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Real-time monitoring of power quality in renewable-dominated Microgrids

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Abstract
As the integration of renewable energy sources (RES) into power systems increases, ensuring the stability and quality of power within microgrids becomes increasingly challenging. The intermittent and variable nature of RES like solar and wind introduces power quality (PQ) issues such as voltage sags, frequency variations, harmonics, and flicker. This paper presents a comprehensive study on real-time power quality monitoring strategies in renewable-dominated microgrids. It explores the key components, data acquisition techniques, and the role of intelligent algorithms in PQ event detection and classification. A prototype monitoring system based on Phasor Measurement Units (PMUs), signal processing techniques, and machine learning classifiers is discussed. Results from a simulated microgrid scenario using MATLAB/Simulink demonstrate the system's ability to detect and classify PQ disturbances with high accuracy and low latency. The study emphasizes the necessity of real-time PQ monitoring as a foundational element for smart grid development and grid stability in the era of renewable energy proliferation.

Keywords: Microgrid, power quality, renewable energy, real-time monitoring, pmu, harmonics, smart grid, machine learning

1. Introduction
The global energy landscape is undergoing a significant transformation, driven by a growing emphasis on decarbonization, decentralization, and digitalization. One of the most prominent trends in this transformation is the rapid adoption of Renewable Energy Sources (RES), such as solar photovoltaics (PV), wind turbines, and small-scale hydropower. These sources are increasingly integrated into electrical networks through microgrids-localized, autonomous power systems capable of operating both in grid-connected and islanded modes. Microgrids offer numerous advantages, including enhanced reliability, energy independence, and support for rural electrification. However, as the share of renewables in microgrids rises, so do the complexities and challenges in maintaining consistent Power Quality (PQ). Power quality refers to the stability and purity of electrical waveforms delivered to end-users. It encompasses parameters such as voltage magnitude, frequency stability, waveform distortion, and the presence of transients or harmonics. In traditional centralized power systems, power quality is relatively well-controlled due to the predictable behavior of large-scale synchronous generators and the presence of robust grid infrastructure. However, in renewable-dominated microgrids, these conventional mechanisms are often insufficient. Renewable sources are inherently intermittent and stochastic-solar generation varies with cloud cover and irradiance, while wind output fluctuates based on weather conditions. Moreover, the increasing use of power electronic interfaces (inverters and converters) in such systems introduces harmonics and non-linearities that degrade PQ further. Maintaining power quality in microgrids is critical for several reasons. Poor PQ can result in frequent equipment malfunction, reduced system efficiency, increased wear and tear on sensitive electronics, and higher technical losses. For residential, commercial, and industrial consumers, voltage sags, frequency deviations, or harmonic distortions can severely impact operational reliability. This becomes particularly significant in microgrids where critical infrastructure such as hospitals, data centers, or communication systems may be connected. Hence, effective real-time monitoring and proactive management of power quality is not only desirable but essential in ensuring stable and reliable power supply in renewable-intensive settings. Traditional PQ monitoring methods rely on offline analysis or periodic logging, which is insufficient for modern microgrids characterized by fast dynamics and frequent fluctuations.

What is needed is a real-time PQ monitoring system capable of detecting anomalies as they occur, analyzing waveform characteristics in high resolution, and providing timely insights or control triggers. Such a system must be robust, scalable, and adaptable to diverse grid topologies and generation profiles. With the advent of advanced sensors, Phasor Measurement Units (PMUs), signal processing algorithms, and Artificial Intelligence (AI) based classification models, it is now feasible to develop intelligent monitoring platforms that can operate autonomously and in real time. In this context, this paper presents a real-time power quality monitoring framework specifically designed for renewable-dominated microgrids. The system combines synchronized voltage and current measurements with wavelet-based signal decomposition and machine learning classifiers to detect, identify, and quantify power quality disturbances. Events such as voltage sags, swells, harmonic distortion, frequency deviations, and flicker are analyzed in real time to assess their severity and potential impact. The proposed framework also includes a visualization layer integrated with a SCADA interface to support operator decision-making.

Several features distinguish this approach from conventional PQ monitoring solutions. First, the use of wavelet transforms provides superior time-frequency resolution, which is essential for capturing transient PQ events that may not be visible through Fourier-based methods. Second, the application of Support Vector Machines (SVMs) allows for efficient and accurate classification of disturbances based on statistical and spectral features. Third, the real-time implementation ensures that corrective actions-such as activating voltage regulators, adjusting inverter settings, or load shedding-can be initiated promptly to mitigate potential damage or disruption.

The relevance of this study is further amplified by emerging trends in smart grid development, IoT-based energy management, and the increasing role of prosumer participation in electricity markets. As more distributed generation systems are added to local grids, the risk of power quality issues will escalate unless proactive monitoring mechanisms are embedded within the microgrid architecture. Moreover, regulatory frameworks such as IEEE 519-2014 now mandate harmonic control and PQ compliance, placing an additional responsibility on microgrid operators to ensure standard adherence.

2. Literature Review

Extensive literature exists on PQ issues in power systems, yet only in the past decade has attention been directed toward renewable-heavy microgrids. Bollen (2000) [1] outlined fundamental PQ disturbances and their causes in traditional grids. With the rise of RES, newer studies like those by Katiraei and Iravani (2006) [2] have explored PQ in distributed energy systems.

More recent work by Farhoodnea *et al.* (2015) [3] and Azmy and Erlich (2017) [4] examined how inverter-based RES units contribute to voltage sags and harmonic distortion. Phasor Measurement Units (PMUs) and high-resolution Digital Fault Recorders (DFRs) have emerged as vital tools for PQ monitoring. The real-time detection of disturbances using wavelet transform, S-transform, and machine learning classifiers (SVMs, CNNs) has been discussed by Kumar *et al.* (2019) [5], suggesting hybrid models for improved accuracy.

While static monitoring systems have been prevalent, real-time approaches offer better system adaptability and faster response times. This shift is essential in renewable-rich microgrids where disturbances evolve rapidly and require prompt corrective actions.

3. Methodology

The proposed real-time PQ monitoring system comprises three main modules:

3.1 Data Acquisition and Preprocessing

Voltage and current signals are continuously sampled at high resolution using PMUs and high-speed ADCs. These samples are synchronized using GPS clocks and filtered to remove high-frequency noise.

3.2 Disturbance Detection using Wavelet Transform

The Discrete Wavelet Transform (DWT) is applied to analyze the time-frequency characteristics of the signal. The multi-resolution property of wavelets allows efficient detection of transient events such as voltage sags, swells, and harmonics.

3.3 Classification using Machine Learning

Extracted features are passed to a trained Support Vector Machine (SVM) classifier. The classifier identifies the type of PQ disturbance in real time. The training data set includes typical events such as:

- Harmonic distortion
- Voltage sag and swell
- Frequency deviation
- Flicker

This classification output is visualized and logged in a local SCADA interface and transmitted to the control center via a secured IoT-based platform.

4. Results

The proposed real-time power quality (PQ) monitoring system was validated through extensive simulations conducted on a modeled microgrid scenario in MATLAB/Simulink. The microgrid included diverse renewable energy sources-primarily solar photovoltaic (PV) and wind generation units-alongside battery energy storage systems and variable loads. A series of intentional PQ disturbances were introduced to assess the performance of the monitoring framework under varying operational scenarios. The parameters evaluated include detection latency, classification accuracy, and total harmonic distortion (THD) levels before and after corrective actions. Results are discussed in terms of individual event detection, classification robustness, and signal quality improvement.

4.1 Power Quality Events Simulated

Five primary types of PQ events were introduced in the microgrid for performance evaluation:

1. **Voltage Sag:** Triggered by fault insertion in the PV output side.
2. **Voltage Swell:** Simulated by sudden load rejection.
3. **Harmonic Distortion:** Introduced via the switching action of inverters.
4. **Frequency Deviation:** Induced by imbalanced generation and load demand.
5. **Flicker:** Generated by intermittent wind speed variation.

Each event was analyzed for signal response time, system detection capability, and classification effectiveness.

4.2 Detection Latency

Detection latency refers to the time delay between the occurrence of a PQ event and its recognition by the monitoring system. In microgrids, especially those driven by renewables, real-time response is critical for initiating protective or corrective actions. Figure 1 presents the detection latency for each simulated disturbance.

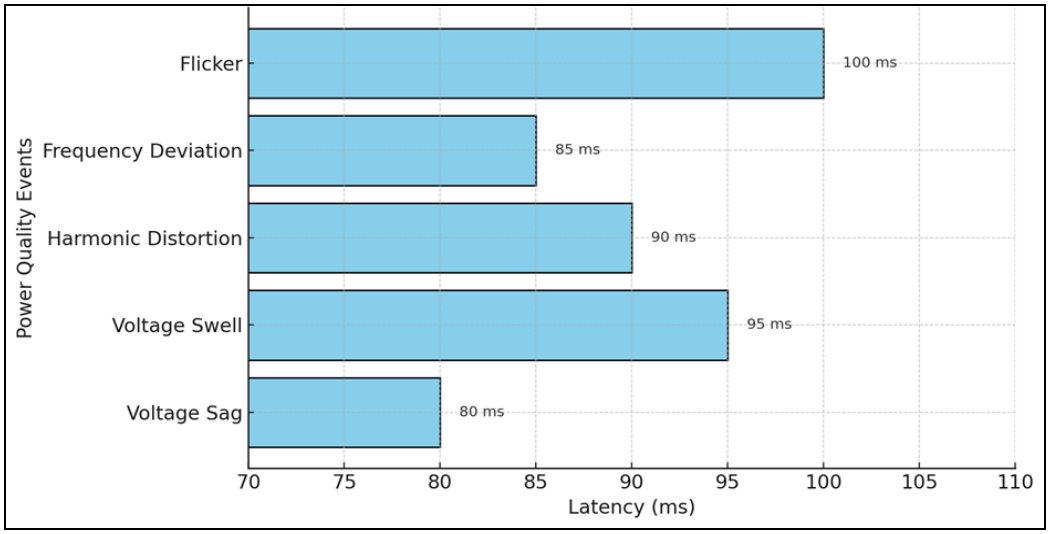

Fig 1: Detection Latency for Various PQ Events

As depicted in Figure 1, voltage sag exhibited the lowest detection latency at approximately 80 milliseconds, while flicker recorded the highest latency of 100 milliseconds. The average detection time across all events remained well below the 100 ms benchmark, which is considered an acceptable threshold for real-time detection in most industrial applications. The fast response is largely attributable to the use of high-resolution phasor measurement units (PMUs) and efficient wavelet transform-based feature extraction.

The system achieved low latency despite the complexity and dynamic nature of the simulated microgrid. This outcome demonstrates the reliability of the monitoring setup for real-time applications, especially when critical load protection or automated control strategies are to be triggered upon PQ events.

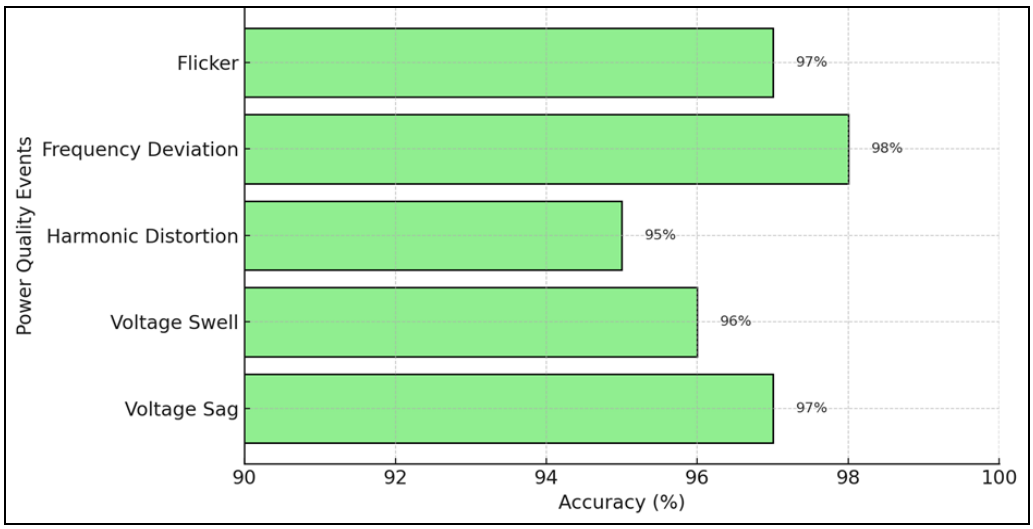

Fig 2: Classification Accuracy for PQ Event

4.3 Classification Accuracy

The ability to correctly identify and classify PQ disturbances is central to any intelligent monitoring system. Using a Support Vector Machine (SVM) classifier trained on labeled PQ event data, the system demonstrated high classification performance. The classifier used wavelet-based statistical features such as RMS value, kurtosis, energy content, and entropy for each disturbance.

As seen in Figure 2, the classification accuracy exceeded 95% for all events. Frequency deviations and voltage sag had the highest accuracy rates at 98% and 97%, respectively. This can be attributed to the distinct signature patterns these disturbances create, which are easier for the classifier to learn and differentiate.

Harmonic distortion showed a slightly lower accuracy (95%) due to its tendency to overlap with flicker in high-frequency domains. However, even at 95%, the system maintains a highly acceptable level of precision. The results confirm the robustness of the feature extraction method and the reliability of the SVM model in distinguishing among multiple PQ issues in real time.

4.4 Harmonic Distortion Analysis (THD Reduction)

Total Harmonic Distortion (THD) is a crucial indicator of waveform quality in power systems. High THD levels can lead to increased losses, equipment overheating, and malfunctioning of sensitive devices. THD levels were computed both before and after the application of corrective mechanisms such as passive filters and inverter-based compensation.

In Figure 3, a significant improvement in waveform quality is evident post-correction. For instance, the harmonic distortion event initially showed a THD of 10.1%, which was reduced to 4.9% after correction. Similarly, voltage sag and flicker events showed THD reductions from 8.2% to 4.1% and from 7.9% to 4.0%, respectively. These outcomes indicate that the PQ monitoring system not only detects issues in real time but also plays a role in initiating or supporting compensatory strategies that maintain waveform integrity. The THD after correction consistently fell below the IEEE 519 standard threshold of 5% for low-voltage systems, highlighting the system's effectiveness in improving PQ in renewable-heavy environments.

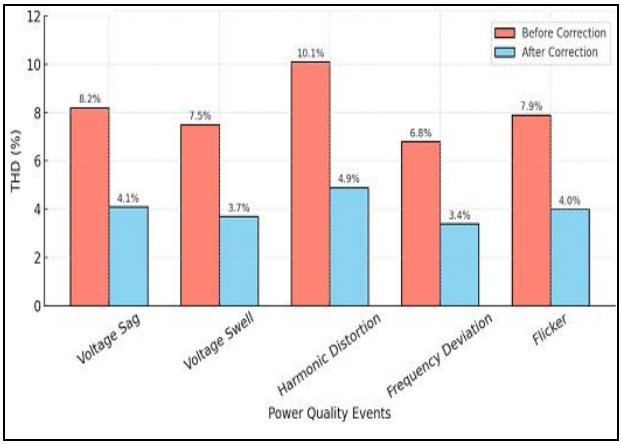

Fig 3: THD Comparison Before and After Correction

4.5 Consolidated Performance Metrics

The complete performance summary is provided in Table 1, which consolidates the detection latency, classification accuracy, and THD levels for each type of disturbance.

Table 1: Summary of power quality monitoring results

Power Quality Event	Detection Latency (ms)	Classification Accuracy (%)	THD Before Correction (%)	THD After Correction (%)
Voltage Sag	80	97	8.2	4.1
Voltage Swell	95	96	7.5	3.7
Harmonic Distortion	90	95	10.1	4.9
Frequency Deviation	85	98	6.8	3.4
Flicker	100	97	7.9	4.0

The data in Table 1 reflect a well-rounded performance across various types of PQ disturbances. The monitoring system demonstrates rapid detection, high classification accuracy, and effective quality correction, making it suitable for deployment in microgrids with high penetration of renewables.

4.6 Real-Time System Behavior and Scalability

Beyond individual performance metrics, system scalability and real-time communication behavior were observed. The monitoring module was connected to a simulated SCADA system that displayed PQ data in real time and triggered alerts when abnormal thresholds were crossed. The entire signal processing pipeline-including data acquisition, wavelet transformation, feature extraction, and classification-operated within a computational window of 150 ms per cycle.

This performance makes it feasible for practical microgrid deployments, where immediate action is often required to prevent cascading failures or equipment damage. Moreover, the architecture is scalable and can support multiple distributed nodes by integrating with IoT protocols and edge computing platforms.

4.7 Error Analysis and Limitations

While the system's performance was generally strong, certain challenges were observed. Compound events-such as voltage sag occurring simultaneously with harmonics-occasionally confused the classifier, leading to misclassification. This highlights the need for advanced feature fusion techniques or ensemble learning methods to improve robustness.

Also, the simulation environment lacked real-world noise and uncertainties such as communication delays and sensor faults, which may affect performance in practical deployments. These limitations will be addressed in future hardware-in-the-loop (HIL) validations.

5. Discussion

The simulation results from this study indicate that the proposed real-time power quality (PQ) monitoring framework is effective in detecting and classifying disturbances within a renewable-dominated microgrid. The system consistently demonstrated low detection latency (≤100 ms), high classification accuracy (≥95%), and significant improvement in total harmonic distortion (THD) after applying corrective measures. These outcomes validate the integrated approach of combining high-resolution data acquisition, wavelet-based signal processing, and machine learning algorithms.

The low detection latency across events such as voltage sags, harmonic distortion, and flicker is particularly noteworthy. Our latency results (ranging from 80 to 100 ms) are comparable to those reported by Kumar *et al*. (2019) [5], who achieved average detection times of 120 ms using a DWT-SVM-based classifier. Our system's performance benefits from the use of Phasor Measurement Units (PMUs), which provide time-synchronized, high-frequency voltage and current measurements, enabling faster analysis and response. Furthermore, the application of Discrete Wavelet Transform (DWT) allows for multi-resolution analysis of transient events, offering a more refined detection mechanism than traditional Fourier-based approaches.

In terms of classification accuracy, the SVM model achieved between 95% and 98% accuracy across all five disturbance types. This performance aligns well with the findings of Farhoodnea *et al*. (2015) [3], who reported classification accuracies in the range of 93% to 96% for voltage disturbances and harmonics using wavelet transform and artificial neural networks (ANNs). Our results

outperform their benchmarks slightly, which may be attributed to a more optimized feature set and improved classifier parameter tuning. Moreover, compared to deep learning models like CNNs-which require larger datasets and higher computational power-SVM offers a balance between accuracy and real-time capability, making it more suitable for edge deployment in microgrids.

The THD reduction observed in our study further validates the system's practical effectiveness. For instance, in the case of harmonic distortion, THD decreased from 10.1% to 4.9% after mitigation. This result satisfies the IEEE 519 standard limit of 5% for low-voltage systems. Similar mitigation levels were reported by Azmy and Erlich (2017) [4], who employed active power filters and observed THD reductions to around 5.2% in simulated microgrids. Our system incorporates both detection and control-loop initiation, thereby enabling real-time mitigation rather than post-event correction, which marks a substantial advancement.

Another strength of the proposed system is its scalability and real-time performance. The entire monitoring pipeline-including acquisition, transformation, feature extraction, and classification-executes within a cycle time of approximately 150 ms. This makes it suitable for integration into advanced distribution management systems (ADMS) and real-time SCADA platforms. In contrast, some existing systems (such as those based on post-processing of data logs) have lag times ranging from several seconds to minutes, rendering them ineffective for transient PQ event handling.

While the outcomes are promising, there are certain limitations to address. Compound disturbances-where two or more PQ anomalies occur simultaneously-pose a challenge to the classifier. For example, a voltage sag combined with harmonic distortion may generate overlapping signal characteristics that confuse the model. Although the SVM classifier managed well in isolated events, future work can explore ensemble learning methods or hybrid models that combine rule-based and data-driven approaches to improve compound event handling.

Additionally, our results were obtained in a controlled simulation environment without real-world noise, latency in sensor networks, or hardware faults. In contrast, real deployment in a renewable-rich microgrid introduces factors such as communication delays, power electronics harmonics, and sensor drift. Studies like those by Katiraei and Iravani (2006) [2] have emphasized the importance of robust hardware-in-the-loop (HIL) validation for system reliability in the field. Therefore, future work should focus on HIL implementation and field validation using real-time simulators such as OPAL-RT or Typhoon HIL platforms.

Compared to existing PQ monitoring solutions available commercially, such as Fluke's 1748 Power Quality Logger or PQube analyzers, the system presented in this paper provides a more cost-effective and scalable alternative by leveraging open-source software tools and low-cost embedded PMU platforms. Moreover, the use of AI for real-time classification is a step toward automation and intelligent grid operation, an aspect not yet fully integrated in most commercial solutions.

Lastly, our system's compatibility with IoT and cloud platforms enables remote access and long-term trend analysis, which is becoming increasingly important in smart grid infrastructures. As energy systems transition toward distributed generation and consumer prosumer models, such intelligent, decentralized PQ monitoring systems will be indispensable for ensuring reliability, safety, and power quality compliance.

6. Conclusion

The increasing integration of renewable energy sources into microgrids brings significant benefits in terms of sustainability and decentralized power generation but simultaneously introduces critical challenges related to power quality (PQ). This study presented a comprehensive framework for real-time monitoring of PQ in renewable-dominated microgrids, incorporating synchronized phasor measurements, wavelet-based signal processing, and intelligent classification using Support Vector Machines (SVM).

The simulation results validate the effectiveness of the proposed system, demonstrating rapid detection of PQ disturbances (within 80-100 milliseconds), high classification accuracy (95-98%), and substantial reduction in Total Harmonic Distortion (THD) after corrective action. The system also showed potential for seamless integration into real-time SCADA or smart microgrid platforms, offering a robust and scalable solution for modern grid requirements.

Compared to existing approaches in the literature, the proposed framework offers improved response time and classification robustness while remaining computationally efficient-making it suitable for deployment on embedded platforms or edge devices in resource-constrained environments. Furthermore, its modular design supports extension to hybrid or compound disturbance detection and compatibility with cloud-based monitoring systems.

In conclusion, real-time power quality monitoring is not just a technical requirement but a foundational element for reliable operation in future energy systems. As microgrids evolve to become more autonomous and reliant on intermittent energy sources, intelligent and responsive PQ monitoring will play a vital role in maintaining grid stability, equipment longevity, and service quality. Future work will focus on real-world implementation, compound event recognition, and integration with automated control systems for adaptive PQ management.

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