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An advanced IoT system for monitoring and analysing chosen power quality parameters in micro-grid solution

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Abstract: This paper proposes an advanced Internet of Things (IoT) system for measuring, monitoring, and recording some power quality (PQ) parameters. The proposed system is designed and developed for both hardware and software. For the hardware unit, three PZEM-004T modules with non-invasive current transformer (CT) sensors are used to measure the PQ parameters and an Arduino WeMos D1 R1 ESP8266 microcontroller is used to receive data from the sensors and send this data to the server via the internet. For the software unit, an algorithm using Matlab software is developed to send measurement data to the ThingSpeak cloud. The proposed system can monitor and analyse the PQ parameters including frequency, root mean square (RMS) voltage, RMS current, active power, and the power factor of a low-voltage load in real-time. These PQ parameters can be stored on the ThingSpeak cloud during the monitoring period; hence the standard deviation in statistics of the voltage and frequency is applied to analyse and evaluate PQ at the monitoring point. The experimental tests are carried out on low-voltage networks 380/220 V. The obtained results show that the proposed system can be usefully applied for monitoring and analysing chosen PQ parameters in micro-grid solutions.

Key words: energy management, Internet of Thing (IoT), micro-grid, power quality (PQ), ThingSpeak cloud

1. Introduction

Power quality (PQ) is commonly defined as the power grid's capability to supply a clean and stable power flow, as a constantly available PQ. The power flow should have a pure sinusoidal waveform within specified voltage and frequency tolerances. Deviations from these ideal conditions are frequent due to increasing non-linear and other loads disturbing the grid. The consequences of poor PQ can inflict serious losses to business and economy. According to a recent study published by the Electric Power Research Institute, large industrial facilities in the United States lose over $100 billion every year due to power problems, including PQ variations and voltage disturbances [1–3]. Good PQ can save money and energy for customers and utilities. In order to overcome PQ challenges, it is necessary to monitor inputs and disturbances generated by nonlinear loads. The PQ monitoring can provide appropriate protection to equipment and can help to select suitable mitigation solutions that help to improve PQ in micro-grids [4–6].

Alongside Industry 4.0, the Internet of Things (IoT) cloud-based platform is a technology that its applications are not restricted to some groups of areas but, above all, in the healthcare industry, home and building automotive industry, environment industry, electrical power industry, transportation industry, etc. For the electrical power system, the IoT has been an integral part, such as Supervisory Control and Data Acquisition (SCADA), smart metering, building automation, public lighting, smart grids, and especially used for measuring, controlling, monitoring, and managing PQ [7–9]. A data visualization proposition for wireless sensor networks (WSNs) was developed in [10] as an IoT system, in which the data accumulated by nodes with distinct sensors can be used for monitoring environmental conditions such as temperature and humidity.

Because of the rapid growth of IoT technology, some developed countries have applied the advanced metering infrastructure, automatic meter, or smart energy meter technology for measuring and monitoring the energy consumption in households via monitoring and analysing energy information reports in real-time [11, 12]. That can help customers to see their electric energy usage in real-time. As a result, they are able to manage energy consumption and save their finance. In recent years, many studies have developed various techniques based on the metering and control of distributed generation via communication technologies, sensors, and information to monitor and analyse the electrical energy production and consumption [13–20]. The authors in [13] presented the research work that applied the communication technologies between electricity smart grids and households to save energy. The remote energy monitoring system using the IoT was designed in [14] to manage, schedule, optimize, and save the energy in smart grid and home automation. A dedicated system for maximizing energy efficiency in micro-grids using the IoT platform with a big data system via the energy information collection, management, and sharing was proposed in [15]. The advanced energy management system based on the semantic framework was implemented in buildings [16]. The system presented in [17, 18] used the cloud computing framework to design the system to control and monitor the system parameters and to allow the users to access, control, and monitor the data. The IoT application of remotely monitoring the metering infrastructure in real-time for an energy management system through the internet and LabView software was illustrated in [19, 20].

Several studies have proposed intelligent energy management systems for micro-grids. In [21], the authors proposed an energy management scheme based on particle swarm optimization (PSO). The smart monitoring system was introduced in [22] for measuring and monitoring the current and voltage using Arduino Nano V3.0. In order to create a network indoor more intelligently and automatically, the authors in [23] proposed a smart home management system based on IEEE 802.15.4 and ZigBee sensor network.

Apart from the use of the IoT for smart energy management, the PQ is an important issue in a power supplying process because of its large detrimental effect on industrial processes and commercial sectors when the PQ is low. Thus, in order to enhance PQ, several research studies have applied the IoT technologies in recent years. The authors in [24] presented the smart sensor network based on field-programmable gate array (FPGA) technology for monitoring PQ in electrical installations. The real-time energy monitoring system based on the IoT, computing, and big data was proposed in [25] for analysing PQ. The authors in [26] proposed an energy monitoring solution using the IoT, communicating with digital energy meters via the Modbus protocol to categorize PQ. Today, some loads require a high level of PQ during the manufacturing process to ensure high-quality products, and especially for loads that are sensitive to PQ disturbances. Therefore, PQ needs systematic monitoring to know how to control it [27]. The time synchronisation of smart-meter measurements carried out via the Precision Time Protocol (PTP) is applied in a novel approach for monitoring the distribution system and state estimation [28].

Based on actual demands, this paper develops an advanced IoT system for monitoring and analysing some chosen PQ parameters in real-time in the micro-grid solution. The developed system uses three PZEM-004T modules connected to the Arduino WeMos D1 R1 microcontroller to perform its functions and it has the salient features as follows:

(*i*) it can monitor and analyse chosen PQ parameters at different positions of a micro-grid in real-time and record those parameters in online historical data;
(*ii*) it can store the big data on a web server;
(*iii*) it can perform monitoring and analysing both online and offline;
(*iv*) and most importantly, it is a neat and low-cost system.

The remaining parts of this paper can be divided into three sections. Section 2 develops the material and method including hardware implementation and embedded software for efficient monitoring and analysing some chosen PQ parameters of micro-grids in real-time. Section 3 presents the experimental results and discussion. Finally, the conclusion is presented in Section 4.

2. Material and method

2.1. Hardware implementation

The proposed advanced IoT-based platform system for monitoring and analysing some chosen PQ parameters is described in this paper, as shown in Fig. 1. The energy monitoring node includes three PZEM-004T sensor modules, one Arduino WeMos D1 R1 microcontroller, and four relays. The PZEM-004T is a sensor made by Peacefair Electronic Technology Co., Ltd. and it is equipped with 8 pins, in which 2 pins are considered to be voltage and current sources for operating the sensor; 2 pins are considered to create a serial communication; 4 pins have functions of voltage and current inputs. Its operation is based on the principle of a current transformer (CT) at a frequency of 50 Hz or 60 Hz in a single-phase network. This PZEM-004T module uses a non-invasive CT sensor and SD3004 energy measurement SoC chip, which are very good to measure single-phase voltage, frequency, current, active power, a power factor, and energy consumption at the monitoring needed point via the CT as a sensing part that has input/output with a ratio to be 100 A:100 mA.

The PZEM-004T module is a new low-cost power sensor and can measure some PQ parameters including frequency, current, voltage, active power, and a power factor [29]. The current can be measured by putting a wire through the hole in a sensor's iron core. This sensor can

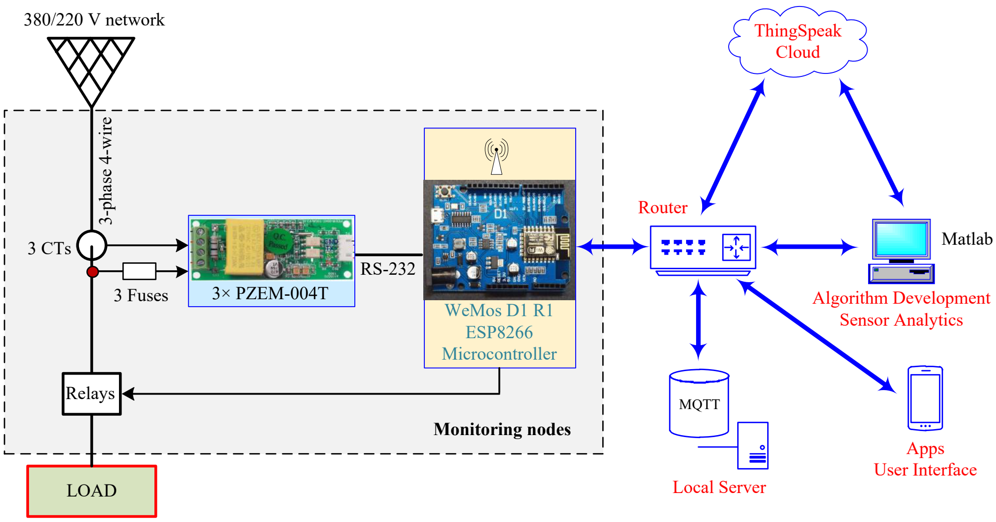


Fig. 1. The proposed ThingSpeak platform-based system overview

measure current up to 100 A. The output from PZEM-004T is via transistor-transistor logic (TTL) serial communication. It is not an analog voltage level as in the previous three sensors, so we do not need to create any additional circuit. Besides, we can get the measurement value by using the PZEM004T library [30] to obtain the measurement data directly. Moreover, the study results in [29] show that PZEM004T is a low-cost power sensor and gives the best performance among sensors mentioned in the work for measuring those PQ parameters. In order to send the measurement data from PZEM-004T modules to the ThingSpeak cloud, an Arduino WeMos D1 R1 microcontroller is used to communicate with PZEM-004T via RS-232 and interact with an ESP8266 module. The programming for this WeMos D1 R1 microcontroller is developed based on the Arduino IDE software environment to congregate all of the measurement data from three PZEM004T modules and send to the web server of the ThingSpeak cloud through Wi-Fi. It will take about twenty minutes to send data to the server. Thus, the users can access data to monitor and analyse the PQ parameters at monitoring points from any places in the world by using a personal computer (PC) or smartphone which is connected to the Internet. The real image of the proposed system is shown in Fig. 2.

The PQ assessment is today one of the main ways to improve energy efficiency. The PQ at a monitoring node can be assessed by frequency quality and voltage quality. The frequency quality is a global index in a power system and it is controlled by electric generation plants. The power frequency is measured and compared with the allowable range in normal operating conditions [1]. Besides, the latest version of the international standard IEC61000-4-30: Edition 3 [31] explains how PQ instruments should make measurements and defines the precise measurement algorithms and methods for PQ parameters such as power frequency, magnitude of supply voltage, flicker, voltage dips and swells, voltage interruption, voltage unbalance, voltage and current harmonics, etc. In this work, the advanced IoT system is designed based on the hardware unit in which PZEM-004T is a main unit used to measure some PQ parameters among those in IEC61000-4-30.

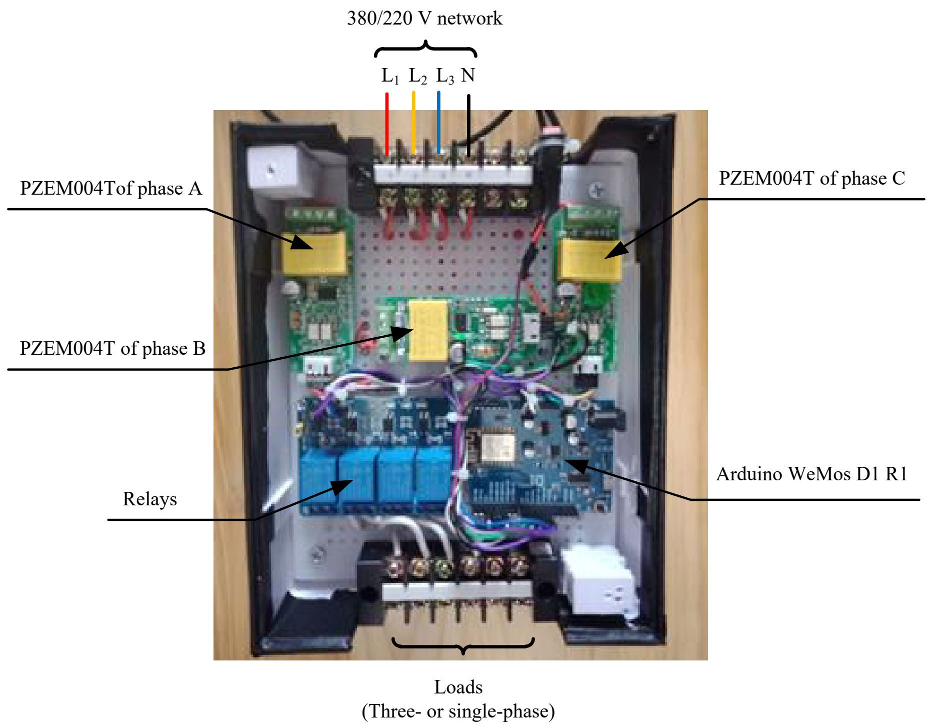


Fig. 2. The real image of the advanced IoT system

The PQ parameters the system can measure, monitor and analyse consist of power frequency, magnitude of supply voltage, current, active power, and a power factor. The following subsection will program the embedded software for the Arduino Wemos D1 R1 microcontroller to carry out the system's functions.

2.2. Embedded software

In this advanced IoT system, three PZEM-004T modules are applied as sensors to acquire and measure some chosen PQ parameters at a monitoring point. The measurement data is sent to the Arduino Wemos D1 R1 microcontroller via the communication protocol and sending – receiving commands. In order to read the measurement data from the PZEM-004T modules, a program on Arduino IDE software is programmed and embedded into the Arduino Wemos D1 R1 microcontroller. Besides, for sending the measurement data to the web server and monitoring the PQ parameters on the ThingSpeak platform, an algorithm is designed and uploaded on the Arduino Wemos D1 R1 microcontroller as illustrated in Fig. 3.

The flowchart of the proposed system for monitoring and analysing the PQ issue is described in detail as follows:

Firstly: Start

Step 1: Set up the inputs and outputs of the Arduino WeMos D1 R1 microcontroller to get the measured data from three PZEM-004T modules.

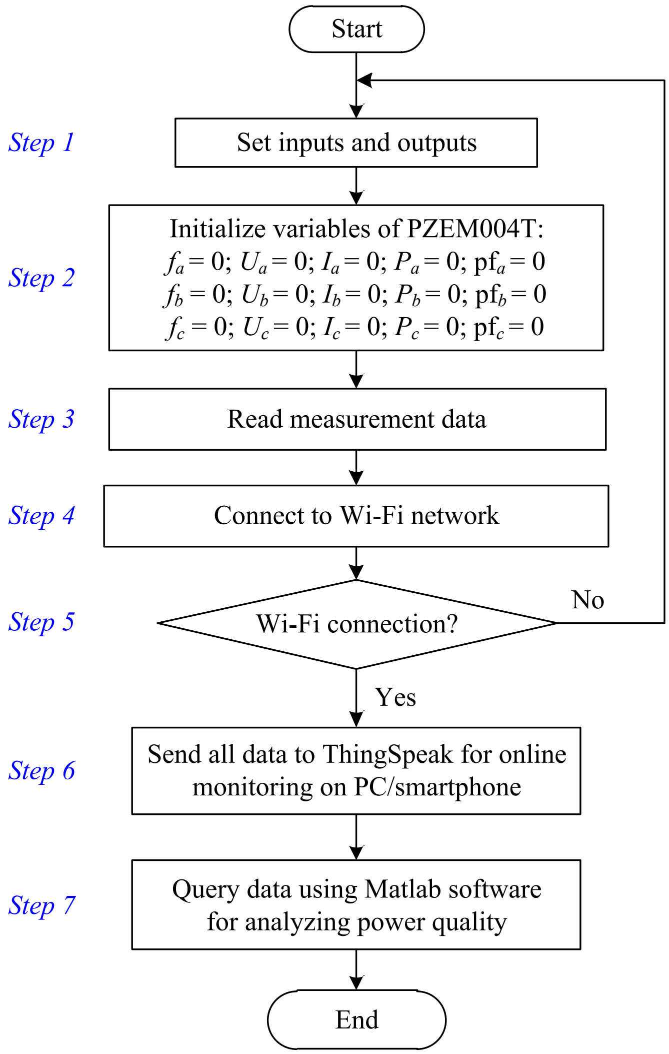


Fig. 3. The flowchart of the proposed system for monitoring and analysing the PQ

Step 2: (*i*) Initialize the measurement variables of three PZEM-004T modules according to the following initial conditions:

$$
\begin{array}{lclll}
\text{Frequency} & : & f_a = 0; & f_b = 0; & f_c = 0, \\
\text{Voltage} & : & U_a = 0; & U_b = 0; & U_c = 0, \\
\text{Current} & : & I_a = 0; & I_b = 0; & I_c = 0, \\
\text{Active} & : & P_a = 0; & P_b = 0; & P_c = 0, \\
\text{Power factor} & : & pf_a = 0; & pf_b = 0; & pf_c = 0,
\end{array}
$$

(*ii*) These variables will be continuously updated in real-time after their next reading process ready to do.

Step 3: (*i*) Read and send the measured data from three PZEM-004T modules to the Arduino WeMos D1 R1 microcontroller when the RX pin of the PZEM-004T modules established the command of the sending signal.

(*ii*) The process of (*i*) will be continuously executed during the operation of the system.

Step 4: Select the Wi-Fi network, connect the Arduino WeMos microcontroller, and allow the signal transmission from the system to the Internet with the purpose of monitoring the measurement data based on the IoT technology.

Step 5: Check the Wi-Fi connection status between the system and the Internet network.

Step 6: Sent all of the measured data from the system to the ThingSpeak cloud to monitor the data online. This process will be continuously executed each duration time. In this paper, the duration time is set to 15 seconds.

Step 7: Query all the measured data after storing it in the ThingSpeak cloud on the web server by using the PQ analysis program based on Matlab software.

Finally: End

The electric PQ measurement data at the monitoring point is sent to the ThingSpeak cloud via a communication protocol by using the proposed system. The communication protocol that has been applied in this system is the message queuing telemetry transport (MQTT) protocol to communicate between an ESP8266 module and the ThingSpeak cloud. In order to send all the measured data at the monitoring point to the ThingSpeak cloud, Arduino IDE software is used to program and upload the Arduino WeMos D1 R1 microcontroller. It is done according to the international standards IEC61000-4-30 [31] and EN50160 [32] that determine the main characteristics of the voltage at network user's supply terminals in public low voltage and medium voltage electricity distribution systems under normal operating conditions. In fact, considering PQ issues, the RMS voltage should be assessed on the basis of 10 ms for the purposes of detecting the rapid voltage changes or 200 ms for the statistical purposes. Some chosen PQ parameters are measured by the proposed system for monitoring and analysing in a long duration and they cannot be used to detect the rapid voltage changes such as voltage dips and swells, voltage interruption. Therefore, the commands for reading the RMS voltage and current shown in Table 1 are carried out on the basis of 10 cycles (200 ms).

For the proposed system, the electric PQ measurement data at the monitoring point is remotely monitored via channels on the ThingSpeak platform. The channels are designed to display the measurement variables including frequency, voltage, current, active power, and a power factor. As a result, we designed three channels for monitoring and analysing the electric PQ at the monitoring point, namely PQM1, PQM2, and PQM3, as shown in Fig. 4. In addition, the list of the measurement variables of each field in each channel is presented in Table 2.

The measurement data monitored by the system in this paper is stored on the ThingSpeak cloud during the monitoring time. In order to query the data, a program based on Matlab software is designed for analysing PQ. The commands in Matlab software applied in the proposed system for reading the measurement data on ThingSpeak are presented in Table 3.

Besides, a user interface of the PQ analysis program is designed by using the GUIDE of Matlab software. An example is shown in Fig. 5. For this user interface, we can select the starting and ending time. The measurement data from the ThingSpeak cloud can be displayed in the

Table 1. The commands for reading the measurement variables from PZEM-004T

Syntax	**Function**
pzem_info pzemData = pzem.getData()	Get data from PZEM-004T
float voltage = (pzemData.volt)	Read voltage data from PZEM-004T and then set to the *voltage* variable
float current = (pzemData.ampe)	Read current data from PZEM-004T and then set to the *current* variable
float freq = (pzemData.freq)	Read frequency data from PZEM-004T and then set to *freq* variable
float power = (pzemData.power)	Read active power data from PZEM-004T and then set to *power* variable
float Energy = (pzemData.energy)	Read energy consumption data from PZEM-004T and then set to *energy* variable
float pf = (pzemData.powerFactor)	Read power factor data from PZEM-004T and then set to *pf* variable

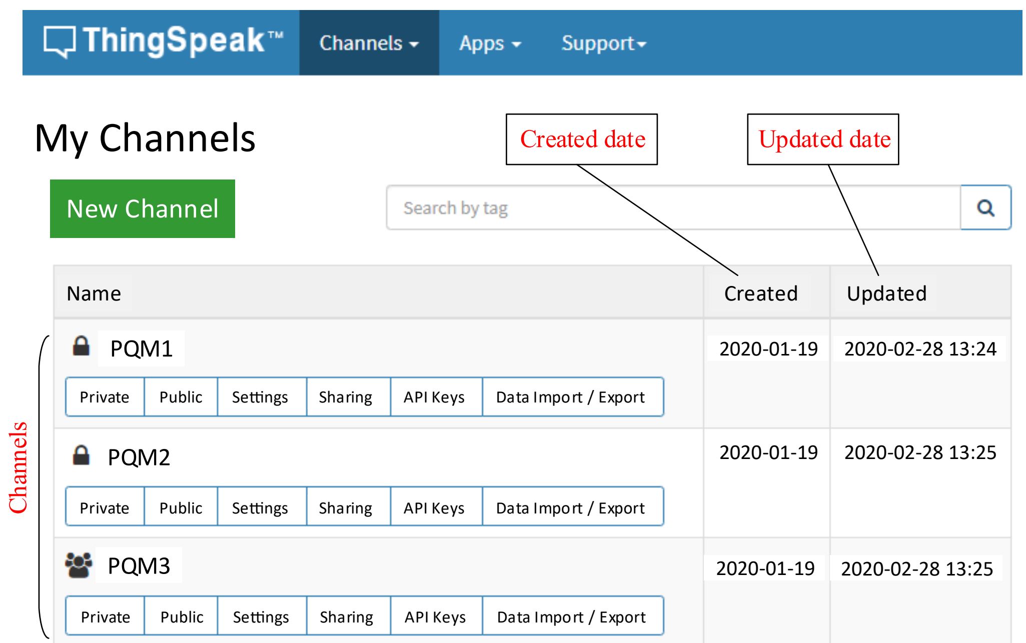
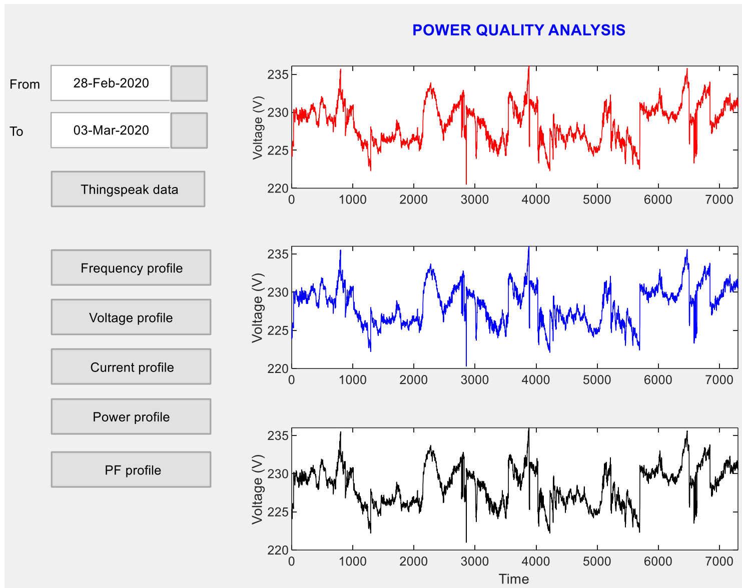


Fig. 4. Three used channels on ThingSpeak



(a)

	Ua (V)	Ub (V)	Uc (V)	Ia (A)	Ib (A)
1	225.3000	225.2000	225.2000	0.1500	0.15
2	225.3000	225.2000	225.3000	0.1500	0.15
3	224.2000	223.9000	224.1000	0.1400	0.15
4	224.2000	224.1000	224.1000	0.1400	0.14
5	224.2000	224.1000	224.1000	0.1400	0.15
6	224.4000	224.4000	224.3000	0.1500	0.14
7	224.3000	224.1000	224.2000	0.1400	0.15
8	224.2000	224.1000	224.1000	0.1400	0.15
9	225.1000	224.9000	225.1000	0.1500	0.15
10	225.4000	225.3000	225.3000	0.1400	0.15
11	225.5000	225.3000	225.4000	0.1400	0.15
12	225.7000	225.6000	225.6000	0.1500	0.15
13	225.7000	225.5000	225.6000	0.1500	0.15
14	226	225.8000	225.9000	0.1500	0.15
15	225.6000	225.4000	225.5000	0.1500	0.15
16	225.7000	225.6000	225.6000	0.1400	0.15
17	225.9000	225.7000	225.7000	0.1400	0.15
18	226.2000	226	226.1000	0.1400	0.15
19	226.2000	226	226	0.1500	0.15
20	226.2000	226	226	0.1500	0.15

(b)

Fig. 5. GUI interface for analysing PQ: (a) the graphical trend results; (b) the tabular results

Table 2. Three used channels and fields on ThingSpeak

Field	**Function**		
	Channel 1 (PQM1)	**Channel 2 (PQM2)**	**Channel 3 (PQM3)**
1	Phase A voltage	Phase A current	Phase A active power
2	Phase B voltage	Phase B current	Phase B active power
3	Phase C voltage	Phase C current	Phase C active power
4	Phase A frequency	Phase A power factor	Phase A energy consumption
5	Phase B frequency	Phase B power factor	Phase B energy consumption
6	Phase C frequency	Phase C power factor	Phase C energy consumption

Table 3. The syntax of ThingSpeak read commands

No.	**Syntax**	**Function**
1	Data = thingSpeakRead(channelID)	This command reads the most recent data from all of the fields of the specified public channel on ThingSpeak.com and returns the data as a numeric type
2	Data = thingSpeakRead(channelID,Name,Value)	This command uses additional options specified by one or more *Name*, *Value* pair arguments
3	Data = thingSpeakRead(___, 'ReadKey', 'channel Read API key')	This command uses the ThingSpeak™ Read API key to read from a private channel

table on this interface. Moreover, we can use the command pushbuttons to display the graphical trend results including frequency, voltage, current, active power, and a power factor. The results allowed us to use the analysis and calculation toolboxes in Matlab software to determine the mean, standard deviation of the frequencies and voltages. It means that we can use the user interface to evaluate the electric PQ at the monitoring point which is stored on the web server of the ThingSpeak cloud during the monitoring time.

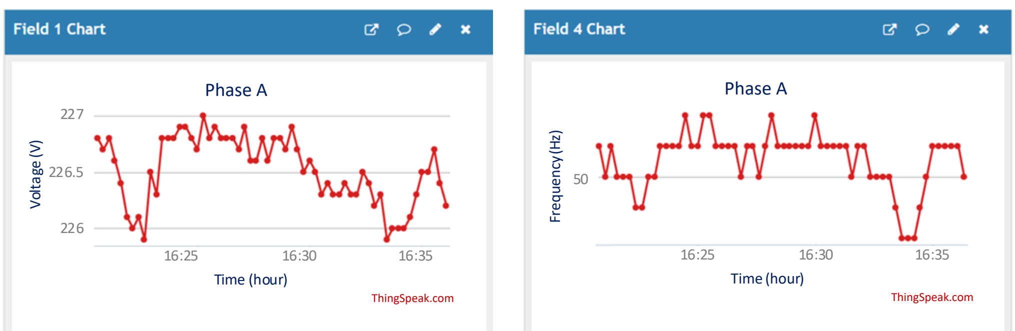
3. Experimental results and discussion

We use the electric system, including the loads installed in the smart grid laboratory room and the types of equipment with the quantity listed in Table 4 and a power supply source of 380/220 V 50 Hz, which is carried out to examine the effectiveness of the proposed system. The proposed algorithm, as discussed in Section 2.2 and shown in Fig. 3, is applied to perform experiments. The real proposed system is set up as shown in Fig. 2. During the experimental test, all measurement variables including frequency, voltage, current, active power, a power factor at the monitoring point are monitored and displayed on three channels of the ThingSpeak platform.

Table 4. Loads of laboratory room

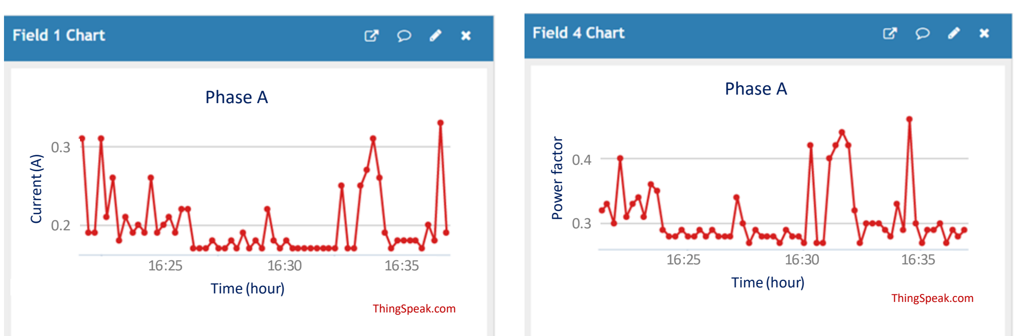
No.	Equipment name	Power (W)	Quantity	No.	Equipment name	Power (W)	Quantity
1	Variable resistor	300	1	5	Wall fan	55	6
2	Laptop	160	1	6	Ceiling fan	100	2
3	Personal computer	200	10	7	Air conditioner	1 200	2
4	Lamp	36	6	8	Exhauster fan	25	1

On the ThingSpeak platform, Channel 1 plots single-phase voltages and frequencies at the monitoring point as shown in Fig. 6. Channel 2 plots the single-phase currents and power factors that are shown in Fig. 7. Channel 3 plots single-phase active powers, as shown in Fig. 8. As a result, Figs. 6, 7, and 8 show clearly the time series of the chosen PQ parameters which the



(a) (b)

Fig. 6. The voltage and frequency on Channel 1: (a) voltage of phase A; (b) frequency of phase A



(a) (b)

Fig. 7. The current and power factor on Channel 2: (a) current of phase A; (b) power factor of phase A

proposed IoT system can monitor and analyse in real-time. All those measurement results in the channels are updated every 15 seconds and recorded by the system during 15 minutes at the monitoring node. Those measurement parameters are useful to assess PQ at the monitoring node because they can also record long monitoring periods for statistical purposes.

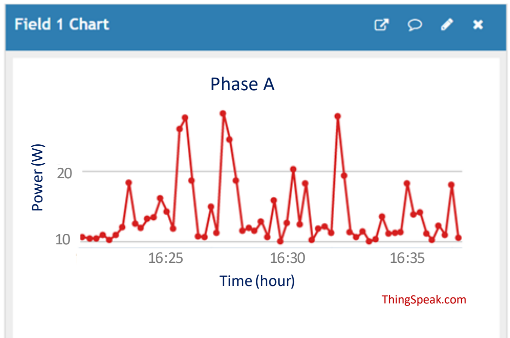


Fig. 8. The active power of phase A on Channel 3

In order to analyse PQ at the monitoring point, the measured data stored on the ThingSpeak cloud is analysed based on the user interface. To solve this problem, the index of how closely the individual data points cluster around the mean, namely the sample standard deviation, is used to calculate and evaluate PQ considering the entire measurement voltage and frequency variables and can be defined as follows [33]:

$$S = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}|A_i - \mu|^2}, \tag{1}$$

where: S is the sample standard deviation, A_i is the individual value, N is the total number of values, and μ is the mean/expected value and can be defined as follows:

$$\mu = \frac{1}{N}\sum_{i=1}^{N} A_i \tag{2}$$

Fig. 9 plots the voltage quality, Fig. 9(a) shows the voltage of phase A in a two-day monitoring time. The voltage samples are continuously recorded and displayed. Observing this Fig. 9(a), with $\mu = 228.58$ V and $S = 2.4861$ V, the voltage of the power supply source is variable as the time, due to the different operating conditions in the electric network. This voltage oscillates around a nominal value of 230 V.

In addition, the frequency at the monitoring point is also monitored and stored on the ThingSpeak cloud. Using the user interface to analyse the frequency quality, the analysis result is shown in Fig. 10. As shown in Fig. 10(a), with $\mu = 50.03$ Hz and $S = 0.0798$ Hz, the frequency of power supply is around a nominal value of 50 Hz. The histogram of the frequency, as shown in Fig. 10(b), is a tool for analysing the frequency quality of the power supply.

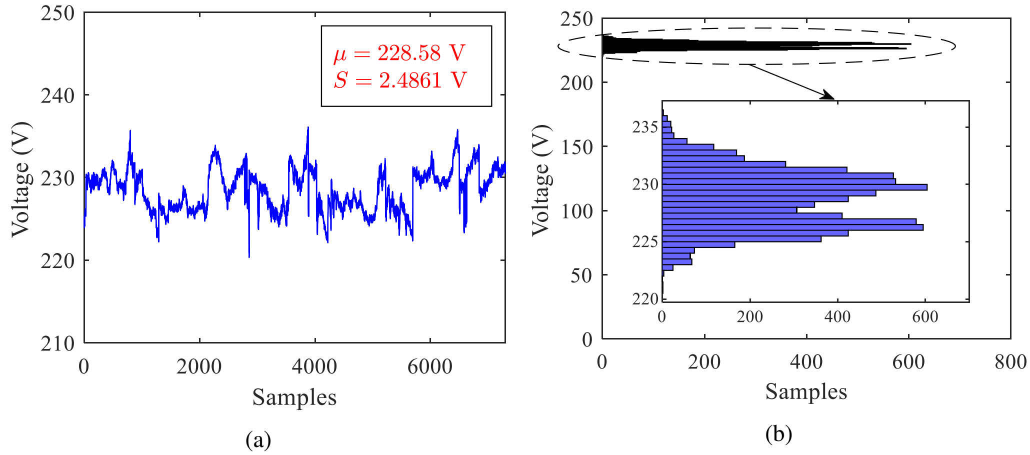


Fig. 9. The voltage quality: (a) the graphical trend result of phase A voltage; (b) the histogram of phase A voltage

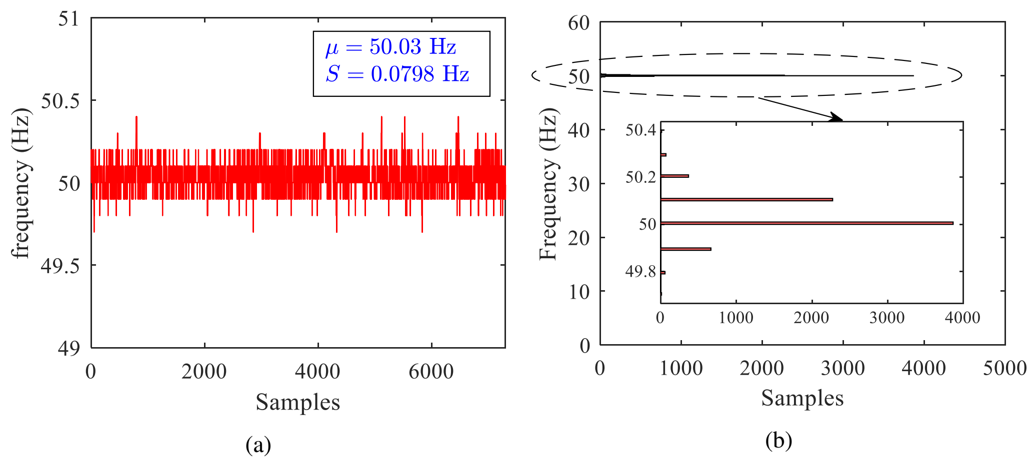


Fig. 10. The frequency quality: (a) the graphical trend result of frequency; (b) the frequency histogram

4. Conclusions

In this work, an advanced system based on IoT devices and the ThingSpeak platform is proposed for monitoring and analysing some chosen power quality (PQ) parameters as an operating solution for the micro-grids. The developed system used three PZEM-004T modules connected to the Arduino WeMos D1 R1 microcontroller to perform its functions. The chosen PQ parameters including frequency, voltage, current, active power, and a power factor at the monitoring point are measured and recorded continuously in real-time by using the channels designed on the

ThingSpeak platform. The graphical trend results of the chosen PQ parameters are visualized online under the time series on the channels. In addition, all measurement data can be stored on the web server of the ThingSpeak cloud, a user interface based on Matlab software is designed to visualize and analyse PQ at the monitoring point, and the histogram of frequency and voltage measurement during a monitoring time is analysed for assessing the PQ in low-voltage distribution networks.

The effectiveness of the proposed system can measure, monitor, and analyse five PQ parameters that most commonly occurs on a 380/220 V network. It enables customers to easily monitor and analyse data on PCs or smartphones connected to the Internet and to easily access the quality of power supply they consume. Moreover, those PQ parameters can be monitored and recorded over long periods and stored for further purposes.

Acknowledgments

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