

Advanced Techniques for Power Quality Management in Electrical Power Systems: A Comprehensive Review

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Abstract

This paper provides a comprehensive review of advanced techniques and technologies for power quality management in electrical power systems. Power quality issues such as voltage sags, harmonics, flicker, and other disturbances significantly impact the reliability and efficiency of power systems. Addressing these challenges requires the implementation of various techniques and technologies to maintain high-quality electrical power. This paper discusses the latest advancements in power quality management, including innovative mitigation strategies, advanced monitoring and diagnostic tools, and emerging technologies for improved power quality. Additionally, case studies and real-world applications are presented to illustrate the effectiveness of different approaches in enhancing power system reliability and performance.

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

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

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.

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.

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 centers, 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.

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.

Objectives and Scope of the Paper

This paper aims to provide a comprehensive review of advanced techniques and technologies for power quality management in electrical power systems. By examining the latest developments in power quality mitigation strategies, monitoring tools, and diagnostic technologies, the paper seeks to address the following objectives:

1. To elucidate the underlying causes and effects of power quality disturbances such as voltage sags, harmonics, and flicker.
2. To evaluate the effectiveness of existing techniques and technologies for mitigating power quality issues and enhancing system reliability.
3. To explore emerging trends and future directions in power quality management, including the integration of renewable energy sources and smart grid technologies.
4. To provide insights into practical applications and case studies demonstrating the implementation of power quality solutions in real-world scenarios across different industries and sectors.

The scope of the paper encompasses a wide range of topics related to power quality management, including voltage sag mitigation techniques, harmonic filtering and compensation methods, flicker reduction strategies, advanced monitoring and diagnostic tools, as well as emerging technologies such as energy storage systems and active power filters. Through an in-depth analysis of these topics, the paper aims to contribute to the understanding and advancement of power quality management practices for the benefit of researchers, practitioners, and policymakers in the field of electrical engineering and energy management.

BACKGROUND AND FUNDAMENTALS

Definition of Power Quality Parameters

Power quality parameters refer to the characteristics of electrical power that determine its suitability for proper operation of electrical equipment and devices. These parameters encompass a variety of aspects including voltage magnitude, frequency stability, waveform distortion, and continuity of supply. Common power quality parameters include:

Voltage Magnitude: The magnitude of voltage supplied to electrical loads, typically expressed in volts (V). Variations in voltage magnitude beyond acceptable limits can lead to equipment malfunction or damage.

Frequency Stability: The stability of the power system frequency, usually measured in hertz (Hz). Deviations from the nominal frequency can affect the synchronization of equipment and disrupt sensitive processes.

Waveform Distortion: The deviation of the voltage or current waveform from its ideal sinusoidal shape. Waveform distortion is often caused by nonlinear loads and can lead to harmonic distortion and increased losses in electrical systems.

Continuity of Supply: The ability of the power system to maintain a steady and uninterrupted supply of electrical energy to connected loads. Interruptions, voltage sags, and transient disturbances can disrupt continuity of supply and impact equipment performance.

Causes and Sources of Power Quality Disturbances

Power quality disturbances can arise from various sources within the electrical power system and external factors. Some common causes of power quality disturbances include:

Electrical Faults: Short circuits, ground faults, and other electrical faults can cause voltage dips, interruptions, and transient disturbances in the power supply.

Nonlinear Loads: Devices such as computers, variable frequency drives, and LED lighting can introduce harmonic currents into the power system, leading to waveform distortion and increased losses.

Switching Operations: Switching of capacitors, transformers, and other power system components can produce transients and voltage spikes that affect the quality of power supplied to connected loads.

Environmental Factors: Lightning strikes, atmospheric conditions, and electromagnetic interference from nearby sources can induce voltage fluctuations and disturbances in the power supply.

Standards and Regulations for Power Quality

To ensure the reliability and compatibility of electrical systems, various standards and regulations have been established to define acceptable levels of power quality and specify compliance requirements. These standards are developed and maintained by organizations such as the International Electro technical Commission (IEC), Institute of Electrical and Electronics Engineers (IEEE), and national regulatory bodies. Common standards and regulations related to power quality include:

IEC 61000 series: International standards covering electromagnetic compatibility (EMC) and immunity of electrical equipment to power quality disturbances such as harmonics, voltage fluctuations, and transients.

IEEE 519: Standard for harmonic limits in electrical power systems, specifying maximum permissible levels of harmonic distortion to ensure compatibility and performance of interconnected systems.

National Grid Codes: Regulations set by national grid operators to define technical requirements and performance criteria for connecting and operating electrical installations within their jurisdictions.

Measurement and Assessment of Power Quality

The measurement and assessment of power quality involve the use of specialized instruments and techniques to monitor and analyze various power quality parameters. Common methods for power quality measurement include:

Power Quality Analyzers: Portable devices equipped with voltage and current sensors, capable of capturing and analyzing waveform data to identify power quality disturbances such as voltage sags, swells, harmonics, and flicker.

Data Loggers: Devices used for continuous monitoring of power quality parameters over an extended period, enabling trend analysis and identification of long-term power quality issues.

Power Quality Monitoring Systems: Real-time monitoring systems installed at substations or distribution points to monitor and record power quality parameters, providing insights into system performance and enabling timely intervention in case of disturbances.

Diagnostic Techniques: Advanced diagnostic tools and software algorithms used to analyze power quality data, identify root causes of disturbances, and recommend appropriate mitigation measures.

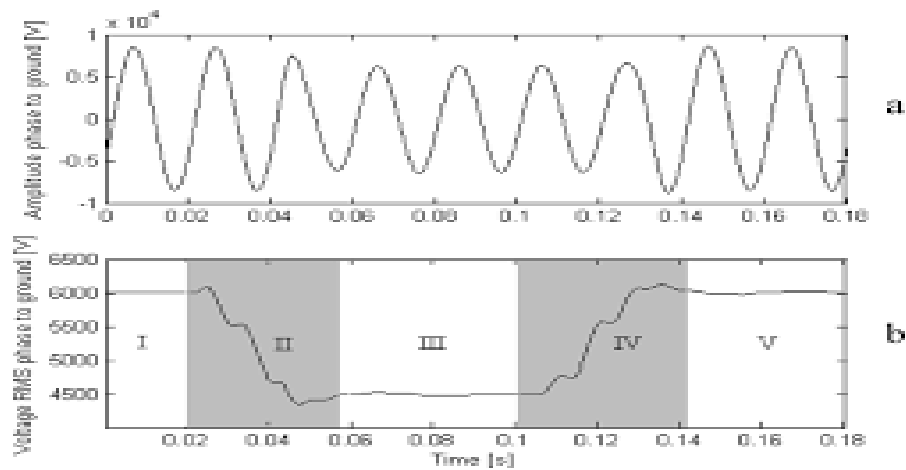


Fig. 1 Voltage Disturbance Waveforms

Table 1 Common Power Quality Standards

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

TECHNIQUES FOR POWER QUALITY MANAGEMENT

Voltage Sag Mitigation Techniques

Voltage Sag Causes and Effects: Voltage sags, also known as voltage dips, are brief reductions in voltage levels typically lasting less than a second. They can occur due to various factors such as sudden changes in load demand, faults in the power distribution network, or starting of large motor loads. Voltage sags can lead to equipment malfunction, production downtime, and damage to sensitive electronic devices.

Voltage Sag Mitigation using Dynamic Voltage Restorers (DVRs): Dynamic Voltage Restorers (DVRs) are advanced power electronic devices designed to mitigate voltage sags by injecting compensating voltage into the system. When a voltage sag occurs, the DVR rapidly detects the disturbance and injects a voltage waveform of appropriate magnitude and phase to restore the voltage to its nominal level at the point of common coupling (PCC). DVRs provide fast and accurate voltage correction, making them suitable for protecting critical loads from voltage disturbances.

Case Study: Application of DVRs in Industrial Power Systems: In industrial power systems, voltage sags can have severe consequences on production processes and equipment reliability. By deploying DVRs at critical load centers, such as manufacturing facilities and industrial plants, voltage sag mitigation can be achieved effectively. A case study of a manufacturing plant implementing DVRs to protect sensitive equipment from voltage sags demonstrates the practical application and benefits of this technology in ensuring uninterrupted operation and minimizing production losses.

Harmonic Filtering and Compensation

Harmonic Distortion Sources and Effects: Harmonic distortion results from the presence of non-linear loads in the power system, such as power electronic converters, variable frequency drives, and arc furnaces. These loads draw non-sinusoidal current waveforms, causing harmonic currents to flow back into the power supply system. Harmonic distortion can lead to overheating of transformers and conductors, interference with communication systems, and malfunction of sensitive equipment.

Passive and Active Harmonic Filters: Passive harmonic filters, consisting of passive components such as capacitors, inductors, and resistors, are commonly used to attenuate harmonic currents by creating a low-impedance path for harmonic frequencies. Active harmonic filters employ power electronic devices to actively inject compensating currents, dynamically adjusting their magnitude and phase to cancel out harmonic currents generated by non-linear loads. Both passive and active harmonic filters offer effective solutions for harmonic mitigation, with each having its advantages and limitations.

Application of FACTS Devices for Harmonic Compensation: Flexible Alternating Current Transmission Systems (FACTS) devices, such as Static Var Compensators (SVCs) and Static Synchronous Compensators (STATCOMs), can be utilized for harmonic compensation in power systems. These devices provide reactive power support and voltage regulation, thereby mitigating voltage fluctuations and improving power quality. By controlling the output voltage of FACTS devices, harmonic currents can be effectively suppressed, reducing harmonic distortion in the system.

Case Study: Harmonic Mitigation in Renewable Energy Systems: Renewable energy sources, particularly wind and solar power, are characterized by intermittent and variable output. The integration of renewable energy systems into the grid can introduce harmonic distortion due to the non-linear characteristics of power electronic converters used in inverters. Harmonic mitigation techniques, including the use of active harmonic filters and FACTS devices, can help ensure grid compatibility and stability in renewable energy installations. A case study of harmonic mitigation in a wind farm or solar PV plant demonstrates the effectiveness of these techniques in minimizing harmonic distortion and maintaining power quality standards.

Flicker Reduction Methods

Flicker Sources and Characteristics: Flicker is the rapid and repetitive variation in luminance or voltage, often perceptible as fluctuations in light intensity. Flicker sources include arc furnaces, arc welding equipment, and large motor starting, as well as rapid changes in electrical loads. Flicker can cause discomfort, visual fatigue, and even trigger seizures in susceptible individuals, making it a concern in residential, commercial, and industrial environments.

Flicker Mitigation using Capacitor Banks and STATCOMs: Capacitor banks are commonly employed for flicker mitigation by compensating reactive power and stabilizing voltage fluctuations caused by varying loads. Static Synchronous Compensators (STATCOMs) are also effective in mitigating flicker by providing dynamic reactive power support and voltage regulation. By injecting or absorbing reactive power as required, these devices can smooth out rapid voltage fluctuations and reduce flicker levels to acceptable limits.

Advanced Control Strategies for Flicker Reduction: Advanced control techniques, such as predictive control and adaptive filtering, can be applied to flicker mitigation systems to enhance performance and efficiency. Predictive control algorithms utilize mathematical models of the power system to anticipate flicker events and proactively adjust compensating actions, minimizing flicker levels and improving system response. Adaptive filtering techniques dynamically adjust filter parameters based on real-time measurements, optimizing flicker reduction performance under varying operating conditions.

Case Study: Flicker Mitigation in Residential Distribution Networks: Flicker caused by household appliances and lighting can degrade power quality in residential distribution networks, leading to discomfort and annoyance for occupants. By implementing flicker mitigation measures such as capacitor banks or STATCOMs at distribution substations or feeder points, utilities can effectively reduce flicker levels and enhance the quality of service provided to residential customers. A case study of flicker mitigation in a residential distribution network demonstrates the practical implementation and benefits of these techniques in improving customer satisfaction and reducing complaints related to flicker.

ADVANCED MONITORING AND DIAGNOSTIC TOOLS

Power Quality Monitoring Devices

Overview of Power Quality Analyzers and Meters: Power quality analyzers and meters are essential tools for monitoring and analyzing electrical parameters to assess power quality levels in electrical systems. These devices typically measure key parameters such as voltage, current, frequency, and waveform characteristics. Power quality analyzers offer advanced features such as harmonic analysis, waveform capture, and event logging, allowing users to identify and analyze power quality disturbances such as voltage sags, swells, harmonics, and

transients. Power quality meters provide continuous monitoring of power parameters and can be integrated into SCADA (Supervisory Control and Data Acquisition) systems for centralized monitoring and control of power networks.

Real-time Monitoring Systems for Power Quality Assessment: Real-time monitoring systems enable continuous and remote monitoring of power quality parameters in electrical distribution networks. These systems consist of sensors, data acquisition units, and communication interfaces that collect and transmit power quality data to a central monitoring station. Real-time monitoring systems provide instant visibility into power quality conditions, allowing operators to detect and respond to abnormalities in a timely manner. Advanced features such as event detection, alarm notifications, and trend analysis enhance the effectiveness of real-time monitoring systems for power quality assessment and management.

Diagnostic Technologies

Use of Machine Learning and Data Analytics for Power Quality Analysis: Machine learning and data analytics techniques are increasingly being applied to power quality analysis to extract valuable insights from large volumes of data collected from monitoring devices. These techniques involve the use of algorithms and statistical models to identify patterns, trends, and anomalies in power quality data. Machine learning algorithms can automatically classify power quality events, predict future occurrences, and optimize control strategies for power quality improvement. Data analytics tools enable users to perform advanced data visualization, correlation analysis, and root cause analysis, facilitating effective decision-making and problem-solving in power quality management.

Fault Detection and Localization Algorithms: Fault detection and localization algorithms are used to identify and locate faults or abnormalities in electrical power systems that may degrade power quality. These algorithms analyze voltage and current waveforms to detect characteristic signatures of faults such as short circuits, ground faults, and insulation failures. By comparing measured data with expected or normal operating conditions, fault detection algorithms can identify deviations and trigger alarms or notifications for further investigation. Localization algorithms utilize information from multiple monitoring points to pinpoint the location of faults within the power system, enabling rapid response and restoration of power quality.



Figure 1 Power Quality Analyzer

Table 1 Comparison of Real-time Monitoring Systems

Monitoring System	Features
Power Quality Analyzer	Advanced features such as harmonic analysis and waveform capture
Real-time Monitoring System	Continuous monitoring with event detection and alarm notifications

EMERGING TECHNOLOGIES FOR POWER QUALITY IMPROVEMENT

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. APFs 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.

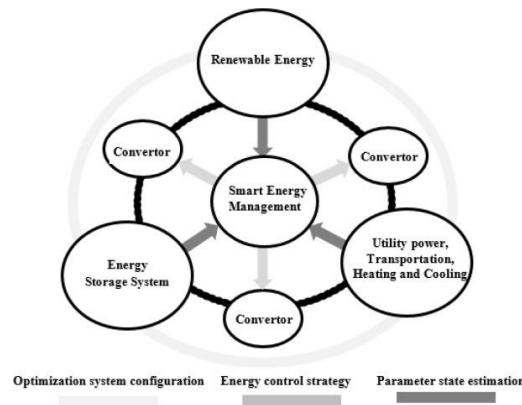


Figure 1 Integration of Energy Storage Systems with Renewable Energy

Table 1 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 harmonics 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

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 harmonic 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.

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.

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 analyzers, 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.

In conclusion, 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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