Hybrid Metaheuristic–Deep Learning Frameworks for Intelligent Detection and Mitigation of Power Quality Disturbances in Renewable-Integrated Smart Grids: A Comprehensive Review

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Abstract

Power quality disturbances (PQDs) have become an increasingly critical concern in modern power systems due to the rising integration of renewable energy resources, widespread use of power-electronic interfaced loads, and the growing complexity of cyber-physical grid infrastructures. These evolving conditions have introduced new sources of variability, uncertainty, and vulnerability into power networks, making it significantly more challenging to maintain voltage stability, waveform purity, and overall system reliability. Traditional deterministic methods for disturbance detection and classification are no longer sufficient to address the nonlinear, nonstationary, and high-dimensional nature of contemporary PQD phenomena. As the operational landscape grows more dynamic, there is a pressing need for analytical frameworks that can adaptively learn, generalize, and respond to diverse disturbance scenarios in real time. This study provides a comprehensive examination of recent advancements in PQD research, emphasizing the evolution toward hybrid analytical frameworks that integrate advanced signal processing, machine learning, and metaheuristic optimization. The literature demonstrates that hybrid models—such as continuous wavelet transform (CWT) combined with convolutional neural networks (CNNs), Stockwell transform integrated with kernel-based extreme learning machines (ELMs), and metaheuristic-optimized classifiers—significantly enhance detection accuracy, robustness against noise, and adaptability to varying operating conditions. These hybrid systems leverage the strengths of each component: signal transforms enrich the representational quality of PQD features, deep architectures facilitate automatic feature learning, and optimization algorithms refine model parameters to achieve optimal performance across complex and uncertain environments. Metaheuristic algorithms including Particle Swarm Optimization (PSO), Grey Wolf Optimization (GWO), Whale Optimization Algorithm (WOA), Differential Evolution (DE), and hybrid variants have proven particularly effective for feature selection, classifier optimization, system-level enhancement, and mitigation strategies. Their ability to handle large, multimodal, and nonlinear search spaces makes them especially suitable for modern PQD challenges, where disturbance signatures may overlap, evolve over time, or be obscured by noise introduced by renewable energy fluctuations. Furthermore, recent work demonstrates the potential of ensemble-based and deep learning models optimized with metaheuristics to outperform conventional approaches in both accuracy and computational efficiency, thereby advancing the state-of-the-art in PQD detection technologies. Additionally, the convergence of PQD analysis with cybersecurity highlights an emerging and increasingly urgent research frontier. As smart grids become more interconnected and reliant on information and communication technologies, they face heightened risks from cyber-attacks capable of inducing, masking, or mimicking PQ disturbances. Such adversarial actions pose significant threats to grid stability, integrity, and operational safety. Metaheuristic-enhanced deep learning methods have shown promise for cyber-physical intrusion detection by enabling classification models to identify subtle, intentionally disguised anomalies within PQ data streams. This hybrid approach provides a pathway toward resilient PQ monitoring frameworks that are capable of learning and adapting to evolving attack strategies. Despite notable advancements, several key challenges persist. First, the lack of standardized real-world datasets limits the generalizability and reproducibility of PQD research, particularly within renewable-dominated or cyber-physical grid environments. Second, the high computational demands of hybrid models hinder their deployment in real-time or resource-constrained settings, calling for advancements in

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lightweight architectures, model compression, and edge-intelligent PQD systems. Third, the field lacks unified frameworks that integrate PQ detection, classification, and mitigation with operational decision-making, economic constraints, and regulatory requirements. Finally, adaptive cyber-physical intrusion detection frameworks remain underdeveloped, especially for zero-day attacks and data-limited conditions. Overall, this review underscores the necessity of holistic, intelligent, and scalable approaches to PQD management. It identifies critical directions for future research, including real-time system integration, computationally efficient hybrid architectures, multiobjective optimization strategies, and robust cybersecurity-aware PQD analytics. These innovations are essential for achieving resilient next-generation smart grids capable of maintaining high power quality under increasingly dynamic, decentralized, and uncertain operating conditions.

Keywords: Power quality disturbances; Continuous wavelet transform; Extreme learning machines; Particle swarm optimization; Grey wolf optimization

1 Introduction

The concept of power quality has become a central concern in the development and operation of modern power systems [1] [2,3]. As the demand for electricity continues to rise and the composition of electrical grids evolves with the integration of renewable energy resources, ensuring the stability, reliability, and efficiency of electrical supply has grown increasingly complex. Power quality disturbances (PQDs) refer to any deviations from the ideal sinusoidal waveform at nominal frequency and magnitude [4–6]. These disturbances, which include voltage sags, swells, harmonics, transients, flicker, and interruptions, can cause significant operational issues across residential, commercial, and industrial sectors [7–9]. Sensitive electronic equipment, which has become ubiquitous in all sectors of modern life, is particularly vulnerable to PQDs, with even small deviations leading to malfunctions, data loss, or outright equipment failure. The economic consequences of such disturbances can be severe, ranging from reduced productivity to large-scale outages with system-wide implications. As global infrastructures increasingly depend on digital platforms, data centers, automation technologies, and power-electronic devices, the tolerance for PQ deviations continues to shrink, heightening the urgency of developing advanced PQD monitoring and mitigation strategies. The importance of PQDs has been consistently underscored in the academic and industrial literature. A foundational perspective on power engineering research emphasizes how power quality has shaped educational and technological priorities within the discipline, highlighting that PQ is not merely a technical challenge but also an educational and institutional priority [10]. As renewable energy systems, electric vehicles, and smart grid technologies continue to expand, PQD research has emerged as a multidimensional field encompassing signal processing, optimization, machine learning, and power system design. Modern grids must accommodate bidirectional energy flow, variable generation patterns, and distributed storage devices, all of which contribute to fluctuating PQ conditions. This expansion has led to a proliferation of techniques aimed at detecting, classifying, and mitigating disturbances, with increasing emphasis on hybrid and intelligent approaches that can operate effectively in conditions where classical analytical models struggle to represent the real-time behavior of the grid. Among the methods that have shaped recent research, signal processing techniques remain foundational. Advanced transforms such as the Stockwell transform, wavelet transform, and empirical mode decomposition have been employed to analyze disturbances that are inherently nonstationary and nonlinear, providing high-resolution feature sets required for classification algorithms. These techniques offer time–frequency localization capabilities critical for distinguishing between transient and steady-state disturbances. However, as systems grow more complex and disturbances become increasingly overlapping or masked by noise, traditional methods have proven inadequate in isolation. Hybrid approaches that combine advanced transforms with optimization-based learning models have demonstrated superior accuracy and noise robustness. A notable example is the use of Stockwell transform features combined with kernel extreme learning machines optimized by improved Grey Wolf Optimization, which achieved strong results in disturbance classification, underscoring the value of integrating signal decomposition with optimization-driven machine intelligence [11]. Such approaches signal a paradigm shift in PQD research toward frameworks that exploit multiple layers of transform-based and algorithmic intelligence. Optimization methods, particularly those inspired by nature and collective behavior, have also emerged as central tools in PQD research. Their application has been demonstrated in feature extraction, feature selection, and classifier parameter tuning [12–15]. Swarm-based methods such as Particle Swarm Optimization (PSO), Grey Wolf Optimization (GWO), and Whale Optimization Algorithm (WOA) are especially well-suited to the high-dimensional and multimodal search spaces characteristic of PQD problems. One approach coupled discrete wavelet transform with WOA for PQD recognition, showing that the adaptive balance

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between exploration and exploitation inherent in swarm-inspired algorithms can enhance classification accuracy under noisy conditions [16]. As PQD datasets grow in size and complexity, these optimization methods have become indispensable not only as complementary tools but also as core drivers of intelligent classification and mitigation strategies. Their capacity to accelerate convergence while avoiding premature stagnation makes them well-suited for real-time PQD applications. Comprehensive reviews have further illuminated the evolution of PQD research, emphasizing the need for approaches that move beyond isolated detection and classification toward integrated frameworks that also address optimization and mitigation [17]. Such reviews show that while individual methods may excel in certain scenarios, the future of PQD research lies in holistic approaches that unify analysis, optimization, and corrective action. This trajectory aligns with the broader vision of smart grids as adaptive and self-healing infrastructures capable of responding to both predictable and unforeseen disturbances. By embedding intelligence into monitoring and control components, future grids are expected to autonomously identify deviations, optimize operating parameters, and deploy corrective mechanisms without human intervention. The idea of hybridization is further reinforced by methods that integrate traditional and optimization-based classifiers. For instance, hybrid algorithms have been developed to recognize disturbances by combining wavelet-based feature extraction with optimization-enhanced classifiers. These systems adaptively tune parameters and select features, improving generalization performance across diverse operating conditions [18]. This adaptive behavior is particularly valuable in real-world scenarios, where disturbances often overlap, exhibit distortion due to inverter-based resources, or occur in noisy measurement environments. Hybridization, therefore, has become a recurring theme in PQD research, with the goal of enhancing robustness, accuracy, and adaptability while reducing dependency on handcrafted feature engineering. The advancement of optimization algorithms has not been limited to commonly used swarm techniques. Recent developments demonstrate the power of novel strategies, such as improved Grasshopper Optimization, when coupled with ensemble learning methods like Adaptive Boosted Random Forests. These systems enhance classification accuracy and resilience in diverse disturbance environments, further validating the trend toward integrating optimization with machine learning for PQD detection and classification [19]. Such work illustrates how progress in algorithm design continues to open new possibilities for PQD analysis, allowing researchers to build classifiers that are not only more accurate but also more interpretable and computationally efficient. Complementary to classification efforts, optimization-driven frameworks for feature selection and classifier training have proven highly effective in simplifying models without sacrificing performance. The application of Grey Wolf Optimization to extreme learning machine models is an example of how feature dimensionality can be reduced while retaining discriminative power, resulting in more efficient and scalable classifiers for PQD analysis [20]. These approaches reflect the growing recognition that efficiency is as important as accuracy, particularly in real-time or large-scale applications where computational resources may be limited. The continued refinement of feature selection through metaheuristics contributes to the development of lightweight models suitable for deployment in embedded systems or distributed monitoring nodes. Metaheuristic techniques have also been applied more broadly in PQD research, addressing not only detection and classification but also enhancement and mitigation strategies. A comprehensive treatment of metaheuristics has shown their effectiveness across a range of PQ problems, demonstrating that their adaptability to nonlinear and high-dimensional problems is particularly suited to the challenges of modern power systems [21]. Such work underscores the universality of metaheuristic methods in addressing PQ issues across diverse contexts, from harmonic suppression and filter tuning to voltage regulation and optimal compensation. Their flexibility enables solution of multiobjective optimization tasks where classical methods fail to capture trade-offs between PQ improvement, system stability, and economic cost. As smart grids evolve into cyber-physical systems, new challenges have emerged at the intersection of PQ and cybersecurity. Cyber-attacks such as data tampering or false data injection can artificially generate PQDs or mask real disturbances, creating vulnerabilities that extend beyond technical failures into security concerns. These threats complicate PQD analysis because they blend physical anomalies with malicious data manipulation. Advanced classification schemes employing deep ensemble learning combined with metaheuristic optimization have been developed to identify cyber intrusions, highlighting the convergence of PQD research with cybersecurity [22]. This expansion of scope reflects the reality that PQD research must now contend not only with physical disturbances but also with digitally orchestrated threats that undermine system resilience, grid stability, and consumer trust. Finally, optimization-based PQ enhancement strategies in distribution systems illustrate another critical dimension of PQD research. Techniques for improving power quality in both balanced and unbalanced distribution networks using metaheuristic optimization have demonstrated the ability to optimize compensating device placement and operation. These methods directly address challenges associated with voltage stability, harmonic mitigation, and system losses, thereby highlighting the role of optimization not only in analysis but also in practical system improvement [23]. Such contributions reflect the broad applicability of optimization techniques in addressing PQ issues from multiple angles, from operational control to

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structural planning and long-term reliability enhancement. The study of power quality disturbances (PQDs) has historically evolved alongside the development of modern electrical networks, gradually shifting from classical analytical approaches toward more advanced computational and hybrid frameworks. In traditional power systems, the predominant concern was with disturbances caused by predictable factors such as lightning strikes, switching operations, or equipment failures. The growing reliance on sensitive electronic devices and the integration of distributed renewable energy sources have significantly altered this landscape, giving rise to increasingly complex and variable forms of disturbances that demand more sophisticated methods of analysis and mitigation. The importance of PQDs extends beyond purely technical concerns; disturbances can impose heavy financial and operational costs, reduce equipment lifespan, and compromise consumer satisfaction. Consequently, the field has attracted sustained interest from both researchers and practitioners seeking to develop solutions that are accurate, scalable, and capable of functioning in real-time. The integration of renewable energy resources into grid infrastructures has introduced a particularly challenging set of PQD problems. Solar photovoltaic (PV) systems, while essential for sustainable energy transitions, are characterized by variability in output due to fluctuations in irradiance and temperature. This variability translates into voltage and current fluctuations that degrade power quality. To address this, advanced signal processing techniques such as continuous wavelet transform (CWT) have been used to generate two-dimensional time–frequency representations of PQ signals. These representations, when coupled with deep learning frameworks such as convolutional neural networks (CNNs), enable highly accurate classification of PQDs in renewable-integrated systems. A hybrid deep learning framework that combines CNN-based feature extraction with dimensionality reduction and machine learning classifiers has demonstrated the ability to correctly identify disturbances in PV-integrated networks, even when the variability of renewable output negatively influences power quality [24]. This development reflects a broader trend in PQD research: the reliance on hybrid methodologies that merge the strengths of different analytical approaches to achieve robustness and accuracy in complex environments. Alongside the rise of deep learning approaches, feature selection has emerged as a vital component of PQD classification systems. Raw signals transformed by time–frequency methods generate vast amounts of data, much of which is redundant or irrelevant for classification tasks. Without careful feature selection, classifiers can become overfitted, computationally inefficient, and less generalizable to unseen data. Particle Swarm Optimization (PSO), a nature-inspired metaheuristic algorithm, has been widely used to optimize both feature selection and classifier parameters. By dynamically balancing exploration and exploitation, PSO has proven capable of identifying compact, informative subsets of features that significantly enhance classification performance while reducing computational burden. Early work applying PSO to PQD classification confirmed that this approach not only increased accuracy but also simplified models, making them more efficient and suitable for real-time applications [25]. These findings established metaheuristic feature selection as a central pillar of PQD research, and subsequent studies have continued to build upon this foundation with increasingly sophisticated optimization strategies. Swarm intelligence techniques, as a broader class of optimization algorithms, have also been extensively studied for their applications to PQD analysis and mitigation. Inspired by the collective behavior of biological populations, these methods have proven highly effective in addressing the nonlinear and multidimensional optimization problems that characterize modern power systems. A comprehensive review of swarm intelligence applications demonstrated their utility in enhancing dynamic response, voltage stability, and overall PQ in microgrid systems. Techniques such as Ant Colony Optimization (ACO), Artificial Bee Colony (ABC), Grey Wolf Optimization (GWO), and Whale Optimization Algorithm (WOA) have been applied to optimize compensating device placement, filter tuning, and system control strategies. These algorithms enable microgrids to operate more adaptively, mitigating PQ issues under varying load and generation conditions. The review further highlighted that swarm-based approaches provide advantages in scalability, robustness, and adaptability, making them well-suited for the challenges posed by distributed and renewable-based microgrids [26]. This body of research underscores the growing importance of swarm intelligence as a cornerstone of PQD research in decentralized energy environments.

2 Literature Review

The exploration of power quality disturbances (PQDs) has led to a steadily expanding body of research, reflecting the critical importance of reliable and high-quality electrical supply in modern power systems. As electrical networks evolve through renewable integration, digitization, and decentralization, the study of PQDs has transitioned from a narrow technical concern into a multidisciplinary research domain spanning signal processing, machine learning, optimization, and cyber-physical system analysis. This literature review synthesizes the key directions, findings, and methodologies that have emerged over the past two decades, focusing

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particularly on the use of optimization, metaheuristic techniques, hybrid deep learning frameworks, and their applications to power systems, renewable energy integration, cybersecurity, and smart grid operation. By examining landmark contributions and thematic trends, this section provides a comprehensive picture of how the field has progressed and identifies the enduring challenges and research gaps that motivate further scientific inquiry. The increasing integration of renewable energy sources into conventional grids has introduced new complexities to PQD analysis. Solar photovoltaic (PV) systems, in particular, present unique challenges due to their intermittent and nonlinear generation characteristics. PV power output fluctuates with irradiance, shading effects, atmospheric conditions, and temperature variations—all of which contribute to voltage instability, fluctuating harmonics, and transient events. Traditional PQD detection frameworks struggle to capture these nonlinearities because renewable-induced disturbances often evolve rapidly and overlap with existing system noise. Deep learning and hybrid machine learning frameworks have thus become prominent tools for PQD classification in renewable-integrated systems. One notable contribution employed continuous wavelet transform (CWT) to convert PQ signals into two-dimensional scalogram images, capturing their time–frequency characteristics with high resolution. These scalograms were processed using convolutional neural networks (CNNs) such as AlexNet and GoogLeNet, enabling automatic extraction of discriminative features. To reduce dimensionality and enhance classifier generalizability, neighbor component analysis (NCA) was used, followed by classification through support vector machines (SVMs). This hybrid system achieved superior accuracy even when solar PV integration adversely influenced power quality, demonstrating the effectiveness of coupling domain-specific signal transformations with powerful learning architectures [24]. Such studies illustrate how hybrid models overcome the limitations of purely statistical or deterministic approaches, especially in environments characterized by high variability and uncertainty. The role of feature selection in PQD classification cannot be overstated. Time–frequency transformations generate large volumes of data that may include redundant, irrelevant, or noisy features. Without effective dimensionality reduction, classifiers face challenges such as overfitting, elevated computational cost, and reduced interpretability. Particle Swarm Optimization (PSO) has been widely employed to address this challenge. PSO is a population-based metaheuristic inspired by the collective behavior of bird flocks and fish schools. Its capacity to efficiently explore continuous search spaces makes it highly suitable for selecting optimal subsets of PQD features. Early work showed that PSO-based feature selection significantly improved classification accuracy while reducing computational overhead compared to deterministic or exhaustive search methods [25]. PSO's ability to balance global exploration and local exploitation enables it to avoid premature convergence while identifying compact, informative feature sets. These contributions laid the foundation for the widespread adoption of metaheuristic-based feature selection in PQD research, and subsequent studies have refined PSO variants to handle complex, multiobjective optimization scenarios present in real-world datasets. The rise of swarm intelligence techniques has further enriched PQD research. These algorithms—including Ant Colony Optimization (ACO), Artificial Bee Colony (ABC), Grey Wolf Optimization (GWO), and Whale Optimization Algorithm (WOA)—mimic natural behaviors such as foraging, hunting, and navigation. Swarm intelligence algorithms possess inherent adaptability, robustness, and scalability, making them particularly effective for high-dimensional optimization tasks in modern power systems. A comprehensive review of swarm-based optimization highlighted their successful application in AC microgrids for PQ enhancement, voltage stability, and dynamic response improvement [26]. Microgrids rely heavily on flexible control schemes to balance fluctuating loads and generation sources, especially under renewable-dominant conditions. Swarm algorithms, with their decentralized decision-making and iterative adaptation, align naturally with the operational principles of microgrids. Their ability to optimize compensating device placement, parameter tuning, and filter settings reinforces their importance as indispensable tools in PQ mitigation strategies. As microgrids continue to proliferate due to their economic and environmental benefits, swarm intelligence is expected to play an even more prominent role in ensuring PQ resilience across distributed energy systems. The ongoing significance of metaheuristic techniques in feature selection is further affirmed by recent research. Algorithms such as GWO, Differential Evolution (DE), and hybrid metaheuristic variants have demonstrated improved classifier performance across multiple PQD datasets, especially in complex environments where disturbances overlap or contain non-Gaussian noise components. These methods systematically reduce input dimensionality while retaining critical information, thereby improving classifier generalization, reducing training time, and mitigating the risk of overfitting. Studies such as [27] reveal that metaheuristic feature selection outperforms traditional statistical techniques like principal component analysis or mutual information-based ranking, particularly when PQ datasets contain nonstationary characteristics. These findings highlight that metaheuristic-based feature selection is now a central component of high-performance PQD classification frameworks, directly contributing to enhanced reliability and operational efficiency in monitoring systems. Beyond classification and feature selection, PQD research has increasingly intersected with cybersecurity. The digitalization of power systems has enabled advanced monitoring, communication, and control; however, it has also created vulnerabilities exploitable by

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malicious actors. Cyber-attacks such as denial of service, false data injection, and coordinated misinformation campaigns can mimic normal PQ disturbances, mask actual events, or disrupt grid operations. As traditional PQD detection methods are designed for physical disturbances rather than malicious manipulations, new tools are required to differentiate between cyber-induced and natural disturbances. Metaheuristics combined with deep learning have been proposed as promising solutions. For example, deep neural networks optimized through swarm intelligence algorithms have shown strong performance in classifying cyber intrusions in smart grids [28]. Optimization enhances the adaptability of learning models, allowing them to better track evolving attack strategies and data patterns. This research direction underscores the growing need for PQD monitoring systems that incorporate both physical and digital dimensions of power system behavior. Optimization techniques also play a central role in the optimal integration of distributed generation (DG), compensators, and other devices into distribution networks. The placement and sizing of DG units have significant impacts on PQ, voltage profile stability, harmonic levels, and system losses. Traditional optimization methods struggle with the multiobjective, nonlinear, and constrained nature of DG planning problems. Metaheuristic algorithms such as PSO, Genetic Algorithms (GA), and DE have been widely deployed to tackle these complex optimization tasks. A review of metaheuristic approaches for DG integration [29] highlighted their superior performance in optimizing multiple objectives simultaneously, leading to improvements in PQ, operational efficiency, and system reliability. Moreover, optimization-driven approaches contribute to enhanced renewable energy utilization and economic performance, emphasizing their importance not only from a technical perspective but also from a sustainability standpoint. Advances in metaheuristic optimization have also benefited active mitigation of PQ issues. Devices such as active power filters, dynamic voltage restorers (DVRs), unified power quality conditioners (UPQCs), and static VAR compensators (SVCs) rely on optimal parameter tuning to achieve high mitigation performance. The high-dimensional, nonlinear nature of compensator tuning makes it a challenging optimization problem. Recent work introduced Levy flight-based variants of the Moth Flame Optimization (MFO) algorithm, which significantly improved compensator performance in smart grids by enhancing global exploration and preventing premature convergence [30]. These developments show that hybrid metaheuristic strategies offer valuable advantages for designing intelligent compensators capable of adjusting adaptively to real-time disturbances. The convergence of PQD research with optimization, machine learning, renewable integration, and cybersecurity highlights several critical themes in the literature. First, renewable energy integration introduces new PQ challenges that require flexible, hybrid analytical models capable of capturing nonstationary behaviors [24]. Second, feature selection remains an indispensable component of PQD classification, and metaheuristic algorithms consistently outperform traditional methods by enabling more compact and informative feature spaces [25, 27]. Third, swarm intelligence and other metaheuristics provide robust solutions for PQ enhancement, compensator tuning, and dynamic control in microgrids [26]. Fourth, the emergence of cyber threats in smart grids necessitates advanced intrusion detection frameworks that leverage both deep learning and optimization to differentiate between natural PQDs and malicious disturbances [28]. Fifth, optimal integration of DG units and mitigation devices underscores the essential role of optimization in supporting stability, PQ improvement, and system efficiency [29,30]. Collectively, these contributions demonstrate that metaheuristics are now deeply embedded in PQD research, shaping both analytical and operational methodologies. Despite substantial progress, several research gaps remain evident. A major gap is the absence of standardized, comprehensive datasets for PQD classification, especially in renewable-integrated and cyber-physical systems. Many studies rely on synthetic or small-scale datasets that lack the diversity and noise characteristics of real-world conditions, limiting the generalizability of reported results. Another challenge is the computational complexity of hybrid models involving deep learning and metaheuristics. While these approaches offer strong performance, their resource requirements hinder deployment in real-time environments or edge-based monitoring systems. Furthermore, the evolving nature of cyber-attacks demands adaptive intrusion detection systems capable of learning from minimal or unlabeled data, an area where current models exhibit limited robustness. Finally, the integration of PQD management with broader considerations such as economic dispatch, regulatory compliance, consumer-side flexibility, and market-based incentives remains underexplored, despite its growing importance in modern grid planning. Table 1 presents a structured summary of the key studies reviewed in the literature, highlighting the objectives, methodologies, and principal findings of representative works in power quality disturbance analysis, renewable energy integration, and intelligent optimization-based classification frameworks. This tabulated synthesis provides a concise comparison of various hybrid deep learning models, metaheuristic feature selection techniques, swarm intelligence applications, and cybersecurity-aware PQD detection methods. By organizing the literature in this manner, the table supports a clearer understanding of methodological trends, performance improvements, and existing research gaps that inform the direction of the present study.

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Table 1: Summary of reviewed literature on power quality disturbances and intelligent detection methods

Reference	Objective	Methodology	Key Findings
[24]	To classify PQDs in PV-integrated systems using hybrid deep learning.	Used Continuous Wavelet Transform (CWT) to generate scalograms; feature extraction via AlexNet and GoogLeNet CNNs; dimensionality reduction using NCA; final classification using SVM.	Hybrid CWT–CNN–SVM structure improved accuracy and robustness under PV fluctuation, outperforming conventional signal-processing approaches.
[25]	To enhance PQD classification by optimizing feature selection.	Applied Particle Swarm Optimization (PSO) to select optimal features and tune classifier parameters.	PSO reduced dimensionality and improved classification speed and accuracy compared to traditional selection methods.
[26]	To evaluate swarm intelligence for PQ enhancement in microgrids.	Reviewed ACO, ABC, GWO, and WOA for voltage stability, filter tuning, and microgrid control.	Swarm intelligence techniques demonstrated strong adaptability and scalability, making them suitable for renewable-dominant microgrid environments.
[27]	To investigate metaheuristic feature selection for robust PQD classification.	Implemented PSO, GWO, and DE to reduce feature sets and enhance classifier generalization.	Metaheuristic selection outperformed statistical methods, especially under noise and overlapping disturbances.
[28]	To detect cyber-attacks that mimic PQDs in smart grids.	Developed a deep neural network optimized using swarm intelligence to classify cyber-induced and natural disturbances.	Hybrid deep learning–metaheuristic models improved cyber-intrusion detection accuracy and adaptability to evolving attack strategies.
[29]	To optimize DG placement for PQ improvement and system reliability.	Applied PSO, GA, and DE to solve multiobjective DG planning problems.	Optimization-based DG integration enhanced PQ indices, reduced losses, and improved voltage stability compared to traditional planning methods.
[30]	To optimize PQD mitigation devices in smart grids.	Introduced Levy-flight-enhanced Moth Flame Optimization (MFO) for DVR tuning.	Improved global search capability led to superior compensator performance and more effective PQ disturbance mitigation.

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3 Discussion

The synthesis of the reviewed literature reveals that research on power quality disturbances (PQDs) has progressed toward increasingly sophisticated, adaptive, and integrated analytical frameworks. This evolution reflects growing system complexity driven by renewable energy penetration, widespread deployment of power-electronic devices, and the emergence of cyber-physical vulnerabilities. As a result, PQD research has shifted decisively from traditional deterministic techniques toward hybrid, optimization-driven, and data-intensive approaches that offer improved accuracy, scalability, and resilience under real-world operating conditions. Rather than treating PQD analysis as an isolated signal processing problem, contemporary work increasingly views it as part of a broader ecosystem that includes system planning, operational control, cybersecurity, and regulatory constraints. A central theme emerging from recent studies is the dominance of hybrid methodologies that combine advanced signal processing techniques, machine learning models, and metaheuristic optimization. Approaches such as the integration of Stockwell transform features with kernel extreme learning machines optimized through Grey Wolf Optimization have demonstrated superior performance in highly nonstationary environments, underscoring the advantage of integrating multiple analytical layers [11]. Likewise, in renewable-integrated networks, hybrid frameworks that merge continuous wavelet transforms with convolutional neural networks (CNNs) have shown strong classification capabilities despite the variability introduced by photovoltaic (PV) generation [24]. These developments highlight that hybridization enables stronger generalization by exploiting complementary strengths across domains: signal transforms provide rich time–frequency representations, deep architectures offer powerful nonlinear mapping capabilities, and optimization algorithms ensure that model parameters and feature subsets are tuned for maximal performance. This hybridization trend also reflects a methodological maturation within PQD research. Earlier generations of work often sought the "best" single method—for instance, a particular transform or classifier—whereas recent studies accept that no single analytical tool can adequately address the diversity of disturbance types, operating conditions, and noise environments encountered in practice. Instead, hybrid methods allow researchers to design layered processing pipelines in which each component addresses a specific aspect of the problem: noise reduction, feature extraction, dimensionality reduction, classification, and decision fusion. As demonstrated in [18, 24], such pipelines can be tailored to specific application contexts (e.g., PV-integrated feeders, microgrids, or industrial plants), thereby enhancing both accuracy and robustness. The literature also affirms the central role of metaheuristic techniques in enhancing the performance and efficiency of PQD detection and classification systems. Algorithms such as Particle Swarm Optimization (PSO), Grey Wolf Optimization (GWO), Whale Optimization Algorithm (WOA), and Differential Evolution (DE) provide effective solutions to high-dimensional optimization problems characteristic of PQ analysis. Their ability to cope with nonlinear, multimodal, and constrained search spaces is particularly valuable when optimizing classifier parameters, selecting features, or tuning filters and compensators. Early applications demonstrated that PSO-based feature selection significantly reduced dimensionality while improving classification accuracy and computational efficiency [25]. More recent findings confirm that metaheuristic feature selection consistently outperforms traditional approaches, particularly when disturbances overlap or signals are corrupted by noise [27]. These results emphasize that metaheuristics have become foundational rather than supplementary tools in PQD research, providing a unifying framework for tackling diverse optimization problems that arise throughout the analysis and mitigation chain. Furthermore, the widespread adoption of metaheuristics in PQD research reflects a shift in how optimization is conceptualized within power systems. Rather than relying solely on gradient-based or convex optimization techniques, which often require simplifying assumptions about system linearity and convexity, metaheuristics enable direct engagement with realistic, high-fidelity models. This allows researchers to incorporate practical constraints such as discrete device placement, nonlinear control characteristics, and multiobjective trade-offs between PQ, cost, and reliability [23, 29]. The success of metaheuristic-based frameworks in applications ranging from DG sizing to compensator tuning suggests that optimization is now viewed as an integral design principle in PQD solutions, influencing both algorithm development and system engineering. The expansion of renewable energy resources has further intensified PQD challenges, particularly due to the stochastic and nonlinear behavior of solar PV and other inverter-based resources. Hybrid deep learning approaches have shown promise in addressing the resulting signal complexity, but they also introduce dependencies on large datasets and computational resources. While studies have demonstrated that deep architectures can achieve high accuracy under fluctuating solar conditions [24], the literature indicates a persistent need for lightweight and real-time-capable models that can operate within distributed grid monitoring environments. Edge computing, model compression, and hardware-aware design are emerging themes that will likely shape the next generation of PQD frameworks. Without careful attention to computational constraints, there is a risk that even highly accurate models will remain confined to offline analysis, limiting their impact on practical system operation. Another significant development is the growing intersection between PQD

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research and cybersecurity. The digitalization of power systems has exposed new vulnerabilities, enabling cyber-attacks that mimic or conceal PQDs. For example, false data injection can create artificial signatures of voltage sags or harmonics, while denial-of-service attacks can hinder the timely detection of genuine disturbances. Recent work combining deep neural networks with metaheuristic optimization has demonstrated the potential for detecting malicious intrusions within PQ data streams [22, 28]. These findings suggest that PQD research must now address threats originating not only from physical disturbances but also from adversarial cyber behavior. The challenge lies in designing models that can jointly analyze cyber and physical indicators, distinguish between natural and malicious patterns, and adapt to evolving attack strategies with limited prior knowledge. This requires a deeper integration between PQD analytics, anomaly detection, and cyber-defense frameworks. Optimization-based PQ enhancement strategies represent an additional dimension of current research, as metaheuristics are increasingly applied to system-level problems such as distributed generation (DG) placement, compensator tuning, and harmonic mitigation. Studies have shown that metaheuristic optimization outperforms classical methods in handling the nonlinear, constrained, and multiobjective nature of distribution system planning [23, 29]. These methods allow operators to trade off PQ indices, energy losses, economic cost, and environmental impacts in a unified decision-making framework. Likewise, Levy flight-enhanced Moth Flame Optimization has demonstrated improved compensator performance, illustrating how emerging algorithms continue to advance PQ mitigation capabilities in smart grids [30]. Such contributions highlight that PQD research is increasingly concerned not only with identifying and classifying disturbances but also with proactively shaping system design and operation to minimize their occurrence and impact. At a higher level, the reviewed literature collectively points to a gradual convergence between several historically distinct research strands: signal processing, optimization, machine learning, power system operation, and cybersecurity. Hybrid deep learning–metaheuristic models for PQD classification [11, 24], optimization-driven feature selection and filter design [25, 27], swarm-intelligence-based PQ enhancement in microgrids [26], and metaheuristic-optimized intrusion detection [22, 28] all suggest that future PQD research will be inherently interdisciplinary. This convergence is not merely methodological but also conceptual, reflecting a shift in how PQ is understood: from a static, waveform-focused metric to a dynamic, system-level attribute shaped by physical infrastructure, control policies, cyber interactions, and market mechanisms. Despite these advancements, several limitations and research gaps persist. A major gap concerns the lack of standardized, realistic PQD datasets that adequately represent the variability introduced by renewable integration and cyber-physical operational contexts. Current datasets often fail to capture real-world noise, overlapping disturbances, device malfunctions, and coordinated cyber-attacks, limiting the generalizability of proposed models. The few available benchmark datasets frequently focus on a limited set of disturbances or idealized conditions, which can lead to overfitting and unrealistic performance expectations. This underscores the need for community-wide efforts to develop open, diverse, and continuously updated PQD repositories that reflect evolving grid technologies and threat landscapes. Additionally, many hybrid deep learning–metaheuristic models impose high computational burdens that complicate real-time implementation. Optimization procedures such as PSO, GWO, or MFO can be computationally intensive when applied to large feature spaces or complex model architectures, particularly when run repeatedly for online adaptation. While offline optimization remains valuable for model design and parameter tuning, real-time and near-real-time applications require more efficient strategies, such as incremental learning, surrogate modeling, or reduced-order representations. The literature therefore points to a trade-off between model complexity and deployability: highly accurate but heavy models may not be practical for embedded or edge devices, whereas simpler models may underperform in highly variable environments. The literature also highlights the need for more adaptive cybersecurity frameworks capable of functioning with minimal labeled data. Most metaheuristic-optimized deep learning intrusion detection systems rely heavily on supervised learning with extensive labeled datasets [22,28]. In practice, however, cyber-attacks are rare, evolving, and often only partially observed, making it difficult to obtain representative training data. Developing semi-supervised, unsupervised, or self-supervised models that leverage metaheuristics for parameter tuning and feature selection is therefore a promising yet underexplored research direction. Such models would align more closely with the realities of smart grid operation, where unknown or zero-day attacks must be detected based on subtle deviations from normal behavior rather than predefined signatures. Finally, the integration of PQD management with economic, regulatory, and consumer-centered considerations remains insufficiently explored, despite its relevance to practical grid operation. Most existing studies optimize PQ-related metrics in isolation from market mechanisms, tariff structures, or demand response programs. However, PQ improvement measures such as installing compensators, reconfiguring feeders, or curtailing generation have direct economic implications for utilities, prosumers, and consumers. Future research needs to embed PQD analysis and mitigation within multi-layer frameworks that account for regulatory requirements, incentive schemes, and customer preferences. This would enable more holistic decision-making, where PQ is treated not merely as a technical constraint but also as an economic and policy variable. Overall, the reviewed studies indicate that

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the future of PQD research lies in the development of holistic, intelligent, and scalable frameworks that seamlessly integrate disturbance detection, classification, mitigation, and cybersecurity functions. Such frameworks should be capable of operating in real time, adapting to changing system conditions, and coordinating actions across multiple layers of the grid—from local controllers and microgrids to transmission-level operators and market platforms. Addressing existing research gaps in data availability, computational efficiency, cybersecurity adaptability, and socio-economic integration will be essential for achieving fully adaptive and resilient smart grid systems capable of maintaining power quality under increasingly dynamic and uncertain conditions. In this context, metaheuristic optimization, hybrid learning architectures, and cyber-physical co-design principles are expected to remain central pillars of PQD research in the coming years.

4 Conclusion and Future Work

The examination of contemporary research on power quality disturbances (PQDs) reveals a field undergoing rapid expansion and methodological transformation. As modern electrical systems shift toward higher penetration of renewable energy resources, increased reliance on power-electronic interfaces, and deeper integration of cyber-physical control architectures, traditional PQD analysis methods have become insufficient for addressing the complexity and variability of emerging disturbance patterns. The literature demonstrates a clear transition toward hybrid analytical frameworks that combine advanced signal processing, machine learning, and metaheuristic optimization. These integrated approaches consistently outperform conventional techniques, offering improved accuracy, adaptability, and robustness, particularly in environments characterized by nonstationarity, measurement noise, and overlapping disturbances. Metaheuristic optimization has emerged as a foundational tool for PQD classification, feature selection, and compensator or device optimization. Algorithms such as PSO, GWO, WOA, and DE play a central role in enhancing model generalization, reducing computational overhead, and improving the effectiveness of mitigation strategies. Furthermore, the development of hybrid deep learning models incorporating time–frequency representations such as continuous wavelet transforms highlights the growing importance of data-driven, high-resolution analytical techniques. Meanwhile, the rise of cyber-physical vulnerabilities in smart grids underscores an urgent need for PQD classification systems that can differentiate between naturally occurring disturbances and cyber-induced anomalies. Recent work integrating deep learning and metaheuristic algorithms into intrusion detection frameworks signals a promising direction for ensuring the security and resilience of future power networks. Despite these advancements, several persistent gaps remain. Many PQD classification models rely on synthetic or limited datasets that do not fully represent real-world operating conditions, reducing their generalizability. Additionally, computational complexity remains a significant obstacle for real-time deployment of hybrid methods, particularly in distributed or resource-limited environments. The challenge of designing intrusion detection systems capable of adapting to evolving cyber threats also remains insufficiently addressed. Finally, the integration of PQD management into broader economic, regulatory, and consumer-centric frameworks is still underexplored, even though such integration is essential for the widespread adoption of advanced PQD solutions. Future research should prioritize the development of standardized, comprehensive, and publicly accessible PQD datasets that reflect the complexities of renewable integration, cyber-physical interactions, and emerging grid architectures. Such datasets would allow for meaningful benchmarking and foster more reliable comparisons across different classification and optimization methods. Additionally, efforts should be directed toward reducing the computational burden of hybrid deep learning–metaheuristic models. Potential avenues include model compression, surrogate optimization, hardware-aware training, and the use of lightweight architectures tailored for deployment in edge devices or distributed monitoring systems. Further research is also needed to strengthen the intersection between PQD analysis and cybersecurity. Developing adaptive intrusion detection models capable of responding to evolving attack patterns, utilizing unsupervised or semi-supervised learning, and integrating physical-layer measurements with network-level data represent promising directions. Beyond detection and classification, future work should explore multiobjective optimization frameworks that jointly consider PQ improvement, system stability, cost efficiency, and regulatory compliance. This includes optimizing the placement of distributed generation, energy storage systems, and power quality enhancement devices under realistic operational constraints. Finally, as smart grids evolve toward autonomous and self-healing architectures, there is a growing need for closed-loop PQD management systems that incorporate real-time monitoring, intelligent decision-making, and automated corrective action. Integrating these capabilities into unified, scalable frameworks represents a significant and impactful direction for future research, with the potential to substantially enhance the resilience, efficiency, and sustainability of next-generation power systems.

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