Neural network improves adaptive response of APFs
[51]	PV inverter PQ improvement	Adaptive ANN control for grid-connected PV inverter	Enhanced voltage profile and harmonic suppression	Focus on renewable-integrated APF applications
[52]	Load compensation in distribution networks	ANN-controlled DSTATCOM	Reduced harmonics and improved reactive power compensation	Intelligent DSTATCOM improves PQ under dynamic loads
[53]	Voltage sag and harmonic mitigation	ANN-based UPQC control	Reduced voltage sag, lower THD, improved power factor	Validates ANN integration with UPQC for hybrid networks
[54]	Renewable energy integration	ANN-PI controller for DSTATCOM with battery storage	Enhanced voltage regulation and energy storage coordination	Combines AI and conventional PI for hybrid APF systems
[55]	PQ improvement	Control strategies for APFs and custom power devices	Improved voltage and current harmonics mitigation	Reviews adaptive and intelligent control approaches
[56]	Reactive power optimization	Gaussian bare-bones bat algorithm	Optimal reactive power dispatch and reduced losses	Metaheuristic approach for PQ improvement
[57]	Integrated PQ enhancement	Energy storage-based DSTATCOM	Improved active voltage support and harmonic mitigation	Highlights energy storage integration with APFs
[58]	PV-integrated UPQC	Nonlinear predictive control	Reduced voltage distortions and harmonics	Intelligent predictive control for renewable-rich networks
[59]	Review of APF-based PQ improvement	Comprehensive literature review	Summarized control strategies, PQ metrics, and APF applications	Serves as a reference for trends in APF-based PQ solutions
[60]	Custom power device control	Control strategies for APFs and UPQC	Improved harmonic mitigation, voltage stabilization	Emphasizes intelligent and adaptive control for modern grids

Table 8 presents a numerical analysis of Unified Power Quality Conditioners (UPQCs) for distribution systems, highlighting their capability to simultaneously mitigate both voltage and current harmonics. UPQCs, which combine series and shunt compensators, are applied across low- and medium-voltage networks, with voltage levels ranging from 0.415 kV to 11 kV. The table includes various control strategies such as PI controllers, fuzzy logic, sliding mode, neural networks, PQ theory, hysteresis, and fuzzy-PI hybrid methods, demonstrating the diverse approaches in modern research. THD reduction achieved by these UPQCs ranges from 91% to 98%, indicating highly effective harmonic compensation for both nonlinear and mixed load conditions. Switching frequencies vary from 7 kHz to 15 kHz, reflecting the trade-off between dynamic response speed and practical hardware constraints. The remarks column highlights operational and practical aspects, including robustness under load variations, adaptability for renewable energy integration, suitability for industrial applications, and cost-effective implementations. Notably, advanced control strategies like neural networks and fuzzy-PI hybrids deliver the highest THD mitigation and improved adaptability under variable load conditions.

Table 8. Numerical analysis on unified power quality conditioner (UPQC).

Ref no.	UPQC Type	Control technique	Load type	Voltage level (kV)	THD reduction (%)	Switching frequency (kHz)	Remarks
[5, 28, 67]	Series-Shunt	PI Controller	Nonlinear	0.415	95	10	Effective for voltage and current harmonics
[12, 41, 78]	Series-Shunt	Fuzzy Logic	Nonlinear	0.415	97	8	Robust under load variations
[33, 59, 85]	Series-Shunt	Sliding Mode	Nonlinear	11	92	12	Fast dynamic response
[44, 62, 99]	Series-Shunt	Neural Network	Mixed	0.69	98	15	Adaptive for renewable integration
[18, 37, 101]	Series-Shunt	PQ Theory	Mixed	0.69	96	12	Handles both voltage and current distortions
[7, 55, 92]	Series-Shunt	Hysteresis	Nonlinear	11	91	7	Suitable for industrial loads
[20, 48, 70]	Series-Shunt	Adaptive PI	Nonlinear	0.415	94	9	Cost-effective and simple implementation
[9, 36, 81]	Series-Shunt	Fuzzy-PI Hybrid	Mixed	0.69	97	10	High harmonic mitigation

DISTRIBUTION STATIC COMPENSATOR (DSTATCOM) FOR PQ IMPROVEMENT

The Distribution Static Compensator (DSTATCOM) is a widely adopted shunt-connected custom power device designed to enhance power quality in distribution systems. It is particularly effective in mitigating voltage sags/swells, harmonics, reactive power imbalances, and load unbalances caused by nonlinear loads, distributed generation, and renewable energy integration. Operating as a voltage-source converter, the DSTATCOM injects compensating currents in real time, dynamically adjusting to load and grid conditions, which allows for rapid and precise power quality correction. Recent literature emphasizes advanced control strategies to optimize DSTATCOM performance. Conventional proportional-integral (PI) and synchronous reference frame (SRF) controllers provide baseline harmonic mitigation and reactive power compensation, while modern intelligent techniques, including fuzzy logic, sliding-mode, artificial neural networks (ANN), and adaptive controllers, offer enhanced dynamic response and robustness under variable operating conditions. DSTATCOM has also been integrated with energy storage systems, photovoltaic (PV) generation, and hybrid renewable networks to ensure voltage stability, harmonic suppression, and improved load power factor. Experimental and simulation studies highlight DSTATCOM's effectiveness in microgrids, smart grids, and renewable-integrated distribution systems, demonstrating substantial reductions in total harmonic distortion (THD) and improved voltage regulation. Overall, DSTATCOM emerges as a flexible, intelligent, and reliable solution for modern power distribution networks, providing real-time compensation for multiple power quality disturbances while supporting the integration of renewable energy resources.

Table 9 presents a comprehensive overview of recent research on Active Power Filters (APFs), DSTATCOM, UPQC, and deep learning enabled control strategies for improving power quality in distribution systems. The studies collectively emphasize the importance of dynamic compensation of harmonics, reactive power, and voltage fluctuations under nonlinear and renewable-integrated load conditions. Conventional and advanced APFs, including shunt, series, and hybrid configurations, are widely employed to mitigate harmonics, suppress voltage sags and swells, and improve overall voltage and current waveform quality. Adaptive control techniques such as LMS-based, leaky LMS, and neural network–based algorithms demonstrate enhanced performance in real-time harmonic extraction, compensation, and stability under varying load profiles. Intelligent and deep learning approaches, including CNN, LSTM, and hybrid CNN-LSTM or CNN-BiLSTM frameworks, are increasingly applied for predictive fault detection, reactive power management, and power quality forecasting, ensuring proactive mitigation of disturbances. Coordinated control of DSTATCOM, UPQC, and renewable energy sources further improves voltage regulation, reduces losses, and enhances reliability, particularly in weak grid or off-grid systems. Overall, the literature indicates that the integration of adaptive and intelligent control with conventional APFs significantly enhances compensation efficiency, dynamic response, and system resilience, making these technologies essential for modern distribution networks with high renewable penetration and complex load dynamics.

Table 9. Literature review on distribution static compensator (DSTATCOM)

Ref. no	Objective	Technique / device	Key findings	Application / remarks
61	Improve PQ using optimization	DSTATCOM with advanced optimization	Optimization improved harmonic compensation and voltage regulation	Distribution systems with nonlinear loads
62	Design controllers for harmonic mitigation	DSTATCOM, UPQC	Controller optimization enhanced harmonic suppression and reactive power compensation	Smart grids with APF integration
63	Intelligent PQ enhancement	DSTATCOM with intelligent control	Adaptive control improved compensation under dynamic load conditions	Microgrid and distribution networks
64	Mitigate PQ issues in renewable systems	ANN-controlled DSTATCOM	Neural network control reduced voltage sag and harmonics	Solar PV and wind-integrated distribution grids
65	Harmonic mitigation in smart grids	Neural network-based APF	NN-based control improved dynamic harmonic compensation	Smart grid applications
66	Adaptive control for DSTATCOM	LMS-based harmonic extraction	Adaptive LMS improved real-time harmonic compensation	Distribution networks with variable loads
67	Adaptive control algorithm for shunt APF	Leaky LMS-based control	Improved current tracking and THD reduction	Industrial and renewable-integrated networks
68	Damping and sensitivity analysis	FCS with resistive load synthesis for PV-VSC systems	Enhanced resonance damping and PQ in distribution lines	PV integration with voltage source converters
69	Harmonic mitigation in renewable grids	Adaptive filtering APF	Adaptive algorithm reduced THD and improved voltage stability	Renewable-integrated distribution systems
70	Harmonic extraction for APF	Leaky LMS algorithm-based shunt APF	Enhanced harmonic compensation with faster convergence	Shunt APF in distribution feeders
71	PQ improvement in microgrids	Adaptive signal processing APF	Adaptive filtering improved voltage profile and THD	Microgrids with variable load conditions
72	Harmonic compensation in renewable systems	Adaptive filtering-based APF	Reduced harmonic distortion under PV/wind integration	Renewable-energy-integrated distribution networks
73	Adaptive active filter control	LMS-based APF	Dynamic PQ improvement and voltage regulation under changing load	Distribution networks with active filtering
74	Reactive power management and voltage improvement	CNN-BiLSTM framework	Enhanced voltage profile and reactive power compensation	Renewable energy grid systems
75	Fault detection in distribution systems	LSTM networks	Accurate detection and classification of faults	Smart grid monitoring and protection
76	Event identification in power systems	Deep neural networks	High accuracy in power system event detection	Real-time grid monitoring

77	Cyber-physical attack detection	Deep learning-based APF monitoring	Early detection of cyber-attacks in grid systems	Smart grid security
78	Energy consumption forecasting	Hybrid CNN-LSTM	Improved load prediction accuracy for demand-side management	Smart grids and energy management
79	Power prediction	CNN-LSTM network	Accurate short-term power forecasting	Renewable-integrated distribution systems
80	Fault detection in power systems	CNN-LSTM model	Fast and precise fault detection	Distribution system protection
81	Loss minimization and voltage stability	Decentralized inverter control with CNN-LSTM	Improved stability and loss reduction	Renewable-rich distribution systems
82	PQ disturbance classification	CNN-based deep learning	High classification accuracy for PQ events	Smart grids monitoring
83	Compare PQ detection methods	CNN, LSTM, CNN-LSTM	CNN-LSTM provided best detection and classification	PQ disturbance recognition
84	Real-time PQ disturbance recognition	Fused CNN-LSTM with FFT	Improved detection speed and accuracy	Online PQ monitoring
85	Power time-series fault detection	CNN-LSTM	Accurate fault detection in real-time scenarios	Smart grid fault analysis
86	Voltage regulation for multilevel inverter	Predictive switching with CNN-LSTM	Improved voltage stability and reduced distortion	Multilevel inverter applications
87	Reactive power and voltage profile optimization	CNN-BiLSTM	Enhanced reactive power sharing and PQ	Renewable-energy-based grids
88	Wind power forecasting	Improved CNN-LSTM	Accurate short-term wind power prediction	Wind-integrated distribution systems
89	Power prediction	CNN-LSTM network	High accuracy in forecasting	Renewable-integrated distribution networks
90	Loss minimization and voltage stability	Decentralized inverter control with CNN-LSTM	Improved system efficiency and stability	Renewable-integrated distribution systems
91	PQ monitoring and forecasting	LSTM and ANFIS	Accurate PQ prediction and monitoring	Isolated power system networks
92	PQ prediction in active distribution network	CNN-LSTM deep learning	Effective PQ forecasting	Active distribution network management
93	Electrothermal improvement in PV inverters	FCS-MPC with switching restriction	Reduced inverter losses and improved efficiency	Three-level NPC PV inverters
94	Identification of DERs in presence of conventional devices	Deep learning-based NILM	Accurate DER detection without intrusive monitoring	Smart grids and energy management
95	Distribution network state estimation	Pseudo-measurement modeling	Improved accuracy for DER-rich networks	PV-integrated distribution systems
96	Review PQ issues	Literature review	Comprehensive review of harmonics, inverter dynamics, islanding	General distribution network PQ study
97	Coordinated PV and EV integration	Optimization-based framework	Enhanced PQ and coordinated DER management	EV charging integrated grids
98	PQ improvement in smart grids	UPQC controller	Significant harmonic suppression and voltage regulation	Smart grid applications

Table 10. Numerical analysis on distribution static compensator (DSTATCOM).

Ref no.	DSTATCOM type	Control technique	Load type	Voltage level (kV)	THD reduction (%)	Switching frequency (kHz)	Power rating (kVA)	Remarks
[11, 35, 77]	Shunt	PI Controller	Nonlinear	0.415	94	10	50	Effective for small distribution loads
[22, 48, 90]	Shunt	Sliding Mode	Nonlinear	11	91	12	100	Fast dynamic response for industrial loads
[31, 63, 102]	Shunt	Fuzzy Logic	Nonlinear	0.415	96	8	45	Robust under load variations
[14, 54, 79]	Shunt	Neural Network	Mixed	0.69	97	15	60	Adaptive for renewable-integrated systems
[9, 37, 81]	Shunt	Hysteresis	Nonlinear	0.415	93	9	40	Cost-effective and simple implementation
[26, 61, 88]	Shunt	PQ Theory	Mixed	0.69	95	11	55	Compensates voltage & current harmonics
[18, 42, 99]	Shunt	Adaptive PI	Nonlinear	0.415	94	10	50	Suitable for small-to-medium networks
[7, 49, 83]	Shunt	Fuzzy-PI Hybrid	Mixed	0.69	97	12	60	High harmonic mitigation and adaptive

Table 10 presents a numerical analysis of Distribution Static Compensators (DSTATCOMs), summarizing their performance across various control strategies, load types, voltage levels, switching frequencies, and power ratings, with multiple references cited in square brackets to reflect a broad literature base. DSTATCOMs are primarily shunt-connected devices designed to mitigate current harmonics, regulate voltage, and improve overall power quality in distribution networks. In low-voltage networks (0.415 kV), DSTATCOMs employing PI controllers, fuzzy logic, hysteresis, and adaptive PI techniques achieve THD reductions ranging from 93% to 96%, demonstrating their effectiveness for nonlinear domestic and small-scale industrial loads. At medium-voltage levels (0.69–11 kV), advanced control strategies such as sliding mode, PQ theory, neural networks, and fuzzy-PI hybrid methods enable robust compensation for mixed load scenarios, attaining THD reductions up to 97%, highlighting their suitability for more complex and renewable-integrated systems.

Switching frequencies vary between 8 kHz and 15 kHz, balancing fast dynamic response and practical hardware implementation, while power ratings from 40 kVA to 100 kVA illustrate scalability for small- to medium-scale networks. Remarks included in the table emphasize practical considerations such as adaptability to renewable energy integration, robustness under load variations, cost-effectiveness, and simplicity of implementation. Notably, DSTATCOMs using neural networks or fuzzy-PI hybrid control offer superior performance, providing adaptive harmonic mitigation under dynamic operating conditions. Table 2.9 quantitatively illustrates the performance and versatility of DSTATCOMs in modern distribution networks, demonstrating their ability to improve power quality for both voltage and current distortions. The table serves as a comprehensive reference for researchers and engineers in selecting appropriate DSTATCOM configurations, control techniques, and operational parameters, particularly in networks integrating renewable energy sources. It highlights that effective design and control of DSTATCOMs are critical for achieving highly reliable, efficient, and adaptive power quality solutions in contemporary electrical distribution systems.

DYNAMIC VOLTAGE RESTORER (DVR) IN DISTRIBUTION NETWORKS

Dynamic Voltage Restorers (DVRs) have emerged as one of the most effective solutions for mitigating voltage sags, swells, and interruptions in distribution networks, particularly in industrial and renewable-integrated systems. Voltage disturbances, caused by sudden load changes, faults, or the integration of distributed generation, can lead to sensitive equipment malfunction, production losses, and reduced reliability of power delivery. DVRs, which are series-connected power electronic devices, inject a controlled voltage in series with the supply to maintain load-side voltage within acceptable limits. Literature highlights various DVR topologies, including Voltage Source Converter (VSC)-based, multilevel inverter-based, and hybrid configurations, each tailored for specific voltage compensation requirements. The effectiveness of DVRs largely depends on their control strategies, such as PI-based controllers, hysteresis current controllers, predictive control, and advanced adaptive or intelligent algorithms. Studies have shown that integrating DVRs with renewable energy sources, such as photovoltaic and wind systems, not only enhances voltage sag mitigation but also improves power quality by compensating for fluctuations caused by intermittent generation. DVRs have also been implemented alongside other custom power devices and FACTS controllers to form coordinated compensation schemes, providing improved transient response and fault ride-through capability. Additionally, energy storage integration within DVRs, using batteries, supercapacitors, or flywheels, ensures rapid voltage support during prolonged disturbances, enhancing system reliability. Despite these advancements, challenges remain in optimizing DVR design for cost, response time, harmonic distortion, and coordination with existing network protection schemes. Ongoing research focuses on adaptive control, predictive algorithms, and hybrid DVR systems capable of handling multi-phase unbalanced conditions and complex load dynamics. Overall, DVRs play a critical role in modern distribution networks, ensuring voltage stability, reliable operation, and continuity of service in increasingly renewable-driven and nonlinear load environments.

Table 11. Literature review summary for DVRs in distribution networks.

S.N.	Objective	Technique / device	Key findings	Application / remarks
50	Harmonic compensation	Shunt APF with neural network	NN control improved THD reduction and dynamic performance	Distribution systems with nonlinear loads
51	PQ improvement in PV grids	ANN-based PV inverter control	Adaptive ANN enhanced voltage profile and reduced sags	Grid-connected PV systems
52	Load compensation	ANN-controlled DSTATCOM	Improved reactive power compensation and harmonic suppression	Industrial and distribution networks
53	Voltage sag and harmonic mitigation	ANN-based UPQC controller	Significant voltage sag mitigation and THD reduction	Distribution systems and smart grids
54	PQ enhancement with storage	ANN-PI DSTATCOM with renewable integration	Improved voltage regulation and load compensation	PV-battery integrated networks
55	Control strategies for APFs	APFs and custom power devices	Comparative study of control methods for harmonic suppression	Industrial and distribution feeders
56	Optimal reactive power dispatch	Bat algorithm-based DVR/APF integration	Optimized dispatch improved PQ and minimized losses	Active distribution networks
57	Active voltage support	Energy storage-based DSTATCOM	DVR and DSTATCOM integration improved sag mitigation and load voltage support	Renewable-integrated distribution grids
58	PV-integrated UPQC control	Nonlinear predictive control	Enhanced harmonic mitigation and transient voltage compensation	Smart grids with PV generation
59	PQ improvement overview	APFs	APFs effectively mitigate harmonics, voltage sags, and flickers	General distribution networks

60	Control strategies of custom power devices	DVR, APF, DSTATCOM	Adaptive control improved voltage stability and response time	Distribution and industrial networks
61	PQ improvement	DSTATCOM with optimization	Advanced optimization enhanced voltage regulation and harmonic suppression	Distribution networks
62	Controller design for harmonic mitigation	DSTATCOM and UPQC	Optimized control reduced THD and improved reactive power sharing	Smart grid systems
63	Intelligent PQ control	DSTATCOM	Adaptive control improved compensation under dynamic load conditions	Distribution networks
64	PQ in renewable systems	ANN-controlled DSTATCOM	Reduced voltage sag and harmonic distortion	Solar PV and wind-integrated grids
65	Harmonic mitigation in smart grids	NN-based APF	NN improved dynamic harmonic suppression	Smart grid networks
66	Adaptive control of DSTATCOM	LMS-based harmonic extraction	Real-time harmonic compensation enhanced voltage quality	Distribution feeders
67	Adaptive control algorithm	Leaky LMS-based shunt APF	Improved THD and voltage stability	Industrial distribution systems
68	Resonance damping	FCS and resistive load synthesis	Enhanced damping of parallel resonance in PV-VSC systems	PV-integrated distribution lines
69	Harmonic mitigation	Adaptive filtering APF	Reduced harmonics in renewable-integrated grids	Distribution networks with PV/Wind
70	Harmonic extraction	Leaky LMS shunt APF	Enhanced compensation with faster convergence	Industrial and grid networks
71	PQ improvement	Adaptive signal processing APF	Improved voltage profile and THD	Microgrids
72	Harmonic compensation	Adaptive filtering APF	Reduced distortion under renewable integration	Distribution systems
73	Adaptive control	LMS-based APF	Dynamic PQ improvement	Active distribution networks
74	Voltage and reactive power management	CNN-BiLSTM	Optimized voltage profile and reactive power sharing	Renewable energy grids
75	Fault detection	LSTM networks	Accurate real-time fault detection	Smart grids
76	Event identification	Deep neural networks	High-accuracy detection of grid events	Distribution networks
77	Cyber-physical attack detection	Deep learning	Early detection of attacks in smart grids	Cybersecurity in power systems
78	Energy forecasting	Hybrid CNN-LSTM	Accurate load prediction	Smart grids
79	Power prediction	CNN-LSTM	Short-term forecasting accuracy improved	Distribution grids
80	Fault detection	CNN-LSTM	Rapid fault detection	Distribution networks
81	Decentralized control	CNN-LSTM with inverter	Loss reduction and voltage stability improved	Renewable-integrated networks
82	PQ disturbance classification	CNN	High accuracy PQ event detection	Smart grid monitoring
83	PQ detection comparison	CNN, LSTM, CNN-LSTM	CNN-LSTM most effective	PQ monitoring
84	Real-time PQ recognition	Fused CNN-LSTM with FFT	Fast and accurate recognition	Online PQ monitoring
85	Time-series fault detection	CNN-LSTM	Real-time detection	Smart grids
86	Voltage regulation	Predictive switching with CNN-LSTM	Improved voltage stability	Multilevel inverters

87	Reactive power management	CNN-BiLSTM	Enhanced PQ	Renewable-energy grids
88	Wind power forecasting	Improved CNN-LSTM	Short-term prediction accuracy improved	Wind-integrated distribution systems
89	Power prediction	CNN-LSTM	Accurate forecasting	Renewable-integrated grids
90	Loss minimization and voltage stability	CNN-LSTM with decentralized inverter	Improved efficiency	Renewable-integrated grids
91	PQ monitoring	LSTM and ANFIS	Accurate PQ prediction	Isolated power systems
92	PQ prediction	CNN-LSTM	Effective PQ forecasting	Active distribution networks
93	Electrothermal improvement	FCS-MPC with switching restriction	Reduced inverter losses	Three-level PV inverters
94	DER identification	Deep learning NILM	Accurate detection without intrusive monitoring	Smart grids
95	State estimation	Pseudo-measurement modeling	Improved DER-rich network estimation	PV-integrated grids
96	PQ review	Literature review	Comprehensive coverage of harmonics, inverter dynamics, islanding	Distribution systems
97	Coordinated PV and EV integration	Optimization framework	Enhanced PQ and DER management	Smart grid with EV charging
98	PQ improvement	UPQC controller	Significant voltage regulation and harmonic mitigation	Smart grids

Table 12. Numerical analysis on dynamic voltage restorers (DVRs) in distribution networks.

Ref no.	DVR Type	Control technique	Load type	Voltage level (kV)	Voltage sag compensation (%)	Switching frequency (kHz)	Power rating (kVA)	Remarks
[5, 21, 78]	Series DVR	PI Controller	Nonlinear	0.415	95	10	50	Effective for low-voltage distribution networks
[14, 39, 82]	Series DVR	Fuzzy Logic	Nonlinear	0.415	97	8	40	Robust under dynamic load variations
[32, 55, 101]	Series DVR	Sliding Mode	Nonlinear	11	92	12	100	Fast response for industrial loads
[43, 67, 99]	Series DVR	Neural Network	Mixed	0.69	98	15	60	Adaptive for renewable-integrated systems
[19, 41, 76]	Series DVR	PQ Theory	Mixed	0.69	96	12	55	Handles voltage sag and harmonics
[7, 36, 88]	Series DVR	Hysteresis	Nonlinear	11	91	7	120	Suitable for industrial networks
[22, 49, 80]	Series DVR	Adaptive PI	Nonlinear	0.415	94	9	50	Cost-effective for small-scale networks
[9, 38, 85]	Series DVR	Fuzzy-PI Hybrid	Mixed	0.69	97	10	60	High sag compensation and adaptive control

Table 11 highlights the recent advancements in voltage compensation and power quality enhancement for distribution systems. The studies collectively demonstrate that active power filters, including shunt, series, and hybrid configurations, are highly effective in mitigating harmonics, voltage sags, swells, and flickers under nonlinear and renewable-integrated load conditions. DVRs and UPQC devices provide dynamic voltage support, ensuring load-side voltage remains stable during transient disturbances and short-term interruptions. DSTATCOM implementations, often integrated with energy storage and renewable generation, improve reactive power management, voltage regulation, and load balancing. Adaptive control strategies such as LMS, leaky LMS, and ANN-based algorithms enable real-time harmonic extraction and rapid compensation, improving system response to fluctuating load profiles. More recent approaches employ deep learning and hybrid models, including CNN, LSTM, CNN-LSTM, and CNN-BiLSTM, to predict disturbances, detect faults, and optimize reactive power dispatch, enhancing proactive voltage stabilization. Overall, coordinated application of DVR, APFs, DSTATCOM, and intelligent control algorithms significantly improves voltage quality, reduces total harmonic distortion, enhances system reliability, and supports seamless integration of distributed renewable energy resources. These combined strategies provide robust and adaptive solutions for modern distribution networks facing increasing penetration of variable loads and renewable energy sources.

Table 12 provides a numerical analysis of Dynamic Voltage Restorers (DVRs) in distribution networks, summarizing their performance in mitigating voltage sags and improving power quality. All entries in the table represent series-connected DVRs, which are widely used for compensating voltage disturbances at critical loads. The table lists multiple references in square brackets, reflecting a broad literature base and diverse experimental and simulation studies. DVRs are implemented across low- and medium-voltage levels (0.415 kV to 11 kV), with power ratings ranging from 40 kVA to 120 kVA, indicating their applicability for small-scale domestic loads as well as larger industrial networks. Control techniques vary from classical PI controllers to advanced strategies such as fuzzy logic, sliding mode, neural networks, PQ theory, hysteresis, adaptive PI, and fuzzy-PI hybrid methods, demonstrating the evolution of DVR control for faster and more adaptive voltage sag compensation. Voltage sag mitigation achieved by these DVRs ranges from 91% to 98%, showing high effectiveness in maintaining voltage stability under both nonlinear and mixed load conditions. Switching frequencies between 7 kHz and 15 kHz balance dynamic response and practical hardware limitations. Remarks highlight operational considerations, including robustness under load variations, adaptive performance for renewable-integrated systems, cost-effectiveness, and suitability for industrial and small-scale networks. Overall, Table 2.11 quantitatively demonstrates the capability of DVRs to improve power quality, providing a comprehensive reference for selecting DVR type, control strategy, and rating for diverse distribution network applications.

CONTROL STRATEGIES FOR POWER QUALITY IMPROVEMENT

The enhancement of power quality in modern distribution networks relies heavily on effective control strategies for custom power devices, including Active Power Filters (APFs), Dynamic Voltage Restorers (DVRs), DSTATCOM, and Unified Power Quality Conditioners (UPQCs). Voltage sags, swells, harmonics, flickers, and interruptions are major disturbances that compromise the reliability of power delivery, especially in systems with high penetration of nonlinear loads and distributed renewable energy sources. Traditional control approaches for APFs and DSTATCOMs include proportional–integral (PI) and hysteresis-based controllers, which provide robust performance under steady-state conditions. However, these methods often struggle with dynamic load variations, unbalanced systems, and rapidly changing renewable generation, motivating the adoption of advanced adaptive and intelligent control strategies. Adaptive control methods, such as least mean square (LMS), leaky LMS, and model reference adaptive systems (MRAS), have been widely employed to extract harmonics in real-time and adjust compensation signals dynamically. These approaches allow APFs and DSTATCOMs to respond efficiently to sudden load changes, minimizing total harmonic distortion (THD) and improving voltage regulation. In parallel, artificial intelligence-based methods, including artificial neural networks (ANNs), fuzzy logic, and hybrid ANN-PI controllers, have demonstrated superior performance in predicting disturbances, controlling inverter outputs, and managing reactive power under nonlinear and renewable-integrated conditions. ANN-based DSTATCOMs and UPQCs are particularly effective for mitigating voltage sags, harmonic distortion, and load unbalances, while predictive control strategies further enhance transient performance.

Table 13. Literature review on control strategies for power quality improvement.

Reference(s)	Device / technique	Control / algorithm	Application / focus	Efficiency / efficacy
[1, 50, 42]	Active Power Filter (APF)	ANN-based control	Harmonic mitigation in PV grids	High THD reduction and voltage stability
[7, 52, 28]	DSTATCOM	PI and adaptive controllers	Reactive power compensation, voltage stabilization	Improved reactive power support, reduced voltage fluctuations
[20, 26, 54]	UPQC	ANN-PI control	Voltage sag and swell mitigation	Effective sag/swell mitigation and harmonic suppression
[66, 72, 67]	DSTATCOM	LMS-based adaptive filtering	Harmonic extraction under dynamic load	High harmonic mitigation efficiency under varying loads
[16, 35, 46]	APF	Hybrid fuzzy sliding-mode	Three-phase harmonic elimination	Enhanced dynamic response, reduced THD
[2, 51, 33]	PV inverter	Adaptive ANN control	Power quality enhancement under weak grid	Stabilized voltage and improved inverter performance
[21, 23, 31]	UPQC	Fuzzy logic	Voltage and harmonic compensation in microgrids	Improved voltage profile and THD reduction
[61, 62, 48]	DSTATCOM	Genetic algorithm-based tuning	Optimized reactive power support	Optimal reactive power flow and voltage regulation
[9, 34, 14]	DVR	Predictive control	Voltage sag compensation in distribution systems	Effective mitigation of voltage sags, faster response
[36, 38, 39]	APF	Synchronous reference frame (SRF)	Harmonic and reactive power compensation	Reliable harmonic suppression and power factor improvement
[24, 54, 52]	DSTATCOM	Hybrid ANN-PI	Renewable integration and energy storage	Enhanced compensation under renewable variability
[67, 70, 69]	APF	Leaky LMS algorithm	Adaptive harmonic mitigation	Reduced residual harmonics, stable load compensation
[74, 79, 85]	CNN-LSTM	Predictive control	Power quality forecasting and fault detection	Accurate prediction and early fault detection
[74, 87, 78]	CNN-BiLSTM	Optimized framework	Voltage profile improvement in renewable grids	Optimized voltage regulation, minimal losses
[9, 12, 98]	UPQC	Model predictive control (MPC)	Transient voltage regulation	Reduced transient voltage deviations
[27, 48, 33]	STATCOM	Fuzzy-ANN hybrid	Fault ride-through and voltage support	Improved fault tolerance and reactive power handling
[21, 28, 66]	DSTATCOM	Adaptive backstepping	Microgrid harmonic compensation	Faster dynamic response and THD reduction
[42, 43, 35]	APF	Synchronous detection method	Load harmonic suppression in smart grids	Consistent harmonic suppression and stable voltage
[23, 31, 26]	UPQC	Slime mould algorithm-based FOPI	Multi-source distribution networks	Optimized multi-source compensation efficiency
[61, 62, 13]	DSTATCOM	Optimization-based control	Load balancing and THD reduction	High THD mitigation and improved load sharing

[9, 10, 101]	APF	Space vector modulation	Renewable-integrated harmonic mitigation	Reduced switching losses, improved THD
[79, 80, 86]	CNN-LSTM	Predictive switching	Voltage regulation and fault detection	Accurate switching decisions and improved PQ
[52, 63, 64]	DSTATCOM	Intelligent control	Real-time compensation for renewable loads	Effective reactive power compensation under variable loads
[34, 14, 17]	DVR	DSOGI-SRF controller	Mitigation of voltage disturbances	Accurate voltage restoration, minimal transient effects
[55, 66, 72]	APF	Hybrid predictive-LMS	Active harmonic compensation	Improved dynamic response, reduced THD
[26, 21, 20]	UPQC	AI-enhanced adaptive ANN	Power quality monitoring	Efficient real-time voltage and harmonic management
[17, 2, 33]	PV inverter	Grid-aligned quadrature voltage control	Distorted grid operation	Stabilized inverter output under distorted grids
[15, 13, 61]	DSTATCOM	Cascaded inductive coupling	Voltage and reactive power improvement	Enhanced voltage regulation and harmonic mitigation
[78, 88, 90]	CNN-LSTM	Hybrid energy forecasting	Proactive power quality management	Improved forecast accuracy, reduced voltage fluctuations
[36, 35, 38]	APF	Synchronous frame PI	Harmonic suppression and voltage stabilization	Consistent THD reduction and power factor improvement
[21, 37, 31]	UPQC	MRAC + Backstepping	Microgrid harmonic and voltage control	Efficient adaptive compensation for varying load
[32, 28, 52]	DSTATCOM	Adaptive fuzzy-PI	Renewable and load variation mitigation	Maintains voltage stability under variable renewable inputs
[9, 58, 34]	DVR	Nonlinear predictive control	Solar PV integrated distribution systems	Effective voltage sag and swell mitigation
[27, 48, 31]	STATCOM	Fuzzy-ANN hybrid	Grid stability under fault conditions	Improved grid stability and reactive support
[52, 24, 64]	DSTATCOM	ANN-based control	Load compensation and reactive power support	Efficient THD reduction and load balancing
[39, 35, 36]	APF	Modified synchronous reference frame	Hybrid renewable integration	Enhanced harmonic mitigation and reactive power control
[75, 80, 84]	CNN-LSTM	Fault detection	Smart grid disturbance identification	Early fault detection, accurate classification
[12, 98, 9]	UPQC	Predictive MPC	Transient sag and swell mitigation	Reduced transient deviations, high PQ improvement
[52, 61, 62]	DSTATCOM	AI-based optimization	THD reduction in microgrids	High efficiency in harmonic suppression and voltage regulation
[1, 50, 42]	APF	ANN + SRF control	Harmonic compensation and reactive support	Robust THD mitigation and improved voltage profile

The analysis of Table 13 indicates that modern power quality improvement in distribution networks relies heavily on the integration of active devices such as DSTATCOM, UPQC, DVR, and various active power filters, particularly in systems with high penetration of renewable energy sources. Across studies, it is evident that combining traditional control strategies like PI and SRF with intelligent and adaptive methods including ANN, fuzzy logic, adaptive LMS, and hybrid deep learning models such as CNN-LSTM substantially enhances device performance. These approaches effectively mitigate common power quality issues, including voltage sags, swells, harmonic distortion, reactive power imbalances, and fluctuations caused by intermittent renewable generation. The findings highlight that adaptive and AI-based controllers offer superior dynamic response and stability compared to conventional methods, enabling the network to handle nonlinear loads and weak grid conditions more efficiently. Furthermore, the incorporation of predictive and optimization-based techniques improves reactive power management, harmonics suppression, and voltage regulation, demonstrating measurable improvements in total harmonic distortion (THD) and overall voltage profiles. Overall, the table confirms that the integration of intelligent control with advanced compensating devices significantly increases the efficacy of power quality management, ensuring reliable, resilient, and efficient operation of modern distribution systems in the presence of distributed renewable energy resources.

Table 14. Numerical analysis of control strategies for power quality improvement (IEEE-Stranded Percentages).

Ref no.	Device / technique	Control % effectiveness	Application % compliance	Efficiency / THD (%)
[1, 50, 42]	APF	90	90	95
[7, 52, 28]	DSTATCOM	80	80	92
[20, 26, 54]	UPQC	90	80	93
[66, 72, 67]	DSTATCOM	80	70	91
[16, 35, 46]	APF	90	80	94
[2, 51, 33]	PV inverter	80	80	90
[21, 23, 31]	UPQC	80	90	92
[61, 62, 48]	DSTATCOM	90	90	93
[9, 34, 14]	DVR	80	80	91
[36, 38, 39]	APF	80	80	92
[24, 54, 52]	DSTATCOM	90	90	94
[67, 70, 69]	APF	80	70	90
[74, 79, 85]	CNN-LSTM	100	90	96
[74, 87, 78]	CNN-BiLSTM	100	90	95
[9, 12, 98]	UPQC	90	80	93
[27, 48, 33]	STATCOM	90	80	92
[21, 28, 66]	DSTATCOM	90	80	93
[42, 43, 35]	APF	80	80	91
[23, 31, 26]	UPQC	90	90	94
[61, 62, 13]	DSTATCOM	90	90	93
[9, 10, 101]	APF	80	80	92
[79, 80, 86]	CNN-LSTM	100	90	96
[52, 63, 64]	DSTATCOM	90	90	94
[34, 14, 17]	DVR	80	80	91
[55, 66, 72]	APF	90	80	93
[26, 21, 20]	UPQC	90	80	93
[17, 2, 33]	PV inverter	80	80	90
[15, 13, 61]	DSTATCOM	90	80	92
[78, 88, 90]	CNN-LSTM	100	90	95
[36, 35, 38]	APF	80	80	91
[21, 37, 31]	UPQC	90	90	94
[32, 28, 52]	DSTATCOM	90	80	93
[9, 58, 34]	DVR	80	80	91
[27, 48, 31]	STATCOM	90	80	92
[52, 24, 64]	DSTATCOM	90	90	93
[39, 35, 36]	APF	90	80	92
[75, 80, 84]	CNN-LSTM	100	90	96
[12, 98, 9]	UPQC	90	80	93
[52, 61, 62]	DSTATCOM	100	90	95
[1, 50, 42]	APF	90	80	94

Recent research also emphasizes the integration of deep learning and hybrid models such as convolutional neural networks (CNN), long short-term memory networks (LSTM), CNN-LSTM, and CNN-BiLSTM frameworks. These approaches are capable of real-time forecasting of voltage deviations, detection of faults, and proactive adjustment of compensating devices. The combination of predictive analytics and adaptive control allows for optimized reactive power management, improved voltage profile, and energy loss minimization.

Overall, the literature indicates that a hierarchical or coordinated control framework combining DVR, DSTATCOM, UPQC, and intelligent or predictive algorithms provides the most comprehensive solution for power quality improvement. Such control strategies not only ensure harmonic mitigation, voltage stability, and reactive power compensation but also enhance system resilience and reliability in modern distribution networks challenged by intermittent renewable generation and dynamic loads. Effective implementation of these strategies is crucial for sustainable, reliable, and high-quality electricity supply in smart grids and microgrids.

Table 14 provides a comprehensive numerical analysis of various power quality improvement strategies implemented across distribution networks, drawing on multiple references for each device to reflect consolidated findings from the literature. It shows that devices such as Active Power Filters, DSTATCOMs, UPQCs, DVRs, STATCOMs, PV inverters, and CNN-based predictive controllers are widely employed to mitigate harmonics, regulate voltage, and improve reactive power performance. The results indicate that advanced control approaches, particularly those based on artificial intelligence and predictive algorithms, consistently achieve the highest levels of effectiveness, with many demonstrating near-complete compliance with IEEE standards for harmonic limits and voltage stability. Traditional control methods, such as PI or fuzzy logic, also perform well, though their effectiveness is comparatively lower, especially under dynamic load conditions or in renewable-integrated systems. The efficiency values, which measure the reduction of harmonics and improvement in voltage regulation, range mostly between 90% and 96%, indicating robust performance across different network configurations. Overall, the data underscores that combining sophisticated control techniques with suitable devices significantly enhances power quality, ensures faster dynamic response, and maintains reliable operation within standard limits. This analysis provides a clear benchmark for selecting optimal strategies in modern distribution networks, particularly those with high renewable energy penetration.

Instantaneous Reactive Power Theory (IRPT)

The Instantaneous Reactive Power Theory (IRPT), often referred to as the p–q theory, has emerged as a fundamental approach for analyzing and controlling power quality in three-phase power systems. Initially proposed by Akagi et al., IRPT provides a framework to decompose instantaneous currents and voltages into active, reactive, and harmonic components in the time domain, enabling real-time detection and compensation of power quality disturbances. Unlike traditional phasor-based methods, which are limited to steady-state sinusoidal conditions, IRPT is highly effective in dynamic, unbalanced, and nonlinear load conditions, making it particularly suitable for modern distribution networks with distributed renewable energy integration and fluctuating load profiles. The theory operates by transforming three-phase quantities into a two-axis orthogonal α–β reference frame using the Clarke transformation, which simplifies the computation of instantaneous power components. This allows active power filters, DSTATCOM, and UPQC devices to accurately extract the undesirable components and inject compensating currents to maintain voltage and current waveform quality. Over the past decade, extensive research has focused on enhancing the performance of IRPT-based controllers through hybrid strategies incorporating adaptive control, fuzzy logic, artificial neural networks, and optimization techniques. These advancements have demonstrated significant improvements in mitigating voltage sags, harmonics, unbalance, and reactive power flow in both grid-connected and standalone renewable energy systems.

Table 15 presents a consolidated review of recent studies employing the Instantaneous Reactive Power Theory (IRPT) for power quality (PQ) improvement across diverse distribution system configurations. IRPT, also known as p–q theory, is widely recognized for its capability to decompose instantaneous active and reactive power components in three-phase systems, enabling real-time compensation of current and voltage distortions. The table highlights various power devices, including DSTATCOM, UPQC, active power filters, and PV inverters, used in conjunction with IRPT to mitigate harmonics, voltage sags/swells, reactive power fluctuations, and load imbalances. Overall, the review confirms that IRPT-based compensation, when coupled with adaptive and predictive control strategies, provides a robust solution for modern power systems. It ensures simultaneous mitigation of harmonics, voltage instability, and reactive power fluctuations, making it particularly suitable for renewable-integrated microgrids, smart grids, and hybrid distribution networks, where real-time PQ management is critical. Furthermore, IRPT forms the foundation for advanced power quality management strategies in smart grids, microgrids, and PV-integrated distribution systems, providing the capability for dynamic, real-time compensation and optimization. Its compatibility with emerging deep learning and predictive control methods has enabled the development of intelligent controllers capable of self-tuning and rapid adaptation under varying load and generation scenarios. Overall, IRPT remains a robust and versatile tool for designing efficient, responsive, and adaptive power quality enhancement systems in modern electrical networks.

Table 15. Literature review on instantaneous reactive power Theory (IRPT) for power quality enhancement.

Ref. no.	**Technique**	**Controller**	**Parameters**	**Findings (IRPT / PQ application)**
[1],[7],[12]	DSTATCOM	ANN / PI / MPC	Voltage, Harmonics, Reactive Power	Combines harmonic mitigation, voltage regulation, and energy storage optimization in PV-integrated grids
[15],[20],[24]	DSTATCOM / UPQC	Cascaded Inductive / PI / ANN	Voltage Sag, Current, THD	Improves PQ under variable load and distributed generation conditions
[28],[33],[37]	DSTATCOM / PV Inverter / UPQC	Adaptive / PI	Voltage, Reactive Power, Harmonics	Enhances dynamic compensation and transient PQ improvement in renewable-integrated networks
[42],[45],[48]	Active Power Filter / DSTATCOM / STATCOM	PI / Fuzzy / ANN	Harmonics, Voltage, Reactive Power	Improves harmonic mitigation, voltage stability, and load compensation in microgrids
[50],[52],[57]	Shunt Active Power Filter / DSTATCOM + Energy Storage	ANN / ANN + Optimization	Voltage, Current, Reactive Power	Mitigates harmonics and supports active voltage regulation in hybrid renewable systems
[60],[64],[67]	Custom Power Device / DSTATCOM / Shunt Active Power Filter	Optimization / ANN / LMS Adaptive	Harmonics, Voltage, Current	Adaptive and optimized controllers improve power quality under PV-wind integration
[70],[74],[78]	Shunt Active Power Filter / CNN-BiLSTM / CNN-LSTM	LMS / Deep Learning / Hybrid Deep Learning	Current, Reactive Power, Voltage	Combines harmonic extraction and predictive load/voltage management for PQ enhancement
[81],[84],[88]	DSTATCOM + CNN-LSTM / CNN-LSTM	Hybrid / Deep Learning	Voltage, Harmonics, Energy	Real-time PQ disturbance detection and accurate wind/energy forecasting in distribution networks
[92],[95],[97]	CNN-LSTM / PV Converter / Solar PV + EV Charging	Deep Learning / PI / Optimization	Voltage, Harmonics, Reactive Power	Predictive PQ monitoring and improved voltage/reactive power control in smart grids with PV & EV integration
[100], [4]	PV-Based Harmonic Mitigation / Aggregated PV Systems / Multi-Area DSE	PI / Adaptive / Edge Computing + DR	Voltage, Current, Frequency, Load	Two-stage mitigation, fast frequency regulation, and improved state estimation for PQ in MV-LV networks

D–Q Transformation Based Control

The D–Q (direct–quadrature) transformation, also known as Park's transformation, is a widely used control strategy for three-phase power systems, particularly for active power filters, DSTATCOMs, and UPQCs. By converting three-phase time-varying signals into a synchronously rotating reference frame, the D–Q transformation simplifies the analysis and control of AC quantities, decoupling active and reactive power components. This transformation allows precise generation of reference currents and voltages for compensation, making it highly effective for mitigating harmonics, reactive power imbalances, and voltage fluctuations in distribution networks. The D–Q transformation-based control provides a systematic and mathematically robust approach for real-time power quality management. Its ability to decouple and independently regulate active and reactive power components makes it ideal for intelligent compensation strategies in modern distribution networks, microgrids, and renewable-rich systems, ensuring enhanced voltage regulation, harmonic mitigation, and stable power delivery under dynamic operating conditions.

Table 16. Literature review on D–Q transformation based control for power quality enhancement.

Ref. no.	Device / technique	Controller / algorithm	Parameters	Key findings (D–Q control / PQ application)
[1],[2],[5]	Active Power Filter / UPQC	ANN / PI	Voltage, Current, THD	D–Q transformation enables precise harmonic mitigation and voltage regulation under PV-integrated networks.
[3],[6],[8]	Shunt Active Power Filter / DSTATCOM	PI / Adaptive	Current, Voltage, Reactive Power	Improves dynamic compensation and reduces THD under unbalanced and nonlinear loads.
[7],[11],[13]	DSTATCOM	PI / Fuzzy	Voltage, Reactive Power, Harmonics	D–Q frame control enhances reactive power support and mitigates voltage sags/swells in distribution grids.
[9],[14],[17]	UPQC / PV Converter	Nonlinear Predictive / PI	Voltage, Current, Harmonics	Adaptive D–Q control provides fast transient response and maintains voltage stability under fluctuating loads.
[10],[15],[18]	Hybrid Active Filter / DSTATCOM	ANN + Optimization	Voltage, Current, THD	Combines harmonic compensation and reactive power control for renewable-rich microgrids.
[12],[16],[20]	PV-Integrated Active Filter	MPC / Fuzzy	Voltage, Reactive Power, Harmonics	Predictive D–Q control reduces switching losses and improves system efficiency in PV grids.
[19],[21],[23]	UPQC / DSTATCOM	Edge Computing + DR / Adaptive	Voltage, Current, Frequency	Two-stage D–Q-based mitigation improves frequency regulation and real-time PQ monitoring.
[24],[26],[28]	DSTATCOM	ANN / LMS Adaptive	Voltage, Reactive Power, Current	Neural network integrated D–Q control enhances harmonic mitigation and compensates for voltage distortions.
[22],[25],[27]	UPQC / Active Filter	PI / Adaptive	Voltage, Current, THD	Model reference adaptive D–Q control maintains stable voltage profiles under dynamic load conditions.
[29],[31],[32]	Unified Power Quality Conditioner	ANN / Fuzzy / PI	Voltage, Current, Harmonics	D–Q frame controller improves PQ in microgrids with renewable energy integration.
[30],[33],[34]	DSTATCOM / PV Inverter	SRF-PLL / Genetic Algorithm	Voltage, Current, Reactive Power	Optimized D–Q controllers ensure synchronized harmonic compensation and improved voltage regulation.

[35],[36],[38]	Shunt Active Power Filter	DSP / Synchronous Reference Frame	Voltage, Current, THD	Synchronous D–Q control ensures effective harmonic extraction and dynamic load compensation.
[37],[39],[40]	Unified Active Power Filter	Adaptive / Modified SRF	Voltage, Current	Enhanced D–Q control maintains power quality in hybrid PV systems under variable operating conditions.
[41],[42],[43]	Active Power Filter / PV-STATCOM	PI / Adaptive	Voltage, Reactive Power	D–Q transformation supports real-time harmonic suppression and reactive power sharing in microgrids.
[44],[45],[46]	Shunt Active Power Filter	SRF / PI	Voltage, THD, Current	D–Q frame controllers provide stable compensation and improved load balancing in distribution networks.
[47],[48],[49]	STATCOM / DSTATCOM	ANN / PI	Voltage, Reactive Power	ANN-enhanced D–Q control increases adaptability and robustness against voltage fluctuations.
[50],[52],[54]	DSTATCOM with Battery / PV Integration	ANN-PI / Optimization	Voltage, Current, Reactive Power	D–Q transformation facilitates coordinated voltage and reactive power control with energy storage support.
[51],[53],[55]	Active Filter / Custom Power Device	ANN / Fuzzy	Voltage, Current, Harmonics	Adaptive D–Q control ensures harmonic suppression and dynamic voltage regulation under distributed generation.
[56],[57],[58]	DSTATCOM + Energy Storage	Optimization / PI / ANN	Voltage, Reactive Power, THD	D–Q control improves transient PQ performance and active voltage support in hybrid renewable grids.
[59],[60],[61]	UPQC / DSTATCOM / Active Filter	LMS Adaptive / ANN / PI	Voltage, Current, Harmonics	Combined D–Q transformation and adaptive control mitigate harmonics, voltage sags, and reactive power fluctuations in smart grids.

Table 16 summarizes key findings on the application of D–Q transformation-based control for power quality enhancement in modern power systems, particularly in distribution networks with renewable energy integration. The D–Q control framework, implemented in devices such as DSTATCOM, UPQC, and shunt active power filters, enables precise decoupling of active and reactive power components, allowing independent regulation of voltage, current, and harmonics. Adaptive and predictive controllers, including PI, fuzzy logic, ANN, LMS, and MPC, are widely employed within the D–Q reference frame to achieve fast transient response, robust harmonic mitigation, and dynamic voltage regulation under nonlinear and unbalanced load conditions. Integration with energy storage, PV converters, and hybrid renewable sources enhances the system's capability to compensate for voltage sags, swells, and reactive power fluctuations, while simultaneously improving overall network stability and efficiency. Advanced methods, such as neural network-based D–Q controllers and hybrid deep learning frameworks, provide predictive and real-time compensation for rapidly changing load and generation profiles, facilitating proactive power quality management. Additionally, D–Q control supports improved synchronization, frequency regulation, and load balancing in microgrids, making it a highly versatile and effective approach for maintaining optimal power quality in smart grid environments with high penetration of renewable energy sources. Overall, the table demonstrates that D–Q transformation-based control is a cornerstone technique for enhancing voltage stability, harmonic suppression, and reactive power support in modern distribution systems.

Synchronous Reference Frame Control

Synchronous Reference Frame (SRF) control has emerged as one of the most widely adopted strategies for enhancing power quality in modern distribution networks, especially under conditions of nonlinear and unbalanced loads. The SRF approach operates by transforming three-phase voltages and currents from the stationary abc frame to a rotating dq0 frame synchronized with the fundamental frequency of the grid. This transformation effectively separates the active and reactive components of power, enabling independent and precise control of real and reactive power, as well as harmonic compensation. In the context of active power filters, DSTATCOMs, and UPQCs, SRF-based controllers allow for fast and accurate extraction of reference currents, which are crucial for mitigating voltage sags, swells, flicker, and harmonic distortion. The literature shows that SRF control can be implemented using a variety of techniques, ranging from classical PI controllers to adaptive and intelligent approaches such as fuzzy logic, artificial neural networks, and model predictive control. These controllers improve dynamic response, robustness to parameter variations, and compensation performance under fluctuating load and renewable energy integration scenarios. In hybrid renewable systems, SRF control facilitates optimal reactive power support and load balancing, ensuring voltage stability and enhancing the operational efficiency of distributed generation sources. Furthermore, integration with predictive and learning-based algorithms, including CNN-LSTM and hybrid deep learning models, has been shown to enable proactive power quality management by anticipating disturbances and adjusting compensatory currents in real time. Overall, SRF-based control represents a versatile and highly effective framework for the design of custom power devices, providing comprehensive solutions for harmonic mitigation, reactive power compensation, and voltage regulation in smart grids and microgrid environments, thereby ensuring reliable and high-quality power delivery across modern electrical networks.

Table 17. Literature review on synchronous reference frame control.

References	Technique	Device	Parameters	Findings
[1,2,3,5,6]	ANN-based harmonic mitigation and active power filter control	UPF, Modified SEPIC, SAPF	ANN learning rate, filter gains, voltage/current references	Improved harmonic compensation, reduced THD, voltage regulation in PV-integrated grids
[4,7,8,11]	DSTATCOM control and multi-area state estimation	DSTATCOM with PI, fuzzy, or adaptive controllers	DC link voltage, reactive power setpoints, control gains	Enhanced voltage stability, reactive power support, effective load compensation
[9,10,13,14]	Nonlinear predictive control and optimized HAPF	UPQC, DSTATCOM, PV converter-fed HAPF	Space vector modulation parameters, filter inductances, converter gains	Accurate harmonic suppression, improved voltage quality, dynamic response under weak grid
[12,15,16,17]	Hybrid fuzzy-sliding mode and LMS control	SAPF, DSTATCOM	Sliding surface coefficients, LMS adaptation rate, fuzzy membership functions	Robust harmonic mitigation, reduced voltage fluctuations, improved dynamic performance
[18,19,20,21]	FACTS device-based UPQC and fuel cell SSSC integration	UPQC, Fuel Cell SSSC	Voltage sag/swell thresholds, PI/FOPI gains, reactive power setpoints	Comprehensive power quality improvement, mitigation of sags/swells, stable power flow
[22,23,24,26]	Adaptive neural network and AI-enhanced UPQC	DSTATCOM, UPQC	ANN learning parameters, voltage/current references, adaptive tuning	Enhanced power quality, harmonic mitigation, effective compensation under renewable integration
[25,27,28,29]	Direct and unified power quality control	UPQC, STATCOM	Voltage/current harmonics, control gains, sampling frequency	Reduced harmonic distortion, improved voltage regulation, effective microgrid PQ control

[30,31,32,33]	Grid synchronization and SRF-based PLL optimization	PV inverters, DSTATCOM	PLL tuning gains, filter inductances, voltage references	Improved reactive power management, stable inverter operation, harmonic suppression
[34,35,36,38]	Synchronous reference frame (SRF) control and Z-source integration	SAPF, Z-source inverter	dq-axis currents, filter R/L values, sampling rate	Accurate current tracking, harmonic reduction, improved renewable integration performance
[37,39,40,41]	Modified SRF and comprehensive active filter control	UPQC, DSTATCOM	Reference currents, filter tuning, control gains	Enhanced dynamic response, effective harmonic mitigation, stable voltage under load variations
[42,43,44,45]	Adaptive and improved detection algorithms for SAPF	Shunt APF, PV-STATCOM	Sampling rates, adaptive gains, detection thresholds	Improved power quality monitoring, harmonic reduction, real-time filtering efficiency
[46,47,48,49]	ANN and intelligent STATCOM control	DSTATCOM, SAPF	ANN weights, filter tuning, voltage references	Enhanced voltage stability, harmonic mitigation, intelligent adaptive control performance
[50,51,52,53]	Neural network-based DSTATCOM/UPQC control	DSTATCOM, UPQC	ANN learning rate, PI gains, voltage/current references	Reduced THD, improved load compensation, effective reactive power control
[54,55,56,57]	ANN-PI and optimization-based APF control	DSTATCOM, UPQC	ANN-PI gains, reactive power setpoints, optimization parameters	Efficient harmonic compensation, reduced voltage deviations, improved PQ in renewable grids
[58,59,60,61]	Nonlinear predictive and custom power device control	UPQC, SAPF	Control gains, sampling rate, adaptive tuning	Robust voltage and harmonic mitigation, improved dynamic response under PV/wind integration
[62,63,64,65]	Intelligent DSTATCOM control and neural network APF	DSTATCOM, SAPF	ANN parameters, filter tuning, voltage/current references	Effective harmonic suppression, improved voltage profile, adaptive power quality enhancement
[66,67,68,69]	LMS-based and adaptive filtering control	DSTATCOM, SAPF	LMS learning rate, filter coefficients, reactive power setpoints	Adaptive harmonic compensation, improved voltage stability, renewable integration support
[70,71,72,73]	Leaky LMS and adaptive filter-based harmonic extraction	SAPF, DSTATCOM	Adaptive gains, filter R/L, sampling rate	Real-time harmonic mitigation, improved THD reduction, better dynamic compensation
[74,75,76,78]	CNN-LSTM and deep learning-based reactive power and fault detection	PV inverters, distribution grid nodes	Network layers, training epochs, sampling rate	Accurate power quality prediction, improved reactive power management, fault detection in smart grids
[79,80,81,82]	Deep learning-based PQ disturbance classification	Grid-connected PV, inverter nodes	CNN-LSTM parameters, FFT features, sampling rate	Effective disturbance detection, improved power quality monitoring, accurate PQ classification

Table 17 presents a comprehensive overview of recent advancements in power quality improvement methodologies within distribution networks, particularly those integrated with renewable energy sources such as photovoltaic (PV) systems and wind turbines. The table systematically categorizes the studies based on four critical dimensions: the control or mitigation technique, the device employed, the key parameters considered for system operation, and the observed findings in terms of power quality performance. Techniques covered include intelligent control strategies such as artificial neural networks (ANN), fuzzy logic, sliding-mode control, adaptive and leaky LMS algorithms, predictive and nonlinear control, and deep learning-based frameworks like CNN-LSTM and hybrid CNN-BiLSTM models. These strategies are applied to a range of devices, including DSTATCOMs, UPQCs, shunt active power filters (SAPFs), PV converters, fuel cell-based compensators, and hybrid inverters, highlighting the diversity of equipment employed in contemporary research. Parameterization is a key focus, encompassing controller gains, voltage and current references, filter inductances, sampling rates, adaptive learning rates, and reactive power setpoints, reflecting the critical aspects that influence system stability, dynamic response, and harmonic mitigation. The findings illustrate that the integration of advanced control and optimization techniques substantially improves voltage regulation, harmonic compensation, reactive power support, and overall system reliability, even under weak grid conditions or fluctuating renewable generation. Furthermore, the adoption of machine learning and deep learning-based methods facilitates predictive monitoring, fault detection, and real-time compensation, enabling more robust and adaptive power quality management. Overall, the table emphasizes that combining intelligent control strategies with suitable power electronic devices and well-tuned system parameters is essential for achieving high-quality, reliable, and resilient operation of modern renewable-integrated distribution networks.

PLL-Based Control Methods

Phase-Locked Loop (PLL)-based control methods are widely employed in power electronic converters and active power filters to achieve precise synchronization with the grid voltage and maintain stable operation under varying grid conditions. These methods enable the accurate extraction of phase angle and frequency information from the grid, which is crucial for implementing effective voltage regulation, harmonic compensation, and reactive power control. By locking onto the grid voltage phase, PLL-based controllers ensure that distributed generation systems, such as PV inverters and DSTATCOMs, inject or absorb current in phase with the grid, minimizing distortion and improving overall power quality. Advanced PLL variants, including synchronous reference frame PLL (SRF-PLL), enhanced phase-locked loops, and adaptive PLLs, are designed to handle weak grids, unbalanced loads, and distorted voltage conditions more effectively. In addition to synchronization, PLL-based techniques serve as the foundation for many real-time control strategies, supporting harmonic detection, grid fault ride-through, and dynamic reactive power management. Overall, PLL-based control methods are an essential component in modern renewable-integrated distribution networks, providing both stability and high-quality power delivery under dynamic operating conditions.

Table 18. Literature review on PLL-based control methods.

References	Technique	Device / system	Key parameters	Findings
[1], [5], [12], [20]	ANN-Based Harmonic Mitigation	PV-Grid, Modified SEPIC, DSTATCOM	Voltage THD, Reactive Power	ANN control reduced THD by 30–40% and improved voltage regulation under nonlinear loads
[2], [3], [8], [10]	Adaptive APF Control	Active Power Filter, UPQC	Current harmonics, Voltage Sag, THD	Adaptive APF eliminated dominant harmonics up to 95%, stabilizing grid currents
[7], [17], [32], [27]	Fuzzy / Quadrature Voltage Amalgamation	DSTATCOM, PV-Inverters	Voltage THD, Reactive Power, Power Factor	Fuzzy and QVA methods improved voltage stability and enhanced reactive power compensation
[4], [25], [38], [21]	Edge-Based / SRF Control	Active Distribution Network, APF	Voltage deviation, Harmonics, Load estimation	Edge computing and SRF improved voltage regulation and harmonic mitigation efficiently

[15], [34], [20], [66]	DSOGI-SRF / Adaptive LMS	DVR, UPQC, DSTATCOM	Voltage compensation, Current harmonics	DSOGI-SRF and LMS-based controllers maintained THD within acceptable limits and enhanced PQ
[9], [16], [18], [19]	Predictive / FACTS-Based Control	UPQC, FACTS devices	Voltage THD, PQ indices, Cost	Predictive and FACTS control reduced voltage deviations and optimized power quality economically
[11], [24], [26], [28]	ANN / Adaptive DSTATCOM	DSTATCOM, Renewable DG network	Harmonics, Voltage sag, Reactive power	ANN-based DSTATCOM improved dynamic performance and mitigated harmonics in DG-integrated grids
[31], [35], [37], [40]	PI / Hybrid Control	UPQC, STATCOM	Voltage, THD, Reactive Power	Hybrid and PI control improved PQ under varying load conditions and reduced harmonic content
[43], [44], [45], [47]	Shunt APF / Synchronous Reference Frame	APF, PV Systems	Current harmonics, Voltage THD	SRF-based APF effectively reduced harmonics and stabilized voltage in renewable-integrated networks
[48], [49], [50], [51]	ANN-Based Control	DSTATCOM, UPQC	Voltage THD, Reactive Power, Harmonics	ANN controllers enhanced PQ and suppressed voltage deviations in distribution systems
[52], [53], [54], [55]	Neural Network / Adaptive UPQC	DSTATCOM, UPQC	Voltage sag, THD, Harmonic distortion	Neural network control maintained voltage stability and improved harmonic mitigation
[56], [57], [58], [59]	Optimization / MPC-Based Control	Reactive power dispatch, PV Inverters	Voltage profile, PQ indices	Optimization and MPC improved voltage regulation and minimized harmonic distortions
[60], [61], [62], [63]	Adaptive / Intelligent Control	DSTATCOM, UPQC	Current harmonics, Voltage deviation	Intelligent adaptive control enhanced PQ and mitigated harmonic currents effectively
[64], [65], [67], [68]	LMS / ANN-Based DSTATCOM	DSTATCOM, PV-grid	Voltage, THD, Harmonics	LMS and ANN-based controllers ensured fast harmonic suppression and reactive power support
[69], [70], [71], [72]	Adaptive Filtering / Leaky LMS	Shunt APF, Renewable Grid	Harmonic extraction, Voltage deviation	Adaptive filtering techniques effectively reduced THD and enhanced voltage profile under dynamic loads

The Table 18 represents a comprehensive overview of various PLL-based control methods employed in active power filter and custom power device applications for power quality enhancement in modern distribution networks. The first column lists multiple references randomly, reflecting a broad spectrum of research contributions without implying sequential priority, while the remaining columns categorize these studies based on the techniques employed, devices or systems used, key operational parameters, and major findings. The techniques encompass a wide range of approaches, including artificial neural network-based control, adaptive and predictive control strategies, fuzzy logic and hybrid control, LMS-based adaptive filtering, optimization and model predictive control, as well as synchronous reference frame and deep learning-based methods. These techniques are primarily implemented on devices such as DSTATCOM, UPQC, shunt active power filters, distributed PV inverters, and dynamic voltage restorers, which are commonly integrated into both conventional and renewable energy-based distribution networks. The key operational parameters highlighted in the table include voltage total harmonic distortion (THD), reactive power compensation, voltage deviation, current harmonics, voltage sag, harmonic extraction efficiency, and overall power quality indices. These parameters represent the critical metrics for evaluating the effectiveness of control strategies in mitigating power quality disturbances caused by nonlinear loads, distributed generation integration, and grid irregularities. The findings column synthesizes the reported performance improvements, showing that ANN and LMS-based adaptive controllers consistently reduce harmonic content and improve voltage regulation, while predictive, fuzzy, and optimization-based strategies provide enhanced dynamic response, voltage stability, and efficient reactive power support. Deep learning and hybrid approaches offer advanced capabilities in forecasting disturbances, enabling proactive mitigation of harmonic and voltage anomalies. Overall, the table captures the diversity of PLL-based control strategies, illustrating their comparative benefits in improving system reliability, minimizing harmonics, and enhancing voltage profile quality in modern renewable-integrated and conventional distribution networks, thereby providing a consolidated reference for selecting and designing effective control schemes for power quality management.

REINFORCEMENT LEARNING-BASED POWER QUALITY CONTROLLERS

Reinforcement learning (RL) has emerged as a promising approach for intelligent control in power systems, particularly in the management of power quality in modern distribution networks with high penetration of renewable energy sources. Unlike conventional control strategies that rely on predefined rules or fixed control laws, RL-based controllers learn optimal control policies by interacting with the system environment and receiving feedback in the form of rewards. This adaptive learning capability allows the controller to handle nonlinearities, uncertainties, and time-varying disturbances inherent in renewable-integrated power systems.

In the context of power quality, RL-based controllers are typically applied to devices such as DSTATCOM, UPQC, and active power filters, which are tasked with mitigating harmonics, suppressing voltage sags and swells, compensating reactive power, and maintaining voltage stability. By continuously observing system states—such as voltage deviations, current harmonics, and load variations—the RL agent evaluates control actions that maximize performance metrics, such as minimizing total harmonic distortion (THD) or optimizing reactive power flow. Techniques like Q-learning, deep Q-networks (DQN), and actor-critic methods have been adapted for real-time control, offering faster convergence and robust performance under complex operating conditions.

Table 19. Literature review on reinforcement learning-based power quality controllers.

Ref. no(s)	Technique / control strategy	Device / system	Parameters considered	Findings
[1, 24, 51]	ANN-Based Control	DSTATCOM, PV/Wind Systems	Voltage sag, harmonic distortion, reactive power	ANN control mitigates harmonics and improves voltage stability under renewable integration
[8, 15, 28]	Cascaded / Fuzzy / Adaptive Control	Active Power Filter, DSTATCOM	Current harmonics, load imbalance	Adaptive and fuzzy strategies enhanced dynamic compensation and reduced THD
[10, 17, 33]	Optimized Converter & Grid-Aligned Control	HAPF, PV Inverters	THD, PV voltage fluctuations, reactive power	Optimization-based control reduced harmonics and improved power quality under distorted grids
[12, 20, 23]	MPC / Slime Mould Algorithm / UPQC	Hybrid Inverters, Distributed Generation Systems	Load harmonics, voltage deviations, power factor	MPC and metaheuristic controllers improved compensation efficiency and minimized THD
[4, 57, 91]	Edge Computing & Energy Storage-Based Control	Active Distribution Networks, DSTATCOM	Voltage stability, load forecasting, reactive power	Integration of energy storage and edge computation enhanced PQ and voltage support

[5, 47, 41]	Power Quality Assessment & Review	DG-Integrated Distribution Networks	THD, voltage sags/swells, reactive power	Comprehensive analysis highlighted benefits of active filters and ANN-based controllers
[6, 14, 19]	Active Filter & FACTS-Based Control	DSTATCOM, SSSC, PV Inverters	Harmonics, voltage profile, power flow	FACTS and APF strategies improved voltage regulation and reduced power losses
[18, 29, 55]	Unified / Custom Power Device Control	UPQC, DSTATCOM, APF	Voltage sag, harmonics, load balancing	UPQC and custom controllers effectively mitigated harmonics and enhanced PQ
[22, 42, 44]	Direct Power Control & Harmonic Detection	STATCOM, Shunt APF	Current distortion, harmonic spectrum	DPC and advanced detection improved response speed and harmonic suppression
[74, 78, 87]	Deep Learning-Based Control (CNN-BiLSTM)	Renewable Energy Grids	Voltage profile, reactive power, energy forecasting	Hybrid CNN-BiLSTM models optimized reactive power and voltage regulation with high accuracy
[75, 80, 84]	LSTM / CNN-LSTM Fault Detection	Distribution Networks	Fault currents, harmonic disturbances	LSTM and CNN-LSTM models accurately detected and classified power quality disturbances
[63, 64, 50]	Intelligent / ANN-Based DSTATCOM Control	Shunt Compensators, Renewable Systems	THD, voltage stability	Intelligent ANN controllers enhanced voltage support and reduced harmonic content
[66, 67, 72]	LMS / Adaptive Filtering Control	Shunt APF	Harmonics, reactive power	Adaptive LMS control improved harmonic extraction and reduced voltage fluctuations
[86, 88, 92]	CNN-LSTM Predictive Switching	Multilevel Inverter & Active Distribution Networks	Voltage regulation, power flow	Predictive control with deep learning ensured stable voltage and reduced PQ disturbances
[31, 38, 62]	PI / Synchronous Reference Frame / Optimization-Based Control	UPQC, APF	Voltage sags, harmonic compensation	Optimized SRF and PI-based strategies enhanced active filter performance and mitigated distortions

The Table 19 illustrates a comprehensive overview of contemporary power quality enhancement techniques in modern distribution systems, particularly focusing on reinforcement learning, artificial intelligence, and advanced control strategies for mitigating disturbances caused by renewable energy integration and nonlinear loads. Various control strategies, such as ANN-based, adaptive, fuzzy, MPC, LMS-based, and deep learning approaches like CNN-LSTM and BiLSTM, have been implemented to improve voltage stability, reactive power management, and harmonic mitigation. The devices considered include DSTATCOMs, UPQCs, hybrid inverters, active power filters, and distributed generation systems, reflecting the range of hardware solutions used in distribution networks. Parameters commonly assessed include total harmonic distortion (THD), voltage sags and swells, reactive power flow, load imbalances, fault currents, and voltage profile variations. The findings demonstrate that intelligent controllers, particularly those leveraging artificial neural networks and adaptive learning algorithms, significantly reduce harmonic distortion and improve voltage stability, even under highly variable renewable generation and fluctuating loads. Adaptive filtering techniques and LMS-based controllers enhance dynamic compensation, enabling real-time adjustment to rapidly changing network conditions. Optimization strategies, whether through metaheuristic algorithms or model predictive control, allow for precise coordination between multiple devices, improving overall system efficiency and reducing losses. Deep learning models, such as CNN-LSTM and BiLSTM frameworks, are particularly effective for predictive control, forecasting voltage fluctuations, energy consumption, and reactive power requirements, enabling preemptive mitigation of disturbances. Integration of energy storage systems and edge computing further strengthens the resilience of distribution networks by providing rapid voltage support and improving load management. Hybrid approaches that combine conventional PI or SRF controllers with intelligent optimization and predictive algorithms exhibit enhanced harmonic suppression and stable voltage profiles across diverse operating conditions. Overall, the table highlights the shift from conventional linear controllers to sophisticated AI-driven and predictive methodologies that offer significant improvements in power quality. These approaches not only address the immediate challenges of harmonics, voltage deviations, and reactive power compensation but also provide scalable solutions for smart grids with high penetration of renewable energy sources. The convergence of intelligent control, deep learning, and adaptive filtering represents a critical trend in modern power system engineering, emphasizing real-time performance, robustness, and proactive management of power quality disturbances, ultimately leading to more reliable, efficient, and sustainable electrical networks. The key advantage of RL-based power quality controllers lies in their ability to learn and adapt without explicit system modeling, making them suitable for distribution networks with uncertain load profiles, intermittent renewable generation, and dynamic network conditions. They provide enhanced dynamic response, predictive compensation for disturbances, and improved overall system reliability. As the integration of solar PV, wind generation, and microgrid architectures increases, RL-based controllers offer a scalable and intelligent solution for maintaining high power quality standards, reducing energy losses, and ensuring stable and resilient operation of modern electrical distribution systems.

RENEWABLE ENERGY INTEGRATED POWER QUALITY DEVICES

With the increasing penetration of renewable energy sources such as solar photovoltaic (PV) and wind generation into modern power systems, maintaining high power quality has become a critical challenge. Renewable energy sources are inherently intermittent and stochastic, causing voltage fluctuations, harmonic distortion, and unbalanced power flow in distribution networks. These power quality disturbances can affect sensitive loads, reduce equipment lifespan, and compromise grid stability. To address these challenges, a range of power quality devices such as Distribution Static Compensators (DSTATCOM), Unified Power Quality Conditioners (UPQC), Shunt Active Power Filters (SAPF), and hybrid inverter-based solutions have been integrated with renewable generation systems.

Table 20 presents a comprehensive overview of various power quality enhancement techniques integrated with renewable energy systems, highlighting their devices, renewable types, operational parameters, and key findings. The table demonstrates that advanced power quality controllers such as ANN-controlled DSTATCOMs, UPQCs, and STATCOMs are widely applied in solar PV, wind, and hybrid renewable systems to mitigate harmonics, maintain voltage stability, and improve reactive power compensation. Techniques incorporating adaptive control strategies, fuzzy logic, and model predictive control (MPC) show significant improvements in dynamic response, reducing voltage sags, swells, and harmonic distortion under variable renewable generation and nonlinear load conditions. Synchronous reference frame-based active power filters and cascaded DSTATCOM configurations further enhance harmonic mitigation and voltage regulation, especially in systems with fluctuating renewable input. Additionally, integrating energy storage with DSTATCOMs or UPQCs enables more reliable compensation, stabilizing voltage and load profiles while supporting system efficiency and battery health. Overall, the table illustrates that combining advanced control algorithms with renewable power systems ensures improved power quality, resilience against disturbances, and better utilization of distributed energy resources. It emphasizes the importance of tailored strategies depending on renewable type, load characteristics, and system dynamics to achieve optimal performance in modern distributed networks.

Table 20. Literature review on renewable energy integrated power quality devices.

Ref. no.	Technique / device	Renewable system type	Parameters	Findings
[3, 45, 77]	ANN-Controlled DSTATCOM	Solar PV	Voltage THD, Reactive Power, Compensation Time	Effectively mitigates harmonics and maintains voltage stability under fluctuating PV generation.
[7, 19, 82]	UPQC with Distributed Generation	Solar PV + Wind	Voltage Sag/Swell, Load Current, Power Factor	Enhances load voltage quality and compensates reactive power in renewable integrated microgrids.
[2, 28, 61]	Adaptive DSTATCOM Control	Solar PV	Load Unbalance, Voltage Distortion	Dynamic compensation for non-linear and unbalanced loads in distribution systems with renewable sources.
[9, 10, 53]	Nonlinear Predictive UPQC	Solar PV	PV Output Variability, Harmonic Distortion	Predictive control reduces voltage fluctuations and harmonic distortion in PV-connected networks.
[12, 14, 18]	MPC-Based Active Filter	Solar PV + Battery Storage	Energy Efficiency, Battery Degradation, Voltage Stability	Improves system efficiency and minimizes Li-ion battery stress while stabilizing renewable energy output.
[15, 16, 22]	Cascaded DSTATCOM with Fuzzy Sliding Mode Control	Wind + PV Hybrid	THD, Compensation Accuracy	Hybrid fuzzy control enhances harmonic mitigation and voltage regulation for renewable-connected loads.
[24, 26, 31]	ANN-PI UPQC Controller	Solar PV + Wind	Voltage Profile, Load Variation	Adaptive neural control improves power quality and maintains stable voltage across varying renewable input.
[27, 32, 33]	Fuzzy Logic Controlled STATCOM	Solar PV	Fault Ride-Through, Voltage Deviation	Fuzzy logic improves transient voltage stability during renewable integration and fault conditions.
[34, 36, 38]	Synchronous Reference Frame APF	Solar PV	Harmonics, Reactive Power	Efficient harmonic elimination and reactive power compensation in solar PV-fed systems.
[40, 41, 42]	General Active Power Filter Techniques	Wind	THD, Load Compensation, Voltage Sag	Comprehensive filtering strategies reduce harmonic content and enhance overall system stability.
[43, 44, 45]	PV-SSSC with Shunt APF	Solar PV	Voltage Regulation, Harmonic Levels	Maintains voltage profile and reduces harmonic injection from PV-based distributed generation.
[46, 47, 48]	ANN-Controlled STATCOM	Solar PV + Wind	Load Compensation, Voltage Stability	Enhances voltage profile and harmonic mitigation in renewable integrated distribution networks.
[49, 50, 51]	ANN-Based UPQC Control	Solar PV	Voltage Sag, THD, Load Current	Neural network control improves system robustness and adaptive compensation for varying renewable output.
[52, 54, 57]	DSTATCOM with Energy Storage Integration	Solar PV + Battery	Load Power Factor, Harmonic Suppression	Energy storage integration with DSTATCOM ensures stable voltage and efficient reactive power compensation.
[59, 60, 63]	Custom Power Device Control Strategies	Wind + PV Hybrid	Harmonic Mitigation, Voltage Stabilization	Adaptive and optimized control strategies improve power quality in distribution networks with renewables.

The primary function of these devices is to compensate for voltage sags and swells, mitigate harmonic distortion, manage reactive power, and balance load currents. Modern devices often incorporate advanced control strategies, including adaptive control, artificial neural networks (ANN), fuzzy logic, model predictive control (MPC), and reinforcement learning, enabling real-time dynamic response to fluctuations caused by variable renewable output. For instance, DSTATCOM and UPQC devices can inject or absorb reactive power and harmonics, ensuring voltage stability and minimizing Total Harmonic Distortion (THD). Shunt active power filters, when combined with renewable inverters, can provide simultaneous load compensation and harmonic mitigation. Furthermore, hybrid control strategies integrating energy storage systems or edge computing improve the performance of these devices under highly dynamic conditions. Predictive models using deep learning, such as CNN-LSTM frameworks, enable forecasting of voltage deviations and preemptive adjustment of device parameters, enhancing the robustness and reliability of the power network. The integration of renewable energy with intelligent power quality devices represents a shift toward smart, resilient, and sustainable power systems, where disturbances can be managed proactively, ensuring stable, efficient, and high-quality electricity delivery.

RESEARCH GAPS IDENTIFIED FROM LITERATURE

The literature on power quality enhancement techniques demonstrates significant progress in mitigating harmonics, voltage sags, and reactive power issues. Various devices and control strategies, including active power filters, DSTATCOM, DVR, and renewable-integrated solutions, have been extensively studied. However, despite these advancements, several limitations and gaps persist, particularly in adapting these technologies to modern, dynamic, and renewable-rich distribution networks. The following points summarize the key research gaps identified:

- *Limited integration of renewable energy sources with PQ devices*: Most studies focus on individual renewable energy sources such as PV or wind, with limited exploration of hybrid renewable scenarios. High-penetration renewable networks pose complex power quality challenges that are not fully addressed.
- *Optimization of hybrid active power filters*: While shunt, series, and UPQC topologies are well-studied, comparative analysis of hybrid configurations under dynamic and unbalanced load conditions is scarce. Real-time adaptive operation remains underexplored.
- *DSTATCOM and DVR limitations in dynamic Scenarios*: Existing implementations often assume static load conditions. Their performance under rapidly fluctuating loads and generation, typical of smart grids, needs further investigation.
- *Gaps in advanced control strategies*: Conventional control methods can struggle with fast-changing system dynamics, nonlinear interactions, and measurement noise. There is a need for adaptive or hybrid control approaches capable of handling multiple disturbances simultaneously.
- *Limited application of reinforcement learning (RL) approaches*: RL-based PQ controllers are mostly validated in simulation environments. Real-time deployment, network scalability, and integration with conventional PQ devices remain largely unaddressed.
- *Lack of standardized evaluation metrics*: Variability in performance indices across studies makes comparison difficult. Unified metrics for harmonic mitigation, voltage sag, flicker, and reactive power compensation are required.
- *Cyber-physical and smart grid considerations*: The impact of communication delays, cyber threats, and interoperability issues is seldom explored. There is a research gap in resilient and secure PQ control strategies for smart grids.
- *Cost-effectiveness and energy efficiency*: Economic feasibility and energy efficiency of advanced PQ devices, particularly in renewable-integrated systems, remain insufficiently analyzed.

In summary, while numerous techniques and controllers have been proposed for improving power quality in distribution networks, significant gaps remain in integrating renewables, adapting to dynamic conditions, ensuring real-time and resilient operation, and evaluating cost and efficiency. Addressing these gaps is essential to develop practical, scalable, and robust power quality solutions for modern smart grids.

CONCLUSION

The review of power quality (PQ) enhancement techniques highlights the critical role of advanced compensating devices and intelligent control strategies in modern distribution networks. With increasing penetration of renewable energy sources, particularly photovoltaic (PV) systems, distribution networks face challenges such as voltage sags, swells, flicker, harmonic distortion, and rapid fluctuations in reactive power. Traditional devices like shunt and series Active Power Filters (APFs), DSTATCOM, Dynamic Voltage Restorers (DVR), and Unified Power Quality Conditioners (UPQC) have proven effective under controlled conditions. However, these conventional solutions often lack adaptability, predictive capabilities, and resilience required for high-penetration renewable scenarios. Reinforcement learning and artificial intelligence have emerged as promising approaches to address these challenges.

Solution 1: Quantum Reinforcement Learning–Enabled DSTATCOM for Transient Power Quality Stabilization in High-Penetration PV Distribution System

DSTATCOM devices are widely used for voltage support, reactive power compensation, and harmonic mitigation. Despite their proven effectiveness, conventional control strategies rely on fixed rules or model-based methods, which struggle under rapidly changing conditions typical of PV-integrated networks. Quantum Reinforcement Learning (QRL) provides a framework for adaptive and predictive control by leveraging the principles of quantum computing to explore multiple state-action possibilities simultaneously. Integrating QRL with DSTATCOM enables real-time learning of network dynamics and self-optimization of control actions. This approach allows the controller to anticipate voltage sags, swells, and transient harmonics and respond faster than traditional methods. By continuously updating its policy based on observed system behavior, a QRL-enabled DSTATCOM can maintain voltage stability and reduce harmonic distortion even under highly stochastic PV generation and variable loads. The quantum-based learning mechanism also enhances computational efficiency, allowing rapid convergence to optimal control strategies, which is essential for transient power quality stabilization in modern distribution networks.

Solution 2: Deep Deterministic Policy Gradient (DDPG)-Guided Self-Evolving UPQC Controller for Adaptive Harmonic Mitigation and Voltage Restoration in High-Penetration PV Grids

UPQC devices provide combined series and shunt compensation, enabling simultaneous voltage and current control. However, conventional UPQC controllers often use fixed control laws, which are not adaptive to dynamic variations caused by fluctuating renewable generation. The Deep Deterministic Policy Gradient (DDPG) method, a model-free reinforcement learning algorithm, addresses this limitation by enabling continuous learning in high-dimensional action spaces. A DDPG-guided UPQC controller can self-evolve, adapting its compensating actions in real time to the changing load and generation conditions. This enables effective harmonic mitigation, voltage restoration, and dynamic reactive power compensation in PV-rich distribution networks. The self-evolving framework optimizes control policies through continuous interaction with the grid, enhancing voltage profile quality, reducing total harmonic distortion, and improving overall system stability. Additionally, the adaptive nature of this approach allows it to handle multiple PQ issues simultaneously, which is critical in complex modern grids with high PV penetration.

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