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Intelligent Power Quality Enhancement Strategies for PV-Integrated Smart Distribution Networks: A State-of-the-Art Review

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Abstract

The rapid integration of photovoltaic (PV) systems into modern power distribution networks has introduced significant challenges related to power quality. Issues such as voltage fluctuations, harmonic distortion, flicker, and reactive power imbalance arise due to the intermittent and nonlinear nature of solar energy generation. This paper presents a concise literature review of various power quality enhancement techniques employed in PV-integrated networks. Key approaches include the use of active power filters (APFs), dynamic voltage restorers (DVRs), unified power quality conditioners (UPQCs), and advanced control strategies such as fuzzy logic, artificial neural networks (ANN), and model predictive control (MPC). Additionally, grid-connected inverter control techniques and energy storage integration are discussed as effective solutions for mitigating disturbances. The review highlights the comparative performance of these techniques in improving voltage stability, reducing total harmonic distortion (THD), and ensuring reliable grid operation. The findings indicate that hybrid and intelligent control-based approaches offer superior performance in dynamic and uncertain conditions. Power quality issues in PV systems may now be detected and compensated for in real-time thanks to recent advancements in smart grid technology and Internet of Things (IoT)-based monitoring systems. The efficiency, dependability, and fault management capabilities of the system have all been enhanced by the use of adaptive and data-driven optimization techniques. This study provides insights into the current trends and future directions for enhancing power quality in PV-based power systems.

Keywords: Photovoltaic systems, power quality, harmonic distortion, active power filter, UPQC, smart grid, renewable energy integration, voltage stability

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INTRODUCTION

The rapid growth of photovoltaic (PV) generation in modern power systems has significantly transformed distribution network structures. However, large-scale PV integration introduces several power quality issues, such as voltage fluctuations, harmonic distortion, reactive power imbalance, and intermittent power generation. Globally, solar power capacity has increased rapidly owing to the transition toward renewable energy and decarbonization of power systems. The expansion of solar power in India is particularly significant. The country has installed more than 105 GW of solar photovoltaic capacity, representing approximately 22% of the total installed power capacity and forming the largest share of renewable energy sources.

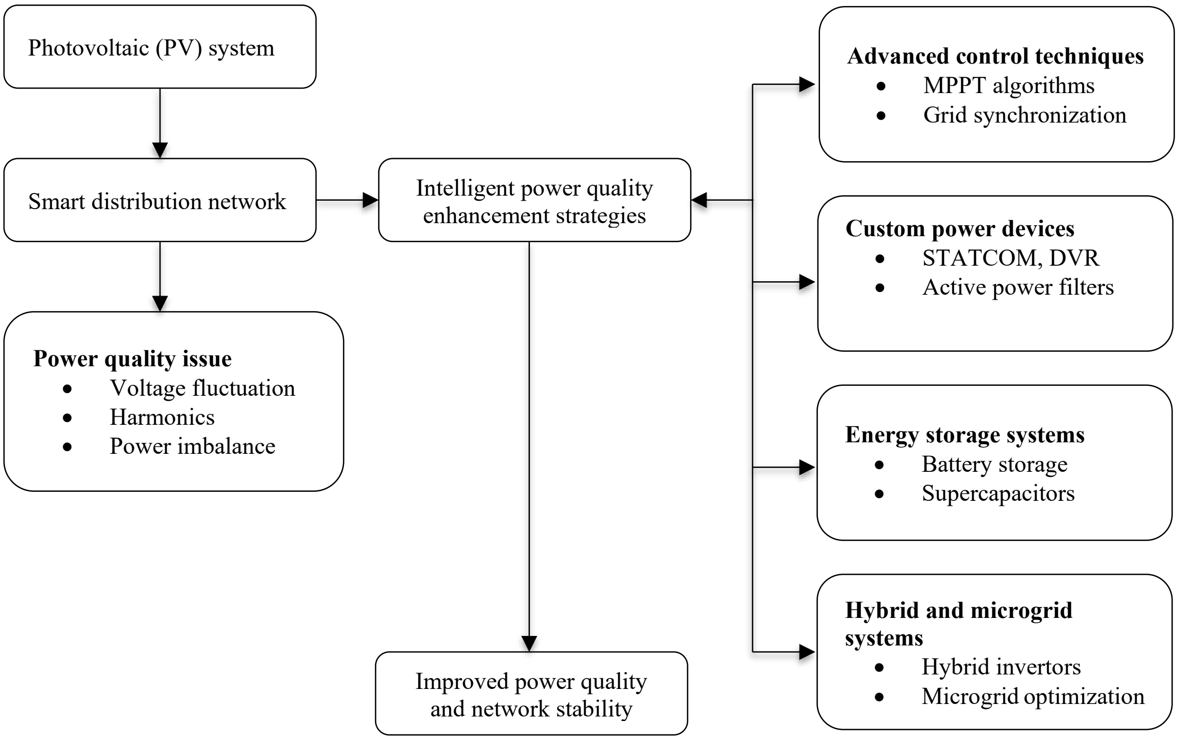

Figure 1. Flowchart of intelligent power quality enhancement strategies for PV-integrated smart distribution networks.

The renewable energy capacity in India exceeded 200 GW, with solar energy contributing nearly 45–50% of the renewable energy mix. Such rapid deployment has increased the penetration of inverter-based generation in distribution networks, which often leads to harmonic injections and voltage instability. In typical PV-connected distribution feeders, harmonic distortion levels can rise above 5–8% THD under nonlinear load conditions, whereas voltage deviation may exceed ±10% during sudden irradiance variations. These disturbances affect sensitive loads, reduce equipment life, and degrade the overall system reliability. Consequently, improving the power quality of PV-integrated networks has become a major research priority. Several power quality enhancement techniques have been proposed to mitigate these problems. Conventional approaches include passive filters and capacitor banks, which provide basic harmonic mitigation and reactive power compensation.

Figure 1 presents a comprehensive flowchart illustrating the framework of intelligent power quality enhancement strategies in PV-integrated smart distribution networks. The diagram begins with the PV system, which acts as the primary renewable energy source. The generated power is fed into the Smart Distribution Network, representing modern grid infrastructure equipped with communication, monitoring, and control capabilities. As PV penetration increases, several power quality issues arise, including voltage fluctuations, harmonic distortion, and power imbalance. These challenges are clearly highlighted as critical problems that degrade system performance and reliability. The central block, intelligent power quality enhancement strategies, serves as the core processing unit where advanced techniques are applied to mitigate these issues. The right-hand side of the diagram outlines key solution domains. Advanced control techniques, such as maximum power point tracking (MPPT) and grid synchronization, ensure optimal energy extraction and stable grid interfacing. Custom power devices, including static synchronous compensator (STATCOM), dynamic voltage restorers (DVR), and active power filters (APFs), are employed to compensate for reactive power, suppress harmonics, and regulate voltage levels. Additionally, energy storage systems, such as batteries and supercapacitors, provide buffering capabilities to smooth power fluctuations and enhance reliability. Furthermore, hybrid and microgrid systems integrate multiple energy sources and intelligent control mechanisms, enabling decentralized and resilient operation. These systems optimize energy management and improve adaptability under varying load and generation conditions. Finally, all these coordinated strategies lead to the desired outcome: improved power quality and network stability. The effectively demonstrates how integrating intelligent control, power electronics, and storage technologies can address the complexities introduced by PV systems, ensuring efficient and reliable operation of modern smart grids. However, these techniques suffer from limitations such as fixed compensation characteristics and resonance problems under varying load conditions. As a result, advanced active compensation devices such as shunt active power filters (SAPF), distribution static compensators (D-STATCOM), DVR, and unified power quality conditioners (UPQC) have been widely adopted in PV-integrated networks. These devices employ power electronic converters and intelligent control strategies to dynamically compensate voltage and current distortions. For example, UPQC systems combine both series and shunt converters to simultaneously mitigate voltage sag, swell, and harmonic currents, thereby improving voltage regulation and maintaining a near-unity power factor. Numerical studies indicate that advanced compensation techniques can reduce THD levels from 8–10% to below 2–3%, while improving the power factor from 0.85 to above 0.98 under dynamic operating conditions. In the Indian scenario, the large-scale deployment of solar parks and rooftop PV systems—such as the installation of over 24.5 GW of new solar capacity in 2024 alone—has increased the need for intelligent power quality control technologies. Modern research, therefore, focuses on integrating artificial intelligence based controllers, predictive algorithms, and hybrid deep learning techniques with power quality devices to achieve faster response times and improved stability in PV-dominated distribution systems. These intelligent control strategies enable real-time adaptation to irradiance variations, load fluctuations, and nonlinear disturbances, making them highly suitable for future smart grids and renewable-energy-driven power systems.

Conventional Control Strategies for DSTATCOM and UPQC

Conventional control strategies have played a crucial role in improving the performance of power quality compensation devices, such as the Distribution Static Compensator (DSTATCOM) and UPQC, in grid-connected renewable energy systems. These controllers are primarily designed to regulate the voltage, compensate for reactive power, and mitigate harmonic distortion in distribution networks. Among the earliest and most widely used approaches are proportional–integral (PI) and proportional–integral–derivative (PID) controllers, which are implemented in the inner and outer current and voltage control loops of power electronic converters, respectively. The PI controller is particularly popular because of its simple structure and ease of implementation in digital signal processors used in power electronic systems. In DSTATCOM applications, the PI controller regulates the DC-link voltage and ensures proper injection of compensating currents to maintain a unity power factor at the point of common coupling (PCC). Similarly, in UPQC systems, PI-based control strategies are used to control both the series and shunt converters for simultaneous voltage and current compensations. Conventional control frameworks typically rely on reference frame transformations, such as the synchronous reference frame (SRF) method and instantaneous reactive power theory (p–q theory), to generate reference signals for compensating currents. These methods allow the extraction of harmonic and reactive components from distorted load currents, such that the compensator can inject appropriate countercurrents. Numerical simulation studies have shown that PI-based controllers in DSTATCOM and UPQC can reduce total harmonic distortion (THD) from approximately 7–9% to approximately 3–4%, while improving the power factor from 0.80–0.85 to approximately 0.95–0.97 under steady operating conditions. Owing to these advantages, PI-based conventional control methods have been extensively implemented in power quality improvement devices across distribution networks.

Table 1 presents the findings from the literature on power quality enhancement techniques. Despite their widespread use, conventional control strategies exhibit several limitations when applied to modern, renewable-energy-dominated power systems. These methods often depend heavily on accurate system modeling and fixed controller parameters, which may not perform effectively under rapidly changing operating conditions, such as fluctuating solar irradiance, dynamic load variations, and nonlinear disturbances. For example, in PV-integrated networks, sudden irradiance changes can cause rapid voltage variations and transient harmonics to which conventional PI-based controllers may not respond quickly enough.

Table 1. Findings from the literature on power quality enhancement techniques.

Citations	Technique/system studied	Key findings
[1]	Power quality assessment with renewable distributed generation	Demonstrated that integration of renewable DG sources significantly affects voltage stability and harmonic distortion in distribution networks. Proper compensation techniques, such as FACTS devices, are required to maintain acceptable power quality limits.
[2]	Voltage control strategy for DSTATCOM	Proposed an improved voltage control algorithm that enhances reactive power compensation and improves voltage regulation in grid-connected systems.
[3]	Nonlinear predictive direct power control for PV-UPQC	It showed that predictive control combined with space vector modulation improves dynamic response and reduces harmonic distortion in PV-integrated UPQC systems.
[4]	Advanced DSTATCOM topology	Introduced an enhanced topology capable of compensating reactive power and mitigating load imbalance, leading to improved power quality in distribution networks.
[5]	DSTATCOM for distribution networks	Confirmed that DSTATCOM effectively reduces voltage sag, improves power factors, and minimizes harmonic distortions in distribution systems.
[6]	Cascaded inductively coupled DSTATCOM	Demonstrated improved harmonic mitigation and voltage stabilization compared with conventional DSTATCOM configurations.
[7]	Hybrid fuzzy sliding-mode control for active filters	The hybrid controller improved robustness and ensured better harmonic compensation under nonlinear load conditions.
[8]	FACTS devices for power quality	Showed that FACTS devices significantly enhance power quality performance and improve economic operation in renewable-integrated power systems.
[9]	Experimental UPQC with distributed generation	Experimental results confirmed that UPQC integration effectively reduces voltage disturbances and harmonics in renewable energy-based distribution networks.
[10]	Adaptive control UPQC in microgrid	Model reference adaptive control with a back-stepping controller improved system stability and dynamic performance in microgrid environments.
[11]	Direct power control for STATCOM	Comparative analysis revealed that multilevel inverter-based STATCOM with optimized control strategies improves reactive power control and voltage stability.
[12]	ANN-controlled DSTATCOM	Artificial neural network controllers enhance harmonic mitigation and power factor correction in PV-wind integrated power systems.
[13]	AI-based UPQC control	Adaptive neural network based UPQC improves real-time power quality management and reduces system disturbances effectively.
[14]	Fuzzy-controlled STATCOM	Fuzzy logic control improves fault ride-through capability and stabilizes the power system during disturbances.
[15]	Adaptive DSTATCOM control	Adaptive control methods provide superior performance in renewable-integrated distribution systems compared with fixed-parameter controllers.
[16]	UPQC for harmonic mitigation	UPQC effectively mitigates current and voltage harmonics simultaneously while maintaining power factors close to unity.
[17]	Grid synchronization techniques	Demonstrated that advanced synchronization techniques improve stability and control accuracy in distributed generation systems.
[18]	Optimized UPQC control strategy	Optimization-based controllers improve voltage compensation efficiency and reduce harmonic distortion in smart grid applications.
[19]	PI versus Fuzzy DSTATCOM controllers	Fuzzy logic controllers outperform conventional PI controllers in terms of faster response and better harmonic reduction.

DG, Distributed Generation; Flexible AC Transmission Systems (FACTS).

Consequently, compensation delays may increase to 80–120 ms, leading to temporary voltage deviations and increased harmonic distortion levels. Furthermore, conventional control methods may experience reduced performance when dealing with complex disturbances, such as voltage sag, swell, or unbalanced loads. In UPQC systems, the coordination between the series and shunt converters becomes challenging when using fixed-parameter controllers, particularly during fault conditions or grid disturbances. To overcome these limitations, researchers have explored several improved versions of conventional control strategies, including adaptive PI tuning, sliding-mode control, hysteresis current control, and model predictive control. These techniques enhance the dynamic response and improve the robustness against system uncertainties. However, even these improved conventional methods still rely on deterministic control structures and may struggle to handle the highly nonlinear and time-varying environments typical of modern smart grids. Consequently, recent research trends have shifted toward integrating intelligent control techniques, machine learning algorithms, and deep learning-based predictive models to enhance the dynamic performance of DSTATCOM and UPQC systems. Such advanced control approaches system behavior, predict disturbances, and adapt control parameters in real time, thereby providing superior power quality compensation in PV-integrated distribution networks.

Synchronous Reference Frame Based Controllers

The synchronous reference frame (SRF) control strategy is one of the most widely adopted techniques for power quality enhancement in grid-connected power electronic systems such as UPQC, distribution static compensator (DSTATCOM), and STATCOM. The SRF method is primarily used to extract the fundamental components of voltage and current signals under distorted and unbalanced operating conditions. In modern power distribution networks, the increasing penetration of renewable energy sources such as solar photovoltaic systems and wind energy introduces significant power quality challenges, including harmonic distortion, voltage sag, voltage swell, and reactive power imbalance. These disturbances arise mainly due to nonlinear loads, switching converters, and fluctuating renewable generation. The SRF controller addresses these issues by transforming the three-phase stationary frame signals into a rotating reference frame using a coordinate transformation technique commonly known as the Park transformation. In this approach, the three-phase currents or voltages (abc) are converted into direct (d) and quadrature (q) components in a rotating frame synchronized with the grid voltage. This synchronization is generally achieved using a phase-locked loop (PLL), which ensures accurate tracking of the grid voltage phase angle. Once transformed into a synchronous reference frame, the DC components represent the fundamental active and reactive power components, while the oscillatory components correspond to harmonics and disturbances. By applying appropriate filtering and control strategies in the d–q domain, the controller can easily separate and compensate undesirable components, enabling precise generation of reference compensating currents for the power conditioning device. As a result, SRF-based control techniques are highly effective in reducing THD, maintaining a near-unity power factor, and improving voltage regulation in distribution systems.

Table 2 illustrates the findings of the SRF-based controllers for power quality enhancement. Another major advantage of SRF-based controllers is their ability to provide a fast dynamic response and stable performance under rapidly changing operating conditions. In applications involving UPQC or DSTATCOM, the SRF controller continuously monitors the grid voltage and load current to generate appropriate reference signals for a voltage source inverter (VSI). The controller ensures that the compensating currents injected by the converter effectively cancel the harmonic components and reactive power demand generated by the nonlinear loads. In addition, SRF controllers can handle both balanced and unbalanced load conditions by separately regulating the direct and quadrature components of the current. This makes the technique particularly suitable for modern smart grid environments, where renewable distributed generation and dynamic load variations are common. The SRF method also provides flexibility in controller design because various control algorithms, such as proportional–integral (PI), fuzzy logic, adaptive control, and artificial intelligence based approaches, can be integrated within the d–q control loop.

Table 2. Findings from SRF-based controllers for power quality enhancement.

Citations	Technique/system	Key findings
[20]	Grid-connected PV with optimized SRF-PLL using Genetic Algorithm	The optimized SRF-PLL significantly improves grid synchronization accuracy and reactive power management in PV systems. Genetic algorithm optimization enhances controller stability and reduces phase detection error.
[21]	DSOGI-based SRF controller with PV-integrated Dynamic Voltage Restorer	The proposed DSOGI-SRF controller effectively compensates voltage disturbances and improves power quality under unbalanced grid conditions. It provides faster harmonic detection and better voltage restoration performance.
[22]	SRF-based Shunt Active Power Filter using digital signal processor (DSP) controller	Implementation using a DSP controller demonstrates efficient harmonic mitigation and improved power factor correction in nonlinear load environments.
[23]	Z-source inverter-based unified active power filter with solar PV	Experimental validation confirms that the SRF-controlled active power filter significantly reduces current harmonics and improves voltage regulation in PV-based systems.
[24]	Adaptive control- based UPQC in a microgrid	Integration of adaptive control with SRF enhances dynamic response, improves harmonic compensation, and ensures stable microgrid operation.
[25]	SRF theory for active power filter in renewable energy systems	The SRF-based control strategy improves the operational efficiency of active power filters by accurately separating fundamental and harmonic components of current.
[26]	Modified SRF controller for shunt active power filter	The modified SRF approach improves harmonic compensation and enhances stability in hybrid renewable energy systems with nonlinear loads.
[27]	SRF controller for PV-fed UPQC	The proposed SRF controller improves voltage compensation capability and reduces THD in grid-connected PV power conditioning applications.

Moreover, the transformation of AC signals into DC quantities simplifies the control process, allowing conventional regulators to be applied effectively for harmonic mitigation and reactive power compensation applications. Owing to these advantages, SRF-based controllers have become a standard control approach in many power quality improvement devices used in renewable-integrated distribution systems. Researchers have also proposed enhanced SRF frameworks incorporating adaptive filtering, predictive control, and machine learning algorithms to further improve the accuracy and robustness of power quality compensation. Consequently, SRF-based control continues to play a crucial role in advanced power electronic converters designed for grid-connected renewable energy systems, enabling reliable operation, improved stability, and efficient power quality management in modern electrical distribution networks.

Active Power Filters: Recent Developments and Challenges

Active power filters (APFs) have emerged as one of the most effective technologies for improving power quality in modern electrical distribution systems, particularly in networks integrated with renewable energy sources and nonlinear loads. Conventional power systems were primarily designed to supply linear loads; however, the widespread use of power electronic converters, variable-speed drives, and renewable energy systems has significantly increased the harmonic distortion and reactive power demand in distribution networks. These disturbances degrade the system performance, reduce the equipment lifespan, and lead to inefficiencies in power delivery. To address these issues, APFs dynamically inject compensating currents or voltages into the system to eliminate harmonics, balance load currents, and maintain a power factor close to unity. The most commonly used APF configurations are SAPF, series active power filters, and hybrid active power filters. Shunt APFs are primarily used for current harmonic compensation and reactive power support, whereas series APFs are employed for voltage distortion mitigation. In many advanced power quality improvement devices, such as the UPQC, both series and shunt filters are combined to simultaneously address voltage and current disturbances.

Table 3. Findings from active power filters for power quality improvement.

Citations	Technique/system studied	Key findings
[28]	Comprehensive review of active power filters	The study provides a detailed analysis of APF technologies and concludes that active power filters are highly effective for harmonic mitigation, reactive power compensation, and voltage regulation in modern power systems. It highlights emerging control strategies and integration with renewable energy sources.
[29]	APF in grid-connected renewable energy systems	The review emphasizes that APFs significantly enhance power quality in renewable-integrated grids by mitigating harmonics generated by power electronic converters and maintaining stable grid operation.
[30]	PV-STATCOM with shunt active power filter	The proposed system improves voltage regulation, power factor, and harmonic compensation in PV-based power systems, demonstrating enhanced stability and power quality performance.
[31]	Harmonic detection algorithm for three-phase shunt APF	The improved harmonic detection method enhances accuracy and stability in compensating nonlinear load disturbances, resulting in reduced total harmonic distortion.
[32]	APF controller for periodic load disturbances	The controller demonstrates improved power quality by effectively compensating for periodic load distortions and maintaining stable operation in distribution systems.
[33]	APF in an industrial plant supplied by a PV station	The study confirms that active power filters significantly reduce harmonic distortion and improve voltage stability in industrial facilities powered by photovoltaic systems.
[38]	Nonlinear predictive control for PV-integrated UPQC	The predictive control strategy improves transient response and harmonic compensation capability in photovoltaic integrated power conditioning systems.
[34]	Power quality assessment in renewable distributed generation systems	The research shows that renewable distributed generation introduces harmonic distortion and voltage fluctuations, emphasizing the need for advanced compensation devices such as active power filters and FACTS controllers.
[35]	Control strategies for APF and custom power devices	The study highlights that advanced control techniques significantly improve the performance of APFs and other custom power devices in mitigating harmonics and enhancing overall power quality in distribution networks.

Modern APF control strategies often rely on techniques such as the SRF control method, instantaneous reactive power theory, and advanced signal processing algorithms to accurately detect harmonic components in distorted signals. With the rapid development of digital signal processors and microcontroller-based controllers, APFs can now operate with higher switching frequencies, faster dynamic responses, and improved compensation accuracy. In addition, the integration of renewable generation systems, such as solar photovoltaics and wind power, has encouraged researchers to develop intelligent APF control strategies that can adapt to rapidly changing operating conditions. These developments have led to the adoption of artificial intelligence techniques, including neural networks, fuzzy logic controllers, and machine learning algorithms, which can enhance the harmonic detection accuracy and improve the system stability under fluctuating load and generation conditions. Consequently, APFs have become essential components of modern smart grid architectures, supporting reliable operation and improved power quality in distributed energy systems.

Table 3 presents the findings for the APFs for power quality improvement. Despite these advancements, several technical and operational challenges continue to limit the widespread deployment and optimal performance of APFs in complex power systems. One of the primary challenges is the accurate detection of harmonic components under highly distorted and unbalanced grid conditions. Conventional control strategies sometimes struggle to separate the fundamental and harmonic components when the grid voltage itself is distorted or when renewable energy systems introduce rapid fluctuations in the power output. Another challenge is the high switching losses associated with the voltage source converters used in APFs, which can reduce the system efficiency and increase the thermal stress on the power electronic components. In large-scale distribution systems, maintaining the stable operation of APFs under varying load conditions and grid disturbances requires highly robust control algorithms capable of handling uncertainties and nonlinear dynamics. Furthermore, the cost of implementing advanced APF systems can be relatively high because of the need for sophisticated sensors, high-performance digital controllers, and power semiconductor devices. The coordination of multiple power quality devices, such as distribution static compensators (DSTATCOM) and STATCOM, with APFs also presents control and communication challenges in smart grid environments. Therefore, researchers are focusing on developing hybrid filtering approaches that combine passive and active filters to reduce system costs and improve overall performance. In addition, modern research trends emphasize the use of predictive control, adaptive control strategies, and deep learning based controllers to enhance the robustness and response speed of APFs under dynamic operating conditions. These intelligent control techniques can improve the harmonic compensation accuracy, reduce the controller tuning complexity, and enable real-time adaptation to grid disturbances. However, integrating such advanced algorithms into practical power electronic converters requires careful consideration of computational complexity and hardware implementation constraints. Consequently, although APFs continue to play a crucial role in modern power quality management, ongoing research is essential to address these challenges and develop more efficient, cost-effective, and intelligent filtering solutions suitable for future renewable-integrated power distribution networks.

Optimization Techniques in Power Quality Control

Optimization techniques play a crucial role in modern power quality control systems, particularly in renewable energy-integrated distribution networks, where system dynamics are highly nonlinear and variable. Power quality problems, such as voltage sag, harmonic distortion, reactive power imbalance, and poor power factor, arise owing to nonlinear loads, fluctuating renewable generation, and switching operations in power electronic converters. Conventional controllers often rely on fixed parameters and linear models, which may not provide optimal performance under changing operating conditions. Optimization techniques address this limitation by automatically tuning the controller parameters and determining the best operating conditions for power quality devices, such as the UPQC, distribution static compensator (DSTATCOM), and STATCOM. These algorithms search for optimal control parameters that minimize objective functions, such as the THD, voltage deviation, and settling time. The optimization process typically involves defining a performance index that represents the quality of system response. The index may include factors such as harmonic levels, voltage stability, reactive power compensation efficiency, and transient response speed. By iteratively evaluating possible solutions and adjusting the control parameters, optimization algorithms can identify the best configuration that ensures stable operation and improved power quality. Consequently, optimization techniques significantly enhance the efficiency, reliability, and dynamic performance of power electronic compensators used in modern smart grid environments.

The working principle of optimization-based power quality control involves integrating an optimization algorithm with the control structure of power electronic devices. In this approach, the optimization algorithm continuously evaluates the system performance and adjusts the controller parameters, such as the proportional–integral gains, switching angles, reference currents, and voltage compensation levels. Popular optimization methods include evolutionary algorithms, swarm intelligence techniques, and metaheuristic algorithms that mimic natural processes, such as biological evolution, swarm behavior, and physical interactions. These algorithms generate a population of candidate solutions and evaluate them based on a defined objective function. Through processes such as selection, mutation, crossover, and position updates, the algorithm gradually converges to the optimal solution. For example, in a UPQC or DSTATCOM system, the optimization algorithm may tune the controller gains to minimize the harmonic distortion in the source current while maintaining voltage stability. This process enables the controller to adapt to varying load conditions and fluctuations in renewable generation. Another advantage of optimization techniques is their ability to handle complex nonlinear systems without requiring detailed mathematical modeling. This makes them particularly suitable for power systems with uncertain parameters and multiple interactions. Furthermore, optimization algorithms can be combined with intelligent control strategies, such as artificial neural networks, fuzzy logic controllers, or deep learning models, to further improve system performance. In such hybrid approaches, optimization techniques are used to train or fine-tune the intelligent controller parameters, leading to a faster response and higher compensation accuracy. Despite their advantages, optimization-based controllers may require significant computational resources, particularly when dealing with large-scale power systems or real-time applications. However, advances in digital signal processing, high-performance microcontrollers, and parallel computing have made it increasingly feasible to implement these algorithms in practical power quality control systems. Consequently, optimization techniques have become an important research direction for enhancing the performance of modern power electronic devices used in renewable-integrated electrical distribution networks.

Bat Optimization Algorithm

The bat optimization algorithm (BA) is a nature-inspired metaheuristic optimization technique widely used for solving complex nonlinear optimization problems in power systems and engineering applications. The algorithm was introduced by Xin-She Yang and is based on the echolocation behavior of microbats, which use sound pulses to navigate and locate prey in the dark. In optimization problems, each bat represents a potential solution, and the algorithm searches for the optimal solution by updating the position and velocity of bats within the search space. The key concept behind the Bat Algorithm is that bats emit ultrasonic sound pulses and listen for echoes to estimate the distance to their prey or obstacles. By adjusting the frequency, loudness, and pulse emission rate of these sound signals, bats can efficiently locate targets.

This natural behavior is mathematically modeled in the optimization algorithm to explore and exploit the search space. In power quality control applications, the Bat Algorithm is often used to optimize controller parameters, minimize harmonic distortion, and improve reactive power compensation in devices such as the UPQC, Distribution Static Compensator (DSTATCOM), and STATCOM. The working process begins with initializing a population of bats with random positions and velocities representing candidate solutions. Each bat has a frequency parameter that controls the step size of movement within the search space. During each iteration, the algorithm updates the velocity and position of each bat based on its current frequency and the location of the best-performing solution found so far. In addition, the loudness and pulse emission rate are dynamically adjusted during the search process to balance exploration and exploitation. Initially, bats explore the search space broadly to identify promising regions, and as the algorithm progresses, the search becomes more focused around the best solution to achieve convergence. In power quality applications, the objective function typically includes minimizing THD, voltage deviation, or reactive power losses while ensuring stable system operation. By iteratively evaluating these objective functions, the Bat Algorithm identifies optimal controller parameters that improve the performance of power electronic compensators. Compared with traditional optimization techniques, BA offers several advantages, such as fast convergence, simple implementation, and the ability to handle nonlinear and multi-objective optimization problems. It also requires fewer control parameters than many other evolutionary algorithms, making it suitable for real-time control applications in smart grids and renewable energy systems. Furthermore, the Bat Algorithm can be integrated with artificial intelligence techniques such as neural networks or fuzzy logic controllers to further enhance system performance.

These hybrid approaches enable adaptive control and improved decision-making in dynamic power system environments. Despite its advantages, the Bat Algorithm may sometimes suffer from premature convergence if the exploration capability is limited. To overcome this limitation, researchers have proposed several improved versions of the algorithm, including adaptive bat algorithms, chaotic bat algorithms, and hybrid optimization methods. Overall, the bat optimization algorithm has become a powerful tool for optimizing controller parameters and enhancing the performance of modern power quality control systems in renewable energy-integrated electrical networks. Table 4 shows the findings from optimization techniques for power quality control.

Table 4. Findings from optimization techniques for power quality control.

Citations	Technique/system studied	Key findings
[36]	Gaussian Bare-Bones Bat Algorithm for optimal reactive power dispatch	The proposed optimization algorithm improves reactive power management and voltage stability while minimizing system losses. It demonstrates faster convergence and better optimization performance compared with conventional algorithms.
[37]	Energy storage-based DSTATCOM	The proposed system integrates energy storage with DSTATCOM to provide both power quality improvement and active voltage support, enhancing grid stability during dynamic load variations.
[38]	Nonlinear predictive control for PV-integrated UPQC	Predictive control enhances dynamic response and improves harmonic compensation capability in photovoltaic-based power quality conditioning systems.
[39]	Review of active power filter techniques	The review highlights that advanced control and optimization methods significantly improve harmonic mitigation, reactive power compensation, and voltage stability in modern power systems.
[40]	Control strategies for custom power devices	The study emphasizes that optimized control strategies enhance the performance of custom power devices such as UPQC and DSTATCOM in mitigating harmonics and improving power quality.
[41]	DSTATCOM with advanced optimization techniques	Optimization-based control methods improve reactive power compensation, voltage stability, and harmonic reduction in distribution networks.
[42]	Optimization-based controller design for DSTATCOM and UPQC	The proposed optimized controller enhances harmonic mitigation, reduces total harmonic distortion (THD), and improves dynamic response compared with conventional PI controllers.

Other Nature-Inspired Optimization Methods

In addition to the bat optimization algorithm, several other nature-inspired optimization techniques have been widely applied in power quality control for modern electrical distribution systems. These algorithms are designed to mimic natural phenomena, such as swarm intelligence, biological evolution, and the collective behavior of animals. Power systems integrated with renewable energy sources often experience nonlinear disturbances, fluctuating power generation, and dynamic load variation. Traditional control techniques may not effectively handle such complex conditions because they rely on fixed parameters and simplified mathematical models. Nature-inspired optimization methods offer a powerful alternative by providing adaptive and flexible solutions for optimizing controller parameters and improving the performance of power quality devices, such as the UPQC, distribution static compensator (DSTATCOM), and STATCOM. Among the most commonly used methods are particle swarm optimization (PSO), genetic algorithm (GA), and ant colony optimization (ACO). PSO is inspired by the social behavior of bird flocks and fish schools, where individual particles move through the search space by adjusting their velocity based on their experience and the best-performing particle in the group. This collaborative search mechanism allows the PSO to efficiently locate optimal solutions for controller tuning and harmonic mitigation problems. Genetic Algorithms are based on the principles of natural selection and genetic evolution, where candidate solutions evolve over generations using operations such as selection, crossover, and mutation. GA is particularly effective in solving multi-objective optimization problems in power systems, including voltage regulation, reactive power compensation, and loss minimization. ACO, inspired by the foraging behavior of ants, uses pheromone-based communication to identify optimal paths and solutions. In power quality applications, ACO can be used to optimize switching strategies and controller parameters in power electronic converters.

These nature-inspired algorithms operate by defining an objective function that represents the desired system performance, such as minimizing the THD, reducing voltage fluctuations, or improving reactive power compensation. The optimization process begins by generating a population of candidate solutions representing different controller configurations. Each candidate is evaluated using an objective function, and the algorithm iteratively improves the solutions by updating their positions or characteristics based on predefined rules inspired by natural processes. Over successive iterations, the algorithm converges with an optimal or near-optimal solution that ensures improved system performance. In renewable-integrated power systems, these optimization techniques are particularly useful for tuning the control parameters of the voltage source converters used in power conditioning devices. By optimizing parameters, such as proportional–integral gains, reference currents, or switching angles, these algorithms enhance the dynamic response and stability of the compensation system. Moreover, nature-inspired optimization methods can be integrated with intelligent control strategies, such as neural networks, fuzzy logic controllers, and deep learning models, to create hybrid control frameworks capable of adapting to rapidly changing operating conditions. These hybrid approaches provide improved harmonic detection accuracy, faster convergence, and better robustness against system uncertainties. However, these algorithms may sometimes require higher computational resources, especially when dealing with large-scale power systems or real-time control applications. Despite this limitation, advances in digital signal processors and high-performance computing platforms have enabled the practical implementation of nature-inspired optimization techniques in modern power quality control systems. Consequently, these algorithms continue to play an important role in enhancing the efficiency, stability, and reliability of renewable energy-integrated electrical distribution networks.

Intelligent Controllers for Power Quality Improvement

Intelligent controllers have become an essential component in modern power quality improvement systems, particularly in electrical networks integrated with renewable energy sources and nonlinear loads. Conventional control strategies such as proportional–integral (PI) controllers often struggle to handle nonlinearities, parameter uncertainties, and rapidly changing operating conditions present in modern power systems. Intelligent control techniques overcome these limitations by incorporating learning capability, adaptability, and decision-making features inspired by artificial intelligence methods. These controllers are widely applied in power conditioning devices such as the UPQC, Distribution Static Compensator (DSTATCOM), and STATCOM to enhance voltage regulation, harmonic mitigation, and reactive power compensation. Intelligent control methods can analyze system behavior in real time and adjust control parameters dynamically to maintain stable operation. Among the most widely used intelligent techniques are artificial neural networks, fuzzy logic controllers, adaptive controllers, and hybrid AI-based algorithms. These methods enable the controller to respond effectively to disturbances such as voltage sag, voltage swell, harmonic distortion, and load imbalance. As renewable energy penetration increases in distribution systems, intelligent controllers play a critical role in maintaining power quality by ensuring smooth interaction between power electronic converters and the grid.

The working principle of intelligent controllers involves learning system patterns and generating appropriate control actions based on input signals, such as voltage, current, and frequency measurements. For example, neural network based controllers can be trained using historical system data to predict disturbances and generate accurate compensation signals for power electronic converters. Similarly, fuzzy logic controllers use rule-based decision systems that mimic human reasoning to determine the appropriate control response under different operating conditions. These controllers are particularly effective in handling uncertain and nonlinear environments because they do not require precise mathematical models of the systems. In many advanced power quality applications, intelligent controllers are combined with optimization techniques and adaptive algorithms to further improve performance. Such hybrid control strategies provide a faster dynamic response, improved harmonic detection accuracy, and better robustness against system disturbances. Moreover, the integration of intelligent controllers with modern digital signal processors and microcontrollers enables real-time implementation in practical power systems. Despite their advantages, intelligent controllers may require extensive training data and computational resources, which can increase the implementation complexity. Nevertheless, ongoing research in machine learning and computational intelligence continues to improve the efficiency and reliability of these types of controllers. Consequently, intelligent control strategies are increasingly being adopted in smart grids and renewable energy systems to achieve superior power quality performance and stable system operation.

ANN-Based Controllers

Artificial neural network (ANN)-based controllers have gained significant attention in recent years for improving the power quality in modern electrical distribution systems. An ANN is a computational model inspired by the structure and function of the human brain, consisting of interconnected neurons that process and transmit information through weighted connections. These networks can learn complex nonlinear relationships between input and output variables, making them particularly suitable for power system control applications.

In conventional control methods, such as proportional–integral controllers, the system parameters are fixed and may not adapt effectively to dynamic operating conditions, such as fluctuating renewable generation, nonlinear loads, and sudden disturbances. ANN-based controllers overcome these limitations by learning from historical data and continuously adjusting the control parameters to maintain optimal system performance.

In power quality applications, ANN controllers are widely used in power conditioning devices such as the UPQC, Distribution Static Compensator (DSTATCOM), and STATCOM. These devices rely on voltage source converters to inject compensating currents or voltages into the power system to mitigate harmonics, correct the power factor, and stabilize voltage levels. ANN controllers analyze real-time measurements of system parameters, such as voltage, current, and frequency, and generate appropriate control signals for the converter switches. Because neural networks can approximate nonlinear system behavior with high accuracy, they provide improved harmonic detection and compensation compared with traditional control strategies. Consequently, ANN-based controllers are increasingly used in renewable energy-integrated systems, where power fluctuations and nonlinear disturbances are common.

Table 5 illustrates the findings of ANN-based controllers for power quality improvement. The working mechanism of ANN-based controllers involves training the neural network using input-output datasets representing different operating conditions of the power system. During the training phase, the network adjusts the weights of the connections between neurons using learning algorithms, such as backpropagation, to minimize the error between the predicted and actual outputs. Once trained, the neural network can rapidly process real-time input signals and generate control actions to improve the system's performance.

In power quality control, an ANN can be used to estimate the reference compensating currents or voltages required for harmonic mitigation and reactive power compensation. These reference signals are then used to control the switching operation of the VSI in devices such as the UPQC or DSTATCOM. One of the major advantages of ANN-based controllers is their ability to adapt to changing system conditions without requiring detailed mathematical models of power systems. They can effectively handle nonlinearities, parameter uncertainties, and time-varying disturbances that are common in renewable-integrated distribution networks. In addition, ANN controllers can be combined with optimization algorithms and other intelligent control techniques, such as fuzzy logic, to form hybrid control frameworks that further enhance system performance. These hybrid approaches improve the convergence speed, increase robustness, and provide better dynamic responses under varying load conditions. However, ANN-based controllers also present certain challenges, including the requirement for large training datasets and the need for careful selection of network architecture and training parameters. Despite these challenges, advancements in machine learning techniques and high-performance digital processors have made it possible to implement ANN controllers in real-time power electronic control systems. Consequently, ANN-based controllers have become a powerful tool for enhancing power quality, improving system stability, and enabling the efficient operation of modern renewable energy-integrated power systems.

Table 5. Findings from ANN-based controllers for power quality improvement.

Citations	Technique/system studied	Key findings
[43]	Intelligent controlled DSTATCOM	The ANN-based intelligent controller improves reactive power compensation and voltage stability, leading to enhanced power quality in distribution networks.
[44]	ANN-controlled DSTATCOM for PV and wind systems	The neural network controller effectively mitigates harmonic distortion and improves power factor in renewable energy-integrated systems.
[45]	ANN-based STATCOM controller	The proposed ANN control strategy enhances voltage stability and reactive power compensation in large-scale power systems.
[46]	ANN-based control for UPQC	The ANN controller improves harmonic compensation, voltage regulation, and dynamic response of the unified power quality conditioner.
[47]	Neural network based shunt active power filter	The ANN-based harmonic compensation technique effectively reduces current harmonics and improves overall power quality in nonlinear load environments.
[48]	Adaptive ANN control for grid-connected PV inverter	The adaptive neural network controller improves inverter stability, enhances power quality, and reduces voltage fluctuations in PV-integrated grids.
[49]	Neural network controlled DSTATCOM	The ANN-based control method effectively compensates reactive power and mitigates load imbalance in distribution systems.
[50]	ANN controller for UPQC	The proposed controller reduces voltage sag and harmonic distortion while improving the reliability of power distribution systems.
[51]	ANN–PI-controlled DSTATCOM with renewable energy and battery storage	The hybrid ANN–PI controller enhances voltage stability, improves energy storage coordination, and reduces harmonic distortion.
[52]	Neural network based active power filter control	The ANN controller improves harmonic detection accuracy and ensures effective power quality management in smart grid environments.

Adaptive Leaky LMS Algorithms

Adaptive filtering techniques have been widely applied in power quality control to improve harmonic detection and signal estimation in electrical distribution systems. Among these techniques, the adaptive leaky least mean square (leaky LMS) algorithm is considered an effective method for identifying harmonic components and generating accurate reference signals for compensation. The conventional least mean square (LMS) algorithm is commonly used in adaptive filtering owing to its simplicity and low computational complexity. However, the standard LMS method may suffer from instability or weight drift when dealing with highly correlated input signals or long-duration disturbances. To overcome this limitation, the leaky LMS algorithm introduces a leakage factor in the weight update equation, which prevents the uncontrolled growth of the filter coefficients and ensures stable convergence. This property makes the leaky LMS algorithm particularly suitable for power quality improvement devices such as the UPQC, Distribution Static Compensator (DSTATCOM), and STATCOM. In these systems, the adaptive algorithm processes the voltage and current signals to estimate the harmonic components generated by the nonlinear loads. By accurately identifying these unwanted components, the controller can generate compensating currents through a VSI, thereby reducing the total harmonic distortion and improving the overall power quality. The adaptive nature of the leaky LMS algorithm allows it to continuously update the filter coefficients in response to changing system conditions, making it highly effective in dynamic environments, such as renewable energy-integrated distribution networks.

Table 6 shows the findings from the adaptive leaky LMS algorithm for power quality improvement. The working mechanism of the adaptive leaky LMS algorithm involves minimizing the mean square error between the desired signal and the estimated output produced by an adaptive filter. The algorithm continuously adjusts the filter weights based on the error signal obtained from the difference between the measured system output and the reference signal.

Table 6. Findings from adaptive leaky LMS algorithms for power quality improvement.

Citations	Technique/system studied	Key findings
[53]	LMS-based adaptive control for DSTATCOM	The adaptive LMS technique enhances the dynamic performance of DSTATCOM by accurately identifying harmonic components and providing effective reactive power compensation.
[54]	Leaky LMS control algorithm for shunt active power filter	The leaky LMS algorithm improves harmonic mitigation capability and ensures stable operation of the shunt active power filter under nonlinear load conditions.
[55]	Adaptive filtering for renewable-integrated grid systems	The adaptive algorithm effectively mitigates harmonics and improves voltage stability in grid systems integrated with renewable energy sources.
[56]	Leaky LMS harmonic extraction for shunt active power filter	The proposed method provides accurate harmonic detection and reduces computational complexity, enabling efficient real-time power quality control.
[57]	Adaptive signal processing for microgrid power quality	Adaptive signal processing techniques improve harmonic compensation and enhance system reliability in microgrid environments.
[58]	Adaptive filtering for renewable energy-integrated distribution systems	The adaptive filtering approach effectively mitigates harmonic distortion and improves the stability of renewable-integrated distribution networks.
[59]	LMS-based adaptive control of active filters	The study shows that LMS-based adaptive control enhances harmonic compensation performance and provides robust operation in dynamic power system environments.

The leakage factor incorporated in the weight update equation helps to stabilize the adaptation process and prevents excessive growth of the filter parameters. In practical power quality control applications, the algorithm is implemented in digital controllers that process real-time voltage and current measurements of the grid. The adaptive filter extracts the fundamental component of the signal while identifying the harmonic components and disturbances.

These extracted signals were then used to generate reference compensation currents for the power electronic converters. Consequently, the system can effectively mitigate harmonics, improve the power factor, and maintain stable voltage conditions in the distribution network. Another advantage of the leaky LMS algorithm is its relatively low computational complexity compared with more advanced machine learning or optimization-based techniques, making it suitable for real-time implementation using signal processors and microcontrollers. Furthermore, the algorithm can be combined with intelligent control methods and predictive algorithms to enhance its performance in highly nonlinear environments. Despite its advantages, the performance of the leaky LMS algorithm depends on the proper selection of parameters, such as the step size and leakage factor. Incorrect parameter settings may lead to slow convergence or reduced filtering accuracy. Nevertheless, owing to its robustness, adaptability, and ease of implementation, the adaptive leaky LMS algorithm remains an important tool for harmonic estimation and power quality enhancement in modern electrical power systems.

Deep Learning Approaches (CNN, LSTM)

Deep learning techniques have recently gained significant attention for improving power quality control in modern electrical distribution systems. Unlike traditional control methods that rely on predefined mathematical models, deep learning algorithms can automatically learn complex patterns and relationships from large data sets. Two of the most widely used deep learning models in power system applications are convolutional neural networks (CNNs) and long short-term memory (LSTM) networks. CNN models are particularly effective for feature extraction from multidimensional data, such as voltage and current waveforms, whereas LSTM networks are designed to capture long-term temporal dependencies in time-series data. In power quality applications, these models analyze real-time measurements of voltage, current, and frequency signals to detect disturbances such as harmonics, voltage sags, voltage swells, and transient fluctuations. Deep learning-based controllers are increasingly integrated into power conditioning devices such as the UPQC, Distribution Static Compensator

(DSTATCOM), and STATCOM. By learning from historical operating data, the CNN and LSTM models can accurately identify abnormal patterns in electrical signals and generate appropriate control actions for harmonic mitigation and reactive power compensation. These capabilities make deep learning particularly useful for renewable-integrated power systems, where power generation fluctuates owing to changing environmental conditions.

Table 7 shows the findings from deep learning approaches (CNN and LSTM) for power quality and smart grid applications. The working principle of deep learning based power quality control involves training neural networks using large datasets obtained from power system measurements or simulation results. During the training phase, the CNN model extracts spatial features from the voltage and current waveforms, such as harmonic patterns and waveform distortions, through convolutional layers. Meanwhile, the LSTM network processes sequential data and learns the temporal relationships between system variables, allowing it to predict future disturbances and system behavior. Once trained, the combined CNN–LSTM framework can process real-time input signals and generate control references for the power electronic converters used in the compensation devices. For example, in a UPQC or DSTATCOM system, the deep learning controller may predict harmonic components or voltage fluctuations and determine the appropriate compensating currents required to maintain stable grid operation. One of the major advantages of deep learning approaches is their high prediction accuracy and ability to adapt to complex nonlinear environments without requiring explicit models. Additionally, these methods can handle large volumes of data and continuously improve their performance as more data becomes available. However, deep learning models also require significant computational resources and extensive training datasets, which can increase implementation complexity. Advances in high-performance processors, graphics processing units, and edge computing technologies have made the real-time deployment of deep learning algorithms increasingly feasible in power system control applications. As a result, CNN- and LSTM-based approaches are emerging as powerful tools for intelligent power quality management in modern smart grids and renewable energy systems.

Table 7. Findings from deep learning approaches (CNN, LSTM) for power quality and smart grid applications.

Citations	Technique/system studied	Key findings
[60]	Optimized CNN–BiLSTM framework for reactive power management	The hybrid CNN–BiLSTM model effectively improves reactive power management and enhances voltage profile stability in renewable-integrated power grids.
[61]	LSTM-based fault detection in distribution systems	The LSTM network accurately detects faults in distribution systems by learning temporal patterns in electrical signals, enabling faster system protection and improved reliability.
[62]	Deep neural networks for power system event identification	Deep neural networks effectively identify different power system disturbances and operational events with high classification accuracy.
[63]	Deep learning-based cyber-physical attack detection	The deep learning model successfully detects cyber-physical attacks in smart grids by analyzing abnormal patterns in system measurements.
[64]	CNN–LSTM model for energy consumption forecasting	The hybrid model accurately predicts energy consumption patterns in smart grids, improving energy management and load forecasting.
[65]	CNN–LSTM model for electric power prediction	The CNN–LSTM framework provides accurate short-term power demand prediction by extracting spatial and temporal features from historical data.
[66]	CNN–LSTM-based fault detection	The hybrid deep learning model improves the accuracy of fault detection and classification in power systems.
[67]	CNN–LSTM forecasting with decentralized inverter control	The integration of CNN–LSTM forecasting with inverter control enhances voltage stability and improves power distribution system performance.
[68]	CNN-based power quality disturbance classification	The CNN model effectively classifies power quality disturbances such as voltage sag, swell, and harmonics with high detection accuracy.

Hybrid CNN–LSTM Control Strategies for Power Systems

Hybrid CNN–LSTM control strategies have recently emerged as powerful tools for improving the monitoring, prediction, and control of modern power systems. CNN are highly effective in extracting spatial features from electrical signals, such as voltage and current waveforms, whereas LSTM networks are designed to capture temporal dependencies and sequential patterns in time-series data. By combining these two deep learning architectures, hybrid CNN–LSTM models can simultaneously analyze the spatial and temporal characteristics of power system signals. This capability makes them particularly suitable for applications such as power quality disturbance classification, harmonic detection, fault diagnosis, and load forecasting in renewable-integrated smart grids. In such systems, electrical signals often exhibit nonlinear and time-varying behavior owing to the presence of distributed generation, power electronic converters, and fluctuating loads. The CNN component extracts meaningful features from raw measurement data, whereas the LSTM component processes these features over time to identify patterns and predict system behavior. Consequently, hybrid architecture provides more accurate detection and prediction than conventional machine learning or standalone deep learning models.

Table 8 illustrates the findings of the Hybrid CNN–LSTM control strategies for power systems. CNN–LSTM models have been widely used for predictive control and adaptive decision-making in power system control applications. These models can process large volumes of real-time sensor data obtained from smart meters, phasor measurement units, and monitoring devices to estimate the system states and anticipate disturbances. For example, CNN–LSTM-based controllers can predict voltage fluctuations, harmonic distortion, or load variations and then generate appropriate control signals for devices such as DSTATCOM, STATCOM, or APFs. This predictive capability significantly improves the system stability, reduces the harmonic distortion, and enhances the voltage profile regulation.

Table 8. Findings from hybrid CNN–LSTM control strategies for power systems.

Citations	Technique/application	Key findings
[69]	Comparison of CNN, LSTM, and CNN–LSTM for power quality disturbance classification	The study shows that the hybrid CNN–LSTM model achieves higher classification accuracy for power quality disturbances compared to individual CNN or LSTM models.
[70]	Fast fourier transform (FFT)-based fused CNN–LSTM model for real-time disturbance recognition	The integration of FFT with CNN–LSTM improves feature extraction and enables accurate real-time identification of power quality disturbances.
[71]	CNN–LSTM model for power quality prediction in active distribution networks	The proposed model effectively predicts power quality variations by capturing both spatial signal features and temporal dependencies.
[72]	CNN–LSTM- based time-series fault detection	The hybrid model improves the accuracy and reliability of time-series fault detection in power systems.
[73]	CNN–LSTM-based predictive switching control for multilevel inverter	The CNN–LSTM controller enhances switching control strategies and improves voltage regulation performance of multilevel inverters.
[74]	Optimized CNN–BiLSTM framework for reactive power management	The optimized model improves the voltage profile and reactive power control in renewable energy-integrated power grids.
[75]	Improved CNN–LSTM model for short-term wind power forecasting	The improved architecture provides highly accurate short-term wind power forecasting, supporting better grid operation and planning.
[76]	CNN–LSTM network for electric power prediction	The model successfully predicts electric power demand by learning spatial and temporal patterns from historical data.
[77]	CNN–LSTM forecasting integrated with decentralized inverter control	The combination of forecasting and inverter control reduces power losses and improves voltage stability in distribution networks.
[78]	LSTM and adaptive neuro-fuzzy inference system (ANFIS) based power quality monitoring	The study demonstrates that LSTM-based forecasting improves monitoring and prediction of power quality variations in isolated power systems.

Furthermore, hybrid deep learning controllers can adapt to dynamic grid conditions without requiring precise mathematical models of power systems. This is particularly beneficial for renewable energy-integrated networks, where system dynamics change frequently. Overall, hybrid CNN–LSTM strategies provide a robust and intelligent framework for advanced power system control, enabling improved reliability, faster disturbance responses, and enhanced power quality in modern smart grid environments.

Limitations of Existing Techniques

Despite the considerable progress achieved in power quality improvement techniques for PV-integrated distribution networks, several limitations remain in the conventional and existing intelligent control strategies. Traditional controllers, such as PI/PID controllers, SRF control methods, and basic active power filter algorithms, have been widely used in devices such as DSTATCOM and UPQC to mitigate harmonics and compensate for reactive power. However, these techniques rely heavily on accurate mathematical models and fixed controller parameters, which limit their performance under dynamic operating conditions. PV systems are inherently intermittent because of fluctuations in solar irradiance, temperature variations, and rapid load changes, which can cause voltage instability, harmonic distortion, and power factor degradation. Under these conditions, conventional controllers may exhibit slower response times and reduced compensation accuracy. For example, sudden irradiance changes or nonlinear load disturbances can lead to temporary increases in the THD and voltage deviations before the controller stabilizes the system. Furthermore, adaptive signal processing methods, such as adaptive LMS and leaky LMS algorithms, are commonly used for harmonic extraction in APFs; however, their effectiveness can be affected by convergence speed and parameter tuning issues.

Major Limitations of Existing Techniques Include

- Conventional controllers are less effective in nonlinear and uncertain environments because they depend on accurate system modeling.
- Slow dynamic response during sudden irradiance variations and rapid load disturbances.
- Higher compensation delay, which may temporarily increase THD and voltage fluctuations.
- Fixed controller parameters, resulting in reduced adaptability under varying operating conditions.
- Sensitivity of adaptive algorithms (LMS, leaky LMS) to step size parameters and convergence stability.
- The limited capability of ANN-based controllers when training datasets are insufficient or when operating conditions change significantly.
- The high computational complexity of deep learning methods when applied individually in real-time control systems.

Owing to these limitations, researchers have increasingly explored hybrid deep learning frameworks for power quality control. In particular, the hybrid CNN–LSTM architecture combines the strengths of convolutional neural networks and long short-term memory networks to achieve a more robust performance. CNN layers can extract complex spatial features from voltage and current waveforms, whereas LSTM networks can effectively capture the temporal dependencies in power system signals. This hybrid approach enables more accurate disturbance detection, improved harmonic prediction, and faster control responses in renewable energy-integrated distribution networks. Consequently, hybrid CNN–LSTM-based controllers are considered superior to conventional, adaptive, and single deep learning models, as they provide enhanced system stability, reduced THD levels, improved voltage regulation, and better adaptability to rapidly changing PV-grid operating conditions.

Traditional control and signal processing techniques, such as ANN, adaptive filtering algorithms, and LMS-based controllers, have been widely used for power quality improvement and harmonic mitigation in power systems. However, these methods often have limitations when dealing with highly dynamic and nonlinear power system environments. Modern power systems, especially those integrated with renewable energy sources, exhibit complex temporal variations and nonlinear characteristics owing to fluctuating loads, intermittent generation, and power electronic converters. Conventional techniques typically rely on predefined mathematical models or limited feature extraction capabilities, which can reduce their effectiveness in accurately identifying power quality disturbances and predicting system behavior under rapidly changing conditions.

Hybrid deep learning models, such as CNN–LSTM, provide more advanced and efficient solutions to these challenges. CNNs are highly effective in extracting spatial features from electrical signals, such as voltage and current waveforms, enabling the detection of patterns related to harmonics, faults, and disturbances. Meanwhile, LSTM networks are designed to learn temporal dependencies in time-series data, allowing them to capture the dynamic evolution of power system signals over time. By combining these two architectures, CNN–LSTM models can simultaneously analyze spatial and temporal information, leading to improved accuracy in disturbance detection, load forecasting, and system control. This hybrid structure allows the controller to respond more effectively to real-time variations in grid conditions than traditional ANN or adaptive filtering methods.

Furthermore, CNN–LSTM models can process large volumes of real-time data obtained from smart meters, sensors, and phasor measurement units, rendering them suitable for modern smart grid applications. Their ability to learn complex nonlinear relationships directly from data reduces the need for detailed mathematical modeling of power systems. Consequently, CNN–LSTM-based controllers can provide faster disturbance recognition, better harmonic mitigation, and improved voltage regulation performance. These advantages make CNN–LSTM a promising and robust approach for implementing intelligent control strategies in advanced power quality management systems.

Identified Research Gaps

Although several intelligent and adaptive control techniques, such as ANN, adaptive filtering algorithms, and LMS-based controllers, have been proposed for power quality improvement in modern power systems, certain limitations remain. Many existing techniques are primarily designed to address specific issues, such as harmonic mitigation or voltage regulation, rather than providing a comprehensive solution for multiple power quality problems simultaneously. Conventional ANN-based controllers rely on static training structures and may struggle to adapt effectively to rapidly changing grid conditions, particularly in renewable energy-integrated systems. Similarly, adaptive algorithms such as the LMS and leaky LMS offer fast convergence and real-time implementation capability, but their performance can degrade when dealing with highly nonlinear and non-stationary signals. These techniques also have limited capability in extracting complex features from large volumes of time-series data that are generated in modern smart grid environments.

Another important research gap is the lack of methods capable of effectively capturing the spatial and temporal characteristics of electrical signals. Traditional signal processing methods generally focus on time-domain or frequency-domain analysis separately, which may not fully represent the dynamic behavior of power systems. Power systems are becoming increasingly complex and data-intensive with the increasing integration of distributed renewable energy sources, electric vehicles, and power electronic converters. In this context, hybrid deep learning approaches, such as CNN–LSTM, provide a more advanced solution. CNN can extract meaningful spatial features from voltage and current waveforms, whereas LSTM networks can analyze temporal dependencies in sequential data. The combination of these two architectures allows CNN–LSTM models to detect disturbances, predict system behavior, and support intelligent control decisions more effectively than many conventional methods.

Key Research Gaps Identified

- Existing ANN controllers have limited adaptability to highly dynamic grid conditions.
- LMS and adaptive filtering techniques have reduced effectiveness for complex nonlinear signal patterns.
- Most traditional methods focus on single-function solutions, such as harmonic mitigation only.

- The limited capability of existing techniques to process large-scale real-time smart grid data.
- Conventional algorithms cannot effectively capture both spatial and temporal features of power signals.
- Insufficient integration of advanced data-driven models for predictive control applications.

Why CNN–LSTM is a Better Approach

- Combines CNN for spatial feature extraction and LSTM for temporal sequence learning.
- Provides higher accuracy in disturbance detection and forecasting.
- Capable of handling large real-time datasets from smart grid sensors.
- Improves voltage stability, harmonic mitigation, and predictive control performance.
- Suitable for complex renewable energy-integrated power systems.

Existing intelligent control techniques, such as ANN, LMS, and adaptive filtering algorithms, have been widely used for power quality improvement; however, they still exhibit several limitations. Many of these methods focus on individual problems, such as harmonic mitigation or voltage regulation, and struggle to handle highly dynamic and nonlinear conditions in renewable-integrated power systems. Moreover, they have a limited capability to extract complex features from large time-series datasets generated in modern smart grids. A major research gap is the inability of conventional techniques to capture the spatial and temporal characteristics of electrical signals. Hybrid CNN–LSTM models address these issues by combining spatial feature extraction with temporal learning, thereby enabling more accurate disturbance detection, prediction, and intelligent control.

CONCLUSION

The primary objective of this research is to develop an advanced intelligent control framework for improving power quality in PV-integrated distribution systems using devices such as DSTATCOM and UPQC. Modern power distribution networks are increasingly integrating renewable energy sources, particularly solar photovoltaic systems, which introduce variability and nonlinear behavior into the grid. These conditions often lead to power quality issues, such as voltage fluctuations, harmonics, reactive power imbalance, and instability in distribution networks. To address these challenges, this study focuses on developing adaptive, optimization-based, and deep learning-based control strategies capable of maintaining stable and efficient grid operation under varying operating conditions.

This study first established strong theoretical foundations by analyzing power quality disturbances, mathematical modeling of grid-connected systems, and adaptive filtering techniques. Reference frame transformations and control strategies for voltage source converters were investigated to develop efficient harmonic detection and compensation methods. The stability of the adaptive controllers was also analyzed to ensure reliable system operation. Subsequently, a comprehensive model of a PV-integrated hybrid distribution system was developed, including photovoltaic arrays, DC–DC converters, nonlinear loads, and power quality conditioning devices such as DSTATCOM and UPQC. The proposed system integrates active power filtering techniques to mitigate harmonics and improve the voltage regulation.

In addition to conventional control methods, optimization-based adaptive control using the bat optimization algorithm was introduced to enhance the performance of the SRF controller for DSTATCOM. This optimization approach improves the controller parameter tuning and enhances the system dynamic performance under varying solar irradiance and load conditions. Furthermore, this study proposes intelligent control strategies using ANN combined with adaptive leaky LMS algorithms for UPQC operation. To further enhance the system's capability to handle complex and dynamic power system behaviors, deep learning techniques such as CNN and LSTM networks were integrated to form a hybrid CNN–LSTM controller. This intelligent controller extracts spatial features from power signals and learns the temporal patterns of grid dynamics, enabling accurate disturbance detection, prediction, and adaptive control. The overall objective of this study is to develop an advanced intelligent control framework for improving power quality in PV-integrated distribution systems using a DSTATCOM and UPQC. This study focuses on modeling PV-based hybrid distribution networks and analyzing power quality disturbances, such as harmonics, voltage fluctuations, and reactive power imbalances. Optimization-based adaptive control using Bat Optimization and intelligent controllers, such as ANN, CNN, and LSTM, is implemented to enhance system performance. A hybrid CNN–LSTM controller is proposed to improve disturbance detection, predictive control, and dynamic stability, ensuring efficient operation, enhanced power quality, and reliable integration of renewable energy into modern smart grids.

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