

EMERGING TECHNOLOGIES FOR POWER SYSTEM QUALITY IMPROVEMENT: A REVIEW

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Abstract— This paper investigates the importance of energy storage systems (ESS) in improving grid stability and integrating renewable energy sources. It provides a detailed overview of different ESS technologies and their applications in power systems, highlighting both the potential benefits and challenges. The paper also identifies areas for future research and suggests recommendations for implementing ESS to enhance grid stability. Additionally, the paper explores advanced techniques for power quality management. It discusses the impact of power quality issues like voltage sags, harmonics, and flicker on power system reliability and efficiency. The paper presents the latest developments in power quality management, including innovative mitigation strategies, advanced monitoring tools, and emerging technologies. Real-world case studies demonstrate the effectiveness of various approaches in improving power system reliability and performance.

Keywords— Power quality, Voltage sag, Harmonics, Flicker, Disturbances, Mitigation techniques, Monitoring tools, Diagnostic technologies.

I. INTRODUCTION

Power systems play a pivotal role in modern society, facilitating the distribution and utilization of electrical energy to meet the needs of various sectors ranging from residential to industrial. However, the quality of electrical power supplied by these systems is crucial for unprecedented challenges for the stability and reliability of electrical power grids. Unlike conventional fossil fuel-based power generation, renewable energy sources are inherently intermittent and variable, leading to fluctuations in power output that can strain grid operations and compromise stability. The intermittent nature of renewable energy poses several critical challenges to grid stability. Variability in generation levels can lead to voltage and frequency deviations, affecting the quality and reliability of electricity supply. Moreover, rapid changes in renewable energy output can exacerbate grid imbalances and increase the risk of power outages. As the penetration of renewable energy continues to grow, these challenges become increasingly pronounced, highlighting the urgent need for innovative solutions to ensure the resilience and stability of modern power systems. In this context, energy storage systems (ESS) have emerged as a promising solution to address the grid stability challenges associated with renewable energy integration. Energy storage technologies, including batteries, flywheels, and pumped hydro storage, offer the ability to store excess energy during periods of high generation and release it

when demand is high or renewable generation is low. By providing grid support services such as frequency regulation, voltage control, and energy balancing, ESS can help mitigate the impacts of renewable energy variability and enhance overall grid stability. Ensuring the reliability and efficiency of electrical devices and equipment. Power quality encompasses a range of factors including voltage stability, harmonic distortion, flicker, and other electrical phenomena that can adversely affect the performance of connected loads.

II. OVERVIEW OF POWER QUALITY ISSUES

Power quality issues arise from various sources and manifest in different forms, posing challenges to the operation of electrical systems. Voltage sags, for instance, are abrupt reductions in voltage levels typically caused by short circuits, equipment faults, or large load fluctuations. Harmonic distortion results from nonlinear loads such as power electronic devices and can lead to increased losses, overheating of equipment, and interference with communication systems. Flicker, characterized by rapid fluctuations in voltage or light intensity, is often associated with large industrial loads or renewable energy sources like wind turbines.

Common Power Quality Standards

Standard	Description
IEC 61000	International standards for electromagnetic compatibility and immunity.
IEEE 519	Standard for harmonic limits in electrical systems.
National Grid Codes	Regulations set by national grid operators for connecting electrical installations

III. IMPORTANCE OF POWER QUALITY MANAGEMENT

Effective power quality management is essential for maintaining the reliability, safety, and performance of electrical systems. Poor power quality can result in equipment malfunctions, production losses, and increased maintenance costs for end-users. In critical applications such as healthcare facilities, data centres, and industrial processes, even minor deviations in power quality can have significant consequences, leading to disruptions and financial losses. Therefore, ensuring high-quality electrical power is paramount for sustaining operations and enhancing productivity across various sectors.

IV. CHALLENGES AND IMPACTS OF POOR POWER QUALITY

The challenges posed by poor power quality are multifaceted, encompassing technical, economic, and regulatory aspects. From a technical perspective, mitigating power quality issues requires the deployment of sophisticated monitoring tools, diagnostic techniques, and mitigation devices. However, identifying the root causes of power quality disturbances and implementing effective solutions can be complex, particularly in large-scale power systems with diverse loads and operating conditions. Moreover, the economic impacts of poor power quality extend beyond direct equipment damage to include indirect costs associated with downtime, reduced efficiency, and lost revenue opportunities.



Figure 1 Power Quality Analyzer

Comparison of Real-time Monitoring System

Monitoring System	Features
Power Quality Analyzer	Advanced features such as harmonic analysis and waveform capture
Real time monitoring system	Continuous monitoring with even detection and alarm notification

Energy Storage Systems (ESS): Role of ESS in Power Quality Management: Energy Storage Systems (ESS) play a crucial role in power quality management by providing dynamic support to the electrical grid. ESS can store surplus energy during periods of low demand and discharge it when demand is high thereby balancing supply and demand and stabilizing grid voltage and frequency. Additionally, ESS can offer fast response times to mitigate voltage sags, frequency deviations, and transient disturbances, ensuring stable and reliable power supply to consumers. **Application of ESS for Voltage Support and Frequency Regulation:** ESS can be deployed for voltage support and frequency regulation in electrical power systems. During voltage sags or swells, ESS can inject or absorb reactive power to maintain voltage levels within acceptable limits, thereby improving power quality for connected loads. Similarly, ESS can respond to frequency deviations by injecting or absorbing active power, helping to stabilize grid frequency and prevent cascading failures.

Integration of ESS with Renewable Energy Systems: The integration of ESS with renewable energy systems such as solar and wind power can enhance power quality and grid stability. ESS can smooth out fluctuations in renewable energy output caused by variability in weather conditions, ensuring consistent and reliable power supply to the grid. By

buffering renewable energy generation and providing ancillary services such as frequency regulation and voltage support, ESS can facilitate the increased penetration of renewable energy sources while maintaining power quality standards.

Active Power Filters (APFS): Principle of Operation of APFS: Active Power Filters (APFS) are electronic devices used to mitigate power quality issues caused by harmonic distortion and reactive power imbalance. APF's operate by sensing the harmonic currents or reactive power components in the system and injecting compensating currents or voltages to cancel out these disturbances. By dynamically adjusting their output to match the load requirements, APFs can effectively mitigate harmonic distortion and improve power quality.

Types of APFS: Shunt, Series, and Hybrid: There are three main types of APFS: shunt, series, and hybrid. Shunt APFS are connected in parallel with the load and are used to compensate harmonic currents generated by non-linear loads. Series APFS are connected in series with the load or feeder and are used to mitigate voltage harmonics and improve power factor. Hybrid APFS combine the functionalities of both shunt and series APFS to provide comprehensive power quality improvement solutions.

Control Strategies for APFS in Mitigating Power Quality Issues: APFS employ various control strategies to effectively mitigate power quality issues. These include hysteresis control, proportional-integral (PI) control, and predictive control techniques. Hysteresis control offers fast response times and robustness to system disturbances, making it suitable for dynamic power quality compensation. PI control provides accurate and stable compensation under steady-state conditions, while predictive control algorithms anticipate future load variations and adjust compensation accordingly, optimizing APF performance in real-time.

Comparison of Active Power Filter Types

APF Type	Application	Characteristics
Shunt APF	Mitigation of harmonic currents	Connected in parallel with the load
Series APF	Voltage harmonic and power factor correction	Connected in series with the load or feeder
Hybrid APF	Comprehensive power quality improvement	Combines functionalities of shunt and series APFs

V. CASE STUDIES AND APPLICATIONS

Industrial Power Quality Enhancement
Case Study: Implementation of Power Quality Solutions in a Manufacturing Plant: In this case study, we examine the implementation of power quality solutions in a manufacturing plant to enhance industrial power quality. The manufacturing plant, which produces sensitive electronic components, was experiencing frequent disruptions and equipment failures due to voltage sags, harmonic distortion, and flicker. To address these issues, a comprehensive power quality assessment was conducted, which revealed the need

for voltage sag mitigation, harmonic filtering, and flicker reduction measures.

Voltage sag mitigation was achieved by installing Dynamic Voltage Restorers (DVRs) at critical points in the plant's electrical distribution system. These DVRS provided rapid voltage correction during sag events, ensuring uninterrupted operation of sensitive equipment. Harmonic filtering solutions, including the deployment of active harmonic filters and passive filters, were implemented to mitigate harmonic distortion caused by nonlinear loads. Advanced control strategies were employed to optimize filter performance and adapt to changing load conditions.

Furthermore, flicker reduction measures such as the installation of capacitor banks and STATCOMS were implemented to minimize flicker levels and improve visual comfort for plant personnel. Real-time power quality monitoring systems were also deployed to continuously monitor power parameters and provide early warning of potential disturbances.

The implementation of these power quality solutions resulted in significant improvements in the reliability, efficiency, and productivity of the manufacturing plant. Equipment downtime and production losses were minimized, leading to increased operational uptime and cost savings. The success of this case study demonstrates the effectiveness of tailored power quality solutions in addressing industrial power quality challenges and ensuring uninterrupted operation of critical manufacturing processes.

Distribution System Power Quality Improvement

Case Study: Power Quality Improvement in a Distribution Network Using Advanced Technologies: In this case study, we explore the implementation of power quality improvement measures in a distribution network to enhance grid reliability and customer satisfaction. The distribution network, serving a large urban area, was experiencing voltage fluctuations, harmonic distortion, and reliability issues, leading to frequent customer complaints and service interruptions.

To address these challenges, advanced power quality monitoring systems were deployed throughout the distribution network to identify areas of concern and assess the magnitude and frequency of power quality disturbances. This data-driven approach enabled targeted interventions to improve power quality in specific areas with the greatest need.

Voltage regulation and stability were improved through the installation of voltage regulators and capacitor banks at strategic points in the distribution network. These devices provided voltage support and reactive power compensation, reducing voltage variations and enhancing grid stability.

Furthermore, active power filters (APFS) were deployed to mitigate harmonic distortion caused by non-linear loads such as commercial and industrial facilities. Shunt APFS were installed at substations and critical feeder points to suppress harmonics currents and ensure compliance with power quality standards.

The integration of renewable energy sources, such as solar and wind power, was also explored to diversify the energy mix and reduce greenhouse gas emissions. Energy storage systems (ESS) were deployed to provide grid support services, including frequency regulation and peak shaving, thereby improving overall grid reliability and resilience.

The implementation of these advanced power quality improvement measures resulted in significant reductions in power quality disturbances, customer complaints, and service interruptions. The distribution network's reliability and performance were enhanced, leading to improved customer satisfaction and operational efficiency. This case study highlights the importance of proactive power quality management and the effectiveness of advanced technologies in addressing distribution system challenges.

Summary of Key Findings: Through our investigation, we have highlighted the importance of understanding power quality parameters, the causes and sources of power quality disturbances, and the standards and regulations governing power quality. Techniques such as voltage sag mitigation using Dynamic Voltage Restorers (DVRs), harmonic filtering and compensation using Active Power Filters (APFs), and flicker reduction methods have been discussed, along with their applications and case studies demonstrating their effectiveness in real-world scenarios. Advanced monitoring and diagnostic tools, including power quality analysers, real-time monitoring systems, and diagnostic technologies, have been examined for their role in power quality assessment and analysis.

Future Trends and Directions in Power Quality Management: Looking ahead, several trends and directions are expected to shape the future of power quality management. The integration of renewable energy sources, energy storage systems, and smart grid technologies will continue to play a significant role in enhancing power system resilience and sustainability. Advanced control algorithms, machine learning, and data analytics will enable predictive maintenance, adaptive control strategies, and optimized operation of power quality mitigation devices. Additionally, the development of standards and regulations tailored to emerging technologies and evolving grid architectures will be essential to ensure interoperability, compatibility, and compliance with power quality requirements.

Importance of Continuous Research and Development: Continuous research and development are crucial for advancing power system reliability and efficiency in the face of evolving challenges and technological advancements. Innovation in power quality management will drive improvements in grid resilience, customer satisfaction, and economic competitiveness. Collaboration among industry stakeholders, academia, and government agencies is essential to foster innovation, share best practices, and address emerging power quality issues. By investing in research, testing, and demonstration projects, we can accelerate the adoption of novel solutions and pave the way for a more resilient and sustainable energy future.

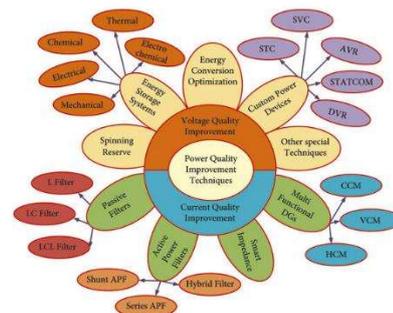


Figure 2 Different methods for power quality improvement

VI. CONCLUSION

Power quality management plays a critical role in ensuring the reliability, efficiency, and stability of electrical power systems. Throughout this paper, we have explored various techniques, technologies, and emerging trends in power quality management, aimed at addressing common power quality issues such as voltage sags, harmonics, flicker, and other disturbances. So, effective power quality management is essential for ensuring the reliable and efficient operation of electrical power systems. By leveraging advanced techniques, technologies, and continuous research and development efforts, we can address current challenges and embrace future opportunities to enhance power system reliability, resilience, and sustainability for the benefit of society as a whole.

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