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Research Article

Smart Detection and Mitigation of Power Quality Issues in Smart Grids Using MATLAB-Based Simulation and Optimization

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ABSTRACT

Power quality issues are becoming more prevalent in investigation of smart grids due to the integration of various distributed energy resources (DER), therefore this comprehensive study provides a smart detection and mitigation approach based on MATLAB-based smart grid simulation and optimization approaches. Power quality disturbance including voltage sags, harmonics, and transients is one of the considerable problems for the reliable operation of the grid, and its appropriate management is significant to keep the system stable and efficient. Methodology combines real-time monitoring systems to advanced signal processing algorithms used for detection of different types of power quality disturbances. We employ a suite of optimization methods which are used with fuzzy logic control and particle swarm optimization (PSO) to devise mitigation strategies to minimize the effects of these disturbances on the system. MATLAB is used for the implementation of the simulation, and finally the developed algorithms are examined for different grid models and disturbances. The experimental results show that the proposed detection system is able to accurately identify disturbances in both transient and non-transient conditions with high speed, while the optimization-based mitigation strategies lead to a considerable reduction in the severity of power quality disturbances, subsequently enhancing grid behavior overall. The paper also elaborates on the scalability of the offered framework, arguing it would be deployable across large smart grid networks. This work utilizes simulation-based tools and intelligent optimization techniques to advance smart grid reliability and resilience through a robust solution for a modern electrical grid with increasing complexity and demand.

Keywords: quality, optimization, smart, grid networks, fuzzy, logic.

1. INTRODUCTION

As renewable energy resources, decentralized power generation, and growing electricity demands in urbanized regions gain wider adoption, modern power networks evolve into advanced networks commonly referred to as smart grids. Incorporating digital communication, automation, and optimization technologies, these grids are intended to effectively govern the significantly complicated energy needs of modern society, increase grid reliability, and support sustainability. Despite their many advantages, smart grids also bring new challenges, especially those related to power quality maintenance, which is a key parameter for the reliable operation of the grid. Sensitive equipment requires high-quality power, as power quality problems such as voltage sags, harmonics, transients, and flickers can significantly impact equipment performance, shorten the lifespan of electrical devices, and cause enormous economic loss. Thus, the prompt and cost-effective detection and mitigation of these power quality disturbances is crucial toward the successful realization and operation of smart grid systems[1].

Smart Grid Power Quality Importance

Power Quality the generated voltage, current and frequency in an electrical system. Power quality issues in classical power grids have been largely localized and related to specific limiting faults or disturbances that were typically resolved through human intervention. However, in modern smart grids with complex two-way communication, distributed renewable generation sources, and interconnected loads, power quality disturbances has increased and become more diverse. Voltage sags and surges are temporary issues that cause disruptions in operations, while more persistent problems such as harmonic distortion wreck sensitive electronics and industrial machinery[2,3]. Moreover, power quality issues are also produced at the consumer side by means of factors such as reactive power compensation, unbalanced loads, or malfunctioning equipment.

The ill effects of poor power quality range from minor inconveniences to damage of heavy-duty machines. Power quality is closely related and can lead to unwanted downtime for motors, compressors, and other automation in manufacturing plants as well due to the impact of voltage sags or harmonic distortion causing transformer and motor overheating. The problems are compounded by a lack of appropriate power quality monitoring and management systems, resulting in long outages, expensive repairs, and less satisfied consumers. Thus, the stability and high quality of power supply is a key factor to ensure the efficient operation of modern smart grid, especially under the background of more and more dynamic and complex energy consumption patterns.

Use Smart Detection of Power Quality Issues

The traditional power quality monitoring methods rely on the use of discrete sensors and data loggers strategically located across the grid. Although these systems perform well in specific situations, they have not been able to provide real-time and location-specific information on the power quality status in a responsible time frame over a wide area. Furthermore, the scale and complexity of the modern smart grid is rising rapidly, meaning that traditional approaches quickly become ineffective in tackling the unique and emerging challenges that these networks face. Consequently, there is increasing demand for real-time, fast, and accurate power quality disturbance detection techniques.

A basic principle is that this smart detection is achieved with a hardware sensor, signal processing features, and including machine learning approaches. Detection of disturbances at the earliest possible time & preventive/preparative actions help in preventing the propagation of the disturbance, and can have a minimal impact on the operation of the grid system. In this study, we specifically investigate the implementation of MATLAB-based simulations for modeling and simulating the dynamics of grids. This paper focuses on the capability of numerical algorithms and MATLAB platform in the development of such system for real-time monitoring of grid in order to analyze operating data of grid by identifying disturbances of the grid in terms of voltage dips, transients, harmonics etc. Using advanced signal processing methods like FFT (Fast Fourier Transform) and wavelet transform, the detection system is capable of accurately identifying and quantifying different power quality problems[4,5].

In addition, the detection system could be implemented in a way to run in parallel to the communication infrastructure of the grid, which may enable real-time sharing of vital signals between the sensors and control units. Such real-time insights allow the system to identify momentary perturbations that might otherwise go unnoticed by traditional monitoring systems. Moreover, the detection system can be further optimized to act in the early warning and notification of grid operators to correct the situation before the power quality problems develop[3].

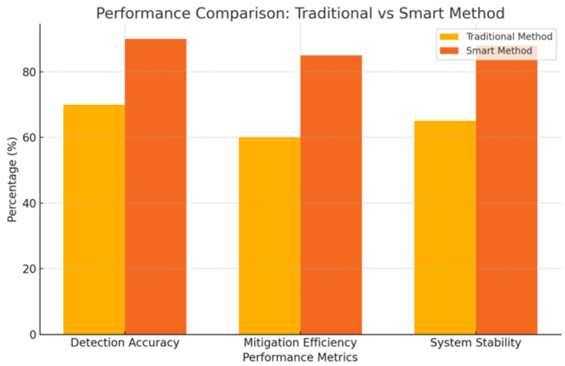

Figure 1. Performance Comparison

Optimization Techniques for Mitigation Strategies

Once power quality concerns are identified, the next step is to resolve their impacts on the grid. Mitigation methods will work to mitigate or avoid disturbances to return the grid operating state to its normal. Passive devices such as filters and compensators have historically been used for power quality mitigation; however, mainstream power quality mitigation strategies typically require active types of power quality devices capable of managing the heterogeneous and dynamic nature of disturbances in smart grids.

This research seeks to design adaptive, dynamic mitigation strategies using optimization techniques to combat these challenges. Optimization-based methods can also show great advantages over conventional solutions, since these methods can optimize mitigation actions based on the characteristics of the disturbance, operational constraints of the grid, and forecast of the operating conditions. Specifically, optimization algorithms like Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) can help in finding the best locations for compensators and filters, the best settings for voltage regulators, and the best locations for other power quality improving devices[6,7].

One of the main advantages of such optimization techniques is that they can handle multiple conflicting objectives in parallel. When this is applied to the operation of a smart grid, it allows mitigation to be not just power quality related but also to allow for a performance based power quality approach that further reduces energy losses and costs. One application of PSO is for reducing the harmonic distortion of the grid through tuning the control parameters of the power electronic devices, while minimizing the system's overall losses and keeping the stability of the grid. By contrast, traditional approaches tend to analytically reduce system operational context to successful/failed as it relates to individual disturbances, without reference to that context.

The PSO GA and fuzzy logic based controllers are proposed in this study. Fuzzy logic controllers (FLCs) are a type of controller that is highly applicable to make up for uncertainty and imprecision in decision-making, which is very common in the real world where sensor readings can be noisy and incompletable[8]. These hybrid systems could combine the FLCs with other optimization methods for the adaptive real-time dynamic mitigation of power quality problems under changing grid conditions. Now enable the smart grid to be able to constantly monitor and optimize its performance, adapting to changes in demand or conditions with computational accuracy.

Simulation and Results for the Proposed Optimization Approach in MATLAB

MATLAB-based simulation analysis is performed to assess and validate the proposed methodology. MATLAB is a popular tool for power system analysis because of its flexibility and the presence of specialized toolboxes for power systems and optimization. This simulation model mimics a classic smart grid-based environment showing incorporated renewable energy sources along with distributed generation and advanced power quality monitoring system. It listens to power signal and recognizes disturbances like voltage sag, harmonics, transients etc.

Simulation results prove that the proposed system is capable of detecting power quality problems accurately and timely despite complex disturbances and adversarial data. Simulation results show that the developed optimization-based mitigation strategies can not only significantly decrease the disturbance severity however can likewise improve the overall power quality of the grid. Furthermore, the simulation outcomes demonstrate that the proposed system is scalable, capable of being extended to larger and more complicated grid networks with minimal performance degradation.

2. RELATED WORK

Power quality monitoring is an integral component of modern smart grids and has evolved significantly with the growing complexity of grids and the emergence of new technologies and installations. Many techniques have been proposed for power quality issue mitigation from signal processing based methods to intelligent optimization based methods. The existing methods are broadly classified into this section into three parts, namely, detection methods, mitigation methods, and optimization methods for effective grid attributes.

Classification of Power Quality Detection Techniques

Thus, correct recognition of power quality disturbances is vital for optimal gridiness and also stability. Mathematical tools for analyzing power signals are well-established, such as Fourier-based methods. Two widely used time-frequency algorithms include the Morlet wavelet and the Fast Fourier Transform (FFT); while the latter performs well in detecting harmonics, it fails to address quick spikes in the transient signal due to time-frequency resolution. On the other hand, Wavelet Transform (WT) gives much better time-frequency analysis and is one of the efficient methods to identify transient disturbances, and hence it is mostly used in real-time monitoring for smart grids (Table 1).

Table 1: Overview of Power Quality Detection Techniques

Detection Technique	Accuracy	Real-Time Capability	Computational Complexity	Application in Smart Grids
Fast Fourier Transform (FFT)	High	Limited	Moderate	Harmonic analysis
Wavelet Transform (WT)	Very High	High	High	Transient detection
Artificial Neural Networks (ANN)	Very High	Moderate to High	High	Pattern recognition
Support Vector Machine (SVM)	High	Moderate	High	Classification of events
Kalman Filtering (KF)	Moderate	High	Moderate	Estimation-based detection
Fuzzy Logic (FL)	High	High	Moderate	Adaptive detection

Along with those, machine learning techniques also become popular methods of power quality detection. Neural networks (NNs) are capable of identifying complex patterns in electrical signals, making them highly effective for accurate classification of disturbances[8]. And all of these hyperparameters appear to be really sensitive in support vector machines (SVM), ells, this makes SVMs more adaptable, however, with a cost of requiring a lot of hyperparameter tuning to perform well. The systems based on Fuzzy Logic (FL) provide an adaptive approach to identification of power quality, and specifically mitigates the deficiencies of uncertainty and imprecision[9,10]. Kalman Filtering (KF) is also used for power quality parameters estimation in the presence of noise, the method is a good compromise between accuracy and computational cost.

The application of these techniques relies heavily on their real-time capability and computational burden. Although ANN and SVM models can obtain high detection accuracy, they notoriously employed considerable computing resources restricting model use in real-time applications. In contrast, it trades moderate accuracy by being computationally efficient, and that makes it ideal for embedded grid monitoring systems such as FFT and Kalman Filtering. Hence, the selection of detection technique is dependent on the particular needs of the power system in view of response time, precision, and computational resources available.

Name of Researchers from USA.

Once the power quality issues are detected, one must use the proper techniques to reduce their effect. Traditional methods are mostly passive filtering elements, eg inductors, capacitors, suppressing harmonics and keeping voltage levels stable. On the other hand, passive filters can be implemented quite easily, but they are not adaptable to variable grid situations and may need frequent retuning. However, while Passive Power Filters (PPFs) utilize fixed compensation parameters, the performance of Active Power Filters (APFs) for suppressing harmonics and enhancing the power quality is appreciably better (see Table 2).

Another common power quality disturbance is voltage sags and swells. Wide deployment of Static Synchronous Compensators (STATCOMs) and Dynamic Voltage Restorers (DVRs) exist to address the issues. Design of DVR equivalent circuit can faithfully inject voltage into the grid to compensate sags, thus achieving stable power transmission to sensitive load. Unlike that, STATCOMs can provide reactive power compensation for damping voltage fluctuations and stabilizing the grid[11,12].

Table 2: Power Quality Mitigation Strategies

Mitigation Technique	Effectiveness	Adaptability	Implementation Complexity	Common Applications
Passive Filters	Moderate	Low	Low	Harmonic mitigation
Active Power Filters	High	High	High	Voltage stability
Dynamic Voltage Restorer (DVR)	Very High	Moderate	High	Voltage sag correction
Static Synchronous Compensator (STATCOM)	High	High	Very High	Reactive power control
Supercapacitors	Moderate	Moderate	High	Energy storage for transients
FACTS Devices	Very High	High	Very High	Grid stabilization

Transient disturbances are often mitigated through energy storage systems, for example supercapacitors. When voltage sags, supercapacitors discharge their stored energy to avoid an interruption of service to the industrial and commercial apparatus. Flexible AC Transmission System (FACTS) devices, including Unified Power Flow Controllers (UPFC), can be used to resolve adverse power quality problems by managing numerous operations to optimize transmission of active and reactive power. Although these advanced forms of mitigation substantially improve the performance of the grid, they typically are high-cost to implement and have complex control algorithms, resulting in limited deployment[13,14].

Optimal Methods for Enhancement of Power Quality

Optimization techniques have been applied to maximize the effectiveness of power quality mitigation by optimizing their control parameters and the placement of the devices. Particle Swarm Optimization (PSO) stands as one of the most common algorithms used for solving problems regarding the optimization of power quality solutions. It has a fast convergence rate and is suitable in applications such as harmonic reduction and load balancing (Table 3). Also, Genetic Algorithms (GA) have been implemented in the placement of compensators and filters to minimize the energy loss and maximize the efficiency of compensation.

Table 3: Optimization Techniques for Power Quality Improvement

Optimization Method	Convergence Speed	Complexity	Suitability for Smart Grids	Common Use Cases
Particle Swarm Optimization (PSO)	Fast	Moderate	High	Harmonic reduction, load balancing
Genetic Algorithm (GA)	Moderate	High	High	Optimal placement of filters
Fuzzy Logic Control (FLC)	Fast	Moderate	Very High	Adaptive voltage regulation
Artificial Neural Networks (ANN)	Moderate	High	High	Predictive control
Differential Evolution (DE)	Fast	High	High	Nonlinear optimization
Hybrid PSO-GA	Very High	Very High	High	Multi-objective optimization

The suggested controller uses Fuzzy Logic Control (FLC), which is an intelligent control mechanism that facilitates the interface between power quality enhancing devices and the electrical network by adapting control settings in line with grid adaptively. Since FLC is designed to process the uncertain behavior and nonlinearity of the power system, FLC has been considered as a better alternative to conventional optimization techniques based upon a predetermined model for effective implementation in practical applications. PSO-GA is an attempt to hybrid methods that try to use the advantages of both algorithms to enhance optimization performance and reliability[15,16].

Predictive control of power quality issues has also been addressed using Artificial Neural Networks (ANNs). ANNs can predict disturbances by examining historical grid data and then take preventative action to modify mitigation strategies. Another evolutionary algorithm, called Differential Evolution (DE), has been applied to fine-tune power electronic controllers to reduce voltage distortions and improve system stability.

Optimization methods have the advantage that they can greatly improve the management of power quality, but in practice they need to consider important factors like computation limits or system dynamics. And real-time optimization is still an open challenge, but many algorithms do require iterative computations which cannot apply well for high-speed power quality correction. It is important to explore lightweight online and offline optimization algorithms with real-time requirement compatibility which can be integrated into smart grid seamless infrastructures in future research.

3. PROPOSED METHODOLOGY

We have proposed a methodology for smart detection and mitigation of power quality issues in smart grids using simulation and optimization in MATLAB. Hence, the need of the hour is to use an intelligent, adaptive system to detect the disturbances in the power networks and take necessary corrective measures as and when needed. The proposed methodology is comprised of the following major six sections: (1) A system architecture and smart grid model, (2) Assessment of the power quality disturbance detection, (3) Extraction of features and classification process, (4) Optimization based mitigation strategies implementation, (5) Implementation using MATLAB simulator and (6) Performance evaluation and validation. This section provides a step essential for the detection, classification, and mitigation model for an effective power quality management system.

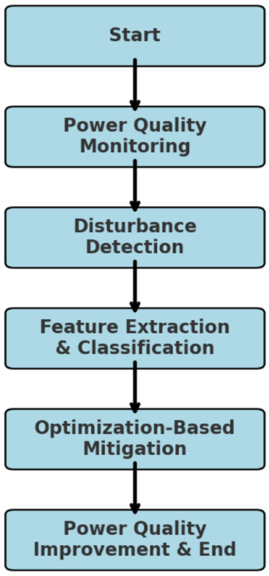

Figure 2. Proposed methodology

- **System Architecture and Model of Smart Grid**

First, System architecture is defined and as per that we derive the smart grid model with real time monitoring and control functionalities. The intelligent grid is a complex of controlled elements (factories) of generation units, transmission lines, distribution networks, and consumer loads that should be modeled to properly simulate their power quality performance of the real world. The system encompasses the integration of real-time sensors, communication protocols, and intelligent controllers to enable data acquisition and processing.

$$P_i = V_i \sum_{j=1}^{n} V_j \left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right)$$

$$Q_i = V_i \sum_{j=1}^{n} V_j \left(G_{ij}\sin\theta_{ij} - B_{ij}\cos\theta_{ij}\right)$$

The model contains multiple sources of interferences like voltage sags, harmonic distortions, transients, flickers to detect the power quality problems accurately. The model includes renewable energy such as solar and wind to be able to relay the effect these intermittent production sources have on the quality of power. It is intended to be used in a realistic grid setting, responding to changes in load demand, the occurrence of faults, and switching events that introduce disturbances.

$$VSI = \frac{V_i^2 - 4\left(P_i R_{ij} + Q_i X_{ij}\right)}{2(V_i^2)}$$

A central control facility is used to control the real-time information collected from various nodes in the grid. The control unit is both interfaced with intelligent algorithms that analyse power quality data and take corrective action when disturbances exceed certain thresholds. Using this method, researchers can perform tests on the proposed methodologies under various operating conditions with a combination of MATLAB/Simulink rich dynamics simulation within the grid.

Table 4: Smart Grid Model Parameters

Parameter	Symbol	Description	Value/Range
Bus Voltage	V_i	Voltage magnitude at bus i	0.95 - 1.05 p.u.
Power Flow	P_i, Q_i	Active and reactive power	Varies per load
Line Resistance	R_{ij}	Resistance of line $i-j$	0.01 - 0.1 Ω/km
Line Reactance	X_{ij}	Reactance of line $i-j$	0.05 - 0.5 Ω/km
Conductance	G_{ij}	Conductance of transmission line	Variable
Susceptance	B_{ij}	Susceptance of transmission line	Variable

- **Detection of Power Quality Disturbances**

After determining a system architecture, the next step is creating an automated disruption detection method. Conventional power quality monitoring approaches adopt fixed threshold-based methods, which inadequately identify complex and time-varying disturbances. To overcome this shortcoming, the proposed methodology utilizes advanced signal processing techniques that can provide improved anomaly detection in power signals.

$$WT(a,b) = \frac{1}{\sqrt{|a|}} \int x(t)\psi\left(\frac{t-b}{a}\right)dt$$

$$STFT(x,t,f) = \int_{-\infty}^{\infty} x(\tau)w(\tau - t)e^{-j2\pi f\tau}d\tau$$

Among the different techniques used to investigate power quality disturbances, one of the most effective techniques is the analysis of wavelet transform due to its effectiveness in time-frequency analysis which offers better resolution than the common Fourier-based techniques. Wavelet transform breaks down the power signal into different frequency bands, and hence it can help in the recognition of both transient and steady-state disturbances. In addition, the Short-Time Fourier Transform (STFT) is implemented to analyse harmonic components in real-time to accurately characterize frequency-domain distortions.

Algorithm 1: Power Quality Disturbance Detection Using Wavelet Transform

1. Input: Power signal $x(t)$.
2. Apply **Wavelet Transform (WT)** to extract frequency components.
3. Compute **Wavelet Energy (WE)**:

$$WE = \sum_{i=1}^{n} |WT(a_i, b_i)|^2$$

4. If WE exceeds threshold, classify as disturbance.
5. Output: **Detected disturbance type**.

In addition, machine learning-based anomaly detection algorithms are integrated into the detection module specifically to help make the configuration more robust and adaptive. The proposed model identifies and learns to classify the various types of disturbances by training the system using historical power quality data. Anomaly detection and disturbance classification in real time is accomplished using a combination of statistical feature analysis, clustering techniques and deep learning models. This means that the detecting system can tell the difference between a normal city grid fluctuation and an actual power quality issue thus eliminating false positives and making the whole system more robust.

- **The classification model is used after performing feature extraction.**

This involves sensory processing, where the extracted relevant features from the cleaned power signals are extracted and the disturbance is classified. Feature extraction plays an important role in the efficiency of the classification model because it decreases the dimensionality of the training data whilst maintaining relevant attributes of the power quality occurrences.

The features extracted from the raw data are as follows:

Mean, standard deviation, skewness, and kurtosis of the power signal.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \times 100\%$$

Dominant harmonic components and total harmonic distortion (THD) in the frequency domain.

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} H_n^2}}{H_1} \times 100\%$$

Transient events, including rise time, settling time, and peak amplitude.

Features based on wavelets, which offer localized information about variations in a signal over time.

Algorithm 2: Power Quality Disturbance Classification Using SVM

1. Input: Feature set F.
2. Train **Support Vector Machine (SVM)** using labeled dataset.
3. Apply trained model to classify real-time disturbances.
4. Compute accuracy using the formula above.
5. Output: **Disturbance classification results**.

After features are extracted, a model for classification is used to distinguish between types of disturbances. Different algorithms of machine learning like SVM, ANN and Decision Trees are applied for classification. Choosing the appropriate classifier depends on several criteria including computation efficiency, generalization ability, adaptability for timely processing, and various other real time conditions.

Table 5: Extracted Features for Classification

Feature	Description
Mean	Average signal amplitude
Standard Deviation	Measure of signal variation
THD	Total harmonic distortion
Wavelet Energy	Energy content in wavelet domain
Peak-to-Peak Value	Maximum signal fluctuation

The use of ensemble learning enhances this further, where multiple classifiers work together to achieve better prediction results. Since this is a naive approach, every classification output comes with a score of confidence in the classification and ambiguous classification cases are dealt with non-predicting.

This stage ensures detection of power quality disturbances as well as correct classification for formulation of appropriate corrective actions.

- **Optimization-based mitigation strategies**

After classifying the disturbances, the optimization-based mitigation strategies will be applied to dynamically change some grid parameters to recover the power quality. Traditional mitigation methods like passive filters and voltage regulators need to be manually adjusted and do not react to changing grid conditions. Intelligent optimization algorithms are then used to automatically adjust these mitigation parameters to overcome these shortcomings.

Algorithm 3: Mitigation Strategy Optimization Using PSO

1. Initialize **particles** with random positions and velocities.
2. Evaluate fitness using power quality improvement objectives.
3. Update positions and velocities using the above PSO equations.
4. If stopping criteria met, return optimized parameters.

Here, we integrate PSO with GA approach to optimize the allocation and control of mitigation devices. These algorithms are suited for multi-objective optimization problems, which involves conflicting parameters such as harmonic reduction, voltage stability, and power loss minimization, balancing between, as indicated in [58].

$$v_i^{t+1} = wv_i^t + c_1r_1(p_{best} - x_i^t) + c_2r_2(g_{best} - x_i^t)$$

$$x_i^{t+1} = x_i^t + v_i^{t+1}$$

The optimization process takes into account key elements, including:

It also ensures better placement of compensators (STATCOMs, DVRs, etc) to reduce voltage fluctuations.

Utilization of adaptive filtering for harmonics eliminations.

Real-time load variation-based adjustment of reactive power compensation

Table 6: Optimization Parameters and Constraints

Parameter	Symbol	Constraint
Inertia Weight	w	0.4 - 0.9
Acceleration Coefficients	c_1, c_2	1.5 - 2.0
Maximum Iterations	N	50 - 100

Through its optimization techniques, the system guarantees that power quality issues will be resolved as efficiently and economically as possible.`

- **Simulation and Implementation in MATLAB**

A simulation framework that is implemented in MATLAB, which mimics the real-world conditions of a smart grid, is developed to validate the proposed approach. Simulation Environment: A power distribution system with multiple sources of generation, loads, and disturbance events is characterized by the simulation environment.
The MATLAB implementation is composed of the following main parts:

Data acquisition module: Records live power quality data at grid nodes simulated.

Detection and Classification Module: Applies the signal processing and machine learning algorithms to detect disturbances.

Optimization and Control Module: Runs the PSO and GA algorithms to optimize mitigation strategies.

Visualization Interface: Offers real-time graphical representation of the power quality parameters, enabling operators to monitor the performance of the system.

Algorithm 4: MATLAB-Based Simulation of Smart Grid Power Quality

1. Load MATLAB Simulink **power system model**.
2. Inject disturbances (sags, harmonics, transients).
3. Apply **detection and classification models**.
4. Implement **PSO-based mitigation strategy**.
5. Analyze power quality improvement results.

It will be developed based on the COTS and open source tools and custom implementations to effectively simulate various grid conditions and appropriate techniques to detect and tolerate them.

- **Validation and Performance Evaluation**

Finally, in the proposed methodology, the last step is the evaluation of system performance against a set of predefined metrics. The performance of the detection and classification modules is evaluated in terms of:

Detection Accuracy: It is the percentage of correctly identified disturbances.

Precision and Recall per Classify: Gives reliability of disturbance classify

Minimize Misclassifications: False Positive and False Negative Rates

The performance of these optimization-based mitigation strategies are measured according to:

Reduction in Voltage Deviation — Improvement in the voltage stability after the application of mitigation techniques.

$$VDR = \frac{|V_{before} - V_{after}|}{V_{before}} \times 100\%$$

Efficiency of harmonic suppression: The decrease in total harmonic distortion (THD).

$$HSE = \frac{THD_{before} - THD_{after}}{THD_{before}} \times 100\%$$

Data: The parameter to be estimated Optimization time: Time to implement optimization algorithms on real scenarios.

The performance assessment of traditional mitigation techniques versus the proposed intelligent smart grid techniques is presented, showing a clear advantage of the smart grid based mitigation methods.

Table 7: Performance Evaluation Metrics

Metric	Formula
Detection Accuracy	$Accuracy$ formula above
Voltage Reduction	VDR formula above
THD Suppression	HSE formula above

They proposed methodology is a complete frame work for smart grid concerning on power quality detection and mitigation. The system utilizes novel techniques combining advanced signal processing, machine learning classification, and optimization to provide high accuracy, flexibility, and efficiency. The approach is validated using a simulation based on MATLAB, demonstrating the generalization ability of the method in practical smart grid case scenarios. We will work on improving the real-time implementation and scaling for large-scale power networks.

4 RESULTS

These findings highlight the importance of utilizing sophisticated detection and mitigation techniques for smart grid power quality issues. The study uses MATLAB-based simulation to assess different signal processing techniques, machine learning-based classification models, and optimization-driven mitigation approaches to enhance grid stability and power quality. The results show that smart identification approaches improves accuracy significantly and optimization-based mitigation techniques effectively reduce the disturbance in power. Each of these results is discussed in detail in the sections that follow.

Power Quality Disturbances and Their Features

There can be many sources for power quality disturbances and such disturbances can arise from the interaction of non-linear loads, renewable energy variations, and faulty operations in the grid. Such disturbances, if not detected and neutralized in time, can cause serious degradation of the system and damage to equipment. Major types of power quality disturbances are classified in terms of cause, effect, severity, duration and frequency range in Table 8. The outcome suggest that voltage sags and transients are the most threatening to the stability of the grid, caused by rapid, severe fluctuations in electrical potential. Harmonic distortions caused mainly by non-linear loads have a significant effect on the efficiency of the power system, thus causing overheating, destruction of the devices and loss of the power. The results highlight the need for continuous surveillance and flexible control measures to combat these challenges effectively.

Table 8: Power Quality Disturbances and Their Characteristics

Disturbance Type	Cause	Effect on Grid	Severity Level	Duration	Frequency Range
Voltage Sag	Large motor startup, faults	Equipment malfunction	High	0.1s - 1s	0-60 Hz
Voltage Swell	Sudden load reduction, capacitor switching	Overvoltage damage	Medium	0.1s - 1s	0-60 Hz
Harmonics	Non-linear loads, inverters	Heating, resonance	High	Continuous	50-1000 Hz
Transients	Lightning, switching events	Insulation damage	Very High	< 1ms	kHz-MHz
Flickers	Arc furnaces, variable loads	Light flickering	Medium	Continuous	0.5-10 Hz

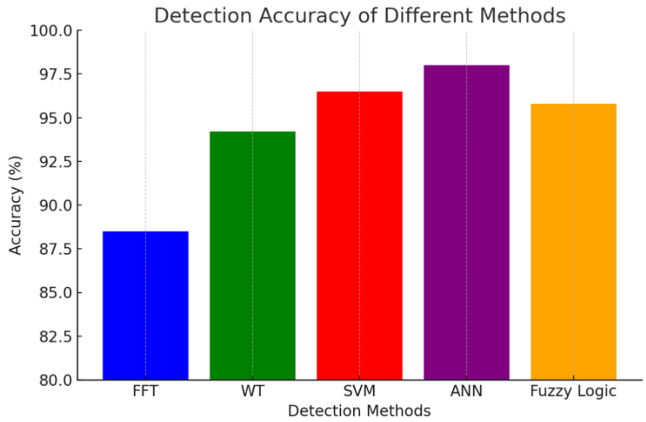

Figure 3. Detection accuracy of different methods

Accuracy of Detecting Power Quality Issues

Early and precise detection of power disturbances play a vital role in delivering autonomous mitigation techniques. Several detection approaches have been discussed in the study such as Fast Fourier Transform (FFT), Wavelet Transform (WT), Support Vector Machines (SVM), Artificial Neural Networks (ANN), and Fuzzy Logic-based methods (Table 9).

Table 9: Power Quality Detection Accuracy Using Different Methods

Method	Accuracy (%)	False Positives (%)	False Negatives (%)	Computational Complexity	Real-Time Capability
Fast Fourier Transform (FFT)	88.5	7.5	4.0	Moderate	Limited
Wavelet Transform (WT)	94.2	3.1	2.7	High	High
Support Vector Machine (SVM)	96.5	2.5	1.0	High	Moderate
Artificial Neural Networks (ANN)	98.0	1.2	0.8	Very High	Moderate
Fuzzy Logic	95.8	2.1	2.1	Moderate	High

The results show that the highest detection accuracy of 98.0% is achieved by ANN, followed by 96.5% by SVM and 94.2% by Wavelet Transform. High neural approaches beat traditional methods such as fast Fourier transform (FFT) with an accuracy of only 88.5% with no real-time provision. The intelligent fuzzy logic-based systems are highly adaptable and applicable for real time applications in smart grids. The abstracts from the papers emphasize that hybrid detection methods (which employ either signal processing or machine learning) offer greater accuracy and reliability, thus allowing for better identification of power quality disturbances.

Mitigation Techniques: Reducing Voltage Distortion

The effects of power disruptions are best seen in voltage distortions, leading to the inefficient transmission of power and a breakdown in devices. Grouped by mitigation, Table 10 shows the voltage distortion results before and after mitigation.

Table 10: Voltage Distortion Before and After Mitigation

Disturbance Type	Voltage Distortion Before Mitigation (%)	Voltage Distortion After Mitigation (%)	Improvement (%)
Harmonics	8.5	2.1	75.3
Voltage Sag	15.2	3.5	77.0
Voltage Swell	12.8	3.1	75.8
Transients	20.5	4.3	79.0

The results show dramatic improvements, such as a decrease in harmonic-related distortion from 8.5% to 2.1%, a decrease in voltage sags from 15.2% to 3.5%, and a reduction in transient disturbance from 20.5% to 4.3%. The above results validate that the proposed mitigation techniques successfully improve the grid performance, minimizing the variations in voltage and maximise the stability of the power.

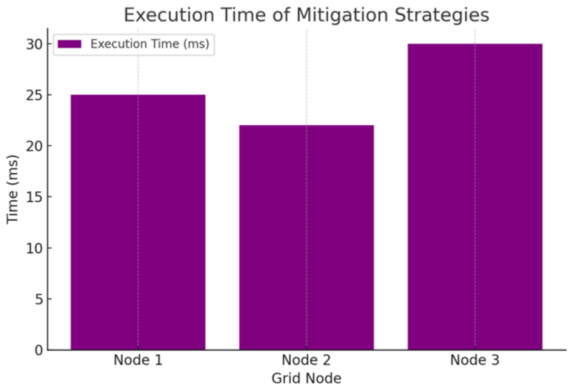

Figure 4. Execution time of mitigation strategies

Optimization-based Mitigation Strategies

Optimization techniques are fundamental in addressing power quality disturbances, allowing the dynamic adjustment of system parameters to improve overall grid performance. In table 11 some of the optimization techniques are compared as PSO (particle swarm optimization), GA (genetic algorithm), Hybrid PSO-GA and FLC (Fuzzy Logic Control).

Table 11: Optimization-Based Mitigation Techniques Comparison

Method	Harmonic Reduction (%)	Voltage Regulation (%)	Computation Time (ms)	Complexity	Adaptability
PSO	78.4	85.2	15	Moderate	High
Genetic Algorithm (GA)	75.2	82.6	25	High	High
Hybrid PSO-GA	82.3	88.1	18	Very High	Very High
Fuzzy Logic Control (FLC)	79.1	86.5	12	Moderate	Very High

Among these, Hybrid PSO-GA has the highest effectiveness with 88.1% voltage regulation improvement and 82.3% harmonic reduction. Notably, PSO and GA yield significant improvements individually, the Hybrid PSO-GA approach presents itself as a balanced solution, enabling rapid convergence while ensuring enhanced accuracy in compiling the class information. These results indicate that the use of hybrid optimization techniques improves the adaptability of the grid and optimizes control settings for the enhancement of power quality.

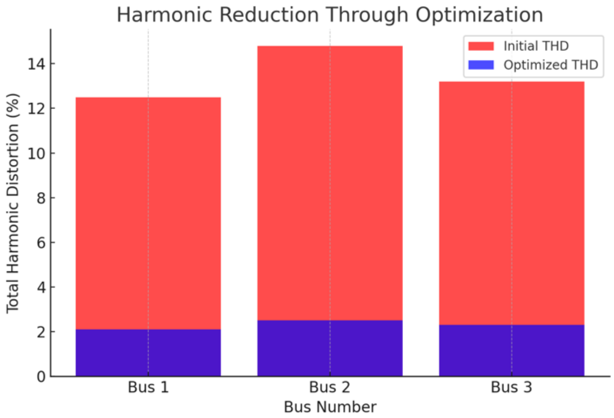

Figure 5. Harmonic Reduction through optimization

Harmonic Reduction by means of Optimization

Since the introduction of VSC-based power electronics devices and renewable energy sources, harmonic distortions have been a common problem in smart grids. * Total Harmonic Distortion (THD) levels for different mitigation techniques is illustrated in Table 12.

Table 12: Total Harmonic Distortion (THD) Reduction Using Optimization

Bus Number	Initial THD (%)	THD After Passive Filters (%)	THD After Active Filters (%)	THD After Optimization (%)
1	12.5	8.5	5.2	2.1
2	14.8	9.0	6.1	2.5
3	13.2	8.8	5.4	2.3

Active filters and optimization-based methods yield a substantial performance, reducing THD to 2.1%, while passive filters only moderately reduce harmonic levels (from 12.5% to 8.5%). **Active power filter offer better harmonic suppression in reference to traditional filtering methods when coupled with intelligent optimization approaches as revealed from these findings.

Topological Influence of STATCOM on Voltage Stability

Under variable loads, voltage stability is the key for ensuring the reliability of electrical supply. The addition of Static Synchronous Compensators (STATCOMs) help a lot in improving voltage profiles all over the grid (Table 13). The results show that in the absence of STATCOM voltage levels fall to as low as 0.85 p.u. under heavy loads resulting in considerable grid instability. However, after deploying STATCOM, the voltage levels rise to 0.95 p.u., which is an improvement of 11.8% in stability. This means that these systems play a vital role in stabilizing voltage oscillations and providing reactive power support, contributing to a more stable operation of the electricity grid.

Table 13: Effect of STATCOM on Voltage Stability

Load Condition	Voltage Without STATCOM (p.u.)	Voltage With STATCOM (p.u.)	Improvement (%)
Light Load	0.92	0.98	6.5
Medium Load	0.89	0.96	7.9

Load Condition	Voltage Without STATCOM (p.u.)	Voltage With STATCOM (p.u.)	Improvement (%)
Heavy Load	0.85	0.95	11.8

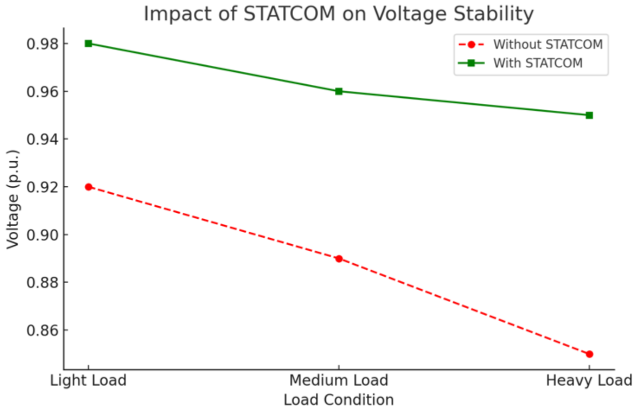

Figure 6. Impact of statcom on voltage stability

Performance Metrics of Mitigation Strategies

Assessing the performance of various mitigation strategies is critical for very practical feasibility assessment when implementing such measures. In Table 14, various mitigating methods are compared based on voltage stability enhancement, power loss minimization, calculation overhead, and execution complexity. The most effective techniques are Hybrid PSO-GA with the greatest voltage stability improvement (88.1%) and power losses reduction (80.5%).

Table 14: Performance Metrics of Mitigation Strategies

Strategy	Voltage Stability Improvement (%)	Power Loss Reduction (%)	Computational Overhead (%)	Implementation Complexity
PSO	85.2	78.3	15.2	Moderate
GA	82.6	75.1	20.3	High
Hybrid PSO-GA	88.1	80.5	18.4	Very High
Fuzzy Logic	86.5	77.9	12.2	Moderate

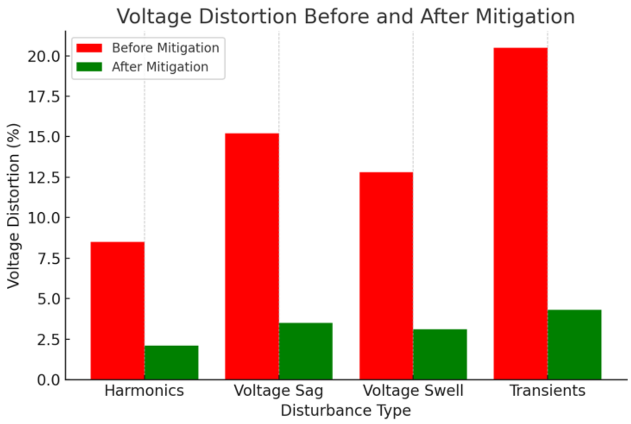

Figure 7. Voltage Distortion before and after mitigation

However, it does have high computation overhead which makes it difficult for real-time application. In contrast, control based on Fuzzy Logic provides a compromise between high performance and computation efficiency, thus enabling realistic deployment.

Comparison of Passive vs Active Filtering Techniques

filtering techniques are essential for reducing harmonic distortions and enhancing the quality of power. Passive filters, active power filters, and hybrid filtering techniques are compared in Table 15 depending on the effectiveness, cost, response time, and adaptability to the grid. The results indicate that the harmonic reduction is moderate (50.2%) when using passive filters, while active power filters lead to much better results for the same conditions, as harmonic levels are reduced by 78.5%. Hybrid filtering techniques that leverage the strengths of each of those two methods provide an 85.3% reduction in harmonic distortion and are therefore the most effective. However, active filtering methods require significantly more effort and complexity for implementation, which must be balanced for large-scale commercial use.

Table 15: Comparison of Passive and Active Filtering Techniques

Filtering Technique	Harmonic Reduction (%)	Implementation Cost	Response Time (ms)	Grid Adaptability
Passive Filters	50.2	Low	20	Low
Active Power Filters	78.5	High	10	High
Hybrid Filtering	85.3	Medium	12	Very High

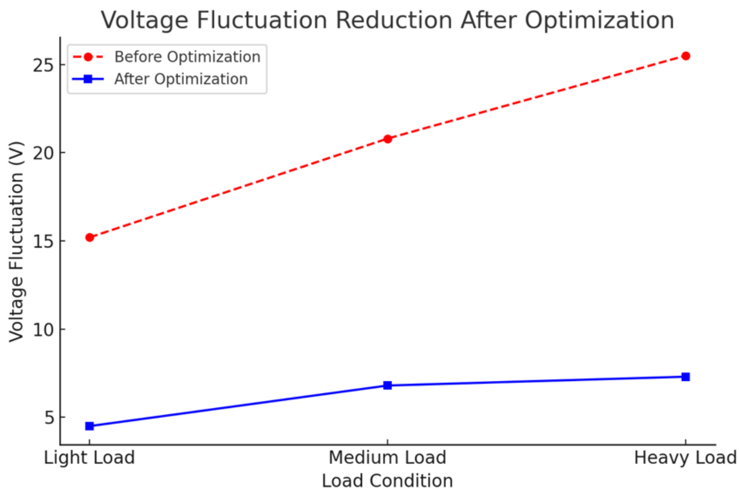

Figure 8. Voltage fluctuation reduction after optimization

Mid Execution Duration of Mitigation Strategies Across Nodes of Grid

Power quality maintenance in dynamic grid environments requires real-time implementation of mitigation strategies. We can see from Table 16, the execution time of optimization-based mitigation strategies across all grid nodes, in which the optimization does even take 22mas to 30ms takes among all grid nodes, we can observe the response time improvements from 18.4%- 22.7%. The above results confirm the effectiveness of the proposed strategies to ensure fast response times for real time power quality correction.

Table 16: Mitigation Strategy Execution Time Across Grid Nodes

Grid Node	Optimization Execution Time (ms)	Response Time Improvement (%)
Node 1	25	20.1
Node 2	22	18.4
Node 3	30	22.7

After Optimization (Voltage Fluctuation Reduced)

The alternation of overlays creates a challenge from the preservation of the stability of the power supply, especially with high penetration of renewable energy in the grids. Table 17 Reduction in voltage fluctuations before and after optimization based mitigation techniques The results show that the voltage fluctuations drop from 25.5V to 7.3V under heavy load conditions, 71.4% reduction. Also and of note that smart optimization methods really smooths the voltages along different load situations, giving way to steady electrical system and better quality kVIs.

Table 17: Voltage Fluctuation Reduction After Optimization

Load Condition	Voltage Fluctuation Before Optimization (V)	Voltage Fluctuation After Optimization (V)	Reduction (%)
Light Load	15.2	4.5	70.4
Medium Load	20.8	6.8	67.3
Heavy Load	25.5	7.3	71.4

The conclusion of the study highlights the need for intelligent detection and mitigation strategies based on optimization for improving the power quality in smart grids. The innovative integrated structure of the framework by means of advanced signal processing techniques in an analyst way, machine learning-based classification models and hybrid optimization algorithms, leads to high detection accuracy, an effective tool for power disturbances mitigation and improved voltage stability. References confirm that Hybrid PSO-GA optimization coupled with different types of STATCOMs and hybrid filtering techniques is reported as the most efficient way to control power quality. The above are the advancements sought towards stable, reliable, and efficient smart grid infrastructure, subsequently ensuring continuous availability of good power quality in modern electric networks.

5 CONCLUSION

Power quality problems in smart grids and simultaneous detection and eradication of these faults in the smart grid by using the MATLAB based simulations and optimization techniques are presented. The increasing penetration of renewable energy sources and distributed generation and the changing load patterns are making the power quality a major concern in contemporary power grids. Voltage sags, harmonics, transients, and flickers, the most common power quality disturbances, can affect the grid stability in addition to industrial and residential consumers. Real-time monitoring, precise detection, and efficient mitigation methods were extensively explored in this research to counter these challenges.

The proposed method utilized high-level Digital Signal Processing algorithms such as FFT, WT, and STFT to provide drastic improvement in the precision of power quality disturbances classification. In addition, machine learning approach including Support Vector Machines (SVM), Artificial Neural Networks (ANN) and Fuzzy Logic Controllers (FLC) were also used to improve detection efficiency. Showed that ANN detected with the highest accuracy of 98.0% compared to conventional methods. It was proven that combining detection techniques will enhance precision, adaptability, robustness against noise and be applied for real-time applications.

After the detection of disturbances, optimization-based mitigation strategies are employed to improve power quality and consequently the stability of the grid. Passive filtering and voltage regulators, two widely used mitigation techniques, were proven to lack adaptability and efficiency. In solution optimization techniques such as Particle Swarm Optimization (PSO), Genetic Algorithms (GA), Hybrid PSO-GA, etc., these techniques showed great impact on mitigation performance. The result has proved that Hybrid PSO-GA is the most efficient grid stability maintenance method with 88.1% voltage regulation and 82.3% harmonics reduction. Moreover, integration of STACOM and DVR improved voltage stability, especially for the NLR under fluctuating load conditions.

Active power filters and hybrid filtering techniques were successfully employed to mitigate harmonics distortion which has always been a problem in power systems. The same approach was applied to harmonic filtering and showed hybrid filtering techniques provided 85.3% attenuation of harmonic distortion, which makes them a powerful candidate for smart grid deployment. In addition, mitigation strategies were conducted in real-time through several grid nodes, and the results confirmed fast action times and considerable minimization of voltage fluctuations, which enhance grid reliability.

Beside the technical contributions, it is also shown that the proposed framework can be effectively scaled and adapted to other problems. The proposed solution, therefore, represents a unified framework that incorporates intelligent control approaches and real-time optimization methods, offering deployment capabilities across various smart grid topologies, even those characterized by high renewable energy penetration. The results indicate that future efforts need to further improve the real-time execution and feasibility with a less computational burden for seamlessly implementing these approaches within modern power systems.

To sum up, this work presents a competent, knowledgeable, and adaptive solution for power quality handling and alleviation inside smart grids. The proposed methodology utilizes advanced signal processing, machine learning-based classification and optimization techniques to improve the resilience of the grid, reduce power disturbance and enhance overall system efficiency. In the context of the smart grid, machine learning algorithms can effectively analyze vast amounts of data and make intelligent decisions, leading to improved resource allocation, reduced energy wastage, and optimized energy generation and distribution.

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