An IoT-Based Sensor Technology for Improving Reliability and Power Quality in Smart Grid Systems

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***Abstract*—An Internet of Things (IoT) based smart grid technology becomes more popular and gained significant attention in present days. Due to the rapid growth of information and technology, the IoT is increasingly used for industrial automation, smart monitoring and control. The work is focused on implementing IoT based smart sensor technology for improving the reliability and power quality of smart grid systems. Typically, the smart sensors are considered as the most essential IoT devices used for improving the reliability of smart grid systems. The proposed framework comprises the major elements of monitoring, communication and analysis components, in which the monitoring element comprises the current and voltage sensors that is directly connected with the consumer loads. Then, the communication component comprises the Arduino sensor and WiFi module, which helps to establish the wireless communication. Here, the analysis component is used as a remote application that is used to get the voltage profiles, energy reports, voltage and current. During analysis, the performance of the proposed framework is validated and tested by using different parameters like, voltage, current, power, apparent power, and energy.**

***Index Terms*—Smart Grid, Reliability, Smart Sensors, Internet of Things (IoT), Communication Technology, and Renewable Energy Sources (RES)**

I. Introduction

In recent times, the smart grid technology [1–3] is widely adopted and deployed in many real time applications, due to their characteristics of smart generation, transmission, distribution, protection, control and communication. Moreover, it supports to use the advanced communication technologies and information for modernizing the standard electrical power system. The major impacts of using the smart grid technology are [4–6], it provided an enormous opportunities to improve the communication technology with reduced cost consumption, and it helps to increase the reliability with minimal power quality disruptions [7]. Specifically, it improves the security of systems with reduced energy consumption and loss. The different characteristics of smart grid systems [8, 9] are shown in Fig. 1, which includes the key factors of reliability, security, integration of renewable sources, demand side management, self-healing, and metering. It uses the components of sensors, actuators, and processing units for network coordination and reconfiguration [10].

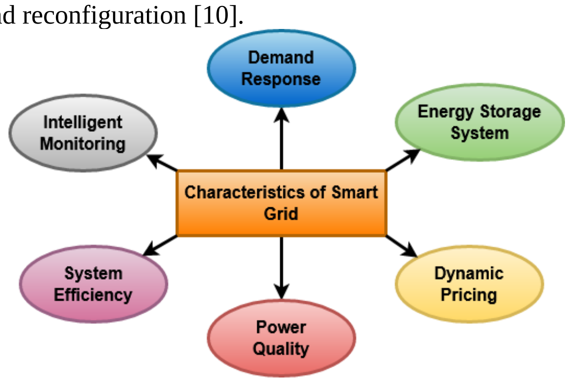

Fig. 1. Smart grid characteristics.

The smart sensors are the modern sensor devices [11] used in the power grid systems, which includes the types of current sensors, weather sensors, humidity sensors, voltage sensors, and temperature sensors. Typically, the smart sensors are mainly used for the following purposes:

1. Sensing
2. Data processing and signal conversion
3. Synchronization
4. Communication

Typically, satisfying the reliability [12, 13] of smart grid systems is one of the important and complex processes due to the problems of grid congestion, high volatility, and increased utilization of distributed devices. The load management, demand response, electric transportation, and storage device are treated as the major reliability impacts [14]. Moreover, the reliability of grid systems [15, 16] is ensured by designing the protection devices having the following characteristics: i) It should have the ability to identify, measure, and adjust the protection settings in a fault situation [17], ii). It must be capable to communicate with other devices for sharing the controlling actions and optimal settings [18], iii). It should speed up the fault detection and isolation

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processes [19, 20]. In the existing works [21, 22], the different types of smart sensors have been designed for improving the reliability and stability of the smart grid systems. However, it faces some problems [23–25] correlated to the following factors: complex to comprehend, cost overhead, high consuming, and lack of security. Therefore, the proposed work intends to utilize an advanced Internet of Things (IoT) based smart sensor device for improving the reliability of smart grid systems. Sensors, actuators, and transducers are anticipated to play a significant role in the provision of real-time energy monitoring services in the next generation of power grids. IoT is now a technology that makes it possible to offer creative answers to problems with the electricity grid. In the power grid system, IoT-enabled sensors are widely employed to convey their valuable information through the internet and web applications, enabling better grid management. Here, the factors such as temperature, size, and protection class, type of input, sensor response time, sensing range, and accuracy are considered while selecting the sensors for IoT. The key objectives focused on this work are as follows:

- To design and develop a new power quality controlling model for the smart grid systems by using an Internet of Things (IoT) based smart sensor technology.
- To improve the reliability with better power quality, the smart monitoring system has been constructed.
- To analyze the controlling performance of the proposed framework by using various simulation parameters.

The other portions of this paper are split into the following units: Section II presents the comprehensive literature review of various smart sensor technologies used for improving the reliability and security of smart grid systems. Also, it discusses about the problems and challenges faced by the conventional works. Then, the clear explanation about the proposed methodology is presented in Section III. The results of the proposed system is tested and validated using different performance indicators in Section IV. Finally, the overall paper is summarized with the findings and future work in Section V.

II. Related Works

This sections reviews some of the fault identification techniques and smart sensors used for improving the reliability of smart grid systems. It also investigates the major effects of using smart sensors in the grid systems.

Rivas *et al.* [16] conducted a systematic review for analyzing the different types of faults in the smart grid systems for increasing its reliability. Typically, the faults may arise in the grid systems due to the following reasons:

1. The component failures can occur, if the physical components not working properly.
2. Then, the communication fault can occur due to the failures in the physical link or channel.
3. Software/Hardware faults are typically occur due to the operation or command failure.

In order to resolve these problems, the fault management techniques could be more useful, because that analyzes the system operations with proper monitoring and control. In addition to that, this work investigated the faults on the renewable energy sources (i.e. PV panels and wind turbine), power transformers, converters, and energy systems. Ourahou *et al.* [26] presented a comprehensive analysis about the different types techniques used for improving the reliability and stability of smart grid systems. Here, the major problems associated to the grid defects were investigated, which includes the types of endogenous causes and exogenous causes. These types of issues were highly harmful to the electronic materials and people, hence which must be properly identified and rectified by using the proper tuning systems. This work also investigated some of the imbalances associated to the grid systems, which includes frequency deviation, overloads, synchronization loss, and voltage collapse. Once the fault is detected, it is more important to take the necessary actions like preparation, monitoring, and curative actions. Nasrallah *et al.* [27] discussed about the importance and benefits of deploying smart grid systems. Generally, the smart grid is defined as the advanced grid technology, which is integrated with the renewable energy sources. Also, it helps to obtain an improved system reliability and stability according to the load demand. Ai-Turjman *et al.* [9] provided a detailed overview about an IoT enabled smart grid technology. Generally, the power quality and reliability were considered as the most essential and critical problems of the conventional of grid systems. But, an IoT integrated smart grid systems provides an effective solutions to resolve the management problems. Here, the different types of Artificial Intelligence (AI) mechanisms used for improving the reliability of smart grid systems have been investigated. The different types of reliability indices investigated in this work were as follows:

1. Sustainable interruptions
2. Load based
3. Momentary interruptions

According to this study, it is analyzed increasing the lifetime and reducing the cost were must be concentrated in the design of smart sensors. Khan *et al.* [28] developed an IoT based power monitoring systems for the smart grid systems. The purpose of this work was to efficiently monitor and control the statistics of grid systems with increased reliability and power delivery. Norshahrani *et al.* [29] stated to mitigate the major effects (synchronization and stability) of renewable distribution in the distribution systems. Here, the different types of protection strategies have been investigated to improve the fault ride through capability of distributed systems. Eissa *et al.* [30] deployed a centralized protection scheme for reducing the time delay and improving the reliability of smart grid systems. Elsisi *et al.* [31] intended to develop a smart energy systems for the grid applications by using an IoT technology. The purpose of this work was to implement an intelligent reliable system in a smart grid systems by using the decision tree based machine learning algorithm. Also, it objects to analyze, control, and secure the data of smart meters with the help of decision tree algorithm. Panda and Das [32] investigated about the current practices and recent trends of reliability and security in smart grid systems.

TABLE I. COMPARATIVE ANALYSIS BETWEEN THE TRADITIONAL GRID AND SMART GRID SYSTEMS

Characteristics	Traditional grid	Smart grid
Active collaboration with energy consumers	Homogeneous & no collaboration	Consumers are active and well informed
Quality of energy	Low level responsibility	Better quality & price relation factor
Operating efficiency	Low degree of incorporation	Fully integrated
Reaction to disturbances	It requires system restoration	Automated problem detection and rectification
Flexibility	Chance for vulnerability	Very fast in nature
Energy storage	Dominance of main sources	Distributed generation

Sarathkumar *et al*. [33] examined about the different types of classification techniques used for detecting faults in the smart grid systems. Typically, the fault detection and mitigation were the most essential processes in the smart grid systems. Among others, the series fault and shunt faults were the major types of faults affect the grid system operations. Due to the rapid growth of information and communication technology, the smart sensors were increasingly used in the modern grid systems. Also, it plays an essential role in many application systems for improving voltage profile, self-healing ability, and transient stability. Kousar *et al.* [34] analyzed the major problems in the distribution management systems, which includes power load maintenance, centralized communication, user profile maintenance, and system malfunctioning. Also, a conceptual model was constructed in this work with the components of substations, smart meters, and distribution lines. Here, an IoT assisted monitoring technology was utilized for properly monitoring and controlling the electrical parameters of the load data. Matos *et al.* [35] intended to protect the distributed grid systems under varying faults with better reliability. It also aims to protect the device from overcurrent with improved voltage profile. Table I presents the comparative analysis of among the traditional [36, 37] and smart grid [38–40] systems.

According to this review, it is analyzed that the smart sensors are increasingly used in many grid application systems for fault management, reliability enhancement, voltage profile improvement and electric components protection.

III. PROPOSED METHODOLOGY

This section provides the complete explanation about the proposed IoT sensor based smart monitoring and controlling model for smart grid systems. The main contribution of this work is to monitor and control the smart grid systems with the use of IoT based wireless communication network. It also motivates to improve the power quality of smart grid systems with high reliability and voltage profile. Typically, the smart sensors are considered as the most essential IoT devices used for improving the reliability of smart grid systems. The smart sensor is defined as the kind of device that senses the environmental information to inform the controlling systems. Here, the primary objectives of using the smart sensors are to efficiently handle the unusual situations in the smart grid systems with increased reliability and system quality. The architecture representation of the smart grid systems is shown in Fig. 2, and the working flow of the proposed framework is depicted in Fig. 3.

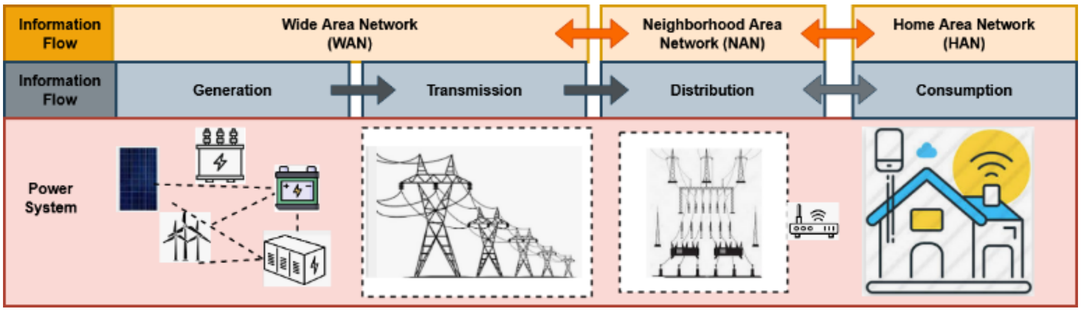

Fig. 2. Smart grid architecture.

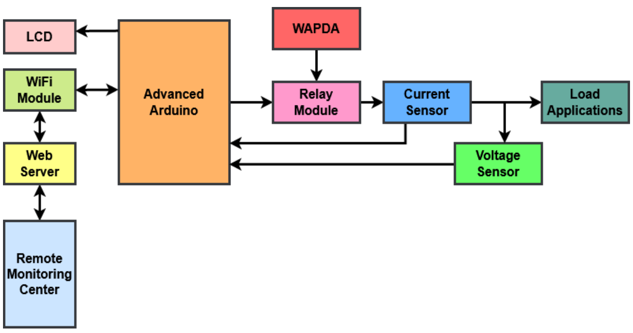

Fig. 3. Proposed framework.

The proposed framework comprises the major elements of monitoring component, communication component and analysis component. The monitoring component of the proposed framework consists of current and voltage sensors that are directly attached to the consumer loads. The communication component and analytical component are the other two primary components. Then, the communication component comprises the Arduino sensor and WiFi module, which helps to establish the wireless communication. Here, the analysis component is used as a remote application that is used to get the voltage profiles, energy reports, voltage and current. As shown in Fig. 2, the Arduino is interlinked with the sensor devices for collecting and storing the load information. Then, the WiFi application can get the collected data from Arduino with the use of

UART (Universal Asynchronous Receiver Transmitter) exchanges serial data transfer between two devices interface. In this framework, the WiFi is acts like a gateway between the server and monitoring component. Moreover, an IoT platform is implemented to collect and analyze the load information. These stored data provides the dynamic bills and load patterns for demand balancing according to the electricity generation and consumption. Specifically, this framework is beneficial to both utility companies and customers for properly managing their resources. By using this proposed framework, the customer can obtain the electrical parameters about the load information.

A. Operating Components

The major components used in the proposed power monitoring and controlling system are as follows:

- Arduino Uno - Arduino is a PC device and programming organization, commercial entity, and user network that develops and produces microcontroller units to make sophisticated devices and smart components that can detect and control substances in the system.
- Relay module – The grid protection relay is a device that makes sure the power quality is suitable for export to the grid. It includes the operations of over voltage or under voltage protection, over current or under current protection, and frequency resistance.
- Current and Voltage sensors – In the smart grid systems, the voltage and current sensors are mainly used to monitor the voltage and current level, and validate the proof-of-operations.
- Remote monitoring center – The remote monitoring agents are used to monitor the power quality and detect faults in the grid systems, which are increasingly used in the distribution sectors.

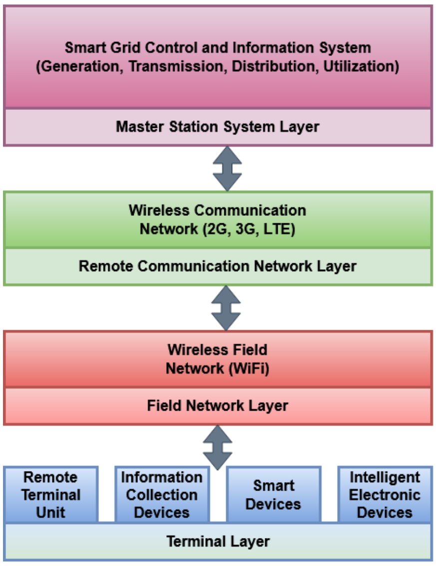

Fig. 4. Four layered architecture model of smart grid-IoT systems.

B. Integration of IoT with Smart Grid

Here, the integration of IoT with smart grid systems ensures an increased reliability, reduces the cost, and offers an intelligent features for communication. Moreover, an IoT enables two way communication among the smart devices and electrical components. In this work, the four layered IoT-smart grid architecture is deployed, which comprises the layers of remote communication layer, networking layer, terminal layer, and master station layer. In which, the smart grid functions are executed in the terminal layer by using the IoT devices, where the operations like electricity generation, transmission and distribution have been performed. Also, this layer is responsible for gathering information from various IoT devices, and the collected data is transmitted to the network layer. Moreover, the communication is established by using the remote communication layer, which is done according to the type of IoT devices. Finally, all smart functions are properly managed and controlled with the use of master station layer, which acts as the interface for the smart grid IoT systems. The four layered IoT-smart grid architecture is represented in Fig. 4.

C. Functional Operations

Here, the IoT assisted smart grid system is implemented for an automated monitoring and control. In this platform, the sensors' data are stored in IoT cloud environment through the web server. The consumer can read the all the sensors' data for deciding that which part of grid is under control. It helps to protect the environment from overcurrent issues like under voltage, short circuit faults, reverse power flow and etc. Moreover, the output grid DC voltage, current obtained from the storage, and power are displayed in customer interfaces through wireless. The distributed generation unit's most beneficial volume and ideal capability location are chosen by this problem. Characterizing the target is the first step in this technique. It demonstrates multi-objective operation based on a voltage stability index and a power quality problem. Eqs. (1) − (7) indicate the general problem formulation models. The proposed controlling model could efficiently handle the power quality problems with improved voltage stability. The power quality indices are calculated as follows:

$$P_I = \frac{|\mathrm{AP}_L| - |\mathrm{NAP}_L|}{|\mathrm{AP}_L|} \tag{1}$$

where P_I means power quality index, AP_L indicates the actual power loss without compensation, and NAP_L denotes not actual power loss. Consequently, the voltage stability indices is estimated by using the following model:

$$V_{SI} = \frac{2\frac{X}{Y}\sqrt{P_m^2 + Q_n^2}}{\frac{V_T^2}{Y} - 2\frac{X}{Y}P_M\cos(\omega_1 - \omega_2) - 2\frac{X}{Y}Q_M\sin(\omega_1 - \omega_2)} \le 1 \tag{2}$$

where V_{SI} represents the voltage stability index, P_m and Q_m indicates the real and reactive power at the receiver side, V_T is the total amount of voltage at the transmitter side, $X<\omega_1$ and $Y<\omega_2$ are the limits of the transmission line. If the index value is <1, it is considered as the system is in stable state. Moreover, the objective functions are formulated for improving the voltage stability and power quality by using the following models:

$$\min \mathrm{OFun}_1 = \sum_{i-1}^{k} I^2 K \tag{3}$$

$$\max \mathrm{OFun}_2 = 1/V_{\mathrm{SI}} \tag{4}$$

where i=1, 2, ⋯, k, OFun_1 and OFun_2 are the objective functions. Here, the actual operation is accountable for the regulated standard output power under impartiality criteria or imbalance demands. Similarly, the actual and apparent output power limits are calculated as follows:

$$\mathrm{Vol}_{I\min} \le \mathrm{Vol}_I \le \mathrm{Vol}_{I\max} \tag{5}$$

$$P_{I\min} \le P_I \le P_{I\max} \tag{6}$$

$$Q_{I\min} \le Q_I \le Q_{I\max} \tag{7}$$

In addition, the apparent power App_p, actual power Act_p and power factor are also estimated by using the following models:

$$\mathrm{App}_P = I_{\mathrm{RMS}} V_{\mathrm{RMS}} \tag{8}$$

$$I_{\mathrm{RMS}} = \sqrt{\sum_{k=0}^{K-1} i(K)^2} \tag{9}$$

$$V_{\mathrm{RMS}} = \sqrt{\sum_{k=0}^{K-1} u(K)^2} \tag{10}$$

$$\mathrm{Act}_P = \sqrt{\sum_{k=0}^{K-1} i(K)u(K)} \tag{11}$$

$$\mathrm{Pow}_{\mathrm{Fa}} = \mathrm{Act}_P / \mathrm{APP}_P \tag{12}$$

By using this proposed system, the environment monitoring is performed with the atmospheric information of voltage, power quality, and noise. The system operations are illustrated in below:

$$H_{\mathrm{DPr}} = H_D H_L + H_{\mathrm{Pr}} \tag{13}$$

where H_{DPr} indicates the amount of time required to handle the data, H_L is the load, and H_{Pr} denotes the preparation time.

IV. Results and Discussion

In this section, the simulation assessment has been carried out to validate and test the results of the proposed IoT based controlling and monitoring framework for the smart grid system. Here, the electrical parameters such as voltage and current of the load unit are also analyzed. Fig. 5 shows the actual current analyzed at varying time in terms of seconds, and the grid voltage and current are also validated under changing time instances in Fig. 6.

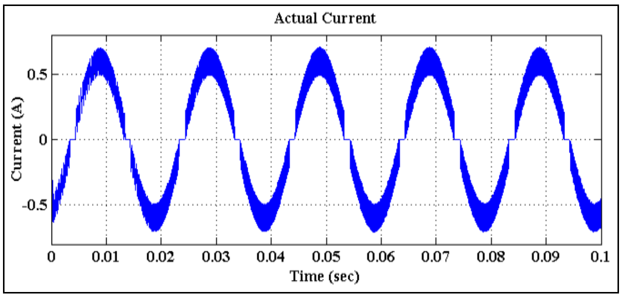

Fig. 5. Actual current analysis.

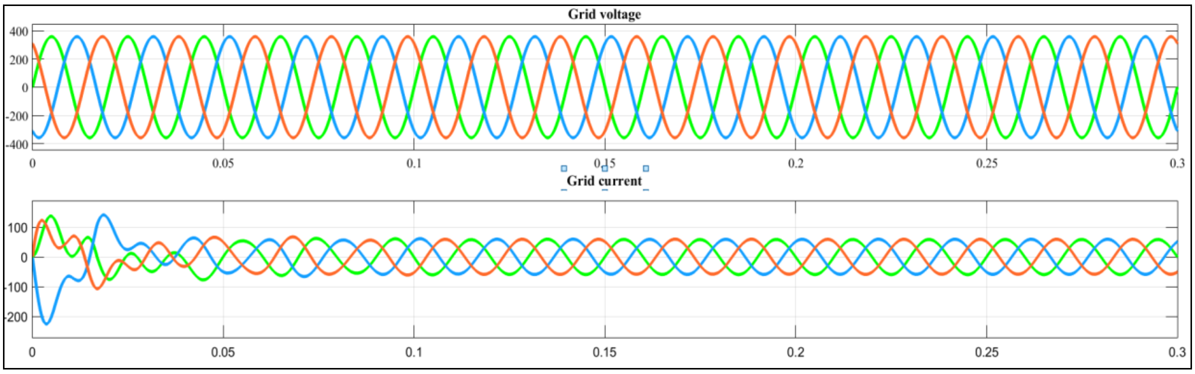

Fig. 6. Grid voltage and current.

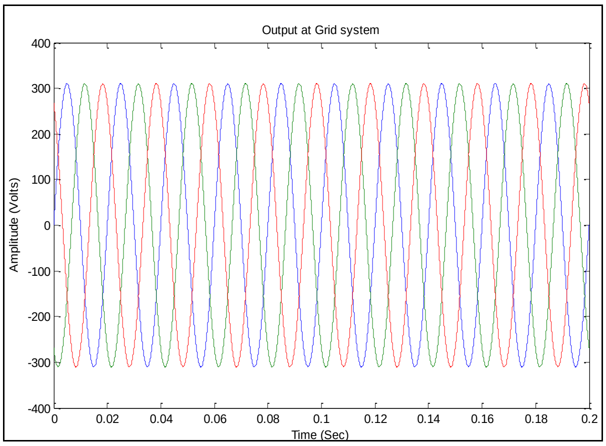

Fig. 7. Output of grid system.

Moreover, the output of grid system is represented in Fig. 7, which helps to analyze the load information of smart grid systems. These electrical measurements are mainly estimated to analyze the status of loads at varying time periods.

There are various tariff rates for each category, with Time of Usage (ToU) and penalty charges based on characteristics such as demand limit and power factor. Due to the fact that the industrial sector generates the highest profit for utilities and is therefore classified in the high priority section, tariff rates are low for residential customers and high for industrial customers. Monitoring electrical characteristics including voltage, current, active power, and power factor, among others, is essential for increasing grid efficiency at the distribution level of the SG. When the voltage and current are in phase and have a low harmonic content, the power factor is 1. When the power factor is 0, the voltage and current are out of phase by 90 degrees. Table II presents the power consumption analysis results of the proposed system, which includes the parameters of RMS voltage, RMS current, apparent power, power factor, and energy. Then, its separate graphical illustrations are presented in Fig. 8 to Fig. 11. In a smart grid systems, the data collection unit gathers the electrical parameters of RMS voltage, RMS current, apparent power, and energy. Based on this evaluation, the power consumption is analyzed at varying loads.

TABLE II. POWER CONSUMPTION ANALYSIS

Time	RMS voltage (V)	RMS Current (A)	Apparent power (VA)	Power factor	Energy in Watts
19:41:36	228.42	0.00	0.00	0.00	27.39
19:41:50	226.32	0.78	174.35	1.00	27.96
19:42:05	226.38	0.78	174.32	1.00	28.64
19:42:20	225.92	0.78	172.99	1.00	29.52

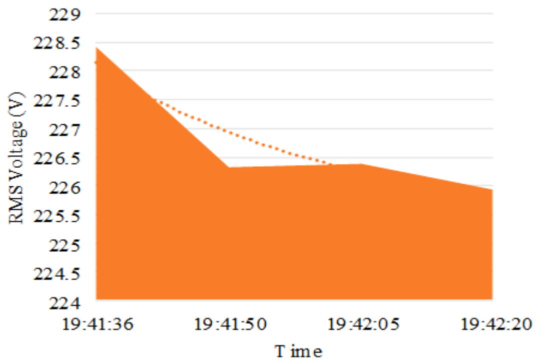

Fig. 8. RMS voltage.

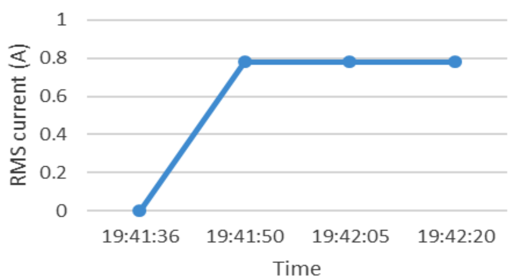

Fig. 9. RMS current.

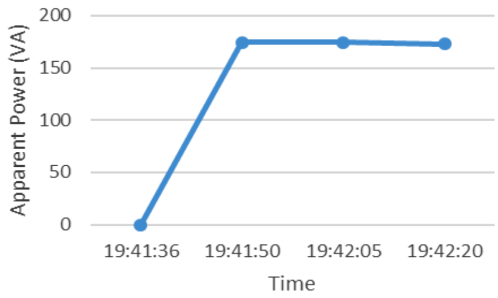

Fig. 10. Apparent power.

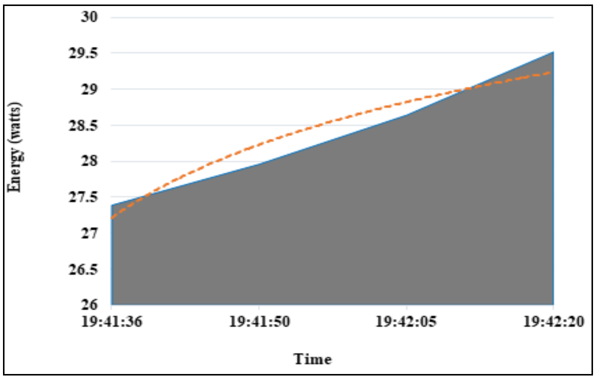

Fig. 11. Energy.

In order to validate the results, various situations have been considered and, the simulation assessment has been performed by using the parameters of packet delivery ratio, % of received packets, and energy consumption. Typically, the controller module has the responsibility to protect the system from voltage breakdown for ensuring the safe operations and functioning of the working zone. Here, the wireless communication network is considered for testing the proposed IoT-smart grid framework. Fig. 12 shows the number of packets transferred by the wireless network, and the results illustrate that the delivery ratio has been gradually increased with the increased number of nodes. Similarly, the percentage of delivered packets and energy consumption of the wireless communication network are validated as depicted in Fig. 13 and Fig. 14, respectively. Due to the proper monitoring and control of the system by using the IoT sensors, the performance of wireless communication network is highly improved.

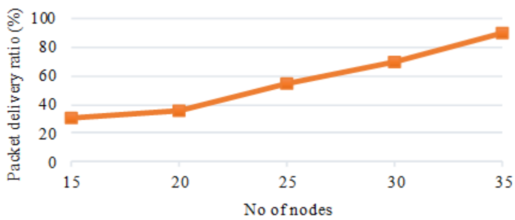

Fig 12. Packet delivery ratio

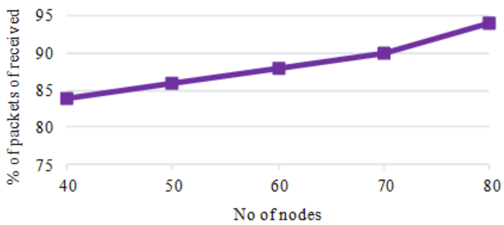

Fig. 13. Analysis on % of packets received.

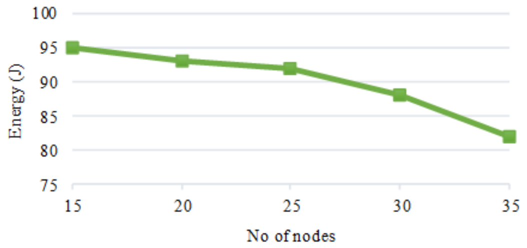

Fig. 14. Energy consumption.

V. Conclusion

The modern grid systems typically have an intelligent operation capability in their power infrastructure. The smart grid is one of the new and improved grid architecture that efficiently addresses the problems of the traditional grid systems with increased efficiency and reliability. In this paper, a new prototype for IoT-based power monitoring is implemented for the smart grid systems. This system improves the reliability in a variety of scenarios that differ for control methodology demands including dynamic power control and single power quality control. Here, the primary objectives of using the smart sensors are to efficiently handle the unusual situations in the smart grid systems with increased reliability and system quality. The major components used in the proposed power monitoring and controlling system are Arduino Uno, relay module, current and voltage sensors, and remote monitoring center. Specifically, this framework is beneficial to both utility companies and customers for properly managing their resources. By using this proposed framework, the customer can obtain the electrical parameters about the load information. During evaluation, the performance of this framework is validated and tested by using different electrical parameters such as voltage, current, energy, apparent power, RMS parameters, and power factor. From the evaluation, it is analyzed that the proposed framework demonstrates how the IoT based sensor technology can be effectively used to improve the reliability and power quality of the smart grid systems.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

S. Poorna Chander Rao designed a small prototype of the system, carried out the simulation, performed the measurement of voltage, current and power calculations in the paper, and analyzed the characteristics. Dr. M. Sushama supervised the work and provided suggestions for improving the reliability of the system, and helped with the mathematical derivations and proofread the paper. Both authors had approved the final version.

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