A New Design of IoT-Based Network Architecture for Monitoring and Controlling Power Consumption in Distribution Grids

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Abstract- Nowadays, the electric power sector is accomplishing many essential improvements on power networks to respond to power supply reliability and energy consumption demand as well as to exploit effectively distributed generators integrated into the networks. The smart grid, a new modern solution for future power networks, uses digital technologies and Internet of Things (IoT) solutions to intelligently respond and adapt to changes in the power networks. This paper develops a new design of IoT-based network architecture applied for measuring, monitoring, and controlling substations on low-voltage distribution networks. In this proposed system, transmitting and receiving measurement data from the substations is based on the IoT platform via the LoRaWAN and WiFi communication technologies. This aims to increase the reliability and accuracy of the communication system. Once access permissions for the system are established, network operators and managers can easily monitor all electrical measurement parameters and control circuit breakers at the substations using smartphones or personal computers. The obtained experimental results in this paper show that the proposed system is a low-cost and feasible design for applying to future power networks.

Keywords Low-voltage distribution network, Thingsboard platform, IoT technology, monitoring and controlling, LoRa communication.

1. Introduction

Distribution power networks, known as the last apart of power systems, carry electric energy from transmission or sub-transmission networks to electric consumers. They are distinguished from transmission networks by their voltage level and topology to which the electric loads are directly connected. Therefore, power quality and reliability issues of power supply are the most important critical standards for distribution power networks [1]. Smart grid is a definition which is considered and developed for distribution networks in recent years. In fact, smart grid technology is to use modern science and technology development in many fields such as information technology, communication technology, automation technology, etc. into the available networks for improving reliability, power quality, energy management [2-4].

One of the interesting technology solutions applied to the smart grid is Internet of Things (IoT) technology, which can be used for monitoring, controlling, and managing all electrical equipment on the distribution networks. Utilizing IoT technology in the smart grid is a vital application to speed up the informatization of the networks, and it is beneficial for the effective management of distribution network infrastructure [5-7]. Focusing on the characteristic of monitoring and controlling the distribution networks, a new design of IoT-based network architecture built up by various types of IoT devices to measure, monitor, and control electric loads on the distribution networks is developed in this paper.

There are several published works to design and implement the IoT technology in distribution networks [8-17]. The authors in [8, 9], presented state-of-the-art research about IoT, its applications, architectures, and technologies.

This helps to open the doors to develop many technological solutions for many projects. The ZigBee-based communication system for data transfer within future microgrids [10] and the architectures for smart buildings to optimize and manage their energy [11] were considered as the IoT practical applications. For energy management in the distribution network, the IoT was studied to measure [12, 13], monitor [14, 15], and control [16] in low-voltage distribution networks. Jorge *et al.* in [17] proposed a solution for integrating the LoRaWAN with 4G/5G mobile networks to exploit their current infrastructures.

The wireless sensing network including sensor node, power management, and data communication was developed in the work [18], it was effectively utilized on the switchgear cabinet and power cable. Related to data transfer using communication technologies, Thomas *et al.* in [19] developed a system based on the IoT technology for monitoring and visualizing streams of data received in real-time by sensor devices. In the system, the Constrained Application Protocol (CoAP) protocol was used via a Raspberry Pi and sensors. On the other hand, the wireless sensor network was based on proposing a scheme using both open-source hardware and software for data collection at the nodes in the network [20-26]. Reference [27] presented challenges and solutions about the application of IoT technology in future smart grids. Shahinzadeh *et al.* in [28] pointed out that the joint integration between 5G and IoT was more flexibility and reliability. In [29], the theory of game was applied to implement the rephasing algorithm based on IoT technology for balancing load in smart grids.

Motivated by the discussion above, it is essential to develop an IoT-based system that aims to monitor electrical parameters and control electric equipment on distribution networks. A new design of IoT-based network architecture is proposed in this paper for measuring, monitoring, and controlling electrical parameters, electric loads in low-voltage distribution networks. In summary, the main contributions of this paper cover three aspects: (*i*) Firstly, we introduce an experimental design of an IoT-based system for monitoring and controlling low-voltage distribution networks via a web-based monitoring platform in real-time; (*ii*) Secondly, the LoRaWAN and WiFi communication technologies are simultaneously applied in the proposed IoT system to enhance the system reliability; and (*iii*) Thirdly, the feasibility of the proposed system is analyzed and evaluated through experimental results in the laboratory environment. The rest of this paper is organized as follows. Section 2 illustrates all steps for designing the proposed IoT system. Section 3 contains the main experimental results carried out by running the proposed system in the laboratory environment and presents a discussion related to the experimental results. Finally, Section 4 concludes this paper.

2. Proposed System

This section depicts a procedure to design the proposed system in which new network architecture is developed for acquiring measurement data from low-voltage distribution networks. This network architecture consists of a Gateway station and Node stations. These stations can communicate via the LoRa communication technology by themselves and communicate to the Thingsboard, an open-source IoT platform, via the WiFi Internet network [20]. The Gateway station is responsible to acquire and display all measurement data of the stations on the monitoring screen as well as transmitting the data to the Thingsboard for monitoring, controlling, and sharing the data with the users. Besides, the Node stations are applied to acquire all measurement parameters of their stations and then transmit these parameters to the Gateway station via the LoRa communication technology. Moreover, the Node stations can receive the control signals from the Gateway station to control their circuit breakers. Therefore, the network architecture of the proposed system follows the specifications of the LoRa technology [30] including measurement modules at the nodes, a Gateway station for acquiring information at the nodes, and an open-source Thingsboard cloud platform for supplying web-based applications. To develop the system, the following procedure is carried out in this work:

Step 1: Design and develop the nodes for monitoring all electrical parameters and transmitting these parameters to the Gateway using the LoRaWAN Class A features [17].

Step 2: Configure the Gateway for acquiring all electrical parameters from the nodes and forward them to the Thingsboard platform for saving and/or processing the data.

Step 3: Use the Thingsboard platform to collect and display all electrical parameters from the stations using MQTT, CoAP, or HTTP protocols [19, 20]. Besides, it can be used to define new rules to confirm received data between different features.

In summary, the proposed system is structured by a group of LoRa nodes to acquire measurement data of electrical parameters at the monitoring locations in low-voltage distribution networks. These parameters are transmitted to the Gateway station for displaying on the monitoring and controlling the user interface. Besides, the measurement data is also uploaded continuously to the Thingsboard platform for storing, processing, and displaying on the designed web-based program. The proposed network architecture of the system is shown in Fig. 1.

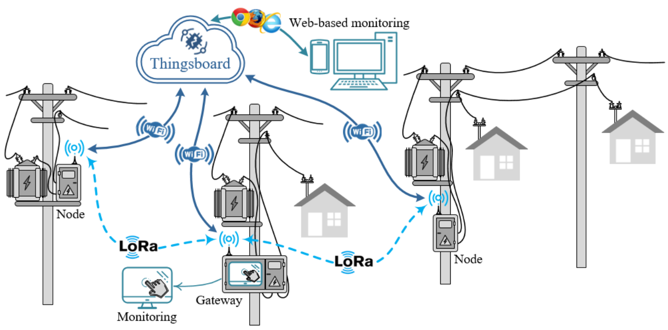


Fig. 1. The proposed network architecture.

2.1. Design of Gateway Station

The connection diagram of devices at the Gateway station at which the electrical parameters will be transmitted by a power quality measurement device namely PAC4200 [31] is shown in Fig. 2. These parameters are then sent to the Raspberry Pi via the Ethernet TCP/IP in order to process and display them on the monitoring and controlling screen. The WiFi LoRa 32 board at the Gateway station is used to communicate with the WiFi LoRa 32 board at the Node stations as well as to receive the electrical measurement parameters from the Node station and then send them to the Raspberry Pi at the Gateway station. In addition, it is to transmit the control signal from the Raspberry Pi at the Gateway station to the Node station. In this station, the PAC4200 is a measurement device for measuring electrical parameters in a low-voltage distribution network including frequency, voltage, current, power, power factor, etc. This device is capable of a single-, two-, or three-phase measurement unit and can be used in two-, three-, or four-wire low-voltage electric networks.

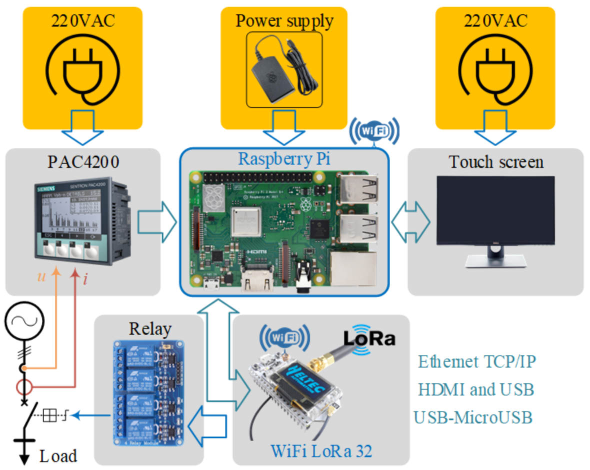


Fig. 2. The connection diagram at the Gateway station.

The state diagram used for programming the Raspberry Pi of the Gateway station is described in Fig. 3. In the first stage, the Raspberry Pi will initialize the initial parameters and read the electrical parameters from the PAC4200. It then read measurement data from the WiFi LoRa 32 board which is transmitted to by the Node station. Depending on the user selection, the measurement parameters of the Gateway station or the Node station will be displayed on the monitoring screen located at the Gateway station. The electrical parameters at the Gateway station are measured by the PAC4200 and they are then transmitted to the Raspberry Pi via the Ethernet interface [20]. The WiFi LoRa 32 board of the Node station transmits its electrical parameters to the WiFi LoRa 32 board of the Gateway station via the LoRa or Internet communication. After that, the WiFi LoRa 32 board of the Gateway station transmits the parameters to the Raspberry Pi to display them on its monitoring screen. In addition, to make a control signal at the Gateway station and the Node station the Raspberry Pi can run a sub-program that is programmed and selected by the users at the Gateway station. The measurement parameters of the two stations: Gateway and Node will be transmitted to the Thingsboard cloud platform. The users can therefore monitor these parameters everywhere via a mobile device connected to the Internet network. The Pycharm software [32, 33], applied to program the Raspberry Pi at the Gateway station, is to receive and process the measurement parameters at the Gateway station and Node station as well as to transmit the control signals from the Gateway station to the Node station. Besides, it is programmed to send data to the Thingsboard platform, to create the user interface, and to display the parameters on the monitoring screen.

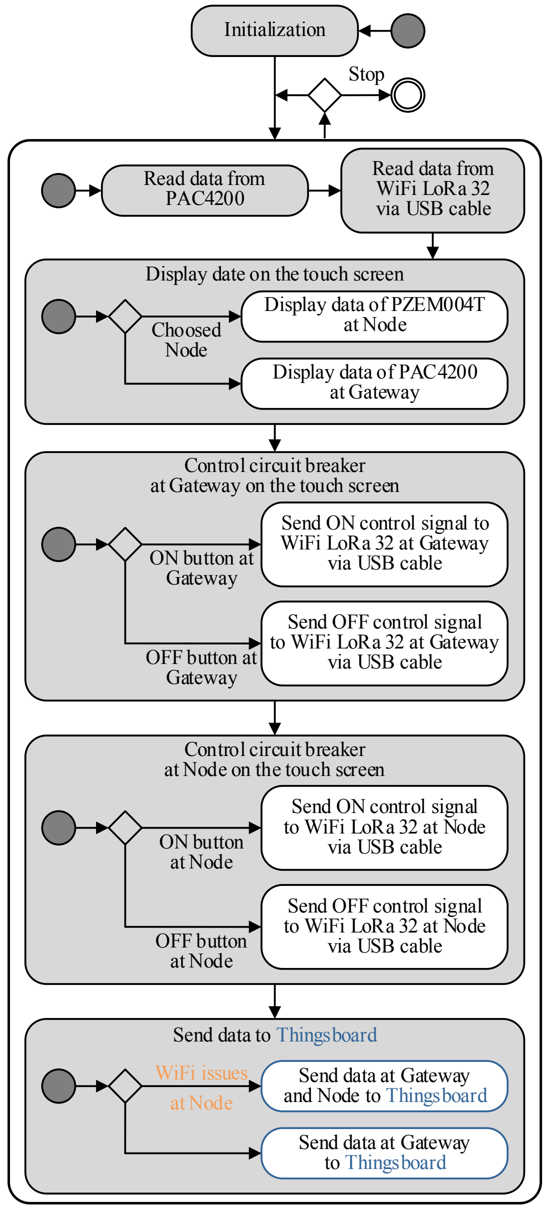


Fig. 3. The state diagram for the Raspberry Pi of the Gateway station.

The state diagram for the WiFi LoRa 32 at the Gateway station is designed as Fig. 4. After the initial parameters are initialized, the WiFi LoRa 32 board of the Gateway station receives the signal from the Raspberry Pi to control the circuit breaker at the Gateway station. Moreover, the WiFi LoRa 32 board of the Gateway station can forward the signal for controlling the circuit breaker of the Node station to the WiFi LoRa 32 board of the Node station. It is also to forward the electrical parameters from the WiFi LoRa 32 board of the Node station to the Raspberry Pi via the LoRa and USB communication. In this paper, the Arduino IDE 1.8.13 software [34] is used to program the WiFi LoRa 32 board.

The program of the WiFi LoRa 32 board at the Gateway is to receive and transmit the measurement data between the WiFi LoRa 32 board of the Gateway station and the other one of the Node stations. Besides, it can be used to control the relay module at the Gateway station.

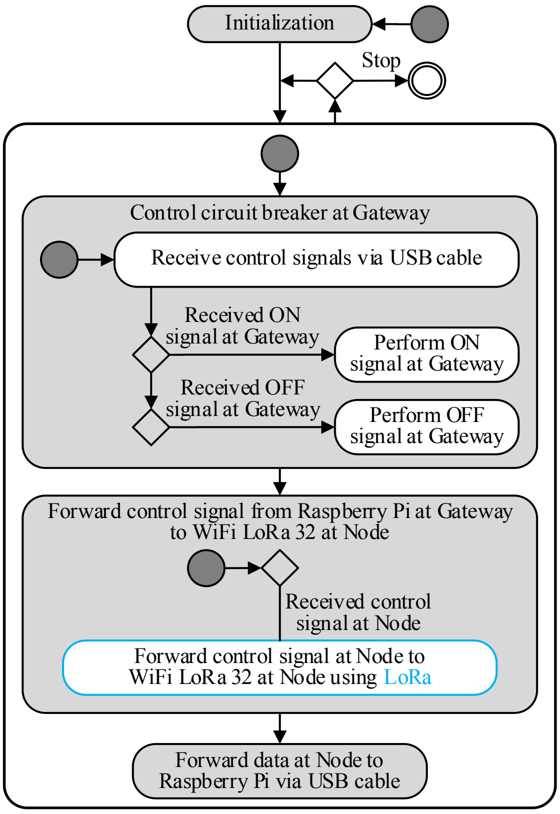


Fig. 4. The state diagram for the WiFi LoRa 32 board of the Gateway station.

2.2. Design of Node Station

The connection diagram of devices of the Node station is shown in Fig. 5. Looking at Fig. 5, the electrical measurement parameters such as voltage, current, frequency, power, etc. at the Node station are measured by three PZEM004T modules. These parameters are then transmitted to the Raspberry Pi at the Gateway station via the LoRa communication between two WiFi LoRa 32 boards of the Node station and the Gateway station. In addition, the control signals from the Raspberry Pi at the Gateway station are also transmitted via the same way to control the circuit breaker at the Node station. Transmitting the electrical parameters at the Node station to the Thingsboard platform can be performed via one of two following channels. The first channel uses the Internet connection at the Node station as the main channel if the WiFi LoRa 32 board of the Node station is completely connected to the Internet via the WiFi network. The measurement data will be transmitted over the Internet by this channel and stored on the master computer of the Thingsboard platform. The second channel is through the Internet connection of the Raspberry Pi if the Internet connection at the Node station has an error. When the Raspberry Pi receives the error signal of the Internet connection from the Node station, it will transmit the measurement data of the Node station to the Gateway station via the LoRa.

Additionally, the users can also use the web browser to directly access the address of the Thingsboard for monitoring all measurement data at the Node station as well as the Gateway station by using the personal computer or smartphone connected to the Internet. On the Thingsboard platform, the user guides are designed to easily monitor and control the devices at the stations. These user guides are like the program designed in the Raspberry Pi. The control signals of the circuit breakers at the Node station are transmitted to the WiFi LoRa 32 board of the Node station via the LoRa. Once these signals are received, the WiFi LoRa 32 board at the Node station will control its circuit breakers by the relay modules.

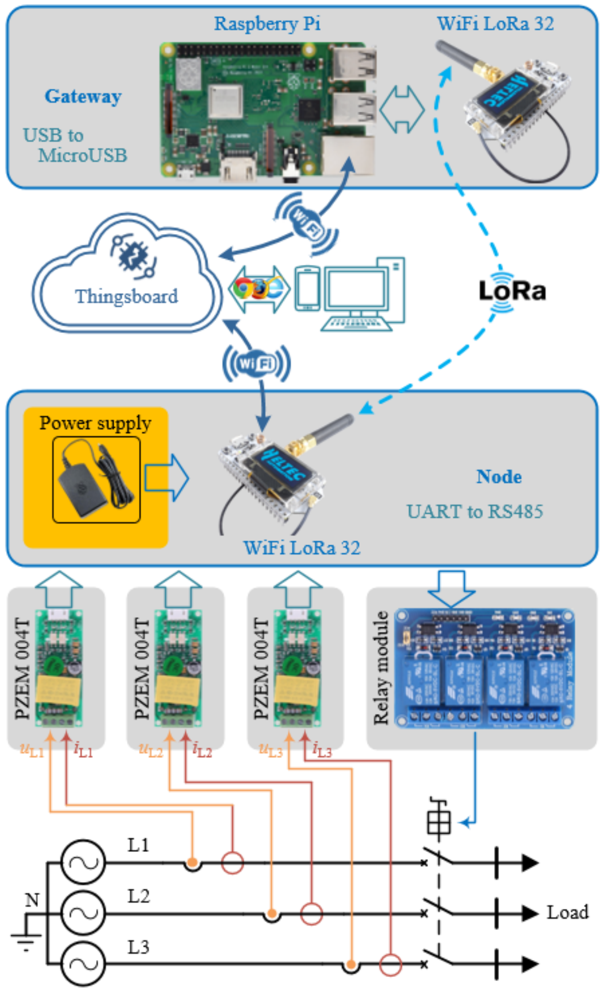


Fig. 5. The connection diagram at the Node station.

The state diagram of the WiFi LoRa 32 board of the Node station is designed as shown in Fig. 6. The program purpose of the WiFi LoRa 32 board at the Node station is to read all measurement data from the PZEM004T, it then transmitted the data to the Gateway station via the LoRa communication technology. Besides, it is also programmed to receive ON/OFF control signals sent to the Node station from the WiFi LoRa 32 board of the Gateway station. The signals are used to control circuit breakers of the Node station via a relay module. The measurement data of the Node station is pushed up to the Thingsboard platform via the WiFi connection of the WiFi LoRa 32 board at the Node station.

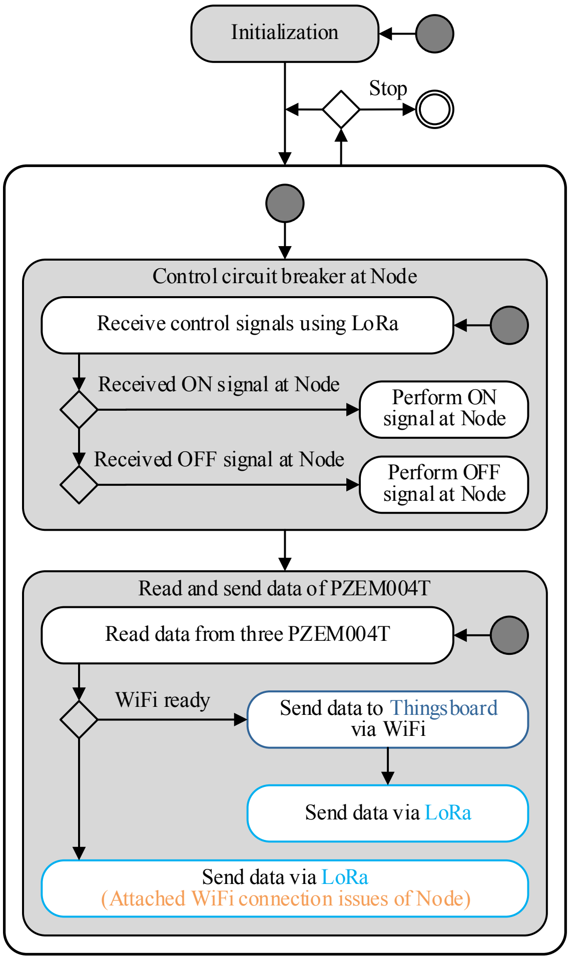


Fig. 6. The state diagram for the WiFi LoRa 32 board of the Node station.

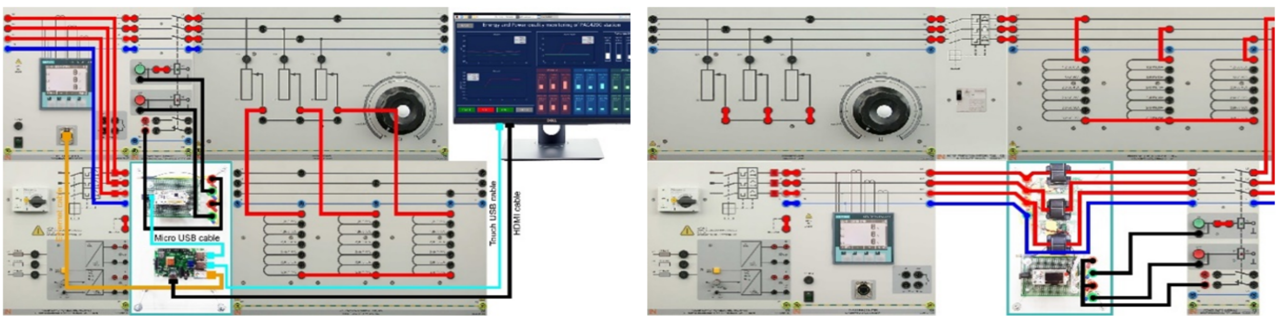
3. Experimental Results

3.1. System Implementation and Execution

In order to implement and execute the proposed system in this work, the experimental setup shown in Fig. 7 is established for the Gateway station and Node station. Figs. 7 (a), (c) is the wiring diagram and experimental setup, respectively for evaluating the performance of the Gateway station. Looking at Figs. 7 (a), (c), the main units obtained from the Gateway station consist of a monitoring and controlling module, a power supply, a PAC4200, a circuit breaker, a resistance load, an inductance load, and a monitoring screen. The Raspberry Pi is programmed according to the algorithms as mentioned in Section 2. This program is to display all measurement parameters of the two stations on the monitoring screen on the Thingsboard platform and to perform ON/OFF control signals from the users.

The WiFi LoRa 32 at the Node station transmits all its data to the Raspberry Pi via a MicroUSB/USB cable and receives measurement data from the WiFi LoRa 32 at the Node station via LoRa communication. Reversely, it is to transmit control signals from the user interface of the Raspberry Pi to the relay module at the Gateway station via a MicroUSB/USB cable or to the WiFi LoRa 32 board at the Node station via LoRa communication. In this experimental setup of the Gateway station, the PAC4200 aims to read all electrical measurement parameters at the Gateway station. These parameters are then transmitted to the Raspberry Pi via an Ethernet cable. The circuit breaker is used to ON/OFF its loads at the Gateway station according to the status of its relay modules. The monitoring screen displays all measurement data on a user guide which is programmed in Raspberry Pi. In general, the Gateway station is an important role in the proposed system because it is a center that can perform all designed functions for monitoring and controlling the stations. Moreover, it is to transmit all measurement parameters of the two stations to the Thingsboard platform in case of an internet connection error occurred for the Node station.

Meanwhile, Figs. 7 (b), (d) are the wiring diagram and experimental setup, respectively for evaluating the performance of the Node station. The laboratory devices used to carry out this test include a measurement and control module, a power supply, a PAC4200, a circuit breaker, a resistance load, and an inductance load. In order to measure electrical parameters, three PZEM004T modules are used in this setup. These parameters are then transmitted to the WiFi LoRa 32 board at the Node station. After that these parameters are sent to the Thingsboard platform via the Internet connection as well as being sent to the WiFi LoRa 32 at the Gateway station via the LoRa communication. Besides, the WiFi LoRa 32 at the Node station is to receive the ON/OFF control signals from the Gateway station using the program on the Raspberry Pi.



(a) Wiring diagram at Gateway station (b) Wiring diagram at Node station

Fig. 7. Cont.

(c) Experimental setup at Gateway station (d) Experimental setup at Node station

Fig. 7. The experimental setup in the laboratory for the Gateway station and the Node station.

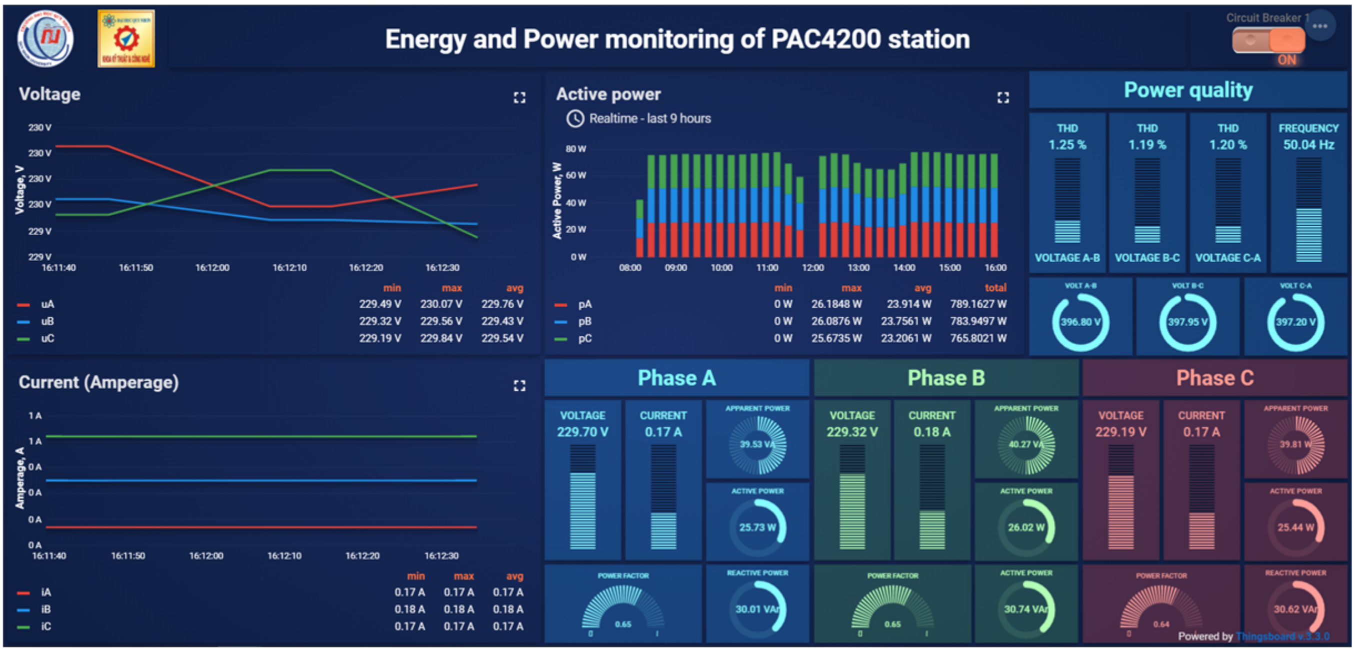


Fig. 8. The monitoring and controlling screen on Thingsboad of the Gateway station.

3.2. Experimental Results

The experimental setup of the Gateway station is shown in Figs 7 (a), (c). Looking at Figs 7 (a), (c) the three-phase modules such as a power supply, a circuit breaker, a resistance load, an inductance load. The bulbs are connected to phase A to establish an unbalanced load condition. Measuring electrical parameters at the Gateway station is carried out by a PAC4200, the entire measurement data is transmitted to the Raspberry Pi via an Ethernet cable. The electrical parameters at the Gateway station are displayed on the monitoring and controlling screen on the Thingsboard as shown in Fig. 8. The parameters include voltage, current, active power, reactive power, apparent power, power factor, frequency, and total harmonic distortion of each phase. These all parameters are illustrated in the types of the bar chart. In addition, for conveniently monitoring the variation of voltage and current, the two parameters are shown in a type of line graph in real-time. In this guide, two buttons (ON and OFF) are used to control the circuit breaker of the Gateway station. Moreover, the ON/OFF command can be also made by each station to protect its load when an over- or under-voltage occurs in the grid. The command is created by comparing the measured voltage with the maximum and minimum voltages and it is transferred from the LoRa module to the relay module of each station.

(a) (b) (c)

Fig. 9. The monitoring and controlling screen on the smartphone of the Node station: (a) Active power monitoring, (b) Voltage and current monitoring, (c) Total harmonic distortion monitoring.

The experimental setup of the Node station is depicted in Figs. 7 (b), (d). The electrical parameters of this station are measured by three PZEM004T modules connected to the WiFi LoRa 32 board; therefore, monitoring and controlling this station are programmed on the Thingsboard platform. Furthermore, the electrical parameters of this station can be monitored and controlled via a smartphone shown in Fig. 9.

In this proposed system for monitoring and controlling low-voltage distribution networks, two modules are applied to measure electrical parameter measurements at the substations. The first one is the power quality meter PAC4200, which can measure many electrical parameter measurements and it is high reliability and accuracy. The second one is the PZEM004T modules, which can also measure basic electrical parameter measurements and cost lower than the first one. Therefore, depending on the cost and demand the user can correctly select the two devices. This work has proposed two communication channels including LoRaWAN and WiFi technologies. The two channels are simultaneously used to increase the system reliability; therefore, we can use one channel to control the circuit breakers at the stations and another channel to feedback the control results. Connecting to the Internet at the Node stations can use the local infrastructure where the Node stations are located. In this work, the measurement results of the Node station are compared with the standard measurements which are measured by a commercial standard meter in our laboratory as shown in Table 1. These compared results show that the accuracy of this proposed system is satisfied to apply in practical systems for monitoring and controlling distribution power networks.

Table 1. Comparing the accuracy of the proposed system with the standard meter.

The voltage measurement					
Measurement value by standard meter (V)	160	180	200	220	230
Measurement value by proposed system (V)	160.02	179.99	200.00	219.98	230.03
Deviation (V)	0.02	-0.01	0.00	-0.02	0.99
The current measurement					
Measurement value by standard meter (A)	20.0	30.0	40.0	50.0	100.0
Measurement value by proposed system (A)	20	30	40	50	100
Deviation (A)	0	0	0	0	0
The active power measurement					
Measurement value by standard meter (kW)	0.220	0.440	1.100	2.200	4.400
Measurement value by proposed system (kW)	0.221	0.438	1.103	2.201	4.400
Deviation (kW)	0.001	-0.002	0.003	0.001	0.000
The power factor measurement					
Measurement value by standard meter	0.5	0.7	0.8	0.9	1.0
Measurement value by proposed system	0.500	0.700	0.801	0.901	0.999
Deviation	0.000	0.000	0.001	0.001	-0.001
The total harmonics distortion measurement					
Measurement value by standard meter (%)	1	2	3	4	5
Measurement value by proposed system (%)	1.01	2.00	3.01	3.99	5.00
Deviation (%)	0.01	0.00	0.01	-0.01	0.00

4. Conclusions

In this paper, the authors had designed, developed, and implemented a simple and low-cost IoT-based system for monitoring and controlling power consumption in low-voltage distribution networks. The hardware and software of the system were carefully designed and analyzed based on the requirements of measurement modules as well as the specifications of low-voltage distribution networks. The experiments were carried out in the laboratory environment to demonstrate the effectiveness of the proposed system. Besides, the experimental results also showed that the accuracy of measurement results of the proposed system is reliable and flexible for controlling and monitoring power consumption in low-voltage distribution networks. The wireless connection between LoRa and WiFi communication is to ensure the basic requirements of data communication, real-time and remote monitoring, and controlling the electrical power parameters at monitoring locations as well as visually display on personal computers or smartphones. In the future, the system will be expanded more features to apply in the smart grid.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

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