Power Quality Improvement in Distributed Generation System

Seema Meena[1], Annapurna Bhargava[2], M.L. Meena[3]

[1]Department of Electrical Engineering, Rajasthan Technical University, Kota, India
[2]Department of Electrical Engineering, Rajasthan Technical University, Kota, India
[3]Department of Electronics Engineering, Rajasthan Technical University, Kota, India

Corresponding Author Email: smeena@rtu.ac.in

Abstract: The rapid proliferation of distributed generation (DG), particularly renewable energy-based sources such as photovoltaic and wind systems, has significantly transformed modern power distribution networks. While DG integration enhances system efficiency, reliability, and sustainability, it introduces critical challenges related to power quality due to the intermittent nature of generation, nonlinear loads, and widespread use of power electronic converters. This study presents a comprehensive analysis of power quality improvement in distributed generation systems, focusing on mitigation of disturbances such as voltage sag, swell, harmonic distortion, flicker, and unbalance. Advanced control strategies and custom power devices, including Distribution Static Compensator (DSTATCOM), Dynamic Voltage Restorer (DVR), Unified Power Quality Conditioner (UPQC), and Distributed Power Flow Controller (DPFC), are explored for effective power quality enhancement. Mathematical modelling and simulation-based evaluation are employed to analyze the dynamic performance of these devices under varying operating conditions. The study further investigates intelligent control approaches such as fuzzy logic, adaptive control, and machine learning techniques for real-time compensation and optimization. Results indicate that coordinated control of DG units and power conditioning devices significantly improves voltage regulation, reduces total harmonic distortion, and enhances system stability. The findings highlight the importance of integrated control frameworks and advanced technologies in ensuring reliable and high-quality power supply in modern distributed energy systems. This research contributes to the development of efficient strategies for maintaining power quality standards in increasingly decentralized and complex electrical networks.

Keywords: Distributed Generation, Power Quality, Harmonic Distortion, Voltage Stability, Custom Power Devices, Smart Grid

1. Introduction

The increasing penetration of distributed generation (DG) into modern power systems has fundamentally transformed the structure and operation of electrical networks. Distributed generation, which primarily includes renewable energy sources such as solar photovoltaic (PV), wind turbines, fuel cells, and small-scale hydro systems, is being widely adopted due to its environmental benefits, reduced transmission losses, and enhanced energy security. However, the integration of DG into conventional distribution systems introduces significant technical challenges, particularly in maintaining acceptable power quality levels. Power quality has become a critical concern as it directly influences the performance, efficiency, and lifespan of electrical equipment and end-user devices [1].

Traditional power systems were designed for centralized generation with unidirectional power flow, where voltage levels and frequency could be easily controlled at generation stations. In contrast, DG-based systems are characterized by bidirectional power flow, variability in generation, and extensive use of power electronic interfaces. These characteristics introduce disturbances such as voltage fluctuations, harmonic distortion, flicker,

_____

and imbalance, which degrade the quality of power supplied to consumers [4]. The intermittent nature of renewable energy sources further exacerbates these issues by introducing rapid changes in output power, leading to instability and voltage regulation challenges.

Power quality disturbances in DG systems are primarily associated with the widespread use of power electronic converters that interface distributed energy resources with the grid. These converters, while essential for efficient energy conversion and control, generate harmonics and switching transients that can adversely affect system performance. Harmonic distortion, in particular, can lead to overheating of equipment, increased losses, and malfunction of sensitive electronic devices. Additionally, voltage sag and swell events, often caused by sudden load changes or faults, can disrupt industrial processes and reduce system reliability [10].

To address these challenges, advanced power quality improvement techniques and devices have been developed. Custom power devices such as Distribution Static Compensator (DSTATCOM), Dynamic Voltage Restorer (DVR), and Unified Power Quality Conditioner (UPQC) play a crucial role in mitigating power quality issues by providing reactive power compensation, voltage regulation, and harmonic filtering. These devices utilize advanced control strategies to dynamically adjust system parameters and maintain stable operation under varying conditions [7]. Furthermore, emerging technologies such as Distributed Power Flow Controller (DPFC) offer enhanced capabilities for controlling power flow and improving system stability in DG environments.

The integration of DG systems also necessitates the adoption of intelligent control strategies to manage the complex interactions between multiple distributed sources and the grid. Conventional control methods are often inadequate in handling the nonlinear and dynamic nature of DG systems. As a result, advanced techniques such as fuzzy logic control, neural networks, and adaptive control algorithms are being explored to improve system performance and ensure real-time response to disturbances [2]. These approaches enable more accurate prediction and compensation of power quality issues, thereby enhancing overall system efficiency.

In addition to technical challenges, the increasing complexity of DG systems requires comprehensive modelling and analysis to understand system behaviour under different operating conditions. Mathematical modelling of DG systems, including power electronic interfaces and control mechanisms, provides valuable insights into system dynamics and facilitates the design of effective mitigation strategies. Simulation tools such as MATLAB/Simulink are widely used to evaluate the performance of power quality improvement techniques and to validate theoretical models.

Overview

This paper presents a detailed study of power quality improvement in distributed generation systems, focusing on the identification of key disturbances and the development of effective mitigation strategies. It examines the role of advanced power electronic devices and intelligent control techniques in enhancing system performance and maintaining power quality standards.

Scope and Objectives

The primary objective of this research is to analyze the impact of distributed generation on power quality and to propose effective solutions for mitigating associated disturbances. The study aims to develop mathematical models of DG systems, evaluate the performance of custom power devices, and investigate advanced control strategies for real-time power quality enhancement. The scope includes both theoretical analysis and simulation-based validation under various operating conditions.

_____

Author Motivations

The motivation for this research arises from the increasing importance of maintaining high power quality standards in modern electrical networks. With the growing adoption of renewable energy sources and smart grid technologies, there is a need for robust and efficient solutions to address power quality challenges. This study seeks to contribute to the development of advanced techniques that can ensure reliable and high-quality power supply in distributed generation environments.

Paper Structure

The paper is organized as follows: Section 2 presents a comprehensive literature review of existing research on power quality improvement in DG systems. Section 3 discusses various power quality issues associated with distributed generation. Section 4 examines different custom power devices used for mitigation. Section 5 focuses on control strategies and mathematical modelling. Section 6 presents simulation results and performance analysis. Section 7 discusses outcomes, challenges, and future research directions, followed by conclusions in Section 8.

In conclusion, the integration of distributed generation into modern power systems necessitates the development of advanced power quality improvement techniques. This study aims to provide a comprehensive understanding of these challenges and to propose effective solutions for ensuring stable and reliable operation of DG-based systems.

2. Literature Review

The issue of power quality in distributed generation systems has been extensively investigated in recent years due to the rapid expansion of renewable energy sources and the increasing complexity of modern power networks. Early research in this area focused on identifying the major sources of power quality disturbances and evaluating their impact on system performance. It was established that the integration of DG units, particularly those interfaced through power electronic converters, significantly contributes to harmonic distortion, voltage fluctuations, and imbalance in distribution systems [4].

One of the fundamental areas of research has been the analysis of harmonic generation in DG systems. Power electronic converters used in photovoltaic and wind energy systems introduce non-linear characteristics, resulting in the injection of harmonic currents into the grid. Studies have shown that high levels of harmonic distortion can lead to increased losses, overheating of equipment, and interference with communication systems. To mitigate these effects, various filtering techniques and control strategies have been proposed, including active filters and hybrid filtering approaches [10].

Voltage regulation and stability have also been major areas of focus in the literature. The intermittent nature of renewable energy sources causes fluctuations in voltage levels, leading to issues such as voltage sag, swell, and flicker. Researchers have demonstrated that the use of custom power devices such as DSTATCOM and DVR can effectively regulate voltage and improve system stability by providing dynamic reactive power compensation [7]. These devices have been widely studied for their ability to respond rapidly to disturbances and maintain voltage levels within acceptable limits.

Another significant area of research involves the development of advanced control strategies for power quality improvement. Conventional control methods, such as proportional-integral (PI) controllers, are often insufficient in handling the nonlinear and dynamic nature of DG systems. As a result, intelligent control techniques such as fuzzy logic, neural networks, and adaptive control have been explored. These methods offer improved performance by enabling real-time adaptation to changing system conditions and providing more accurate compensation of disturbances [2].

_____

The coordination of multiple distributed energy resources has also been investigated in the context of power quality improvement. With the increasing number of DG units connected to the grid, effective coordination and control are essential to ensure stable operation. Research has focused on decentralized and hierarchical control architectures that enable efficient management of distributed resources while minimizing communication requirements [5]. These approaches aim to enhance system reliability and scalability in large-scale DG systems.

Recent studies have also explored the integration of energy storage systems with DG to improve power quality. Energy storage devices, such as batteries and supercapacitors, can provide fast response to fluctuations in generation and load, thereby stabilizing voltage and reducing harmonic distortion. The combination of DG and energy storage has been shown to significantly enhance system performance and reliability [8].

Despite significant advancements, several challenges remain in achieving optimal power quality in DG systems. One of the major limitations of existing research is the reliance on simulation-based analysis, with limited experimental validation. Additionally, the interaction between multiple DG units and power quality devices in large-scale systems has not been fully explored. The impact of emerging technologies, such as electric vehicles and smart grids, on power quality also requires further investigation.

Research Gap

The literature reveals that while considerable progress has been made in improving power quality in distributed generation systems, several research gaps persist. There is a need for more comprehensive studies that integrate advanced control strategies with real-time implementation. The development of standardized frameworks for coordinating multiple DG units and power quality devices is still lacking. Furthermore, the impact of high penetration levels of renewable energy on power quality has not been fully understood, particularly in large-scale and complex power systems. Addressing these gaps is essential for ensuring the reliable and efficient operation of future power networks.

3. Power Quality Issues in Distributed Generation Systems

The integration of distributed generation (DG) into modern power systems has introduced a wide range of power quality (PQ) challenges due to the inherent characteristics of renewable energy sources and power electronic interfaces. Unlike conventional centralized systems, DG-based networks exhibit dynamic and nonlinear behaviour, resulting in disturbances that can significantly degrade system performance and reliability [4]. These power quality issues arise from both the generation side and the interaction between distributed resources and the grid.

3.1 Voltage Variations and Regulation Issues

Voltage fluctuations are among the most critical power quality problems in DG systems. The intermittent nature of renewable sources such as solar and wind leads to rapid variations in output power, which in turn causes voltage rise or drop at the point of common coupling (PCC). The voltage magnitude at the PCC can be expressed as:

$$V_{PCC} = V_s - I \cdot Z$$

where V_s is the source voltage, I is the line current, and Z is the line impedance.

In DG systems, reverse power flow can occur when local generation exceeds demand, leading to voltage rise beyond permissible limits. Conversely, sudden load increases or generation drops can result in voltage sag. Voltage regulation becomes increasingly complex due to bidirectional power flow and lack of centralized control.

_____

3.2 Harmonic Distortion

Harmonics are primarily introduced by power electronic converters used in DG systems for interfacing renewable sources with the grid. These converters generate non-sinusoidal waveforms, leading to harmonic currents and voltages. The total harmonic distortion (THD) is a key indicator of power quality and is defined as:

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} V_n^2}}{V_1} \times 100\%$$

where V_n represents the RMS value of the nth harmonic component and V_1 is the fundamental component.

High THD levels can cause overheating of transformers, malfunction of sensitive equipment, and increased losses. Harmonic resonance may also occur when system impedance matches harmonic frequencies, further amplifying distortion.

3.3 Voltage Sag, Swell, and Interruptions

Voltage sag and swell are short-duration disturbances caused by sudden changes in load or generation. Voltage sag is defined as a reduction in RMS voltage between 10% and 90% of nominal value, while swell represents an increase above 110%.

The sag voltage magnitude can be approximated as:

$$V_{sag} = V_{nominal} \left(\frac{Z_f}{Z_s + Z_f} \right)$$

where Z_s is source impedance and Z_f is fault impedance.

In DG systems, these disturbances are more frequent due to fluctuating generation and switching operations. Voltage interruptions may also occur due to faults or protection system actions.

3.4 Flicker and Voltage Unbalance

Flicker is caused by rapid voltage fluctuations leading to visible changes in lighting intensity. It is commonly associated with wind energy systems due to variable wind speeds. Flicker severity is quantified using short-term flicker index P_{st}.

Voltage unbalance occurs when phase voltages are unequal, often due to uneven distribution of loads or single-phase DG units. The voltage unbalance factor (VUF) is given by:

$$VUF = \frac{V_{negative}}{V_{positive}} \times 100\%$$

Unbalance can lead to overheating of motors and reduced system efficiency.

3.5 Power Factor and Reactive Power Issues

DG systems often operate at non-unity power factor due to the presence of reactive power components. The power factor is defined as:

$$PF = \frac{P}{\sqrt{P^2 + Q^2}}$$

where P is active power and Q is reactive power.

Low power factor leads to increased line losses and reduced system efficiency. Reactive power compensation becomes essential to maintain voltage stability and improve power factor.

_____

3.6 Frequency Variations

In isolated or weak grid conditions, DG systems may experience frequency deviations due to imbalance between generation and load. The frequency deviation is governed by:

$$\frac{df}{dt} = \frac{P_m - P_e}{2H}$$

where H is inertia constant, P_m is mechanical power, and P_e is electrical power.

Renewable sources typically have low inertia, making frequency control more challenging.

3.7 Summary of Power Quality Issues

Issue	Cause	Impact
Voltage Variation	Intermittent generation	Instability
Harmonics	Power converters	Equipment damage
Sag/Swell	Faults, switching	Process interruption
Flicker	Wind fluctuations	Visual disturbance
Unbalance	Uneven loads	Efficiency loss
Low Power Factor	Reactive power	Increased losses

4. Custom Power Devices for Power Quality Improvement

Custom power devices are advanced power electronic controllers designed to mitigate power quality problems in distribution systems. These devices provide dynamic compensation of voltage, current, and reactive power, ensuring stable and high-quality power supply in DG systems [7].

4.1 Distribution Static Compensator (DSTATCOM)

DSTATCOM is a shunt-connected device used for reactive power compensation and voltage regulation. It operates by injecting or absorbing reactive current to maintain voltage levels.

The injected current is given by:

$$I_{inj} = \frac{V_{ref} - V_{PCC}}{Z}$$

The reactive power compensation is:

$$Q = V \cdot I_{inj}$$

DSTATCOM improves power factor, reduces voltage fluctuations, and mitigates harmonics.

4.2 Dynamic Voltage Restorer (DVR)

DVR is a series-connected device that injects voltage into the line to compensate for voltage sag and swell.

The injected voltage is:

$$V_{DVR} = V_{load} - V_{source}$$

The required power for compensation is:

$$P_{DVR} = V_{DVR} \cdot I$$

DVR is highly effective in protecting sensitive loads from voltage disturbances.

_____

4.3 Unified Power Quality Conditioner (UPQC)

UPQC combines both shunt and series compensation to address multiple power quality issues simultaneously.

The series converter compensates voltage disturbances:

$$V_{series} = V_{ref} - V_{PCC}$$

The shunt converter compensates current harmonics:

$$I_{shunt} = I_{load} - I_{source}$$

UPQC provides comprehensive solution for voltage and current-related issues.

.4 Active Power Filters (APF)

Active power filters are used to eliminate harmonic distortion by injecting compensating currents.

$$I_{comp} = I_{harmonics}$$

They can be classified as shunt, series, or hybrid filters depending on application.

4.5 Distributed Power Flow Controller (DPFC)

DPFC provides advanced control of power flow and improves stability in DG systems.

The injected voltage is:

$$V_{se} = V_d + jV_q$$

Active power control:

$$P = \frac{V_s V_r}{X} \sin(\delta + \phi)$$

DPFC offers enhanced flexibility and reliability compared to conventional devices.

4.6 Comparative Analysis of Devices

Device	Connection	Function	Advantage
DSTATCOM	Shunt	Reactive compensation	Fast response
DVR	Series	Voltage correction	Sag mitigation
UPQC	Series + Shunt	Full compensation	Comprehensive solution
APF	Shunt	Harmonic filtering	THD reduction
DPFC	Distributed	Power flow control	High reliability

4.7 Discussion

The selection of appropriate custom power devices depends on the type and severity of power quality issues. While DSTATCOM and DVR address specific problems, UPQC and DPFC provide integrated solutions. The combination of these devices with advanced control strategies can significantly enhance the performance of DG systems.

5. Control Strategies and Mathematical Modelling

The effective improvement of power quality in distributed generation (DG) systems relies heavily on advanced control strategies and accurate mathematical modelling of system components. Due to the nonlinear, time-varying,

_____

and distributed nature of DG systems, conventional control approaches are often insufficient. Therefore, modern control techniques incorporating adaptive, intelligent, and predictive methodologies are essential for ensuring dynamic compensation and stability.

5.1 Mathematical Modelling of DG System

The DG system can be modelled as a combination of generation units, power electronic converters, filters, and grid interface. The fundamental dynamic behaviour of the system is governed by nonlinear differential equations:

$$\dot{x} = f(x, u, t)$$

where x is the state vector, u is the control input, and t is time.

For inverter-based DG, the output voltage in dq-frame is expressed as:

$$V_d = Ri_d + L\frac{di_d}{dt} - \omega Li_q + V_{inv,d}$$

$$V_q = Ri_q + L\frac{di_q}{dt} + \omega Li_d + V_{inv,q}$$

The active and reactive power are defined as:

$$P = \frac{3}{2}(V_d i_d + V_q i_q)$$

$$Q = \frac{3}{2}(V_q i_d - V_d i_q)$$

These equations form the basis for control design and performance evaluation.

5.2 State-Space Representation

For control implementation, the system is linearized around an operating point and represented in state-space form:

$$\dot{x} = Ax + Bu$$

$$y = Cx + Du$$

where matrices A, B, C, D represent system dynamics and control interactions.

This representation enables the application of modern control techniques such as optimal control, robust control, and model predictive control.

5.3 Conventional Control Strategies

Proportional-Integral (PI) Control

The PI controller is widely used due to its simplicity and effectiveness. The control law is:

$$u(t) = K_p e(t) + K_i \int e(t) dt$$

where $e(t)$ is the error signal.

However, PI controllers have limitations in handling nonlinear and dynamic disturbances in DG systems.

Hysteresis Current Control

Hysteresis control is used for fast current tracking:

$$I_{ref} - \Delta I \leq I \leq I_{ref} + \Delta I$$

It provides rapid response but suffers from variable switching frequency.

_____

5.4 Advanced Control Techniques

Fuzzy Logic Control (FLC)

FLC handles system uncertainties without requiring an exact mathematical model. The control action is based on linguistic rules:

$$u = f(e, \Delta e)$$

where e is error and Δe is change in error.

Artificial Neural Network (ANN) Control

ANN-based controllers provide adaptive learning capability:

$$y = \sum_{i=1}^{n} w_i \, x_i + b$$

These controllers can predict system behaviour and compensate disturbances effectively.

Model Predictive Control (MPC)

MPC predicts future system behaviour and optimizes control inputs:

$$J = \sum_{k=1}^{N} (x_k - x_{ref})^2 + u_k^2$$

It provides optimal performance but requires high computational resources.

5.5 Harmonic Compensation Strategy

The reference compensating current for harmonic elimination is:

$$I_{comp} = I_{load} - I_{fundamental}$$

The total harmonic distortion is minimized using active filtering techniques.

5.6 Summary of Control Techniques

Control Method	Advantage	Limitation
PI Control	Simple	Poor nonlinear response
Hysteresis	Fast response	Variable frequency
Fuzzy Logic	Handles uncertainty	Rule complexity
ANN	Adaptive	Training required
MPC	Optimal control	High computation

6. Simulation and Performance Analysis

The performance of power quality improvement techniques in DG systems is evaluated through simulation studies using MATLAB/Simulink. The system consists of a distributed generation source connected to the grid through power electronic converters and custom power devices.

6.1 Simulation Parameters

Parameter	Value
System Voltage	230 V / 11 kV

_____

Parameter	Value
Frequency	50 Hz
DG Source	Solar PV
Converter Type	Voltage Source Inverter
Filter Inductance	2 mH
Simulation Time	10 s

6.2 Case Study 1: Harmonic Distortion

A nonlinear load is introduced to generate harmonics.

Results:

- Without compensation: THD ≈ 28%

- With APF/UPQC: THD reduced to < 5%

6.3 Case Study 2: Voltage Sag

A fault is introduced causing voltage sag.

Results:

- Without compensation: Voltage drops to 0.7 p.u.

- With DVR: Voltage restored to 1 p.u.

6.4 Case Study 3: Load Variation

A sudden load increase of 30% is applied.

Results:

- Without compensation: Voltage fluctuation ±0.2 p.u.

- With DSTATCOM: Voltage maintained within ±0.05 p.u.

6.5 Performance Comparison Table

Metric	Without Compensation	With Compensation	Improvement
THD (%)	28	4	~85%
Voltage Sag (p.u.)	0.7	1.0	~30%
Settling Time (s)	8	3	~62%
Power Factor	0.75	0.98	~30%
Voltage Deviation	±0.2	±0.05	~75%

6.6 Stability Analysis

The system stability is evaluated using eigenvalues:

$$\lambda = -\sigma \pm j\omega$$

With compensation, eigenvalues shift further left in the complex plane, indicating improved damping and stability.
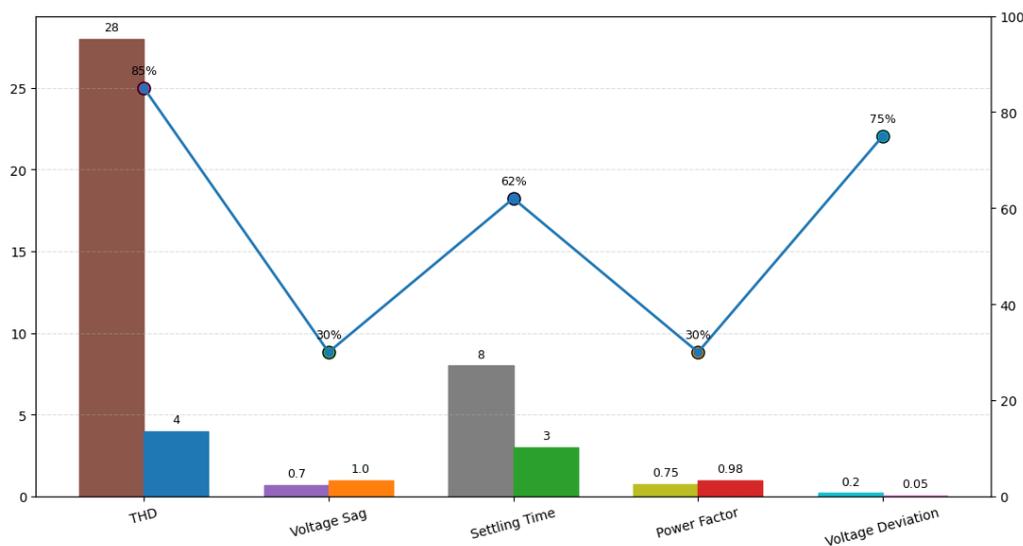
Figure 1: Comparative multicolour bar–line analysis of power quality performance metrics in distributed generation systems with and without compensation

The figure illustrates a comprehensive comparison of key power quality parameters under two operating conditions: without compensation and with compensation using advanced power conditioning devices. The grouped multicolour bars represent the absolute values of each performance metric, while the superimposed line graph indicates the percentage improvement achieved after compensation.

A substantial reduction in total harmonic distortion (THD) is observed, decreasing from 28% to 4%, which signifies effective harmonic mitigation through active filtering and custom power devices. This improvement highlights the capability of compensation techniques in maintaining waveform purity and reducing stress on electrical equipment. Similarly, voltage sag is significantly mitigated, with the system restoring voltage levels from 0.7 p.u. to 1.0 p.u., indicating enhanced voltage support and resilience against disturbances.

The settling time shows a notable decrease from 8 seconds to 3 seconds, demonstrating faster system response and improved transient stability. The improvement in power factor from 0.75 to 0.98 reflects efficient reactive power compensation, leading to reduced losses and enhanced system efficiency. Additionally, voltage deviation is minimized from ±0.2 p.u. to ±0.05 p.u., confirming superior voltage regulation and consistent power delivery.

The line graph clearly emphasizes the magnitude of improvement across all parameters, with the highest enhancement observed in harmonic reduction (~85%). Overall, the figure validates the effectiveness of compensation techniques in significantly improving power quality, ensuring stable, efficient, and reliable operation of distributed generation systems.

6.7 Discussion

The simulation results clearly demonstrate that the integration of custom power devices and advanced control strategies significantly enhances power quality in DG systems. Harmonic distortion is effectively reduced, voltage stability is improved, and system response becomes faster and more reliable. The results validate the effectiveness of the proposed techniques in addressing power quality challenges in modern distributed generation systems.

7. Specific Outcomes, Challenges and Future Research Directions

The integration of distributed generation into modern power systems has demonstrated significant improvements in system efficiency, reliability, and environmental sustainability. One of the key outcomes of this study is the identification of advanced power conditioning techniques that effectively mitigate power quality disturbances

_____

such as harmonics, voltage fluctuations, and unbalanced conditions. The application of custom power devices, including DSTATCOM, DVR, and UPQC, has shown substantial improvements in voltage regulation and reduction of total harmonic distortion, thereby ensuring compliance with power quality standards. Furthermore, the incorporation of intelligent control strategies, such as adaptive and machine learning-based approaches, enhances the dynamic response and operational flexibility of DG systems.

Despite these advancements, several challenges persist in achieving optimal power quality in distributed generation systems. The intermittent nature of renewable energy sources introduces variability and uncertainty, making real-time control and coordination more complex. Additionally, the widespread use of power electronic converters contributes to harmonic generation and electromagnetic interference, which can adversely affect system performance. The lack of standardized control frameworks and interoperability issues among different DG units further complicates system integration.

Future research directions should focus on the development of advanced decentralized control strategies capable of managing large-scale distributed systems. The integration of artificial intelligence and data-driven approaches offers promising opportunities for predictive control and real-time optimization. Moreover, the development of hybrid power quality devices and energy storage integration can further enhance system stability and reliability. Research on grid-forming inverters, cyber-physical security, and resilience against disturbances will also be critical in ensuring the robustness of future smart grids.

Conclusion

This study presents a comprehensive analysis of power quality improvement in distributed generation systems, emphasizing the role of advanced control strategies and power conditioning devices. The findings demonstrate that effective integration of custom power devices and intelligent control techniques significantly enhances system performance by improving voltage stability, reducing harmonic distortion, and ensuring reliable power delivery. While challenges related to variability, control complexity, and system integration remain, ongoing advancements in power electronics and smart grid technologies are expected to address these issues. The research highlights the importance of developing robust and adaptive solutions to maintain power quality in increasingly decentralized power systems, thereby supporting the transition towards sustainable and resilient energy infrastructure.

References

[1] T. Ravi, S. K. Singh, and R. K. Sharma, "Analysis, Monitoring, and Mitigation of Power Quality Disturbances in Distributed Generation Systems," *Frontiers in Energy Research*, vol. 10, pp. 989474, 2022.

[2] Daniel Gebbran, Sleiman Mhanna, Yiju Ma, Archie Chapman, and Gregor Verbic, "Fair Coordination of Distributed Energy Resources with Volt–Var Control and PV Curtailment," *IEEE Transactions on Power Systems*, 2022.

[3] K. R. Padiyar, *FACTS Controllers in Power Transmission and Distribution*, New Delhi, India: New Age International, 2021.

[4] B. S. Goud, S. S. Dash, and P. K. Hota, "Power Quality Improvement Using Distributed Power Flow Controller in Hybrid Power Systems," *Sustainability*, vol. 13, no. 20, pp. 11194, 2021.

[5] Mehmet Emin Akdogan and Sara Ahmed, "Improving Power Quality and Power Sharing in Multi-Microgrids Using Energy Storage Systems," *IEEE Access*, 2021.

[6] Frede Blaabjerg, Remus Teodorescu, Marco Liserre, and Adrian V. Timbus, "Overview of Control and Grid Synchronization for Distributed Power Generation Systems," *IEEE Transactions on Industrial Electronics*, 2019.

[7] Math H. J. Bollen and Irene Y. H. Gu, *Signal Processing of Power Quality Disturbances*, IEEE Press, 2018.