

A comprehensive exploration of IoT-enabled smart grid systems: power quality issues, solutions, and challenges

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Received: 11 May 2024 / Accepted: 18 July 2024

Abstract. The potential for Internet of Things (IoT) technology to transform energy management has led to significant interest in its incorporation into smart grid systems. This review discusses the state of IoT-powered smart grids today, focusing on applications, current technology, and power quality (PQ) issues. Key problems including harmonics, transients, and voltage fluctuations are identified, and mitigation techniques using sophisticated filters and intelligent systems like fuzzy logic control (FLC) and artificial neural networks (ANN) are investigated. Concerns about interoperability and scalability are among the other challenges the review lists for IoT implementation. The revolutionary potential of IoT in improving smart grid efficiency and dependability is highlighted in our findings, which provide valuable insights for scholars and practitioners seeking to develop this sector.

Keywords: Artificial intelligence, Cloud computing, Data analytics, Edge computing, IoT, Machine learning, Power quality, Smart grid.

Abbreviations

ANN	Artificial Neural Network
ANFIS	Adaptive Neural Fuzzy Interface System
AI	Artificial Intelligence
APF	Active Power Filter
BPNN	Back Propagation Neural Network
CC	Cloud Computing
CPD	Custom Power Device
DC	Direct Current
DVR	Dynamic Voltage Regulator
EC	Edge Computing
EV	Electric Vehicles
FC	Fixed Capacitor
FLC	Fuzzy Logic Controller
HAPF	Hybrid Active Power Filters
HVDC	High Voltage Direct Current
IoT	Internet-of-Things
ML	Machine Learning
MMC	Modular Modified Converters
PID	Proportional Integral Derivative
PQ	Power Quality

PPF	Passive Power Filter
PFC	Power Factor Correction
PWM	Pulse Width Modulation
QoS	Quality of Supply
SST	Solid State Transformer
SG	Smart Grid
STACOM	Static Synchronous Compensator
SVC	Static VAR Compensator
SSTS	Solid-State Transfer Switch
UPDC	Unified Power Quality Controller
UPS	Uninterruptible Power Supply
WSN	Wireless Sensor Network

1 Introduction

In conventional power grids, electricity travels in a unidirectional manner, moving from the utility provider to the end-users. This unidirectional flow is a defining characteristic of conventional power systems. Centralized control and monitoring are vital in these grids to maintain a balance between power generation and consumer demands within the constraints of the power system. Utility companies are responsible for overseeing the entire process, which includes

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generating, transmitting, and distributing electrical energy [1–3]. Their role extends to supplying electricity to consumers and implementing billing practices that ensure cost recovery and profitability. However, with the emergence of electronic devices as a rapidly growing segment of electricity demand, particularly with new high-consumption sources like electric vehicles (EVs), traditional grids are facing significant challenges like energy losses, inconsistent communication and surveillance, inefficient routing and distribution, insufficient presence of advanced technological solutions, and so on [4, 5].

The introduction of smart grid technologies aims to address these challenges. Smart grids incorporate advanced metering infrastructure, two-way communication technologies, and automated control systems [6, 7]. This incorporation enables more effective handling of energy distribution, improved assimilation of renewable energy sources, enhanced surveillance and response capabilities, and elevated grid reliability and resilience on the whole. As a result, transitioning from conventional to smart grids is seen as a critical step in modernizing power infrastructure to meet the evolving demands of consumers and the challenges posed by new high-consumption devices and technologies. Indeed, traditional power grids confront numerous challenges that go beyond just managing the flow of electricity [8, 9]. These challenges include escalating energy demands, reliability concerns, security threats, the incorporation of renewable energy sources, and the difficulties associated with aging infrastructure. The smart grid paradigm emerges as a pivotal solution to these multifaceted challenges, harnessing a spectrum of advanced information and communication technologies. The smart grid plays a crucial role in facilitating informed decision-making in response to energy demand [8, 10, 11]. This involves live pricing mechanisms, autonomous recovery abilities, scheduling of power consumption, and maximizing the efficient use of electrical energy. Certainly, these choices can significantly improve both the power quality (PQ) and efficiency of the grid. By ensuring a harmony between power generation and usage, the smart grid fosters an optimized and more dependable power infrastructure.

The diversity of load types in modern smart grids indeed plays a crucial role in the challenge of maintaining PQ. The task of ensuring high PQ is becoming increasingly complex due to the varied nature of the loads and their distinct characteristics. Advanced grid interfacing technologies, especially those controlled by artificial intelligence (AI), are key to addressing these challenges. Maintaining PQ in the era of smart grids requires sophisticated, AI-driven grid interfacing technologies capable of adapting to a wide range of load demands and conditions [12, 13]. This is essential not only for the efficient and safe operation of the grid but also for ensuring the reliability and longevity of the connected equipment, both on the consumer and utility sides [14]. The challenge lies in developing and implementing AI systems that can effectively manage these complexities in real-time while being adaptable to future technological advancements and changes in energy consumption patterns. AI-powered power quality monitoring chips represent a significant advancement in managing PQ in smart grids [15, 16]. They offer a comprehensive solution by not only addressing current PQ issues but also predicting and

preventing future problems, thereby enhancing the overall effectiveness, dependability, and sustainability of the Smart Grid framework. Indeed, problems with PQ can manifest in various contexts, including data centers, home power systems, and renewable energy collector systems. These issues offer valuable insights and serve as a starting point for discussions about the potential advantages and implementation of direct current (DC) distribution systems [17, 18]. Various data analysis processes to ensure sustained power quality enhancement within the smart grid are as follows (Fig. 1).

However, transitioning to DC distribution also involves challenges, such as the need for new infrastructure, safety considerations (as DC can be more dangerous at high voltages), and compatibility issues with existing AC appliances and systems. Therefore, while DC distribution presents a promising avenue, especially in terms of the effectiveness of evolving PQ challenges and renewable energy integration, it requires careful consideration and planning for effective implementation. The integration of new technologies like the Internet of Things (IoT), machine learning, and data analytics represents a significant advancement in addressing PQ issues [19, 20]. The application of artificial neural networks (ANNs) in power quality management is quite accurate. The flexibility and learning capabilities of ANNs make them particularly well-suited for dealing with the complexities and dynamics of electrical power systems. Additionally, as ANNs continue to evolve, their integration into power systems is likely to become more sophisticated [21, 22].

This includes the use of deeper neural networks for more complex pattern recognition and predictive analytics, as well as the integration with other emerging technologies such as IoT devices for more comprehensive grid monitoring and management [23, 24]. The role of FLCs in handling PQ issues, particularly in scenarios characterized by uncertainty or imprecision, is indeed advantageous in environments where the data is not strictly binary (true or false) or where human-like reasoning is required. FLCs offer a robust and effective means for managing complex and uncertain situations in PQ, complementing traditional control methods and contributing to a more reliable and efficient power grid. ANFIS indeed represents a sophisticated approach to managing PQ issues, particularly because it merges the learning capabilities of neural networks with the reasoning approach of fuzzy logic [25, 26]. This hybrid system is particularly effective in dealing with complex, nonlinear systems like electrical grids. Overall, the ability of ANFIS to learn from data, adapt to changing conditions, and handle uncertainties makes it a powerful tool in the realm of PQ management, especially in modern, complex, and dynamic power systems. These technologies, individually and in combination, offer sophisticated methods for monitoring, analyzing, and managing the power quality of smart grids. Table 1 illustrates the overall literature review on power quality issues in smart grids.

1.1 Emerging smart grids

A smart grid represents an improved electrical grid system employing digital communication technology to oversee, assess, manage, and convey information throughout the

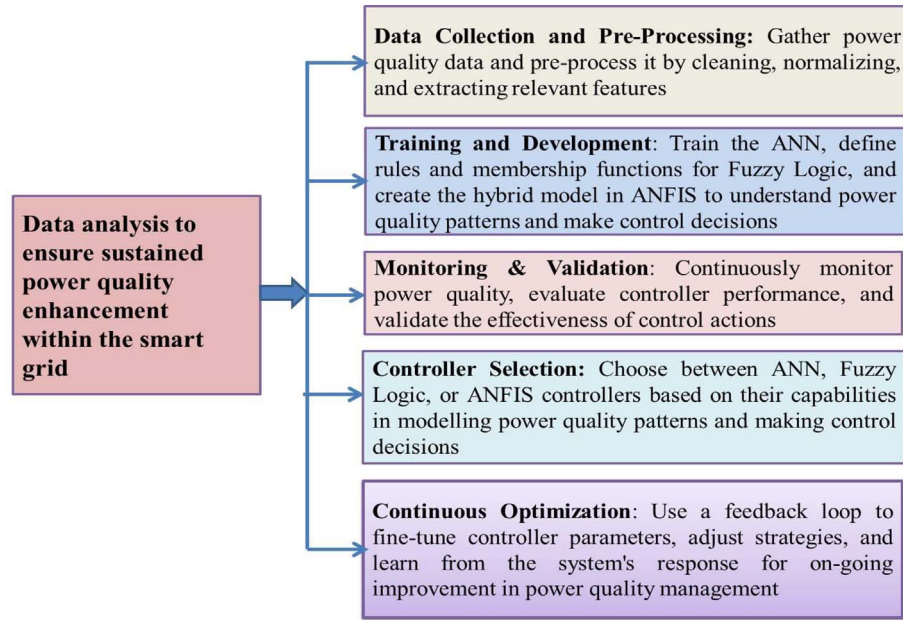


Fig. 1. Data analysis process to ensure power quality.

supply chain from utility providers to consumers in a manner that is more efficient, dependable, and environmentally sustainable [27]. It integrates modern information and communication technology into traditional electrical grids, enabling two-way communication between the utility and its customers and between different components of the grid itself. It represents a significant transformation in electricity distribution and management, leveraging digital technology to create a more efficient, reliable, and sustainable electricity supply system while providing consumers with enhanced control over their energy consumption [28, 29]. It collects data from various grid components and analyzes it to forecast power supply and demand, which may be used to control power. Utility companies and customers can interact with each other thanks to the Smart Grid. What makes the grid intelligent is the visualization needed to detect the power along the power wires. It is possible for consumers to receive data on how much electricity they use periodically from smart meters, which integrate communication networks into the grid and allow users to monitor their use [21, 30]. By controlling electricity usage, Smart Grid can assist the consumer in making financial savings. Our requirement for further capacity might be reduced by the potential energy efficiency provided by the smart grid. A smart grid needs to be created by combining numerous technologies. Additional components are being designed, developed, and put into effect as well. The basic components of a smart grid are represented in Figure 2.

1.1.1 Wireless sensors

On our high-voltage grid, the currently installed sensors typically give measurements for grid operation and control in a single direction. Operators can quickly find, recognize, and correct abnormalities with wireless sensor-sensing devices. Power can be automatically directed to avoid

blackouts in specific conditions. Increased information provided by additional sensors will boost electricity supply efficiency, enable higher utilization of existing lines, and strengthen the grid's reliability [31].

1.1.2 Integrated communications system

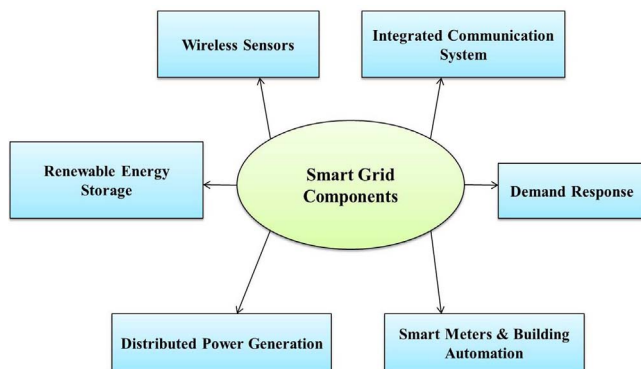
Systems that are used for gathering information, communication, and control are crucial to the smart grid. It can be achieved by integrating a more advanced information infrastructure with the current electrical infrastructure. Wireless communication systems on specific radio frequencies and wavelengths are a strong contender to become the industry standard in order to exchange data from the new sensors and connect with other electronic devices. Wired communications (fiber optics, power lines) will also be part of it [32, 33]. A combination of current commercial communications infrastructure and specialized communications systems must be compatible with providing the necessary security and control. To enable two-way flow, more flexibility, automation, and monitoring technology must be expanded via the distribution systems.

1.1.3 Demand response

The primary aim of a smart grid is to lower peak power demand. Customers expect to have access to power whenever they need it. Utilities can predict the broad consumption pattern, but the majority must keep extra generation equipment in a "spinning reserve" due to demand fluctuations. By better matching supply and demand, they may reduce these losses by half. Customers are encouraged via demand response programs to reduce their use during peak electricity consumption times [34, 35]. Critical peak pricing is one of the rate structures utilities use in demand response programs. When demand is excellent, they raise prices to discourage use.

Table 1. Overview of literature survey on power quality mitigation techniques used in smart grid.

Ref, Year	Feature/Technique	Key findings and conclusion	Research gaps identified
[6], 2024	Grid automation and control	Automated voltage regulation and reactive power control to mitigate fluctuations and enhance stability.	Current automation techniques mainly address reactive power control. There is a need for research on proactive control strategies that respond dynamically to changing grid conditions.
[7], 2024	Advanced filtering and conditioning	Deployment of active/passive harmonic filters, DVRs, and STATCOMs for harmonic mitigation and stability.	Current filtering techniques focus on harmonic mitigation, but research on integrating multiple PQ improvement techniques is lacking.
[8], 2024	Data analytics and AI	Application of AI for predictive maintenance and anomaly detection in PQ data.	AI in predictive maintenance is advancing, but research is needed on integrating AI with real-time data analytics for proactive PQ management.
[9], 2024	Intelligent control strategies	Adaptive control algorithms for dynamic load management and voltage stability.	Current intelligent control strategies focus on voltage stability, but research is needed on integrating these strategies with DERs to enhance grid resilience.
[10], 2023	Communication and networking	Advanced communication protocols and networks for reliable data exchange in smart grids.	Advanced communication networks are crucial for reliable data exchange, but research on cybersecurity challenges and resilience in smart grids is needed.
[8], 2022	Advanced monitoring and measurement	Continuous monitoring of voltage, current, and frequency parameters using smart meters and sensors.	Advancements in real-time monitoring technologies exist, there is a need for studies on standardizing monitoring protocols across smart grids.
[11], 2021	Integration of renewable energy sources (RES)	Use of energy storage systems (ESS) and hybrid energy systems to manage variability from renewables.	While ESS and hybrid systems help manage RES variability, research on optimizing their grid integration for PQ improvements is limited.
[12], 2021	Synchrophasor applications	Real-time monitoring and control using synchrophasor technology for grid stability.	Synchrophasor technology enhances real-time monitoring, but research is needed to improve its accuracy and reliability under diverse grid conditions and complexities.

**Fig. 2.** Smart grid components.

1.1.4 Advanced metering infrastructure (AMI)

Traditionally, data on electricity usage was manually gathered on-site with predetermined values and periods. This practice results in accuracy and timeliness deficiencies. Using public or private communication networks, IoT enables AMI reading systems based on WSN and optimal PLC. AMI meters are upgraded digital electric meters kept outside homes that replace conventional electric meters. The use of the IoT and AMI meters measures power used and sends costs from utility power stations to client premises. As a result, based on the energy and cost data that is received from AMI, consumers can adjust their energy consumption to save money. The timeliness, effectiveness, and accuracy of the data on power use make this system so important [36, 37].

1.1.5 Distributed power generation

The electric grid was designed to deliver power from several use points to huge, centralized power facilities in a single direction [38]. The system must transport electricity from numerous producers dispersed across the system using small-scale renewable energy sources and route the power as necessary. Due to their erratic nature, wind and solar energy require modern automation and control methods to integrate into the grid successfully. As the amount of renewable energy generated globally increases, new strategies are being created with growing attention [39, 40]. The types of controls utilized show the impact on the efficiency and dependability of solar and wind power plants. Better controls can potentially lower the cost of power production and extend their useful operating periods in the Indian energy portfolio.

1.1.6 Renewable energy storage

By allowing some degree of decoupling between energy production and usage, the capacity to store energy can offer a significant amount of flexibility in grid work. This could be particularly beneficial for renewable energy sources. Renewable energy sources may be temporarily stored for future use or supplied back to the network as needed with the help of a smart grid. There are many choices for storing electricity, and their use could grow more prevalent if storage technology developments result in lower costs, more reliability, higher energy, and higher power densities [41, 42]. Electric utilities have to deal with various new challenges due to the complexity of their networks, the increasing incorporation of renewable energy sources, issues with voltage profiles, and losses at fundamental and harmonic frequencies. A custom power device (CPD) combines a controller to provide clients with high-quality electricity, while a condenser functions as a compensator.

1.2 IoT-enabled smart grid

With its bidirectional communication and distributed computational capabilities, the IoT offers potential solutions for the challenges of transitioning traditional energy networks to smart grids. In a smart grid setup, essential services include integrating distributed renewable energy sources, establishing real-time data communication between consumers and providers regarding tariffs and energy usage, and building infrastructure to collect and analyze grid parameters for informed decision-making [43, 44]. The intelligent power grid produces substantial data that requires effective transportation, processing, and storage to enable informed decision-making [45]. Given its diverse benefits across various industries, the IoT emerges as a promising solution with considerable opportunity for integration into smart energy systems. Leveraging the intelligent and proactive capabilities of IoT can enhance the system's accuracy and efficiency, facilitating a seamless transition from legacy power grids to smarter energy systems [46]. By amalgamating sensing and actuation systems within the Advanced Metering Infrastructure (AMI), IoT offers significant potential for enhancing and controlling energy usage efficiently. Advanced IoT technologies can efficiently collect, transmit,

and analyze this data, leading to improved grid management [47–49].

IoT technologies find application in several areas within smart energy grid systems, such as power generation infrastructure management, supervisory control and data acquisition (SCADA) systems for transmission and distribution operations, advanced metering infrastructure, and environmental monitoring for carbon footprint management [50, 51]. Leveraging advanced cloud and edge computing technologies allows for distributed monitoring and management of distributed energy resources while addressing cybersecurity vulnerabilities inherent in traditional centralized SCADA systems. Moreover, IoT-enabled smart grids can boost efficiency by smoothly integrating with other intelligent entities such as appliances, residences, structures, and urban areas. This integration enables remote access and control through the internet [52, 53]. Nevertheless, deploying IoT-enabled smart grids poses challenges, such as the requirement for advanced computational capabilities and effective resource allocation mechanisms. Despite the efficiency benefits of monitoring and managing the energy system, hurdles persist in the implementation of IoT-enabled smart grids. Table 2 illustrates a comparison between conventional smart grids and IoT-enabled smart grids across various facets of power systems.

1.3 Novelty and contributions of this paper

Our survey on smart grid systems, focuses on power quality issues, IoT-based monitoring and control techniques, and data processing methods. However, we acknowledge that existing surveys have not comprehensively covered all major factors of power quality issues in smart grids, nor have they detailed open problems and future research directions extensively. Our primary goal is to address this gap by conducting a comprehensive survey. This survey aims to cover all significant aspects of power quality issues in smart grid systems, including identifying key factors contributing to these challenges and providing insights into open research questions and future research directions.

The contributions of the survey are summarized as follows:

- **Examination of Smart Grid Concepts:** Detailed exploration of smart grid concepts and architectures designed for IoT-enabled systems.
- **Role of IoT, AI, and Data Analytics:** Discussion on how IoT, AI techniques, and data analytics contribute to smart grid systems.
- **Insights and Subsections:** The survey provides insights categorized into subsections under each topic, covering power quality issues, monitoring techniques, control methods, and data processing techniques.
- **Comprehensive Presentation:** A thorough presentation of challenges, discussions, and future research directions related to IoT-enabled smart grid systems.

1.4 Framework of the article

Overall, the article is structured to provide a comprehensive understanding of how IoT technology can improve smart

Table 2. Comparison between traditional smart grid and IoT-enabled smart grid.

Features	Traditional smart grid	IoT-enabled smart grid
Connectivity and communication	Limited to proprietary or standardized protocols.	Utilizes internet protocols (IP) for seamless device communication.
Data exchange and analytics	Data collection primarily for monitoring and basic analysis.	Advanced data analytics for predictive maintenance and optimization.
Scalability and flexibility	Limited scalability and flexibility due to rigid architectures.	Greater scalability and flexibility for integrating new devices.
Real-time monitoring and control	Provides real-time monitoring and control, but may be limited.	Granular real-time monitoring and control of diverse grid assets.
Cybersecurity and privacy	Requires robust cybersecurity measures.	Faces additional cybersecurity challenges due to device complexity.

grid systems, particularly in managing power quality issues, and sets a direction for future research in this evolving field. [Section 2](#) focuses on applications of IoT in smart grids, detailing various applications such as data processing, management, visualization, and integration. [Section 3](#) details advanced technologies within smart grids, including grid automation, integration of renewable energy sources, AI and machine learning applications, and electric vehicle integration. [Section 4](#) explores power quality issues in IoT-enabled smart grids, defining terms like harmonic distortions, voltage fluctuations, transients, etc. It discusses practical implementation of control and monitoring techniques, AI methods, data analysis, and wireless sensor networks (WSNs). [Section 5](#) outlines challenges specific to IoT-enabled smart grids and includes a brief discussion. [Section 6](#) serves as the conclusion, summarizing key findings from the survey and presenting future research directions in the field of IoT-enabled smart grids.

2 Architecture and data processing techniques in IoT-enabled smart grid

With various ICT tools, the smart grid concept has emerged as a possible way to address power quality issues. These technologies have the potential to improve the efficiency, reliability, safety, system stability, and scalability of the traditional power grid [54]. Advanced metering infrastructure (AMI), tolerance, unauthenticated data usage identification, load sharing, detection, and recovery are the main features of the smart grid. The most crucial concerns for smart grid are the connectivity, automation, and tracking of many devices, which require distributed surveillance. These advancements hold promise for enhancing the efficiency, reliability, safety, system stability, and scalability of the conventional power grid [55].

2.1 Architecture of an IoT-enabled smart grid

Smart grid is considered one of the biggest applications of IoT. The main aim of standard communication in IoT-enabled smart grid systems is to achieve interoperability among different components, such as devices, meters, and protocols. By modifying their electricity usage habits in

response to an analysis of power consumption, users of IoT technology may be able to save money. The IoT server comprises four basic parts: data management, message dispatcher, storage, a configuration unit, and a secure access manager with a user database. This architecture consists of the terminal layer, field network layer, distant communication layer, and master station system layer, as depicted in [Figure 3](#). IoT devices include wireless sensor networks, remote terminal units, data-gathering devices, smart meters, and intelligent electronic equipment [56, 57]. This layer transfers the data gathered from IoT devices to the network layer.

The IoT technology is crucial for implementing the smart grid's data sensing and transmission infrastructure, helping with network setup, operation, safety, maintenance, cyber security monitoring, data gathering, and other tasks. Additionally, the IoT allows a smart grid to integrate information, power, and distribution flow [58, 59]. Derived from the characteristics of smart grid information and communication systems, a four-layer architecture was formulated. There are wired and wireless network layers. For instance, sensor nodes use ZigBee to communicate the data they have gathered to the layer responsible for remote communication networks [60, 61]. It is made up of different communication networks that connect to the Internet. This layer provides a midway point between IoT devices and the application layer. The application layer is the control and information-gathering system of a smart grid. It controls and manages all the smart grid functions and interfaces to the IoT in smart grid applications [62, 63].

2.2 Data processing techniques in an IoT-enabled smart grid

It is crucial for handling the massive volumes of data generated by various grid-connected devices and sensors. These techniques involve collecting, transmitting, analyzing, and using data to enhance grid performance, reliability, and efficiency [64]. [Figure 4](#) illustrates a detailed description of data processing techniques in an IoT-enabled smart grid.

- **Collection and Aggregation:** Collect real-time data on electricity usage, voltage levels, current, power factor, and more. Data from multiple sources

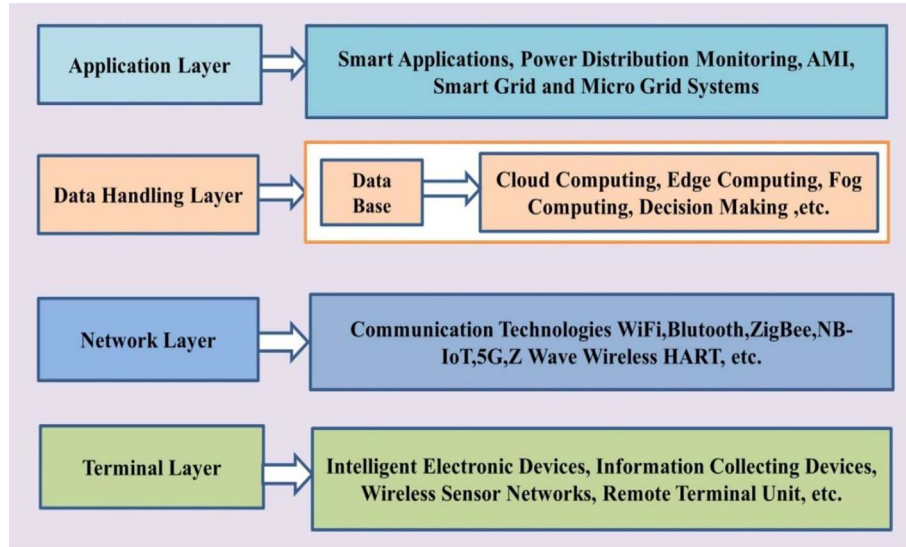


Fig. 3. Architecture of IoT-enabled smart grid.

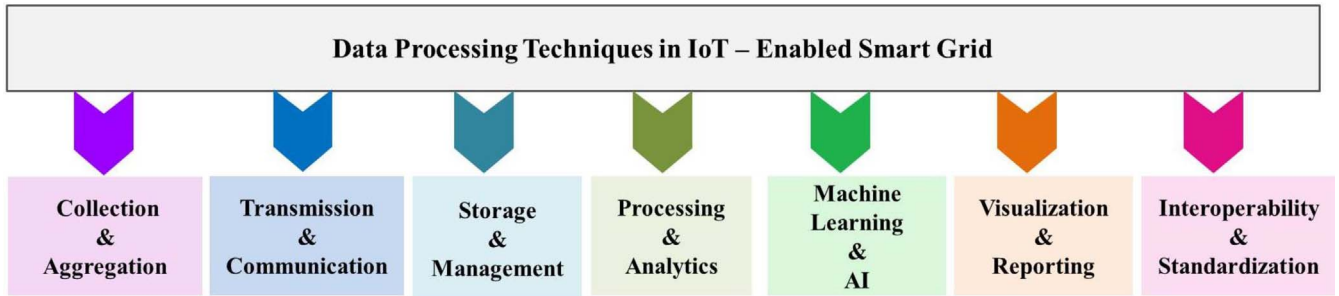


Fig. 4. Data processing techniques in IoT enabled smart grid [65, 66].

is aggregated at local nodes or in the cloud for initial processing and reduction of data volume [67, 68].

- **Transmission and Communication:** Wireless Communication Technologies uses Wi-Fi, ZigBee, LoRaWAN, and cellular networks for data transmission. Includes power line communication (PLC), Ethernet, and fiber optics for more reliable and high-capacity data transmission.
- **Storage and Management:** Large-scale data storage solutions, often in the cloud, to accommodate the vast amounts of data generated. Utilization of edge computing or on-premise data storage solutions for faster access and processing [69].
- **Processing and Analytics:** Handling and analyzing large datasets to extract meaningful insights. Immediate processing of data for monitoring and decision-making in real-time. To predict historical data, demand, faults, and maintenance are needed.
- **Machine learning and AI:** Identifying patterns in consumption, generation, and anomalies for efficient grid management. For predictive maintenance, various AI algorithms are used to predict equipment failures before they happen. AI models are used to predict electricity demand, enhancing grid balancing and resource allocation [70, 71].

- **Visualization and Reporting:** Interactive platforms for visualizing data trends, anomalies, and performance metrics are used.
- **Interoperability and Standardization:** Data Standards and Protocols ensure compatibility and seamless integration across different devices and systems.

Data processing in IoT-enabled smart grids encompasses a wide range of technologies and methodologies, from the collection and transmission of data to sophisticated machine learning algorithms and AI-driven analytics. These techniques are pivotal in transforming raw data into actionable insights, ensuring the smart grid's efficiency, reliability, and adaptability to changing energy demands and generation patterns [72, 73].

3 Advanced Technologies and Latest Trends in the IoT-Enabled Smart Grid

IoT-Enabled smart grids utilize various cutting-edge technologies to improve efficiency, reliability, and sustainability. These technologies facilitate monitoring, control, and optimization of the grid, enabling a more dynamic and

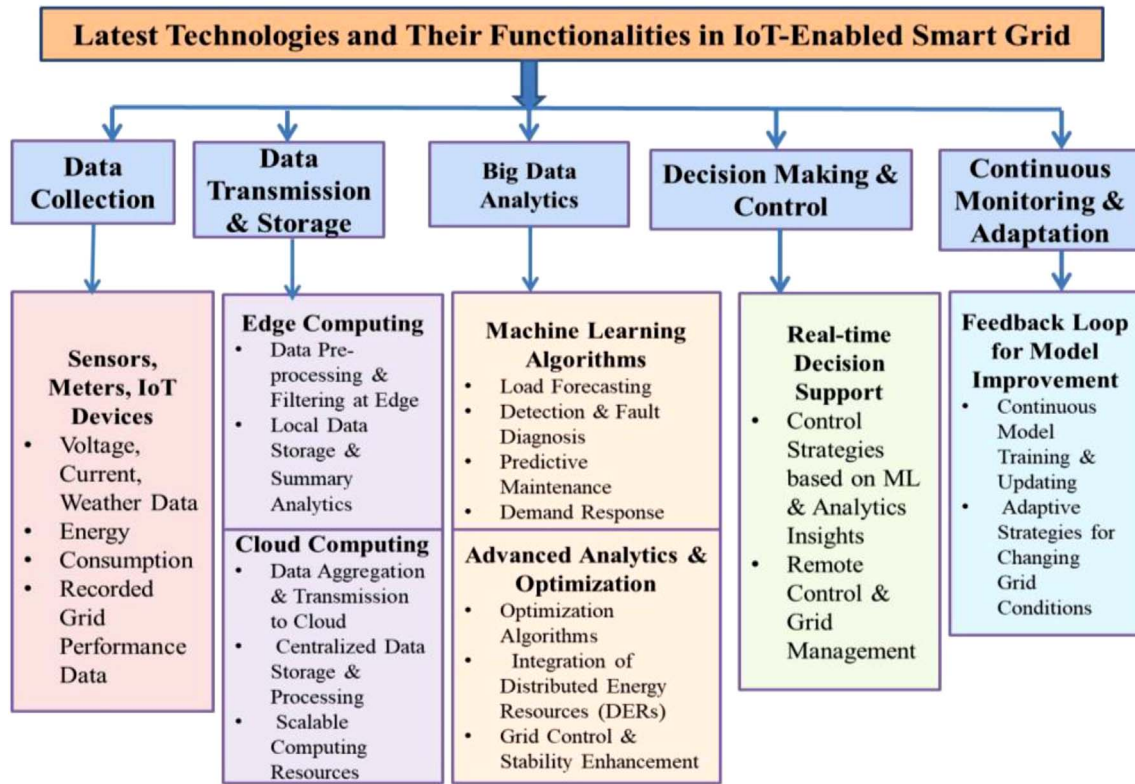


Fig. 5. Comprehensive process of utilizing advanced technologies in IoT-enabled smart grid.

responsive power delivery system [74, 75]. Figure 5 illustrates the functionalities of several cutting-edge technologies within an IoT-enabled smart grid.

3.1 Data collection and automation

Data collection lies at the heart of IoT-enabled smart grids, facilitating the real-time monitoring of energy consumption, grid performance, and environmental conditions. Smart meters serve as fundamental components, transmitting energy usage data to utilities through communication networks, empowering them to analyze consumption patterns and offer personalized services. Sensor networks deployed across the grid further enhance data collection by providing insights into voltage, current, temperature, and power quality, which aid in detecting anomalies, prioritizing maintenance, and preventing failures. Supervisory control and data acquisition (SCADA) systems monitor and manage grid operations, collecting data from sensors to enable real-time decision-making and support functions like load balancing and outage management [76].

Advanced analytics techniques, including machine learning, extract actionable insights from collected data, optimize grid performance, and predict equipment failures. Weather data is also integrated into data collection processes to forecast energy demand and manage renewable resources effectively. Additionally, utilities gather customer data to understand preferences and tailor services, while cybersecurity measures ensure the protection of sensitive information against cyber threats. In sum, effective data

collection is pivotal in driving the optimization, reliability, and resilience of smart grids, allowing utilities to meet the evolving needs of customers and stakeholders alike. Grid automation and control systems are foundational to the modernization of electrical grids, enabling more reliable, efficient, and responsive operations. The two systems you've mentioned, SCADA and distribution management systems (DMS), play pivotal roles in this transformation. Integrating SCADA and DMS into grid operations offers a comprehensive approach to grid management, from high-level monitoring and control to in-depth distribution network optimization. As the grid advances through the integration of renewable energy sources, electric vehicles, and other distributed energy resources, these systems become increasingly crucial in maintaining grid stability, efficiency, and readiness to meet future demands [77].

3.2 Edge and cloud computing

Edge computing represents a shift in data processing and intelligence deployment closer to the origin of data generation rather than relying on centralized data centers or cloud-based services. This approach is particularly beneficial in the context of modern power grids, which are becoming increasingly complex and distributed with the integration of renewable energy sources, smart devices, and IoT technologies. Edge computing introduces a paradigm shift in how energy grids are managed and operated. By enabling local data processing and distributing intelligence across the grid, edge computing improves response

times, enhances grid resilience and scalability, and supports the integration of renewable energy sources and smart technologies. This distributed approach aligns well with the evolving needs of modern power systems, offering a pathway to more efficient, reliable, and sustainable energy production and distribution [78].

Cloud computing is integral to the functionality and efficiency of IoT-enabled smart grids. It provides a scalable and flexible infrastructure for storing, processing, and analyzing the vast amounts of data generated by smart grid devices such as smart meters and sensors [79]. With cloud storage solutions, utilities can securely store historical data for analysis and compliance purposes. Cloud platforms also offer powerful data processing and analytics capabilities, enabling utilities to derive actionable insights from IoT data in real time. Remote monitoring and control applications hosted in the cloud allow operators to manage grid assets efficiently from anywhere with an internet connection. Additionally, cloud computing offers cost-efficiency through a pay-as-you-go pricing model, eliminating the need for large upfront investments in on-premises infrastructure. Security measures implemented by cloud providers ensure the protection of sensitive smart grid data against cyber threats and unauthorized access [29]. Overall, cloud computing empowers utilities to leverage the full potential of IoT technologies to enhance grid reliability, efficiency, and sustainability.

3.3 Machine learning and advanced analytics

AI and ML are revolutionizing the way power grids operate, bringing unprecedented levels of efficiency, reliability, and adaptability. These technologies are particularly adept at handling the complexities and dynamic nature of modern electrical networks, especially with the increasing integration of variable renewable energy sources. Utilizing AI and ML in the energy sector marks a transformative shift towards smarter, more efficient, and more robust power systems. By leveraging predictive analytics and automating decision-making processes, these technologies not only improve the operational performance of the grid but also facilitate the transition to a more sustainable and renewable energy future [80]. As AI and ML technologies continue to evolve, their role in shaping the future of energy is expected to grow even more significant, enabling smarter grids that can meet the challenges of tomorrow.

3.4 Real-time decision support

Real-time decision support systems play a pivotal role in IoT-enabled smart grids, revolutionizing how energy is distributed and managed. Through a network of sensors and IoT devices, these systems continuously collect and analyze vast amounts of data on energy consumption, grid conditions, and equipment performance. Advanced analytics algorithms leverage this data to optimize grid operations, predict energy demand, and detect anomalies in real time. This proactive approach enables utilities to mitigate potential issues before they escalate, improving grid reliability and resilience. Additionally, real-time decision support facilitates dynamic control of grid assets, enabling efficient

energy routing, voltage regulation, and the integration of renewable energy sources. By empowering grid operators with actionable insights and enabling consumers to make informed decisions about their energy usage, these systems pave the way for a more efficient, sustainable, and resilient energy infrastructure [21].

3.5 Continuous monitoring and improvement

Continuous monitoring and improvement are integral aspects of IoT-enabled smart grids, ensuring optimal performance and resilience. Through a network of interconnected sensors and devices, smart grids continuously gather real-time data on energy consumption, grid conditions, and equipment status. This data is analyzed using advanced algorithms to detect anomalies, predict potential issues, and optimize grid operations. Continuous monitoring allows utilities to proactively identify and address inefficiencies, potential faults, or cybersecurity threats before they escalate, minimizing downtime and improving reliability. Moreover, ongoing improvement efforts involve refining algorithms, upgrading infrastructure, and integrating emerging technologies to enhance grid efficiency, accommodate renewable energy integration, and meet evolving regulatory requirements. By embracing a culture of continuous monitoring and improvement, IoT-enabled smart grids can adapt to changing demands, optimize resource utilization, and pave the way for a more sustainable and resilient energy future [31].

4 Power quality issues, monitoring and controlling methodologies in IoT-enabled smart grid

4.1 Power quality issues in IoT-enabled smart grid

IoT technologies into Smart Grids bring numerous advantages in terms of efficiency, automation, and energy management. However, this integration also introduces various PQ issues that need to be addressed. Figure 6 shows the Power Quality issues, causes and their impact in IoT-enabled smart grid.

- **Harmonic Distortion:** IoT devices, along with other non-linear loads like variable-speed drives and compact fluorescent lamps, can introduce harmonics into the power system. Harmonic distortion may result in equipment overheating, diminished efficiency, and the possible malfunctioning of delicate electronics.
- **Voltage Fluctuations and Flickers:** Rapidly changing loads or intermittent power generation (as seen with renewable energy sources) can cause voltage fluctuations. This can lead to flickering lights and affect the performance of sensitive equipment.
- **Transient Disturbances:** Switching events and fault conditions in the grid, often exacerbated by the high-speed switching mechanisms of IoT devices, can cause transient disturbances. These can result in equipment malfunction, data corruption, and, in

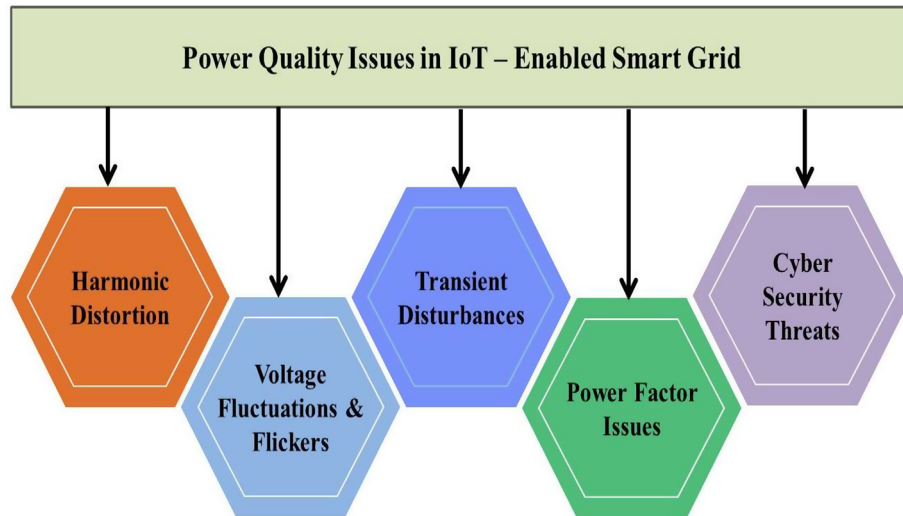


Fig. 6. Power quality issues in IoT-enabled smart grid [32, 33].

severe cases, equipment failure. High penetration of RES and the varying load demand due to IoT-controlled devices can lead to voltage and frequency instabilities. This instability can affect the lifespan of electrical appliances and challenge the overall stability of the grid.

- **Power Factor Issues:** IoT devices, especially those with inbuilt switching power supplies, can lead to a low power factor. A low power factor results in inefficient power usage, leading to increased energy costs and strain on the grid infrastructure. The widespread use of wireless communication technologies in IoT devices can introduce electromagnetic interference. It can disrupt the operation of sensitive electronic equipment and interfere with the grid's communication systems.
- **Cybersecurity Threats:** The extensive network of IoT devices increases the threat of cyberattacks, which can lead to manipulation of power control systems. Cybersecurity threats can lead to operational disruptions and compromise the reliability and safety of the grid.

While IoT-enabled smart grids offer significant benefits, addressing these power quality issues is crucial for ensuring the reliability, efficiency, and safety of the grid. This requires a combination of technological solutions, grid management strategies, and regulatory policies. Various AI technologies for addressing PQ issues are comprehensive and well-rounded [34]. Incorporating these technologies and strategies into a power grid addresses a wide range of PQ issues, from ensuring the longevity and reliability of equipment to maintaining the overall stability and efficiency of the power system. As the grid evolves, particularly with the increasing integration of renewable energy sources and smart grid technologies, these solutions will continue to be integral to managing the challenges that come with these advancements. The sending and receiving of control signals in real-time is the fundamental measurement of a smart network;

however, delay time in smart grid communications is an important consideration. The real-time monitoring of crucial power facilities may be compromised, increasing the risk of a disaster affecting the entire power system [35].

There are several ways to locate and implement the best techniques for resolving power quality issues. Smart grid systems utilize innovations like IoT, AI, data analysis, WSN, and others to alleviate power quality issues. In summary, the five phases of smart grid systems used to assess power quality issues are depicted in Figure 7. The first two phases of issue definition and categorization seek to identify the sources and effects of the equipment through data collection or measurement [36]. Several solutions are found in the third stage to reduce the problems with the customer interface for the end user. Technical analysis must be taken into consideration when completing the fourth and fifth stages of the evaluation technique in order to achieve the most cost-effective outcome and enhance the quality of the electricity in smart grids.

- **Identification of the Problem:** Domain finding many types of issues, such as transients, voltage regulation, harmonic distortion, voltage sag, flickers, time delays, and missing data packets, is a crucial initial step. These issues impact the smart grid's reliability and electricity quality [37].
- **Characterization of the Issue:** The next step is categorizing the issue according to its cause, characteristics, and equipment impact.
- **Identify the scope of the solution:** To lessen these issues, we must look for solutions in equipment design, end-user systems, distribution systems, gearbox systems, and end-user interfaces.
- **Solution Assessment:** After locating the issue, the next step is to develop a precise remedy using techniques like design analysis, procedure analysis, or any other technological option.
- **Ideal Response:** The problem is solved with power electronics devices, including STATCOM, UPQC, DVR, SST, and UPS, at the last stage of the process.

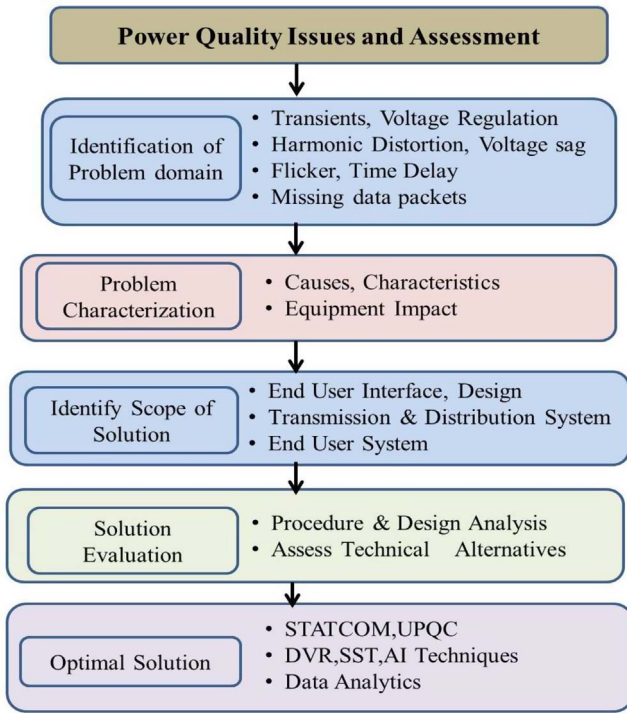


Fig. 7. Assessment procedure of power quality issues.

The latest technologies are also incorporated into the solution approaches, such as IoT and AI techniques, where we can use ANN, FLC, ANFIS filters, and data analytics to reduce huge data packets and time delays. Therefore, by adopting the above procedure, we can increase the quality of power supply in smart grid systems by reducing various power quality issues [38].

4.2 Monitoring and control methodologies

Monitoring and control methodologies in IoT-enabled smart grids are vital for the efficient, reliable, and sustainable operation of modern power systems. IoT-enabled smart grids utilize a complex and interrelated set of methodologies for monitoring, control, and optimization [81]. The future of these systems lies in the continuous advancement of IoT technologies, data analytics, and cybersecurity measures, ensuring a resilient and efficient power grid.

4.2.1 Monitoring techniques

Power quality monitoring in IoT-enabled Smart grids involves the use of advanced technologies and methodologies to ensure that the electricity supply is consistent, reliable, and within the required quality standards. IoT devices play a critical role in continuously monitoring various aspects of power quality and providing real-time data for analysis and decision-making [82]. The integration of IoT in smart grids has revolutionized how energy is monitored, controlled, and distributed. An overview of the methodologies used is shown in Figure 8.

Voltage and current monitoring smart sensors are deployed throughout the grid; these sensors continuously

monitor voltage and current levels at various points, including substations, distribution lines, and consumer premises [83]. Smart meters provides detailed information about voltage levels, current flow, and power factor at the consumer end. Harmonic sensors detect and measure harmonic distortions in the electrical system. Harmonics can cause inefficiencies and damage to both the grid and connected devices. IoT-enabled systems analyze harmonic data in real time, allowing immediate corrective actions. For flicker measurement, flicker meters monitor the rapid variations in voltage amplitude, which can lead to perceptible light flicker, affecting both comfort and industrial processes. IoT devices assess the power factor by monitoring the nature of the loads (capacitive or inductive) connected to the grid. Automated switching of capacitors or inductors to correct the power factor.

For sag and swell detection, voltage variation sensors identify and record instances of voltage sags (short-term decreases in voltage) and swells (short-term increases in voltage). Infrared sensors are used to detect overheating in grid components like transformers and conductors, which can be indicative of larger power quality issues. Advanced analytics leverages machine learning and AI for predictive analysis of power quality issues. Generating detailed reports for utility providers and consumers on power quality metrics [42]. Ensuring different IoT devices and systems can effectively communicate and work together. Handling the large volumes of data generated by IoT devices in a meaningful and efficient manner. Protecting the power quality monitoring system from cyber threats. IoT-enabled power quality monitoring in smart grids encompasses a wide range of techniques and technologies, from basic voltage and current monitoring to sophisticated harmonic analysis and thermal imaging. The real-time data provided by IoT devices is invaluable for maintaining high power quality standards and ensuring the reliability and efficiency of the electrical grid.

4.2.2 Controlling methodologies

Power quality management in a smart grid's primary concept is to mitigate and transform electric power to meet quality compliance criteria, maximize efficiency, and reduce end-to-end data transmission delay. There are three categories of power quality mitigation technologies in smart grid systems: passive controllers, active controllers, and artificial intelligence controllers. Figure 9 shows the types of controllers and their applications in controlling power quality issues in the IoT.

4.2.2.1 Passive controllers

More devices using the passive control technique must be installed to mitigate the consequences of recent power quality problems in smart grid systems. The three categories of approaches for reducing harmonics are hybrid active power filters (HAPF), passive power filters, and passive power filters. A PPF, which resonates at a single frequency or a range of frequencies, comprises an inductor [84]. These filters reduce voltage distortion and stop harmonic currents from growing in sensitive system components. Harmonics significantly below the system frequency are filtered by

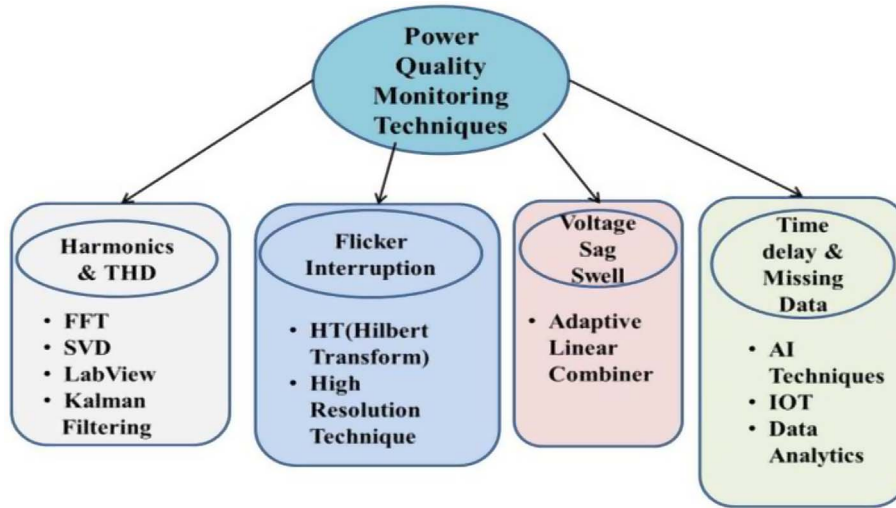


Fig. 8. Power quality monitoring techniques.

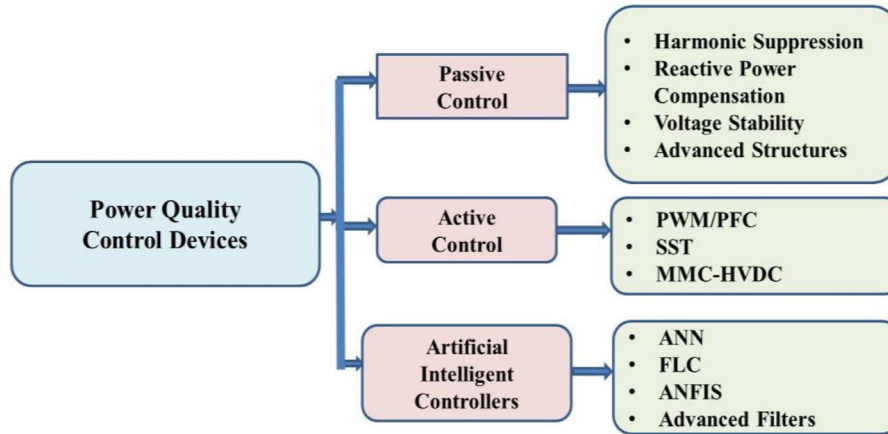


Fig. 9. Power quality controllers.

the power system using APF. HAPF features a series-parallel architecture and is less expensive. Both the PPF and the APF benefits are included. The many categories of smart grid-mediated issues are shown in Table 2.

Voltage swings and flickers can be lessened with the VAR compensator. Some examples of VAR compensators in [44] are the static var compensator (SVC), static synchronous compensator (STATCOM), and fixed capacitor (FC). The STATCOM devices are used because of their many features, which include the suppression of grid voltage fluctuations and adjustment for unbalanced loads. Voltage sag and brief interruptions are thought to be the two most common and hazardous types of transient power quality concerns. An uninterruptible power supply (UPS) called a solid-state transfer switch (SSTS) can greatly reduce the depth and duration of voltage sag. The dynamic voltage regulator (DVR) can immediately correct for sudden voltage sags and swells. The grid can receive extensive voltage and current correction via the unified power quality controller (UPQC), which consists of the APF connected in series and shunt, respectively power quality

control techniques with various methods are illustrated in Table 3. Cascaded power converters based on modular multilevel converters (MMC) have undergone significant investigation in scientific research due to their same module structure, which reduces the complexity of constructing high- and medium-voltage converters [45].

4.2.2.2 Active controllers

Enhancing the electrical equipment's impedance attributes with active control methods can prevent the bulk of power quality problems. Because of the instrumented, networked, and intelligent transmission and distribution networks, the power electronics conversion system will not cause as many problems with power quality. Power-factor correction (PFC) and pulse-width modulation (PWM) technologies have improved the power quality of rectifiers. The output voltage and current quality in distributed systems are improved by distributed generation and microgrid inverters using active control, which also increases the compensating capacity for the nearby grid. Additionally, a solid-state transformer (SST) will stop various power quality problems

Table 3. Power quality control techniques.

Control techniques	Mitigated issues	References
UPQC	Voltage-sag/swell, flickers, unbalances, harmonics, power factor, load harmonics currents	[42, 44]
STATCOM	Power transients, voltage imbalances/flickers, power swings, and power damping's	[43–45]
DVR	Voltage-sag/swell	[46, 48]
UPS	Emergency power shortage	[49]
SST	Interruptions and voltage dips	[48, 49]
ANN	Power system stability, fault detection	[49, 50]
FLC	Frequency regulations, settling time	[50]
ANFIS	Non-linear load currents, load forecasting	[50, 51]

that can be transmitted and emitted between the power distribution and consumer sides. The multi-terminal HVDC technology and MMC-based high-voltage direct current will increase power quality throughout the whole power system (HVDC transmission) [46].

4.2.2.3 Artificial intelligent controllers

The smart grid gathers massive amounts of multi-type, high-dimensional streaming data about how the grid is run. It is becoming increasingly obvious that AI approaches have applications in the smart grid because the constraints of conventional modeling, optimization, and control techniques in terms of data processing are numerous [47]. Security concerns, fault detection, and power grid stability evaluation are addressed using AI techniques within the smart grid. Smart grid system dependability and resilience may be strengthened and improved by implementing AI techniques. In general, AI methods allow for quick and accurate decision-making. The techniques utilized to develop AI systems include fuzzy logic, neural networks, the adaptive neuro-fuzzy interface system, and natural language processing [48].

AI systems can be supported by the smart grid both physically and virtually. Virtual AI systems contain information technology that can improve grid operators ability to do their duties. AI systems, known as ANI, such as an AI system that executes load predictions using various databases, were created for specific activities with appropriate requirements and restrictions. BPNN is frequently utilized in a variety of neural network paradigms. The term multilayer perception refers to a feed-forward neural network technique. The AI 2.0 stage has been reached due to the development of new AI algorithms supported by powerful computer hardware [49]. This is because more data is required and more complicated problems are to be solved. Deep-learning (DL) was first used for image processing using multilayer deep neural networks.

Traditional analytical systems are significantly less comparable to human reasoning and natural language than fuzzy logic, which is the basis of fuzzy control. Creating a fuzzy logic controller for integration into fuzzy logic works better than PID controllers and is similar to human reasoning. In-depth research has been done on FLC functions to

increase their capacity for handling expert system problems. Fuzzy logic control offers a faster settling time and is more adaptive in nonlinear systems than traditional PID controllers [50]. One of these applications is frequency regulation in the smart grid. Maintaining the balance between output and consumption is the primary objective of frequency management in smart grid systems. Fuzzy controllers successfully address a variety of control issues because of their durability and dependability. The construction of the ANFIS will result from using ANN and FLC concurrently, which is the best option. The ANFIS control approach makes it possible to govern non-linear systems and regulate electrical grid currents. For the system to respond to changing instructions and compensate for variations in irradiation, this control technique employs a mechanism that gathers knowledge about the system from the gathered data [51].

5 Challenges in IoT-enabled smart grid

Implementing an IoT-enabled smart grid comes with a set of challenges that span technical, regulatory, security, and operational domains, which are illustrated in detail in Figure 10.

- **Interoperability and Scalability:** IoT devices from different manufacturers often use different communication protocols and standards, making it challenging to ensure seamless integration and interoperability across the smart grid ecosystem. Developing common standards for communication and data exchange is crucial. As the number of IoT devices deployed in the smart grid increases, managing and scaling the infrastructure becomes increasingly complex. Ensuring that the system can handle large volumes of data while maintaining reliability and performance is a significant challenge.
- **Data Management and Security:** IoT devices generate vast amounts of data, including real-time sensor data, energy consumption patterns, and operational metrics. Managing, storing, processing, and analysing this data efficiently is a significant challenge, requiring

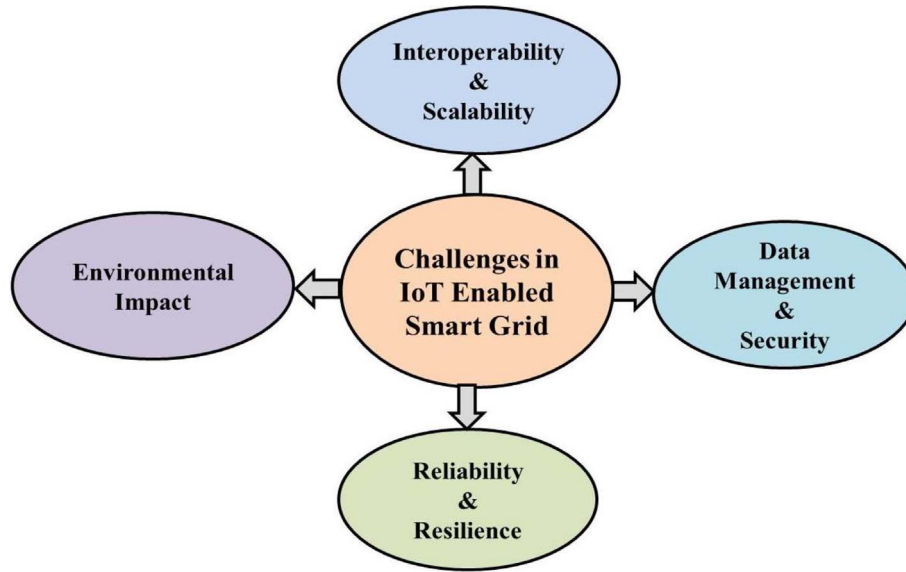


Fig. 10. Challenges in IoT-enabled smart grid [52, 53].

robust data management and analytics solutions. With a large number of interconnected devices and communication networks, the smart grid becomes vulnerable to cyberattacks. Securing IoT devices, communication channels, and data against threats such as unauthorized access, data breaches, and ransomware attacks is critical to maintaining the integrity and reliability of the smart grid.

- **Reliability and Resilience:** The smart grid must remain operational under various conditions, including natural disasters, equipment failures, and cyberattacks. Designing the system to be resilient and implementing redundancy measures to ensure uninterrupted service is essential. IoT devices collect a wide range of data, including personal information and behavioral patterns. Protecting consumer privacy and ensuring compliance with data protection regulations while leveraging this data for grid optimization is a delicate balance that needs to be addressed.
- **Environmental Impact:** While IoT-enabled smart grids offer potential benefits such as improved energy efficiency and grid optimization, the environmental impact of manufacturing, deploying, and disposing of IoT devices should be carefully considered. Implementing sustainable practices and minimizing carbon footprints is essential for the long-term viability of smart grid solutions [54].

A complete analysis of all present power quality issues is carried out to combine data collection techniques and mitigation measures in an IoT-enabled smart grid. Figure 11 covers potential research questions for future research gaps found during the review process.

- **Enhanced Monitoring and Control:** IoT devices provide real-time monitoring and control capabilities, allowing for more efficient grid management. Advanced sensors and communication technologies

enable precise monitoring of grid parameters and rapid response to changes. Recent advancements in sensor technology are discussed [55].

- **Predictive Maintenance:** IoT-enabled predictive maintenance can significantly reduce downtime and maintenance costs by identifying potential issues before they become critical. Machine learning and data analytics play a key role in predicting equipment failures [56].
- **Demand Response and Energy Efficiency:** IoT devices facilitate demand response programs by providing real-time data on energy consumption patterns. This enables utilities to adjust supply and demand dynamically, improving energy efficiency and reducing peak loads [57].
- **Renewable Energy Integration:** IoT technologies support the integration of renewable energy sources into smart grids by providing accurate data on generation and consumption. This helps in balancing the grid and maximizing the use of renewable energy [58].

6 Conclusion and future directions

The smart grid is poised to tackle inherent problems in traditional power grids, including unidirectional data flow, energy waste, escalating energy consumption, reliability issues, and concerns related to privacy and security. The pervasive connectivity offered by the IoT facilitates continuous and widespread communication. Through the deployment of IoT devices such as wireless sensors, actuators, and AMIs, the smart grid can achieve monitoring, analysis, control, connectivity, automation, and device tracking. This integration of IoT in the smart grid system enhances and optimizes various network functions at all levels of power system operation, spanning from generation and transmission to distribution and utilization. Our research

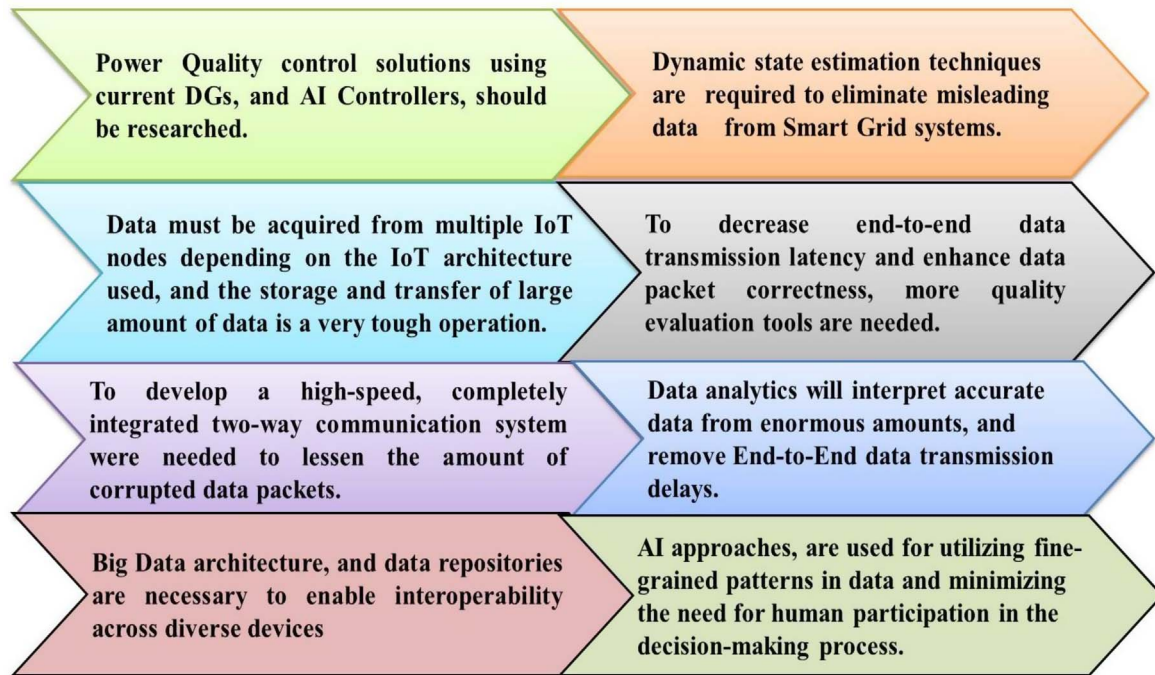


Fig. 11. Research gaps in IoT-enabled smart grid [59, 60].

thoroughly examined the incorporation of IoT into smart grid systems, identifying several challenges that need resolution.

Initially, we delved into power quality issues within a smart grid, elucidating strategies to mitigate them. Subsequently, we provided an in-depth exploration of different control techniques, including artificial neural networks (ANN), fuzzy logic control (FLC), advanced filters, adaptive neuro-fuzzy inference systems (ANFIS), and the application of machine learning. The paper also briefly outlined aspects such as data sharing, control, monitoring, wireless sensor networks, and coordination among smart devices. For optimal performance, smart grids necessitate the integration of IoT, AI methodologies, machine learning, and data analytics. An overview of the IoT, machine learning, artificial intelligence techniques, and sophisticated data analytics methods utilized in the smart grid was presented.

This paper extensively reviewed applications, open challenges, and associated systems, with a primary focus on emphasizing the significance of IoT, AI approaches, and data analytics in addressing vast amounts of data within smart grid systems and mitigating diverse power quality issues. The prospects of integrating IoT, AI, machine learning, and data analytics into smart grid systems are immensely promising, offering opportunities to propel the efficiency, reliability, and sustainability of energy management to new heights. The crux of the smart grid's evolution lies in the on-going exploration and assimilation of state-of-the-art technologies, guaranteeing the establishment of a resilient, secure, and intelligent energy infrastructure. The persistent commitment to research and development in these domains will serve as a cornerstone, actively shaping

the landscape of smart grids and paving the way for innovative solutions in the realm of energy distribution and management.

Acknowledgments

The authors sincerely acknowledge Vignan's Foundation for Science, Technology and Research, Guntur, KSRMCE, Kadapa and NIT Patna for allowing the research to be undertaken.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability statement

No data was used for the research described in the article.

Authors contributions statement

All the authors have equal contributions in writing and reviewing the paper.

Saleha Tabassum: Conceptualization, Writing-Original Draft, Attuluri R Vijay Babu: Writing-Original Draft, Review, Supervision,

Dharmendra Kumar Dheer: Investigation, Writing-Review, Supervision.

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