Energy 250 (2022) 123747

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Ensuring power quality and demand-side management through IoT-based smart meters in a developing country

Md. Tanvir Ahammed [a], Imran Khan [a, b, *]

[a] Department of Electrical and Electronic Engineering, Jashore University of Science and Technology, Jashore, 7408, Bangladesh
[b] Energy Research Laboratory, Jashore University of Science and Technology, Jashore, 7408, Bangladesh

ARTICLE INFO

Article history:
Received 26 August 2021
Received in revised form
25 January 2022
Accepted 13 March 2022
Available online 15 March 2022

Keywords:
Smart grid
Power quality
Demand-side management
Smart meter
Voltage fluctuation
Frequency fluctuation

ABSTRACT

Population increase and the adoption of new power appliances have significantly increased electrical demands. As a result, the utility (electricity supplier) faces difficulties in maintaining the balance between supply and demand. Further, such supply and demand imbalance leads to frequent load-shedding and a drop in power quality (PQ), predominantly in the developing world. Increasing consumer awareness of energy consumption and implementing efficient demand-side management (DSM) algorithms in a metering instrument can be utilized to avoid such issues. Nowadays, access to the internet in developing nations is increasing rapidly. Hence to solve the existing limitations, the internet of things (IoT)-based smart meter (SM) is proposed and its practical application demonstrated in households in Bangladesh as a case study. The proposed SM primarily serves local and online monitoring, bidirectional data transmission, and DSM at the consumer side by maintaining PQ and peak-clipping. The MySql cloud database is used here for data storage and bidirectional data transmission between consumers and the utility. Web applications are developed for real-time data visualization, enabling consumers to track their hourly, daily, and monthly energy consumption by accessing the web page. The SM data shows that the over-voltage varied (from a nominal 220 V) within 15.45−16.36%, and the under-voltage varied between 10.45% and 11.82% from 220 V. The frequency fluctuations are found to be 2.2% under and 2.4% over the nominal value of 50 Hz (standard is nominal value ± 1%). The experimental result showed that the proposed IoT-based SM could ensure the smooth operation of electrical home appliances by maintaining PQ-related parameters (voltage and frequency) within a standard limit. Additionally, the proposed SM also helps to maintain the maximum pre-defined demand of a household during peak times through an appropriate load-clipping algorithm. The utility company can remotely define peak time hours and maximum peak demands when necessary. The real-life demonstration of the SM's operation advocated that this type of IoT-based SM could be easily adapted to maintain the balance between supply and demand through DSM application, and increase consumers' awareness of energy consumption in developing countries.

1. Introduction

The number of people without access to electricity declined from 1.2 billion in 2010 to 759 million in 2019 [1]. Of these 759 million, predominantly 570 million were in Sub-Saharan Africa, followed by Central Asia and Southern Asia (103 million), and Eastern Asia and South-eastern Asia (40 million). The remaining 46 million were from the rest of the world. The latest sustainable development goal − 7 progress report found that "*The SDG 7 goals are now in jeopardy, and some elements of those goals are even more distant than before*" [1]. Thus, to meet the target 7.1 (*By 2030, ensure universal access to affordable, reliable, and modern energy services*) of SDG-7, a different approach needs to be adopted. The rate of access to electricity in the developing world could be increased either by increasing the generation or through energy saving by applying demand-side management (DSM) schemes, including energy efficiency measures. Nowadays, the latter are becoming more popular, as they involve less cost than generation. DSM also helps to reduce greenhouse gas emissions from fossil fuel-dominated electricity systems [2]. DSM could be designed in a number of ways with a

* Corresponding author. Department of Electrical and Electronic Engineering, Jashore University of Science and Technology, Jashore, 7408, Bangladesh.
E-mail addresses: ikr_ece@yahoo.com, i.khan@just.edu.bd (I. Khan).

https://doi.org/10.1016/j.energy.2022.123747
0360-5442/

minimum amount of investment, such as energy-saving behavior. However, energy-saving behavior as one of the DSM schemes does not fit long-term demand management [3]. The most effective tool in designing proper DSM schemes is deploying smart meters at consumers' side. Although there are a few other methods proposed in the literature for DSM, such as in Ref. [4], smart meter-based DSM is more fruitful for long-term demand management in the electricity sector [5]. DSM, along with smart meters, ensures a number of load management opportunities. For instance, consumers can manage their electricity usage and can schedule their appliance usage time. On the other hand, on the supply side, an effective balance between the supply and demand could be facilitated, unexpected peak demand could be avoided, and the security of supply is ensured. Consequently, this system underpins reducing not only the cost of building new generation capacity but also eliminates GHG emissions.

An electrical grid that uses computers, different forms of communication technologies, and data analysis techniques to improve the system efficiency, reliability, security, flexibility, and safety and thus able to communicate between consumers and suppliers (i.e., bidirectional) could be termed a smart grid. One crucial element of the smart grid is the smart meter at the consumer side, a digital device capable of maintaining two-way communication between producers and consumers. Most developed countries have already implemented their smart grids; consequently, they have their smart meters to apply different DSM schemes [6,7]. However, the implementation of the smart grid costs billions of dollars. For example, the Electric Power Research Institute (EPRI) estimated that about $338 billion to $476 billion is required to implement a fully functional smart grid for the USA [8]. Similarly, about BDT 10 billion (BDT: Bangladeshi currency, 1 USD = 84 BDT) is required for smart grid implementation in Bangladesh [9]. In developing countries, smart grid implementation would thus take many years. Nevertheless, DSM through smart meter application could also be possible for the developing world through the internet of things (IoT). The objectives of this study are threefold: first, to design a low-cost IoT-based smart meter for developing countries' electricity networks in the absence of a smart grid. Second, to apply a power quality maintaining technique along with a DSM scheme to reduce peak electricity demand using the developed smart meter. Finally, to demonstrate effective communication between consumers and the electricity authority concerning efficient grid management.

Many recent studies in the literature have considered different DSM schemes for developing countries. For example, China has adopted time-of-use tariff for peak and off-peak demand, curtailable or interruptible DSM programs, and use of off-storage devices [10]. However, the study also highlighted that one of the main barriers for implementing DSM schemes is the lack of advanced metering infrastructure (AMI) such as smart meters and a smart grid. A similar finding is also reported for Bangladesh; that is, supervisory control and data acquisition (SCADA) must be implemented as part of a smart grid to incorporate AMI [9]. Notably, smart meters are one of the indispensable components of smart grids for any country, including Bangladesh. By contrast, a recent study in Pakistan, found that 'inadequate policy and financial infrastructure', 'lack of institutional commitment', and 'low consumer motivation' are the three main causes of effective DSM implementation [11]. In a similar fashion, 'limited consumer knowledge and awareness' were found to be the two most dominant barriers against smart meter adoption in Brazil [12].

A study in Turkey found that "*lack of infrastructure the utilities experience difficulties in monitoring their customers' demand or time of use of electricity and hence it is very difficult to apply DSM (demand side management) programs for peak shifting*" [13]. Thus, the study proposed a DSM scheme using residential water heaters. In a similar fashion, developing countries in South Asia also face DSM implementation challenges due to technical capability along with other factors [14]. Thus, many studies proposed DSM schemes for these countries without smart meter involvement such as energy-saving behavior [3], time-of-use tariff [15], survey-based demand profiling for possible DSM programs [16], or application of new methods for identifying demand-influencing parameters for suitable DSM application [4].

On the other hand, numerous studies in the literature have considered smart meters for many different applications related to electricity consumption management and demand response strategies, such as understanding energy demand behaviour [17]. For instance, Kiguchi et al. (2019) used smart meter data to predict intra-day residential electricity load profiles of Ireland to check the applicability of time-of-use tariff scheme [18]. In another study, Kiguchi et al. (2021) proposed a statistical model that is able to predict households that received benefits or detriments from the time-of-use tariff in Japan [19]. In Switzerland, using smart meter data, residential electricity load profiles were characterized through a clustering method for better applicability of demand-side management schemes [20]. They found three different clusters of load profile and concluded that 'daily raw profiles for a household significantly differ from the average profile for that household'. Similarly, based on smart meter electricity consumption data, Khan et al. (2019) proposed and applied the time-segmented regression analysis method in New Zealand, and found that different household factors contribute significantly at different times of the day [21]. Another study in Switzerland used smart meter data to characterize buildings based on heating energy [22]. In the UK, smart meter data was used to investigate the daily and seasonal energy variations at residences along with peak hours demand change [23].

In a recent study in Bangladesh, a time-of-use tariff scheme was proposed for the residential consumer as a DSM strategy [15]. In this proposed method, gathering of consumers' time-of-use electricity data is required for proper application of the method, but without smart meters this data collection is difficult and time-consuming. Many other studies have explored various application of smart meters, such as hot water flow and energy demand analysis [24], exploring the energy self-sufficiency of households with heat pump in the Netherlands [25], and household profile identification for better demand response scheme selection [26]. Smart meters were also applied to a dynamic energy management system in a microgrid consisting of a renewable generation source, in which energy storage and the microgrid was connected to the main utility grid [27]. One of the reasons of this developed approach was to ensure that power quality would be injected into the main grid.

Studies also focused on the improvement of smart meter features. For example, Mendes et al. (2020) proposed a data compression mechanism so that reduced amounts of data could be sent to the electric power company through IoT [28]. Similarly, a smart meter data driven evaluation method was also proposed as a demand response scheme for residential air conditioning loads [29].

Kumar et al. (2021) proposed an IoT-based smart energy meter to monitor the energy consumption using the fast fourier transform technique [30]. They compared their monitored parameters' values with other standard meters and found them satisfactory. However, they did not apply the proposed smart meter for applications such as DSM or ensuring power quality. In a recent work, Chakraborty et al. (2021) explored some potential applications of smart meters in the protection and monitoring of distribution system [31]. They identified that power quality monitoring can be easily conducted through smart meters at the consumer end, as the professional advanced monitoring systems are "*very professional, expensive and not portable, not suitable for use in general households*". The authors also reported that "*existing power quality measuring devices report the conventional parameters such as the RMS values, harmonics distortion and power factor etc. They have not taken into account of other issues, such as voltage sag-swell, impulses, phase angle displacement and frequency deviation etc.*" [31].

Power quality can be defined as "*the measure, analysis, and improvement of the bus voltage to maintain a sinusoidal waveform at rated voltage and frequency*" [32]. In other words, the totality of the electro-energetic situations responsible for the proper operation of equipment, and which may be hampered predominantly due to deviations in proper values of voltage, currents, or frequencies, is known as power quality [33]. Some common power quality issues are voltage dips, transients, harmonics, and flicker and all these issues have effects [32,34]. For instance, "*voltage dips are short-duration reductions in r.m.s. voltage caused by short-duration increases of the current*", and most electronic devices such as computers experience operational problems if the voltage drops below 85% for 40 ms [35].

Voltage fluctuations, brownouts, and power outages are common in most developing countries in Africa and Asia [36]. Ensuring power quality is crucial for electrical appliances. Although common electrical home appliances can operate with small deviations outside the standard voltage range, they can be damaged with large variations [37]. On the other hand, appliances or equipment with motors such as water pumps and blenders will be overheated due to voltage and/or frequency fluctuations, and consequently, their lifetime will be reduced [38]. Lights such as compact fluorescent lamps (CFL) might operate with voltage fluctuations, but their intensity varies with voltage change [39]. However, the low-quality cheap CFL available in developing countries' markets might be damaged due to large voltage fluctuations [40].

In terms of power consumption due to voltage variations (220–260 V), it was found that one-quarter of modern electrical home appliances might be affected by voltage variations [41]. For example, refrigerators' and lights' power consumption could increase by up to 8%; in appliances with electric motors such as electric fans, washing machines, vacuum cleaners, power consumption could increase up to 10% [41]. Consequently, these power increases will increase consumers' energy costs.

Evidently, power quality variations, predominantly voltage variations will not only damage or reduce the lifetime of appliances but also increase consumers' energy costs. Therefore, ensuring power quality is one of the crucial requirements for electrical home appliances' proper operation and longevity. Nonetheless, this could be accomplished through appropriate technology deployment, and this requires huge investments and time.

Overall, it is evident that power quality in the developing economies are not up to the standard to ensure home appliances' proper operation and longevity. Technically, this power quality problem could be solved through the adoption of appropriate technologies, but this will not only cost billions of dollars but also take years to be implemented. Although a short-term solution to this problem could be possible, this has received less attention in the literature in the context of developing countries. On the other hand, it is not possible to implement the most effective DSM schemes in the developing economies predominantly due to the absence of smart grids [42] and smart meters. In summary, most of the previous studies in the literature used smart meters to (i) identify consumers' load profiles, (ii) apply and test a particular DSM strategy, (iii) understand energy demand behaviour, (iv) predict consumers' seasonal load profile, and (v) identify dominant household factors that contribute to electrical peak demand. However, none of the previous studies considered application of both DSM and power quality management using a low-cost smart meter in developing country contexts.

The present study addresses these gaps in the literature: firstly, by proposing a new low-cost smart meter design that ensures power quality for consumers' appliances through smart monitoring and control with the help of IoT. Secondly, the proposed smart meter is capable of managing electrical demand during grid peak hours without any smart grid. Thirdly, the utility authority will have control over individual consumers' electrical loads and peak demand through IoT and smart meters. Finally, consumers will be able to track their real-time energy consumption, and the related measure could be taken to reduce their demand.

The rest of the article is organized as follows: Section 2 describes the proposed smart meter by explaining its working principle. Section 3 presents the obtained results. Section 4 analyzes the cost and benefit of the proposed smart meter. Section 5 discusses the findings with a comparative analysis, and the final section concludes the article highlighting main findings, limitations, and future research scopes.

2. Description of the proposed smart meter

This section describes the design of the proposed low-power, cost-effective, IoT-based single-phase smart meter (SM) for residential customers to facilitate real-time demand monitoring and load management. The proposal provides a complete SM with hardware and software components. A brief overview of the proposed system is shown in Fig. 1. The smart meter will be connected with the single-phase supply and the measured electricity data will be sent to the real-time cloud database. The SM will be connected through WiFi to the cloud. The cloud database is accessible both by the user and the utility through their dedicated webpages.

2.1. Features of the proposed smart meter

Ensuring good power quality (PQ) at the user end. Nowadays, most household appliances, mainly electronic and computer devices, require good PQ for satisfactory operation. According to the standard EN 50160 [43], the user is entitled to receive a suitable quality of power from the utility. The standard EN 50160 specifies that the supply voltage must be restricted to ±10% (198–242 V, for the 220 V system) of its nominal voltage and frequency within ±1% (49.5–50.5 Hz, for 50 Hz system) during normal load conditions [36]. The American National Standards Institute (ANSI) Standard C84.1–2011 [44] specifies that the voltage at the client premises must be within ±5% (114 V–126 V, for 120 V system) of its nominal voltage. Besides, 'the frequency in a power system is a real-time changing variable that indicates the balance between generation and demand' [45]. Therefore, maintaining sufficient voltage and frequency at the user end is the joint responsibility of the utility and the electricity user. The proposed SM can switch off the user's power supply in the absence of good PQ. That is, the supply voltage and frequency at the user premises should be within the EN 50160 standard. However, the utility can change PQ parameters when required over the internet, and the SM responds accordingly.

Demand-side management through peak-clipping. The proposed SM supports peak clipping. In general, peak clipping can be achieved "*by direct load control, shutdown of consumer equipment, or distributed generation*" [46]. Using the proposed SM, the utility can set peak-hour time and peak-hour maximum demands for users. If a user exceeds the specified peak-hour demands within the peak-hour period, the SM first gives a warning alarm for 30 s and then switches off or clips the user's power supply for 1 min if the user

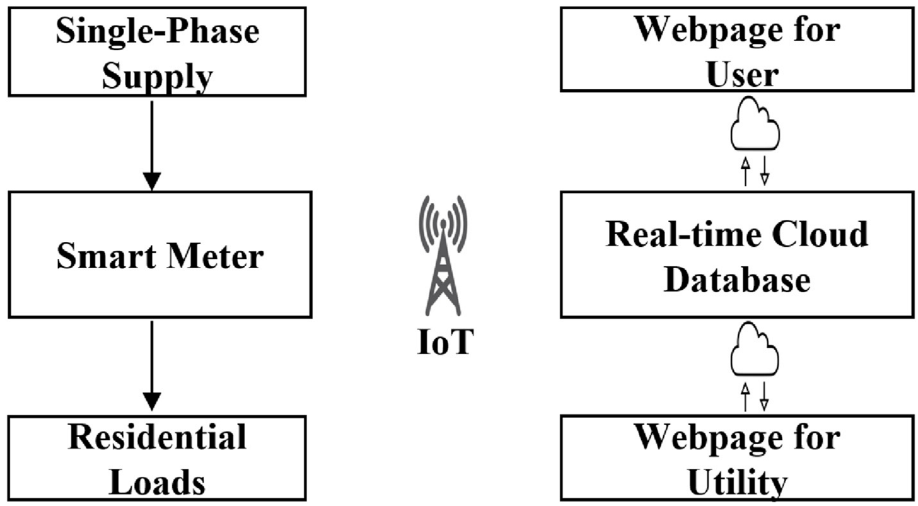


Fig. 1. A brief overview of the proposed smart meter.

does not reduce power demands. This process continues until the user reduces the demand within the allowed limit. Notably, these time periods are customizable.

Effective information exchange. In the proposed SM, the utility can observe detailed energy consumption patterns of any selected user. The utility can notify users through the system. Besides, the utility has the power to update PQ parameters and peak-clipping plans. The user can view their energy consumption history, billing details, energy cost, and messages from the utility on their side.

Prepaid and postpaid metering. The proposed SM can be used as prepaid and postpaid meter within the existing network. In addition, the proposed SM can visually represent energy consumption by changing the display color.

In summary, the proposed SM provides several real-time services, including online and offline metering, prepaid and postpaid metering, power line clipping in the absence of good PQ, peak clipping during peak times, bidirectional data transmission and storage, and visualization of prepaid and postpaid metering details. Although a few existing SM meters might have some of the proposed services, so far the authors are concerned no single piece of equipment has all these features without smart grid integration.

2.2. Architecture of the proposed smart meter

The main hardware components required for the proposed SM can be divided into four distinct units: (i) electricity metering, (ii) processing, (iii) controlling, and (iv) display unit.

(i) **Electricity metering unit:** The purpose of the metering section is to measure voltage (V), current (I), power (P), power factor (PF), energy (E), and frequency (F). For this purpose, PZEM-004T-100A (which comes with a 100 A CT) ac communication module [47] is used, as it can measure the above-mentioned parameters with good accuracy. The measurement data from PZEM-004T can be read through the TTL RS485 serial interface. Fig. S1 in the *supplementary material* is a functional block diagram of the module [47]. The specifications of the selected module are listed in Table S1 in the *supplementary material.*

(ii) **Processing unit:** This unit is responsible for reading TTL serial data from the PZEM-004T module, sending the measured data to a cloud database, and receiving control information (PQ parameters and peak-hour restrictions) from the utility. The ESP32 [48] is selected for processing purposes since the module supports hardware serial communication, SPI, I2C, and has a built-in WiFi chip, which facilitates reading serial data, sending and receiving data to and from a cloud database without any additional hardware. The functional block diagram of ESP32 is shown in Fig. S2 in the *supplementary material*, and the specifications are included in Table S1 in the *supplementary material.*

(iii) **Controlling unit:** This unit turns the power line ON/OFF when required. It consists of two relay modules, and the I/O ports of the ESP32 control the relay modules. In the proposed system, a single pole double throw (SPDT) power relay (30 A, 250 VAC) is used to ON/OFF the power line, and a light relay (10 A, 250 VAC) is used to provide a warning alarm if a user exceeds the peak-hour maximum power limit. The relay consists of a coil, one common terminal, one normally closed (NC) terminal, and one normally open (NO) terminal. When the relay's coil is at rest (not energized), the common terminal and the normally closed terminal have continuity. When the coil is energized, the common terminal and the normally open terminal have continuity.

(iv) **Display unit:** The display unit shows various information along with a visual indication of energy uses in an LCD. RGB Backlight 16×2, I^2C bus module version of LCD from Seeedstudio is employed for this purpose.

The smart meter with all components for post- and prepaid metering are shown in Fig. S3 in the *supplementary material.*

2.3. The system model

The proposed smart meter model is shown in Fig. 2 (a), and is divided into hardware and software sections. A four-layer IoT architecture is used, which is shown in Fig. 2 (b). The device layer has two sub-layers. That is, the measurement sensors are in the things layer, which measures V, I, P, PF, E, and F data; the ESP32 is in the gateway layer, connecting the components from the things layer to the network layer. The network layer uses WiFi communication for data transmission from the device layer to the cloud management layer. The cloud management layer also has two sub-layers: the cloud service layer (which consists of a hosting server and MySQL database) and the management layer (responsible for authentication and data management). The cloud

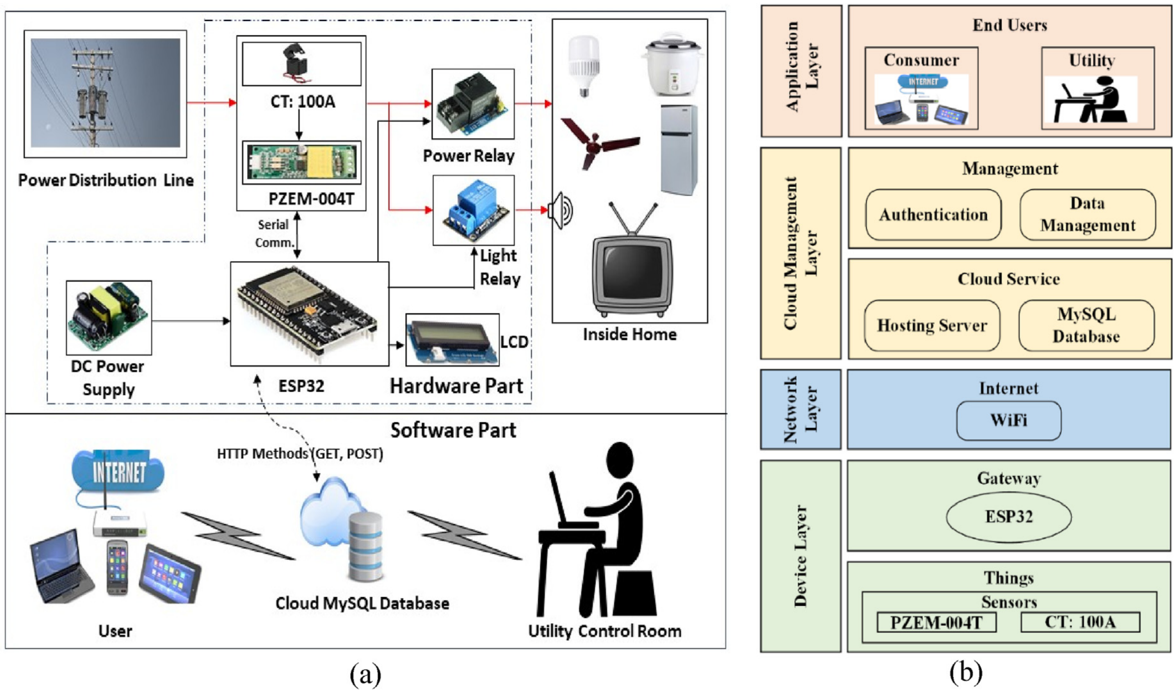


Fig. 2. (a) Proposed smart meter with demand side management scheme, and (b) Four-layer IoT architecture used for the smart meter.

service layer is responsible for storing measurement data from the device layer into the MySQL database. The application layer is the top layer that provides service to the end users.

2.3.1. Hardware section

The hardware section deals with four tasks: (i) measuring electricity (V, I, P, PF, E, and F), (ii) sending the electricity data (V, I, P, PF, E, and F) to a cloud database every 30 s, (iii) receiving PQ and peak-hour control data from the cloud database for demand side management, and (iv) displaying electricity-related data to a local LCD. The SM is built using PZEM-004T (100A), current transformer (CT), ESP32, LCD, alarm system, SPDT power relay, and SPDT light relay. The required components and their specifications are listed in Table S1 in the *supplementary materials*. For better understanding, the hardware block diagram of the proposed SM with proper circuit connection is shown separately in Fig. 3.

Fig. 4 is a flow chart describing the overall operation of the proposed SM. The algorithm of the proposed SM is included in the **Appendix** (Algorithm A1) which also elucidates the overall working process of the SM. The proposed smart meter first measures electricity data (V, I, P, PF, E, and F) and subsequently sends the measured data to a cloud database. Hereafter, the SM reads local time, PQ parameters (maximum and minimum RMS voltage limit (V_{min}, V_{max}); maximum and minimum frequency limit (F_{min}, F_{max})), and peak hour control parameters (peak-hour starting and ending hour, peak-hour maximum demand (MD)) from the cloud database (the utility sets the value of these limiting parameters (a detailed description is provided in Section 3.1)). Based on the control

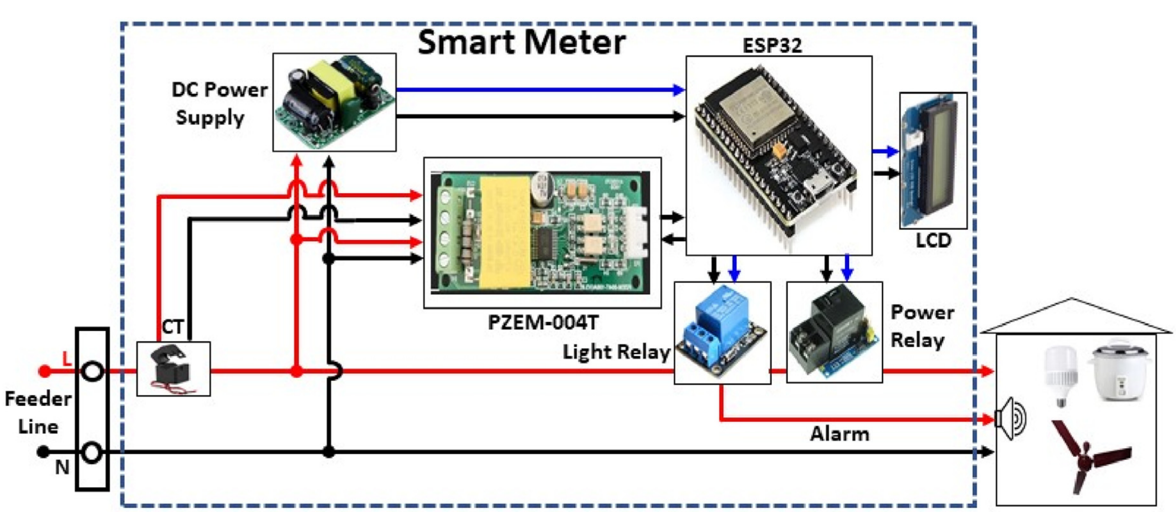


Fig. 3. Hardware block diagram of the proposed smart meter.

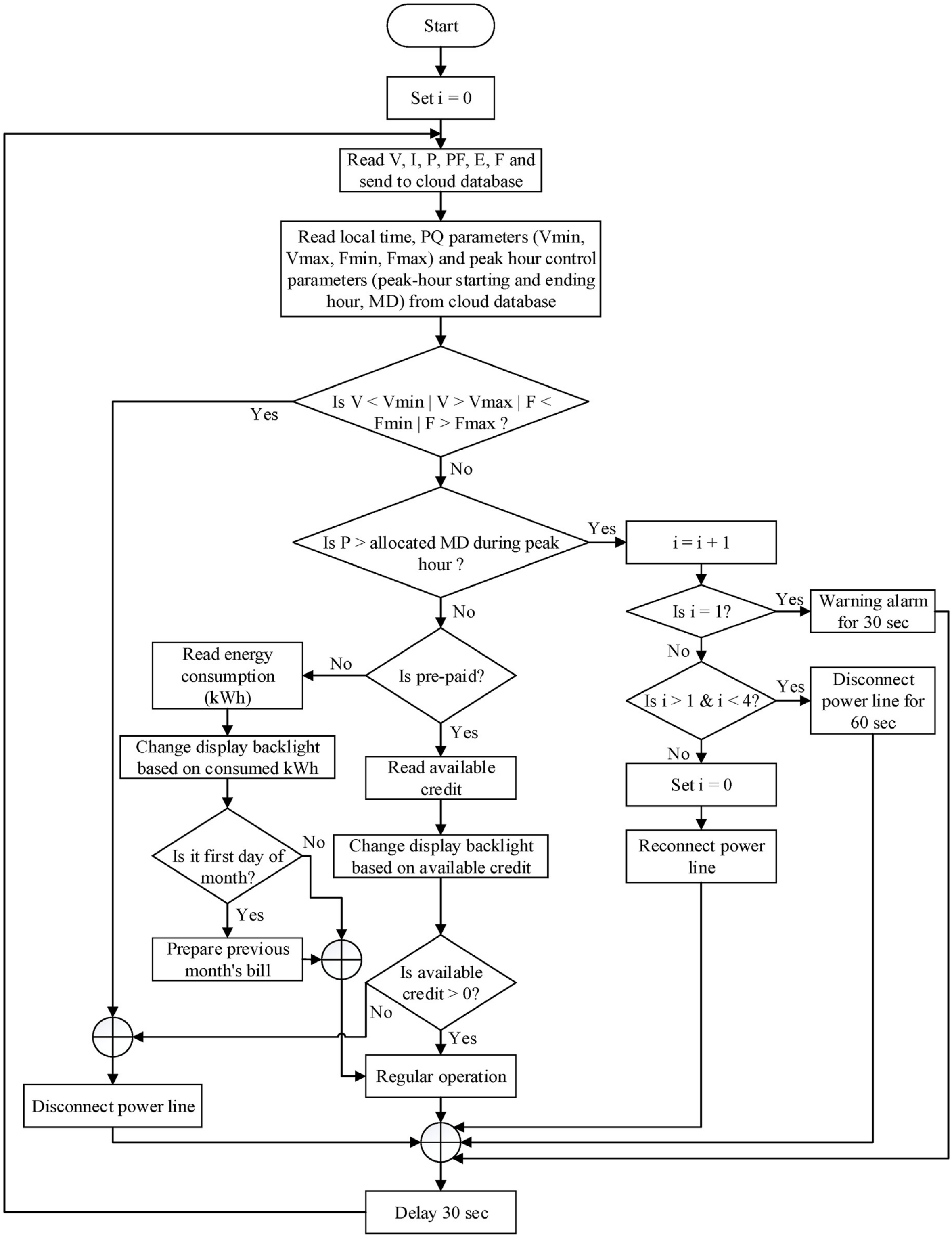


Fig. 4. Flow chart showing the working principle of the proposed smart meter.

parameter, the proposed SM executes a DSM algorithm (detailed description is provided in Section 3.3) to control the relay (see Fig. 3) to give a warning alarm and ON/OFF the main power line of a user if required. Finally, the SM is also configured to provide a visual indication of energy consumption by changing the backlight color of the LCD (detailed description is provided in Section 3.3.1). To facilitate these functions, it is necessary to establish a communication link between the utility and the users for real-time information exchange. A common cloud database is thus required. MySQL cloud database is used for this work, the most popular open-source SQL database management system. For demonstration, a free web hosting service of www.000webhost. is used, which offers absolutely free web hosting with cPanel, PHP, MySQL, and domain name. The SM reads V, I, P, PF, E, and F data and inserts the data into the MySQL cloud database using a PHP script by HTTP GET() method. Hereafter, the SM reads local time (from ntpServer: pool.ntp.org), PQ parameters (from the MySQL database), and peak hour control parameters (peak-hour starting and ending hour, maximum demand (MD) from the MySQL database) by sending HTTP GET() requests to the server.

2.3.2. Software section

Two separate web applications are designed (one for the utility and the other for the user) and hosted on the 000WebHost server. The ESP32 is configured to transmit and receive data to and from the MySQL database every 30 s. Fig. 5 shows a screenshot of the MySQL database, the description of each table name is given in Table 1. Table named **id1** (each user has a unique id) stores the electricity data (V, I, P, PF, E, and F) for a user with date-time information.

3. Result: demonstration and evaluation

To test and evaluate the performance of the proposed smart meter, it was installed in three households in Jashore, Bangladesh. The households were in three different locations of the city and connected with three different electric feeders, and were chosen considering their maximum demands. For instance, household-01 (HH01) was a house with a maximum allowable demand of 2000 W, whereas households-02 (HH02) and 03 (HH03) were chosen as their allowed demands were 3000 W and 4000 W, respectively. Common electrical appliances in those houses and their approximate wattage information are listed in Table S2 in the *supplementary material.*

3.1. Web application for the utility

The utility's web page layout is shown in Fig. 6. After authentication, login, and selection of a user, the webpage provides much useful information, as depicted in Fig. 6. For ease of understanding, Fig. 6 is divided into ten parts. The description of each part is as follows:

Part-1 shows the user's general information such as name, meter ID, address, and phone number.

Part-2 shows the real-time electricity information that is, V, I, P, PF, E, and F.

Through Part-3, the utility can send messages to the users. After typing and pressing **Send Message to User**, the message is stored in the MySQL database under the table named **message**. In this way, the utility can interact with the user; for instance, the utility can send a message such as "*Electricity service will be off tomorrow (July 8, 2021) due to some maintenance work between* 6 a.m. *to 1 p.m.*" to the users. This interaction will increase users' awareness and reduce the utility's manual labor for the announcement.

Part-4 shows previously inserted PQ parameters (maximum and minimum RMS voltage limit, maximum and minimum frequency limit). However, the utility can update the parameters when it is required to ensure good PQ to the users. If any PQ parameters falls beyond the range, the SM cuts off the power line immediately. After pressing **Update PQ Parameters**, the PQ parameters are stored in the MySQL database under the table named **PQC** (see Table 1).

Part-5 shows previously inserted peak-hour restrictions for the selected user. The utility can change maximum demand and the duration of peak-hour any time by selecting starting peak-hour (SPH), ending peak-hour (EPH), and maximum demand (MD) in the peak-hour period. After pressing **Update Peak-Hour Plan,** the parameters are stored in the MySQL database under the table named **User_Details** (see Table 1).

In Part-6, the utility can export the stored data from the MySQL database as comma-separated values (CSV) file by selecting starting and ending dates. The exported data can be used for further analysis for estimating users' load profiles. For instance, Fig. 7 (a) to 7 (e) show the 24-h variations of power, voltage, current, power factor, and frequency, respectively, for HH01.

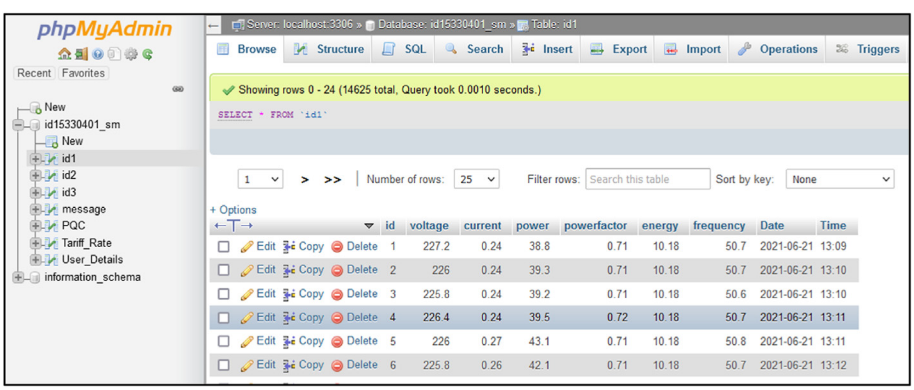
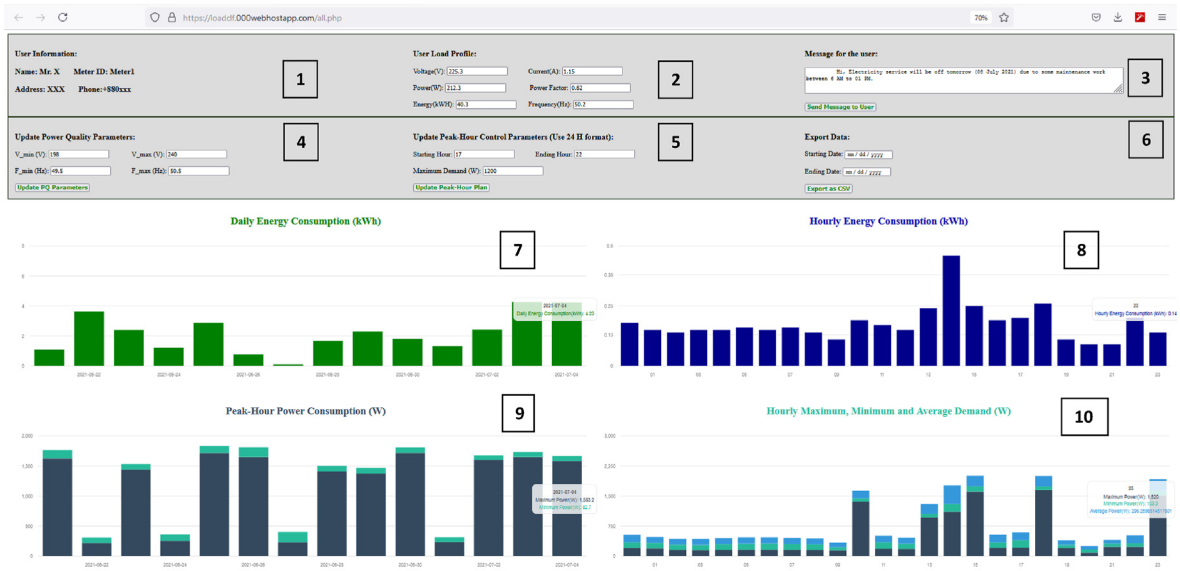


Fig. 5. Electricity data in MySQL cloud database.

Table 1
Description of the MySQL database.

MySQL Table Name	Description
id1, id2, id3, …	Individual user's database (id1 for user1, id2 for user2, and so on) that contains V, I, P, PF, E, F, Date, and Time
message	Contains messages send by the utility to the users.
PQC	Contains PQ parameters (V_{min}, V_{max}, F_{min}, and F_{max}) updated by the utility.
Tariff_Rate	It contains the latest tiered tariff rate, which is used in Bangladesh for single-phase residential users. The utility can update the tariff rates when required.
User_Details	Contains each user's information such as name, meter id, address, phone number, username, password, maximum allowed non-peak hour demand, peak hour starting time, peak hour ending time, maximum demand during peak period. The utility can update user details when required.



(c)

Fig. 6. Utility webpage layout: energy consumption details of a selected user.

In Part-7, the utility can observe selected user's two-week daily energy consumption data in a bar chart.

In Part-8, the utility can observe selected user's 24-h energy consumption data for the present day.

In Part-9, the utility can observe the selected user's two-week daily maximum and minimum demand during peak hour.

In Part-10, the utility can observe the selected user's hourly maximum, minimum and average demand for the current day.

3.2. Web application for the user

The proposed SM supports prepaid and postpaid billing, and two web pages are designed to inform prepaid and postpaid users. The layout of the user's web page is shown in Fig. S4 in the *supplementary material*.

In the proposed system, the utility will provide a unique username and password for each user. After providing correct credentials, the prepaid user can view real-time electricity-related information (i.e., V, I, P, PF, E, and F, which are updated every 30 s), energy used during the month, last credited amount, available credit, messages sent from the utility, daily energy consumption for the last two-week and hourly energy consumption for the present day, monthly energy consumption, and monthly energy cost as shown in Fig. S4 (a) in the *supplementary material*.

Similarly, a postpaid user can see real-time electricity-related information (i.e., V, I, P, PF, E, and F, which are updated every 30 s), energy used during the month, electricity cost of the ongoing month, messages sent from the utility, daily energy consumption for the last two weeks and hourly energy consumption for the current day, monthly energy consumption, and monthly energy cost as shown in Fig. S4 (b) in the *supplementary material*. By clicking on the hyperlink (Click here to view billing details) as shown in Fig. S4 (b) in the *supplementary material*, the postpaid user can view detailed billing information as depicted in Fig. S4 (c) in the *supplementary material*. In the proposed SM, a real payment gateway was not implemented; however, it is possible to build a payment gateway that will support convenient payment options like mobile banking, credit card transactions. For electricity billing, latest tiered tariff rates [49] (used for single-phase residential consumer in Bangladesh) is used.

3.3. Power quality and demand-side management

The proposed SM predominantly performs two objectives: (i) ensuring good quality of power for users and (ii) reducing power demand for each user during peak-hours. Before the application of the power quality control algorithm, a typical day (4th June) data was considered and plotted in Fig. 8.

It can be seen from Fig. 8 that the voltage fluctuations were beyond 242 V at several times of the day. In addition, a voltage dip was also observed on the same day. Although the voltage dip did not go beyond 210 V, it might cause damage to the electrical equipment. Due to the voltage dip, the current increased from about 4 A to more than 20 A, and this is very harmful to domestic electrical appliances. To check further, a month's data were checked for both HH02 and HH03 as the households were in two different locations and connected with two different feeders. Fig. 9 shows these voltage variations for the month of June 2021. For the HH02, the highest fluctuation was 15.45%, and it was 16.36% for the HH03. In contrast, 11.82% and 10.45% fluctuations were observed for the HH02 and HH03, respectively, for the lowest voltage.

Frequency fluctuations went below 50 Hz by 2.2% and 2.4% beyond 50 Hz for the same month in the case of HH02 (see Fig. 10). For 24-h fluctuations, see Fig. 7 (e), for the HH01. In general, the standard deviation is ±1% from 50 Hz. Clearly, the power quality is a concern for electrical home appliances in Bangladesh.

For the DSM, this work presumed that each user provides their maximum power demand during peak-hour to the utility, and the SM is connected to a WiFi network. The flow chart of power quality and demand side management algorithm is shown in Fig. 11.

(i) **Ensuring user power quality:** The ESP32 reads PQ parameter ($V_{min.}$, $V_{max.}$, $F_{min.}$, and $F_{max.}$) limits from the MySQL database in JavaScript Object Notation (JSON) format. After

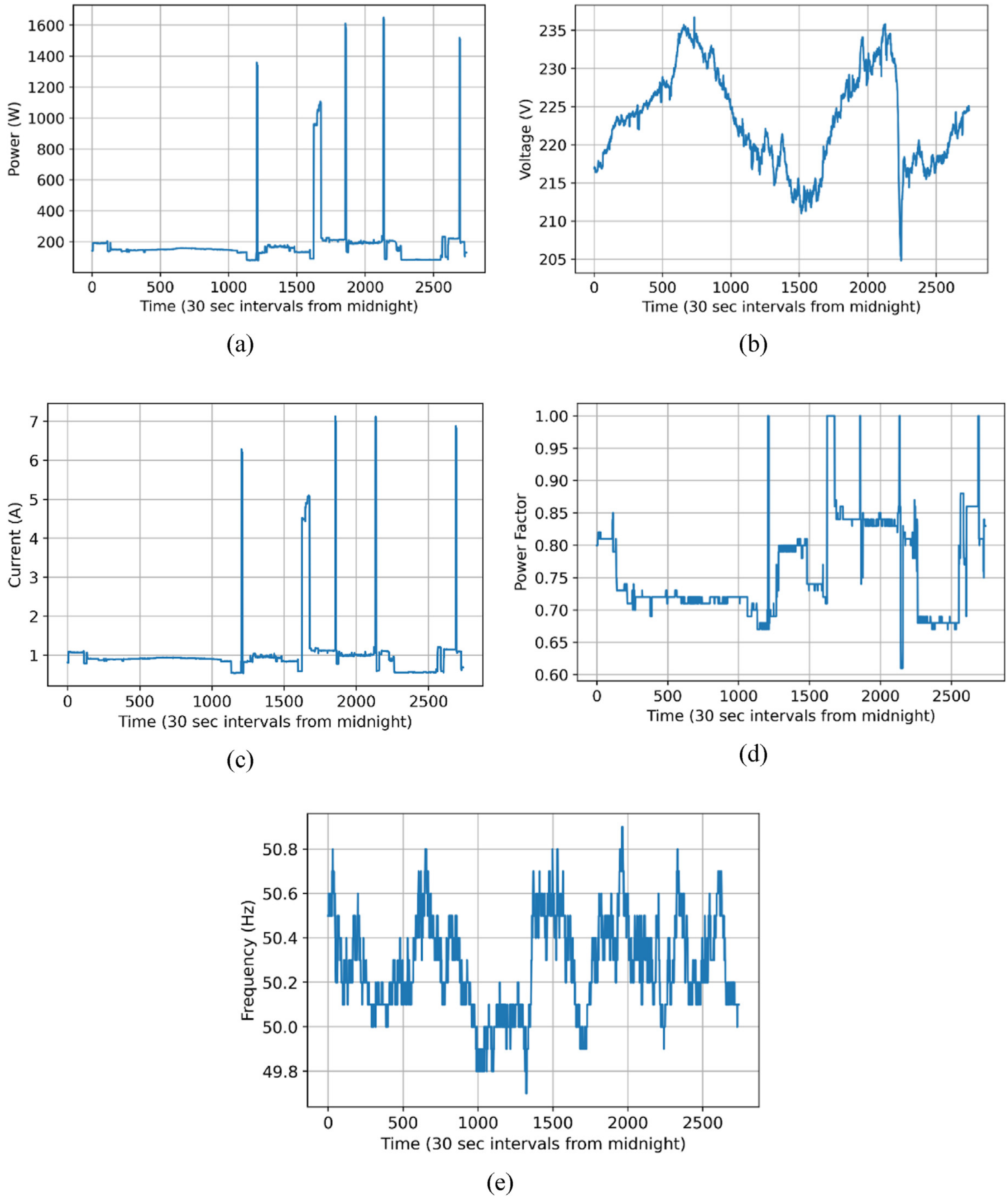


Fig. 7. Variations of (a) power, (b) voltage, (c) current, (d) power factor, and (e) frequency for 24-h with 30 s interval for the household-01 [HH01]. Data for July 3, 2021 was used.

decoding, ESP32 compares these parameters with user-end V and F; if the user-end RMS voltage and frequency fall beyond the PQ range, it cuts off the power line by controlling the power relay. The ESP32 turns on the power line automatically when the user-end RMS voltage and frequency are within the PQ range. The operational characteristic of the proposed smart meter is shown in Fig. 12; the supply voltage is changed using a variac (0–250 V AC, 50 Hz, 3 kV A). Fig. 12 shows that the SM cuts off the power line if the user's RMS voltage is less than 198 V or greater than 242 V.

(ii) **Peak time DSM:** In peak hour-based DSM, the ESP32 reads local time and the peak hour control parameters from the MySQL database in JSON format (i.e., peak hour starting and ending hour, maximum demand during the peak-hour period). When the user end power consumption is greater than the allocated MD during peak hour, the ESP32 turns on

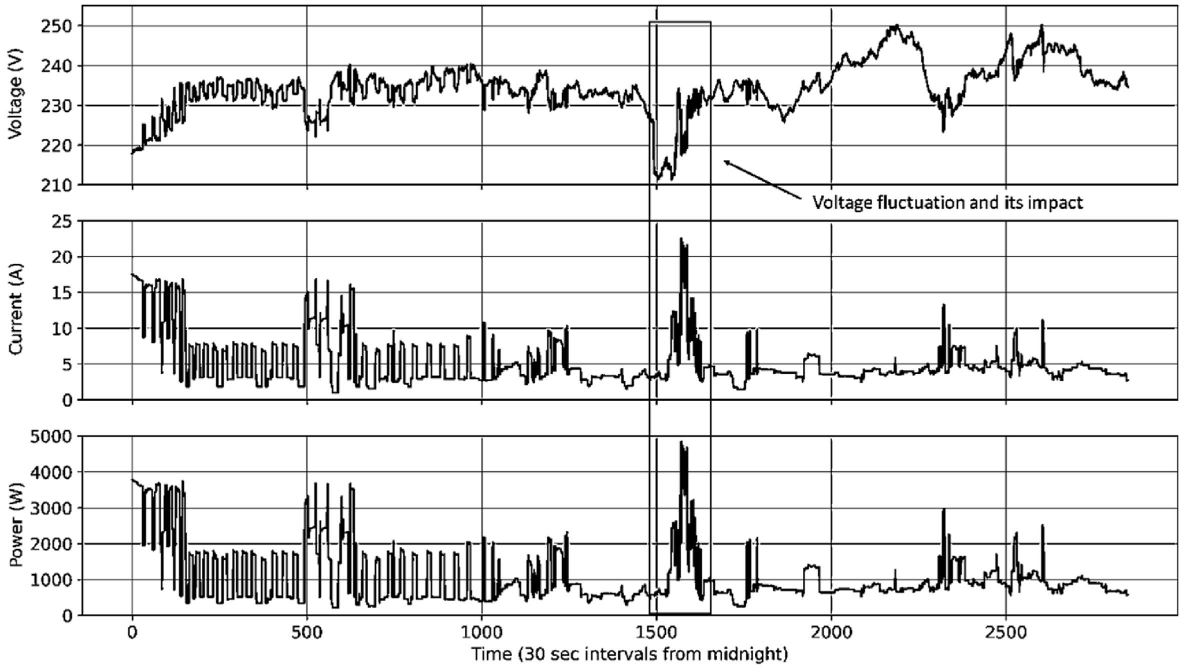


Fig. 8. Power quality for the household-03 (HH03). Data was used for 4th June.

the light relay to give a warning alarm for 30 s (for demonstration 30 s alarm period is used, however, this period can be changed). The SM cuts off the power line for 1 min if the user does not reduce power demand within the allowed limit. This process continues until the user reduces power demand within the allowed limit during peak-hour. When the user reduces power demand within the permitted limit, the regular operation continues. The peak-hour operational characteristic of the proposed smart meter is shown in Fig. 13. The experimental verification of peak time DSM is shown in Fig. 13 (a), where 300-sec experimental data were taken at 1 Hz sampling rate. From Fig. 13 (a), it is observed that when the power consumption at the user end exceeds the allowed 1200 W of MD, the SM gives a warning alarm for 30 s and cuts off the power line when the user end power consumption >1200 W. Fig. 13 (b) −13 (d) shows the peak time DSM characteristics of three different houses, namely HH01 (MD = 1500 W), HH02 (MD = 2000 W), and HH03 (MD = 3000 W). From Fig. 13(b) - 13(d), it is observed that the SM successfully clips the power line if a user exceeds the allotted MD during the peak period.

3.3.1. Visual color-based energy consumption indication

In Bangladesh, a significant portion of the population are not accustomed to web-based applications (many of them are not familiar with internet browsing). In addition, many people in rural areas do not know how to read electricity meters. Considering these issues, the proposed SM is designed in such a way that it changes the backlight color of the LCD depending on the energy consumption of a user, and this is listed in Table S3 in the *supplementary material.*

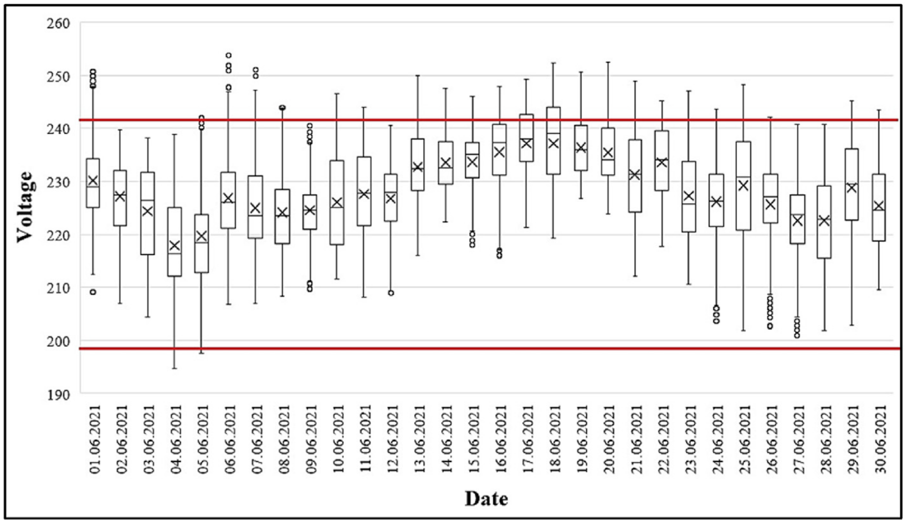
The visual color-based energy consumption indication ensures a number of benefits: people who are not familiar (or illiterate in rural areas) with using the internet can get a rough idea about how much energy is consumed or how much credit is left. Besides, while leaving the home, it is more likely that the user will notice the meter if the color of the entire LCD changes. Therefore, the postpaid user may become more aware of their energy usage to avoid high tariff rates and the prepaid user can decide when to recharge.

3.4. Performance evaluation

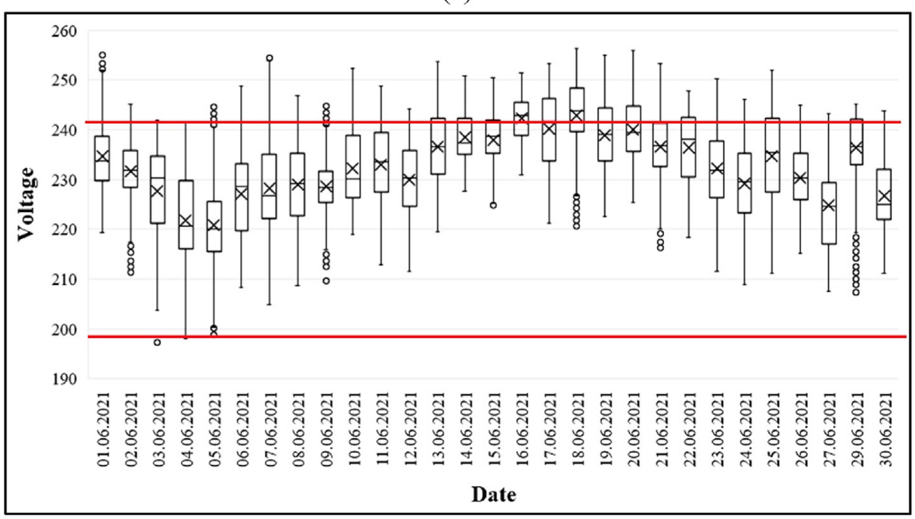
The smart meter is first calibrated with the Fluke 5502A [50], a standard calibration meter to achieve satisfactory measurement accuracy. Hereafter, to confirm the measurement accuracy of the meter, several measurement data (V, I, P, and PF) from 180 to 250 V for three different types of appliances are compared with EVERFINE DPS 1005 [51], which is a variable AC supply source with digital metering interface. The appliances were selected in such a way that they both cover linear (e.g., incandescent lamp) and non-linear loads (e.g., LED, CFL). Table S4 in the *supplementary materials* shows the comparative measurement data in power measurement. It can be seen that there is a slight difference between the measured data of the SM and the EVERFINE DPS 1005. Since this work proposes a smart meter, the energy measurement data of the SM is also compared with a commercially available digital energy meter installed in the house. After 15 and 30 days, the proposed SM recorded the energy consumption of 55.67 kWh and 120.46 kWh, respectively, whereas the digital energy meter recorded 56.19 kWh and 122.14 kWh for the same duration. The percentages of error were found to be 0.93% and 1.38% for these energy measurements. Equation (1) was used to calculate the percentages of error.

$$\%\ \boldsymbol{of\ Error} = \left(\frac{\boldsymbol{Q_{Std}} - \boldsymbol{Q_{SM}}}{\boldsymbol{Q_{Std}}}\right) \times 100 \tag{1}$$

Where $\boldsymbol{Q_{Std}}$ is the quantity measured by the standard meter, $\boldsymbol{Q_{SM}}$ is



(a)



(b)

Fig. 9. Box and whisker plot showing variations in voltage (V) for each day in June 2021 for the (a) household-02 [HH02], and (b) household-03 [HH03]. Within each box, the horizontal line is the median voltage for that day, and the lower (and upper) edges of the box are the 25th (75th) percentile. The crosses represent average voltage. Whiskers represent the upper and lower ranges, and dots represent outliers. The long red horizontal lines represent the standard limit of fluctuation. Note: Data for 28th June was missing in the data set for HH03.

the quantity measured by the smart meter.

3.4.1. *Power consumption of the proposed SM*

The power consumption characteristics of the proposed SM is shown in Fig. 14, the IoT-based SM with DSM system consumes less than 2.75 W of power when the relay is energized, and for the rest of the time, the power consumption is less than 2.25 W.

4. Cost-benefit analysis

The required hardware components for the SM are listed in Table S1 in the *supplementary materials*, and the total cost of the hardware parts is about $35. The software section requires the purchasing of hosting and domain. If the SM sends V, I, P, PF, E, and F data every 30 s to the MySQL database, about 8 Megabytes (MB) of storage is required per month per user. If the utility wants to keep one year of data in the MySQL database, about 96 MB storage/user is required. Therefore, a 50 Gigabytes (GB) hosting storage can store 520 users' yearly data in the database. The price of 50 GB of hosting with a domain is approximately $30 in Bangladesh. However, the cost of web hosting varies from one service provider to another. The storage requirements per user can be minimized by increasing the data transmission delay in the hardware section (if the delay is doubled, the storage requirements decrease by 0.5 times). In the proposed SM, WiFi is used for two-way data transmission; however, it is possible to upgrade the system to work either on WiFi or cellular network (GPRS) using the ESP32 SIM800L module [52]. The total implementation cost would be about $65 and $75 for SM with

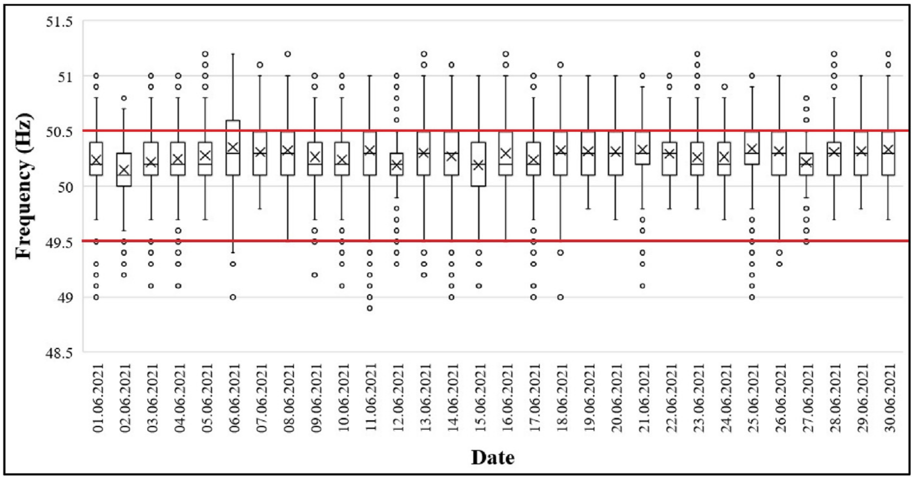


Fig. 10. Box and whisker plot showing variations in frequency (Hz) for each day in June 2021 for the HH02. Within each box, the horizontal line is the median frequency for that day, and the lower (and upper) edges of the box are the 25th (75th) percentile. The crosses represent average frequency. Whiskers represent the upper and lower ranges, and dots represent outliers. The long red horizontal lines represent the standard limit of fluctuation.

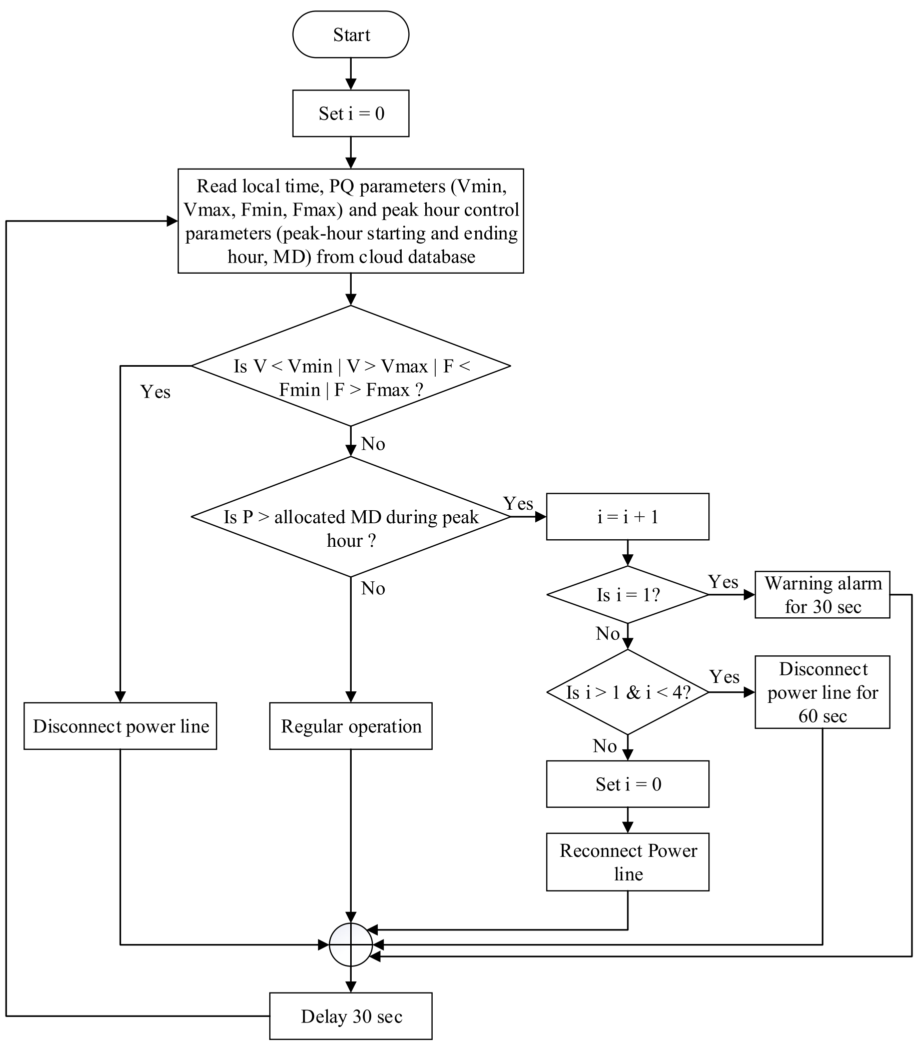


Fig. 11. Power quality and demand-side management algorithm of the proposed smart meter.

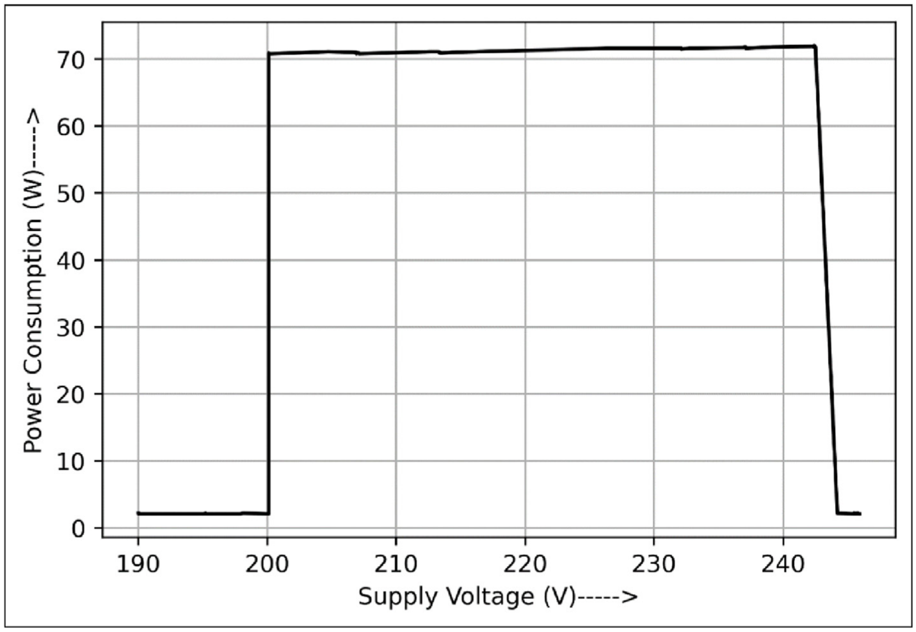


Fig. 12. The proposed smart meter's operation under EN 50160 standard supply voltage limit.

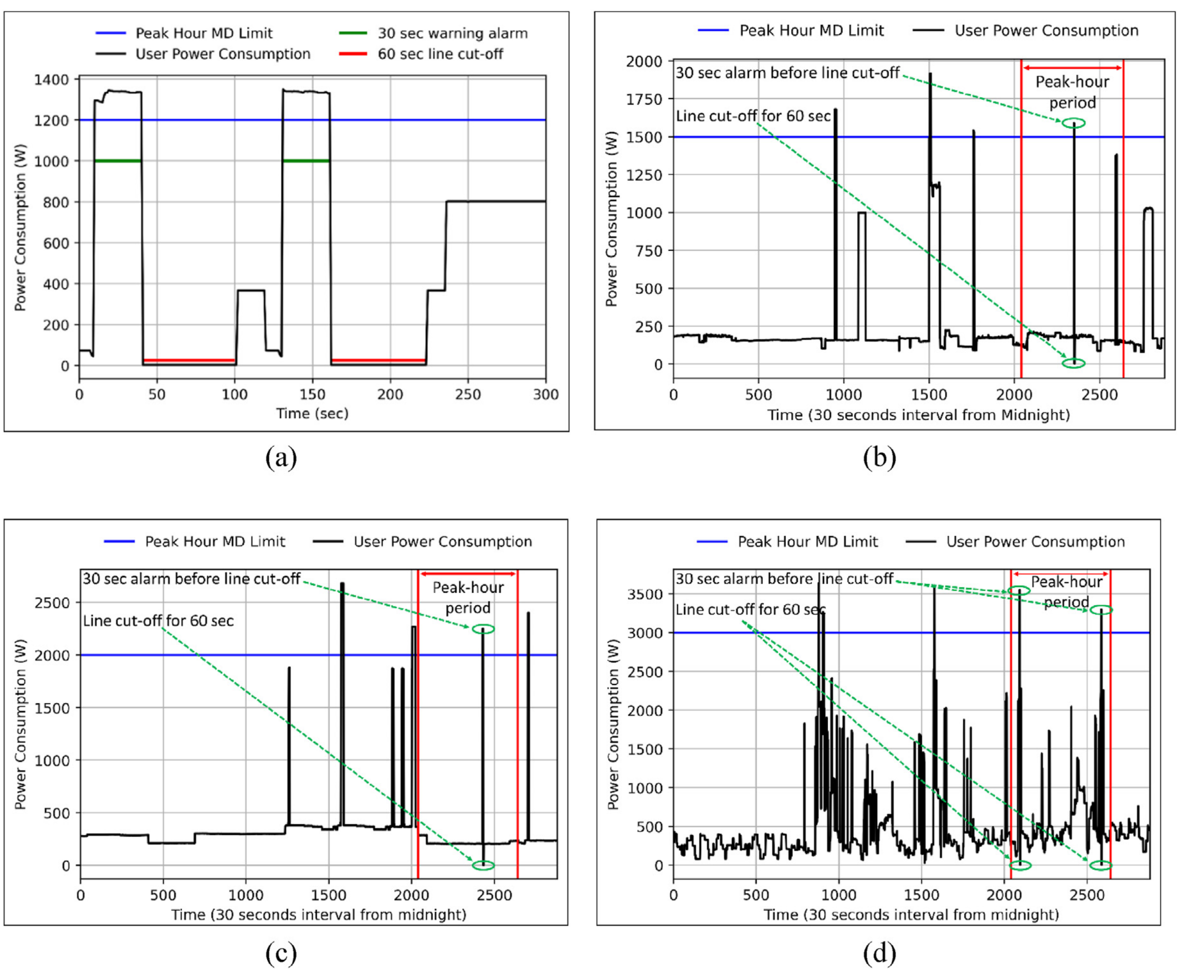


Fig. 13. Smart meter's operational characteristics for peak demand management (a) switching characteristics during peak time only, for maximum demand (MD) = 1200 W, (b) MD = 1500 W for HH01, (c) MD = 2000 W for HH02, and (d) MD = 3000 W for HH03.

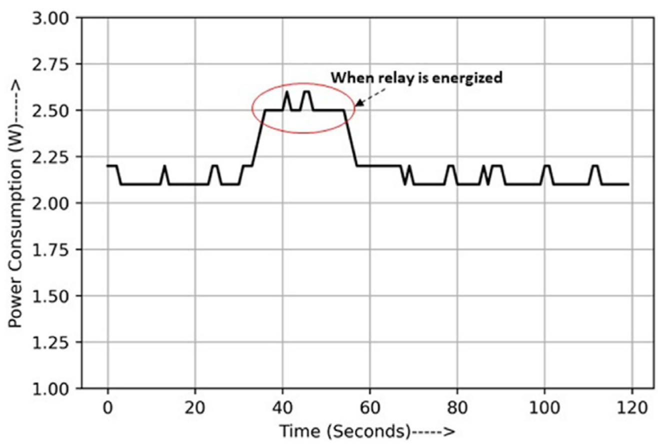


Fig. 14. Power consumption curve of the proposed IoT-based smart meter with DSM.

WiFi and WiFi along with cellular, respectively. These costs include hardware and IoT service, including web hosting. Table 2 is a cost comparison of the proposed SM with existing meters in Bangladesh.

5. Discussion

Power quality in developing countries is one of the critical issues for electrical home appliances. For example, in Unguja, Tanzania, the voltage drop was reported as low as 30% from the nominal value i.e., 220 V [36], whereas in Bangladesh, the voltage was about 15.45%–16.36% higher than the nominal value. With these fluctuations, electrical home appliances and equipment are unable to perform properly and might be damaged [55]. Therefore, with the help of IoT, the proposed smart meter would be able to cut-off the power in case of power quality fluctuations beyond the standard limit. This could be the short-term technological solution to the power quality issues in developing countries, in order to save the appliances from damage, and will increase their lifetime until proper control technologies are deployed.

Implementation of smart grids in the developing world is a challenge for a number of reasons, primarily the cost. It requires billions of dollars to establish a smart grid in developing countries, for example, see Ref. [56]. The other dominant challenges are: (i) to meet the future demand growth of about 10–13%, the focus is still on centralized generation facilities, (ii) grid code, distribution code, and related standards are yet to be implemented, (iii) lack of automatic voltage and frequency control mechanisms, (iv) lack of automation in demand-side management, and (v) lack of affordable and maintainable technologies [57]. The proposed IoT-based smart meter would predominantly solve the 'lack of automation in demand-side management' problem.

In a power grid, peak time generators are the most inefficient type as they only operate during the grid peak demand hours and remain switched-off during other times of the day. "*Although peak demand occurs around 1% of annual hours, it affects networks' stability, security, reliability and most importantly the cost of energy*" [58]. Thus, the electricity authority in each country tries to ensure generation availability during peak hours by establishing new 'peaker plants'. Importantly, establishing these 'peaker plants' not only requires huge costs but they also emit GHGs, as most of the peaker plants are fossil-fuel dominated [59]. Using the proposed smart meter, the utility can limit peak demands for the users during peak hours. Consequently, the utility can select the required number of generators during peak hours. In this way, an efficient electricity grid could be achieved, and electricity generation costs would be minimized.

In the proposed system, all of the users' electricity data, that is, RMS voltage (V), RMS current (I), active power (P), power factor (PF), frequency (F), energy consumption (E) are stored in an online database. Thus, the utility will have the whole year's power consumption pattern of individual users in the database, so it will be easier for the utility to predict future loads. Consequently, this will underpin policymaking regarding future grid expansion plans. Importantly, the utility can implement different tariff plans for different consumers based on their peak demand pattern. For example, if HH03 takes 3 kW of maximum demand (MD) during peak hours and HH01 takes 1.5 kW of MD, then the utility can impose a higher tariff rate for the former and a lower tariff rate for the latter. Therefore, both consumers and utility gain benefits from this system. In addition, the proposed IoT-based SM eliminates manual meter reading, as the utility can check energy usage information remotely using the internet.

Importantly, the average and median percentage of error for different parameters (quantities) as listed in Table S4 in the *supplementary materials* for both linear (i.e., incandescent lamps) and

Table 2
Comparison with existing meters in Bangladesh.

Meter type	Cost	Features
Single-phase post-paid digital energy meter [53]	~$15	Meter type: post-paid Display: real-time V, P, and E in an LCD
Smart pre-paid energy meter [54]	Initial + monthly charge	Meter type: pre-paid Display: real-time V, I, P, PF, E, F, and available credit in a LCD Communication interface: PLC/GPRS
Proposed Smart Meter	(i) ~$65 (with only WiFi), (ii)~$75 (with cellular + WiFi)	Meter type: can be configured to pre-paid/postpaid Display: real-time V, I, P, PF, and E in a LCD Data storage: real-time electricity data storage in a cloud database Application: web application Dominant features: ensuring power quality and peak-hour-based DSM (the control parameters can be updated by the utility remotely), visual color-based energy consumption indication. Communication interface: WiFi/GPRS

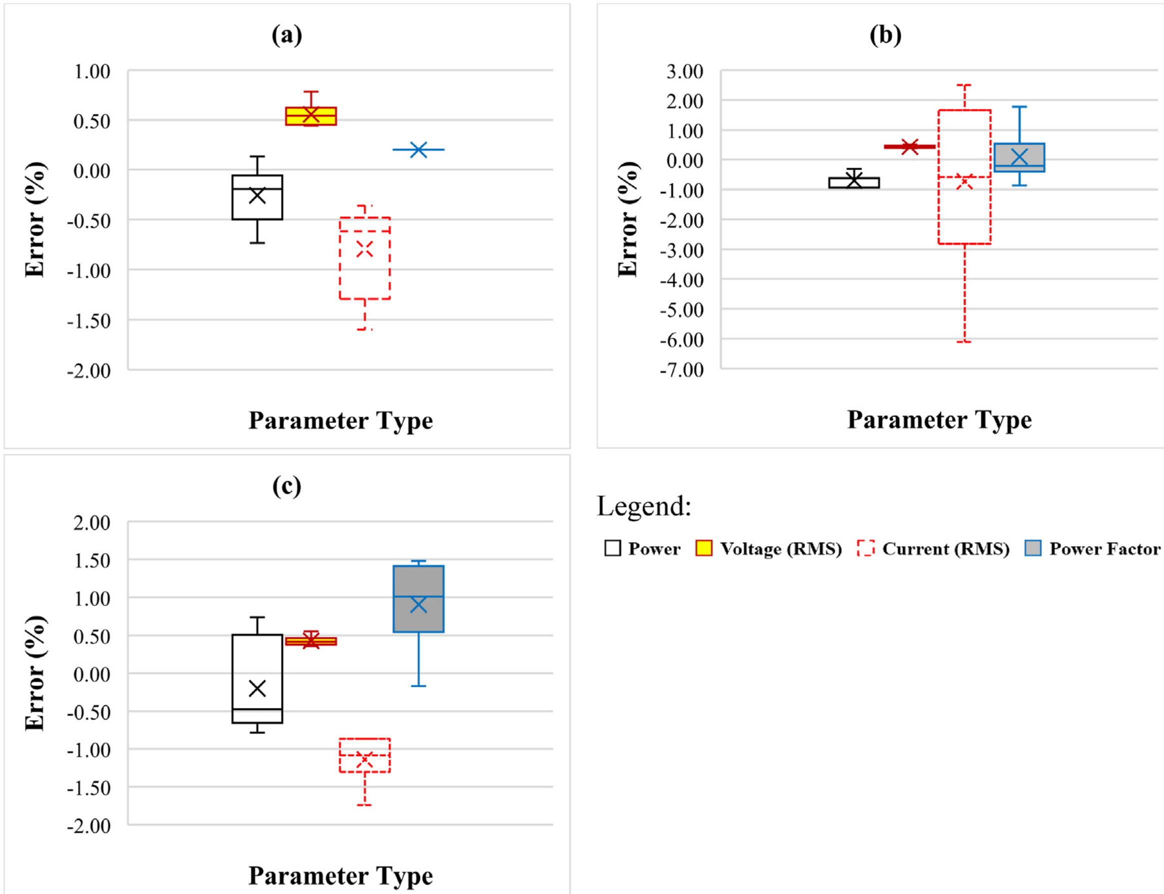


Fig. 15. Box and whisker plot showing variations in percentage of measurement error for power, voltage (RMS), current (RMS), and power factor of (a) incandescent lamp [linear load], (b) LED [non-linear load], and (c) CFL [non-linear load]. Within each box, the horizontal line is the median value, and the lower (and upper) edges of the box are the 25th (75th) percentile. The crosses represent average value. Whiskers represent the upper and lower ranges, and dots represent outliers (if any). (Referring to Table S4 in the *supplementary materials*).

non-linear loads (i.e., LED, CFL) were found to be within 1%, except for current (RMS) of CFL load. Equation (1) is used to calculate the percentage of error for different quantities. Notably, the maximum percentage of error for current (RMS) varied significantly for LED. However, the average and median values were within 1%. All these variations are illustrated in Fig. 15.

5.1. Comparative study

The comparison of existing electricity meters in Bangladesh, and the proposed SM is shown in Table 2. Instead of simply providing metering (prepaid/postpaid) services, the proposed meter provides some additional features like PQ maintenance and DSM through peak clipping during peak-hour. The proposed SM supports remote updates of PQ thresholds, peak hour period, and peak-hour maximum demand limit by the utility. Besides, visual color-based energy consumption indication and real-time monitoring of electricity by accessing the internet can be utilized to promote energy conservation.

Several previous works in the literature reported IoT-based smart meters, as illustrated in Table 3. Muralidhara et al. (2020) proposed an IoT-based smart meter that is able to monitor device-level energy consumption only [60]. Another work also proposed a low-cost SM for IoT application [61]. In India, an IoT-based smart compact energy meter is proposed, which is able to analyze power quality issues such as sag, swell, and transients, and inform the users [62]. The proposed work incorporates the limitations of the existing works. For instance, in the proposed work by Pawar et al. (2019) [63] and Karthick et al. (2021) [62], the utility has no option to update peak-hour maximum demand remotely. It requires reprogramming to make changes in maximum demand, which severely limits the flexible operation of their proposed energy meter. The work presented by Labib et al. (2017) has a maximum demand control facility remotely, and to achieve the goal, the utility needs to send SMS to the meter [64]. However, neither the user nor the utility has any option to monitor real-time electricity consumption-related information. This work incorporates the above-mentioned limitations into the SM design for DSM

Table 3
Comparison between existing IoT-based smart meters and proposed meter.

References	Main Features	Application Area	Limitations	DSM Application
[30]	• IoT-based smart meter for power quality monitoring.	Three-phase Consumer	• Energy measurement was not conducted. • The proposed system is not a plug-in system; each user requires a ThingSpeak account to monitor energy consumption via the internet.	No
[42]	• IoT-based energy monitoring and management.	Consumer side	• The user needs to use third-party software (so a personal computer is required).	No
[60]	• IoT-based cost-effective and efficient smart energy meter for device-level energy consumption monitoring.	Consumer side	• The proposed system is not a plug-in system; each user requires a ThingSpeak account to monitor energy consumption via the internet. • The user can monitor only one device at a time. • The energy meter's measurement accuracy was not compared with any reference meter.	No
[62]	• IoT-based energy monitoring and control for a commercial building. • Able to provide warnings regarding power quality issues to the user. • Priority-based DSM during peak hours by load shifting to reduce electricity cost.	Consumer side	• In the proposed system, high power appliances (like refrigerator, AC, oven, pump) are shifted from peak hour to off-peak hour to reduce energy consumption; however, it may affect human comfort. • Self-power consumption of the proposed system was not explored. • Although it was claimed that the proposed system provides several services at the lowest market price, no cost-benefit analysis was conducted. • If the utility changes peak-hour time, the proposed system requires reprogramming. • In case of power quality issues, the system was not able to cut off the line automatically; instead, it only provided warnings messages.	Priority-based DSM during peak-hour by load shifting
[63]	• IoT-based load monitoring and demand-side management. • Controlled partial load shedding instead of complete shutdown. • Priority-based load cut off during peak-hour.	Consumer side	• Requires an ethernet-based local server for data storage for each user, which is not cost-effective. • For energy management, each appliance should be equipped with a smart socket which is also expensive. • How the utility can change the maximum demand limit (MDL) and how the smart socket interacts with the changed MDL remained unexplored.	Priority-based DSM with maximum demand constraint using smart sockets
[64]	• GSM-based smart energy meter with demand-side load management (DSLM) • Can be used as pre-paid and postpaid energy meter. • Provides emergency power to selected loads during power shortage instead of complete shutdown.	Consumer side	• A user needs to send SMS (short message service) each time to get electricity-related information. • There is no automatic DSLM; the utility needs to send SMS to each user's meter to activate DSM during power shortage.	SMS-based DSM
[65]	• Proposed an 'IoT board' for individual appliance energy consumption and health monitoring by measuring the current drawn by the appliance.	Consumer side	• Only the concept was presented. • No empirical results were presented. • Each appliance needs to be equipped with the 'IoT board'.	No
[66]	• GSM based smart energy meter	Consumer side	• Simulation-based work. • No practical demonstration of the proposed meter was conducted. • No empirical results were presented.	No
[67]	• IoT-based energy consumption and environmental factors (temperature, humidity, activity, luminosity levels, and noise levels) monitoring for educational buildings.	Consumer side	• Real-time monitoring was not demonstrated. • How the proposed system achieves energy efficiency for school buildings remained unclear.	No
[68]	• IoT-based real-time electricity monitoring. • Energy quality monitoring.	Consumer side	• Demonstrated for 3-phase power users only. • The proposed system can record up to 60 days of data. • DSM was not demonstrated. • Cost-benefit analysis was not conducted.	No
Proposed Smart Meter	• IoT-based real-time electricity monitoring. • Web-based application. • Power-quality maintenance and peak time automatic DSM. • Power-quality and peak-hour parameters can be updated at any time. • Can store up to one year of electricity uses data in a cloud database (can be extended). • Two separate web pages for the utility and user, which allows remote monitoring and management. • Supports pre-paid and postpaid metering. • Different tariff plans can be included.	Both consumer and utility	–	• Maintaining power quality. • Peak-time automatic DSM.

application. The features of the proposed smart meter are online and offline electricity monitoring by both consumer and utility, remote update facility to power-quality and peak time automatic DSM control parameters, and a visual color-based energy consumption indication. In addition, different peak time tariff schemes can be designed using this smart meter. All these features thus justify the proposed IoT-based smart meter's novelty.

6. Conclusion

Power quality is one of the crucial parameters in an electrical network that ensures proper functionality and efficient use of electrical home appliances. Deviations from standard power quality could entail a number of problems, such as higher energy and maintenance costs, equipment instability, and appliance damage. For instance, voltage fluctuation, in particular, high voltage (i.e., more than 10% compared to nominal value), is detrimental to electrical home appliances' performance and durability. In developing countries like Bangladesh, voltage fluctuations are very common. In addition, demand-side management is crucial for any nation's electricity sector to balance supply and demand along with network security. For the developing world DSM is indispensable as it could reduce demand and underpin new access to electricity to the unelectrified population and help to achieve UN's SDG goal-7. Although many previous studies in the literature used smart meters for many different applications, none of them considered both power quality and DSM issues through a single smart meter. Thus, in this work, a smart meter is developed and tested which is able to ensure two functions at the same time (i) ensuring power quality at residences, and (ii) reducing demand during grid peak hours. The developed smart meter is used in Bangladeshi households as a case study, and this smart meter can be used in many other developing countries in Africa and Asia with similar electricity network infrastructure. The findings are as follows:

- Maintaining good power quality is a critical issue in the developing economies.
- The smart meter data shows that the over-voltage varied (from nominal 220 V) within 15.45–16.36%, and the under-voltage varied between 10.45% and 11.82% from 220 V.
- The frequency fluctuations are found to be 2.2% under and 2.4% over the nominal value of 50 Hz (standard is nominal value $\pm$ 1%).
- Effective demand-side management schemes such as time of use, peak clipping, dynamic load management are not available in most developing countries in Africa and South Asia due to the lack of smart grids and smart meters.
- The proposed smart meter is capable of ensuring power quality and peak time demand management through peak clipping with the help of the internet of things.

Although the proposed IoT-based smart meter is able to offer a number of benefits to the developing nations, including implementation of smart demand-side management options without a smart grid, it also has a few limitations. First, the availability and quality of internet service in the developing world is still a problem nowadays. Nevertheless, with the help of the international communities and organizations (e.g., *Trans*-Eurasia Information Network (TEIN)[1]) and countries' own plans, access to the internet is increasing rapidly, such as in Bangladesh. For instance, as per the Bangladesh Telecommunication Regulatory Commission (BTRC)[2], at the end of May 2021, the total number of internet subscribers was 117.31 million; this was 112.71 million at the end of January for the same year. Additionally, the proposed system could be implemented for urban areas during the first phase, and consequently, other areas could be covered after securing proper resources.

Second, cybersecurity would be an issue for the IoT-based system as several threats might occur during the operation from many different sources [69]. However, as the security is improving day by day, these threats could be minimized. Although this may be true, further research is necessary to ensure maximum security.

Third, peak clipping or direct demand control during peak hours in a household might increase consumers' dissatisfaction. However, if the users get monetary benefits from this scheme, this could be well balanced. In addition, the peak time permitted demand for a specific household could be fixed by discussion with the head of the household.

Fourth, the developed smart meter was suitable for a single-phase connection only. Three phase connectivity of the meter requires further research and modification in its structure and working procedures.

Credit author statement

Md. Tanvir Ahammed: Methodology, Software, Data curation, Validation, Formal analysis, Investigation, Writing – original draft. **Imran Khan:** Conceptualization, Investigation, Resources, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing 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.

Acknowledgments

This work was supported by the Jashore University of Science and Technology under the research project grant. The authors would like to thank Professor Dr. Md. Rafiqul Islam, Department of Electrical and Electronic Engineering, Khulna University of Engineering and Technology, Bangladesh, for his support.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2022.123747.

[1] https://www.tein3.net/Pages/home.html (accessed 21-Jul-2021).
[2] http://www.btrc.gov.bd/telco/internet (accessed 21-Jul-2021).

Appendix

Algorithm A1. Working principle of the proposed IoT-based SM with DSM

read Wi-Fi credential//Wi-Fi ssid and password
set local time-zone from ntpServer//for time reading from pool.ntp.org using ESP32
read host server address//for two-way data transmission
connect to Wi-Fi network
while(1) do://infinite loop
//Reading V, I, P, PF, E and F from PZEM004T
  V ← pzem.voltage()
  I ← pzem.current()
  P ← pzem.Power()
  PF ← pzem.pf()
  E ← pzem.energy()
  F ← pzem.frequency()
  read local time from ntpServer
  if (host is available) **then**:
//send data to MySQL using HTTP GET() method and PHP script
    send V, I, P, PF, E and F data to the MySQL database
    read current month's E
    set LCD display color based on current month's E
    read DSM control parameters: V_L, P_L, F_L, SPH, EPH and MD from MySQL database
  if ($V < V_L$ **or** $P > P_L$ **or** $F < F_L$) **then**:
cut-OFF power line//by controlling the relay
start counter//to count 30 s delay before turn 0 N power line
  else if (SPH≥local time≤EPH **and** P > MD) **then**:
    cut-OFF power line//by controlling the relay
    start counter//to count 60 s delay before turn 0 N power line
  if (counter≥60 s) **then**:
    turn ON power line//by controlling the relay
  delay (30 s)//data transmission delay
  check Wi-Fi connection status
  if (Wi-Fi not connected) **then**:
    reconnect Wi-Fi

References

[1] IEA, IRENA, UNSD, W. Bank, and WHO. "Tracking SDG 7: the energy progress report," Washington DC, USA. 2021 [Online]. Available: https://trackingsdg7.esmap.org/data/files/download-documents/tracking_sdg_7_2020-full_report_-_web_0.pdf.
[2] Khan I. Importance of GHG emissions assessment in the electricity grid expansion towards a low-carbon future: a time-varying carbon intensity approach. J Clean Prod 2018;196:1587–99. https://doi.org/10.1016/j.jclepro.2018.06.162.
[3] Khan I. Energy-saving behaviour as a demand-side management strategy in the developing world: the case of Bangladesh. Int. J. Energy Environ. Eng. 2019;10(4):493–510. https://doi.org/10.1007/s40095-019-0302-3.
[4] Khan I, Jack MW, Stephenson J. Dominant factors for targeted demand side management—an alternate approach for residential demand profiling in developing countries. Sustain Cities Soc 2021;67(102693):1–17. https://doi.org/10.1016/j.scs.2020.102693.
[5] Khan ZA, Jayaweera Di. Smart meter data based load forecasting and demand side management in distribution networks with embedded PV systems. IEEE Access 2020;8:2631–44. https://doi.org/10.1109/ACCESS.2019.2962150.
[6] Rausser G, Strielkowski W, Štreimikienė D. Smart meters and household electricity consumption: a case study in Ireland. Energy Environ 2018;29(1):131–46. https://doi.org/10.1177/0958305X17741385.
[7] Gelazanskas L, Gamage KAA. Demand side management in smart grid: a review and proposals for future direction. Sustain Cities Soc 2014;11:22–30. https://doi.org/10.1016/j.scs.2013.11.001.
[8] Kanellos M. Smart grid price tag: $476 billion; benefits: $2 trillion. Greentechmedia; Apr. 08, 2011.
[9] Maruf MH, ul Haq MA, Dey SK, Al Mansur A, Shihavuddin ASM. Adaptation for sustainable implementation of Smart Grid in developing countries like Bangladesh. Energy Rep 2020;6:2520–30. https://doi.org/10.1016/j.egyr.2020.09.010.
[10] Tahir MF, Chen H, Khan A, Javed MS, Cheema KM, Laraik NA. Significance of demand response in light of current pilot projects in China and devising a problem solution for future advancements. Technol Soc 2020;63(101374):1–12. https://doi.org/10.1016/j.techsoc.2020.101374.
[11] Ali MR, Shafiq M. Revealing expert perspectives on challenges to electricity Demand-Side Management in Pakistan: an application of Q-Methodology. Util Pol 2021;70(101216):1–11. https://doi.org/10.1016/j.jup.2021.101216.
[12] Dranka GG, Ferreira P. Towards a smart grid power system in Brazil: challenges and opportunities. Energy Pol 2020;136(111033):1–16. https://doi.org/10.1016/j.enpol.2019.111033.
[13] Atikol U. A simple peak shifting DSM (demand-side management) strategy for residential water heaters. Energy 2013;62:435–40. https://doi.org/10.1016/j.energy.2013.09.052.
[14] Khalid H, Amin FR, Chen C. Comparing the status and challenges of demand-side management (DSM) implementation in Asia-Pacific region: a case study of China's power sector. Energy Proc 2018;152:101–8. https://doi.org/10.1016/j.egypro.2018.09.066.
[15] Rahman A, Aziz T, Al Masood N, Deeba SR. A time of use tariff scheme for demand side management of residential energy consumers in Bangladesh. Energy Rep 2021;7:3189–98. https://doi.org/10.1016/j.egyr.2021.05.042.
[16] Khan I. A survey-based electricity demand profiling method for developing countries : the case of urban households in Bangladesh. J Build Eng 2021;42(102507):1–9. https://doi.org/10.1016/j.jobe.2021.102507.
[17] Niu Z, Wu J, Liu X, Huang L, Nielsen PS. Understanding energy demand behaviors through spatio-temporal smart meter data analysis. Energy 2021;226(120493, pp.):1–15. https://doi.org/10.1016/j.energy.2021.120493.
[18] Kiguchi Y, Heo Y, Weeks M, Choudhary R. Predicting intra-day load profiles under time-of-use tariffs using smart meter data. Energy 2019;173:959–70. https://doi.org/10.1016/j.energy.2019.01.037.
[19] Kiguchi Y, Weeks M, Arakawa R. Predicting winners and losers under time-of-use tariffs using smart meter data. Energy 2021;236(121438):1–11. https://doi.org/10.1016/j.energy.2021.121438.
[20] Yilmaz S, Chambers J, Patel MK. Comparison of clustering approaches for domestic electricity load pro fi le characterisation - implications for demand side management. Energy 2019;180:665–77. https://doi.org/10.1016/j.energy.2019.05.124.
[21] Khan I, Jack MW, Stephenson J. Identifying residential daily electricity-use profiles through time-segmented regression analysis, vol. 194. Energy Build; 2019. p. 232–46. https://doi.org/10.1016/j.enbuild.2019.04.026.
[22] Melillo A, Durrer R, Worlitschek J, Schütz P. First results of remote building

characterisation based on smart meter measurement data. Energy 2020;200. https://doi.org/10.1016/j.energy.2020.117525.
[23] Wang Z, Crawley J, Li FGN, Lowe R. Sizing of district heating systems based on smart meter data : quantifying the aggregated domestic energy demand and demand diversity in the UK. Energy 2020;193:116780. https://doi.org/10.1016/j.energy.2019.116780.
[24] Lee JY, Yim T. Energy and flow demand analysis of domestic hot water in an apartment complex using a smart meter. Energy 2021;229(120678):1–15. https://doi.org/10.1016/j.energy.2021.120678.
[25] Walker S, Bergkamp V, Yang D, van Goch TAJ, Katic K, Zeiler W. Improving energy self-sufficiency of a renovated residential neighborhood with heat pumps by analyzing smart meter data. Energy 2021;229(120711):1–14. https://doi.org/10.1016/j.energy.2021.120711.
[26] Wang F, et al. Household profile identification for behavioral demand response: a semi-supervised learning approach using smart meter data. Energy 2022;238:1–12. https://doi.org/10.1016/j.energy.2021.121728.
[27] Mbungu NT, Bansal RC, Naidoo RM, Bettayeb M, Siti MW, Bipath M. A dynamic energy management system using smart metering. Appl Energy 2020;280(115990):1–12. https://doi.org/10.1016/j.apenergy.2020.115990.
[28] Mendes DLS, Rabelo RAL, Veloso AFS, Rodrigues JJPC, dos Reis Junior JV. An adaptive data compression mechanism for smart meters considering a demand side management scenario. J Clean Prod 2020;255(120190):1–11. https://doi.org/10.1016/j.jclepro.2020.120190.
[29] Qi N, et al. Smart meter data-driven evaluation of operational demand response potential of residential air conditioning loads. Appl Energy 2020;279(115708):1–15. https://doi.org/10.1016/j.apenergy.2020.115708.
[30] Kumar LA, Indragandhi V, Selvamathi R, Vijayakumar V, Ravi L, Subramaniyaswamy V. Design, power quality analysis, and implementation of smart energy meter using internet of things. Comput Electr Eng 2021;93(107203):1–15. https://doi.org/10.1016/j.compeleceng.2021.107203.
[31] Chakraborty S, Das S, Sidhu T, Siva AK. Smart meters for enhancing protection and monitoring functions in emerging distribution systems. Int J Electr Power Energy Syst 2021;127(106626):1–15. https://doi.org/10.1016/j.ijepes.2020.106626.
[32] Stones J. Power quality. In: Laughton MA, Warne DJ, editors. Electrical engineer's reference book. second ed. Newnes; 2003. 43-1-43–9.
[33] Beleiu HG, Beleiu IN, Pavel SG, Darab CP. Management of power quality issues from an economic point of view. Sustainability 2018;10:1–16. https://doi.org/10.3390/su10072326.
[34] Khetarpal P, Tripathi MM. A critical and comprehensive review on power quality disturbance detection and classification. Sustain. Comput. Informatics Syst. 2020;28(100417):1–11. https://doi.org/10.1016/j.suscom.2020.100417.
[35] Bollen MHJ. What is power quality? Elec Power Syst Res 2003;66:5–14. https://doi.org/10.1016/S0378-7796(03)00067-1.
[36] Jacome V, Klugman N, Wolfram C, Grunfeld B, Callaway D, Ray I. Power quality and modern energy for all. Proc. Natl. Acad. Sci. U. S. A. 2019;116(33): 16308–13. https://doi.org/10.1073/pnas.1903610116.
[37] Elphick S, Smith V, Gosbell V, Drury G, Perera S. Voltage sag susceptibility of 230 V equipment constraints. IET Gener Transm Distrib 2013;7(6):576–83. https://doi.org/10.1049/iet-gtd.2012.0566.
[38] Bonnett AH. Impact that voltage and frequency variations have on AC induction motor performance and life in accordance with NEMA MG-1 standards. In: IEEE annual pulp and paper industry technical conference; 1999. https://doi.org/10.1109/papcon.1999.779341. August.
[39] Shareef H, Mohamed A, Mohamed K. Sensitivity of compact fluorescent lamps during voltage sags: an experimental investigation. WSEAS Trans Power Syst 2010;5(1):22–31 [Online]. Available: http://www.wseas.us/e-library/transactions/power/2010/89-496.pdf.
[40] Ji Y, Davis R, Chen W. An investigation of the effect of operating cycles on the life of compact fluorescent lamps. J Illum Eng Soc 1999;28(2):57–62. https://doi.org/10.1080/00994480.1999.10748275.
[41] Hood G. The effects of voltage variation on the power consumption and running cost of domestic appliances. In: Australasian universities power engineering conference; 2004. p. 1–6 [Online]. Available: https://core.ac.uk/download/pdf/213012185.pdf.
[42] Saleem MU, Usman MR, Shakir M. Design, implementation, and deployment of an IoT based smart energy management system. IEEE Access 2021;9: 59649–64. https://doi.org/10.1109/ACCESS.2021.3070960.
[43] Markiewicz H, Klajn A. Voltage disturbances: standard EN 50160 -voltage characteristics in public distribution systems. 2004 [Online]. Available: http://copperalliance.org.uk/uploads/2018/03/542-standard-en-50160-voltage-characteristics-in.pdf.
[44] PQW. ANSI C84.1 Electric power systems and equipment - voltage ranges. Power Quality In Electrical Systems 2011. http://www.powerqualityworld.com/2011/04/ansi-c84-1-voltage-ratings-60-hertz.html. [Accessed 30 July 2021].
[45] Obaid ZA, Cipcigan LM, Abrahim L, Muhssin MT. Frequency control of future power systems: reviewing and evaluating challenges and new control methods. J. Mod. Power Syst. Clean Energy 2019;7(1):9–25. https://doi.org/10.1007/s40565-018-0441-1.
[46] Macedo MNQ, Galo JJM, De Almeida LAL, De AC. Demand side management using artificial neural networks in a smart grid environment. Renew Sustain Energy Rev 2015;41:128–33. https://doi.org/10.1016/j.rser.2014.08.035.
[47] PZEM. AC digital display multifunction meter product. 2018. p. 1–4 [Online]. Available: https://innovatorsguru.com/wp-content/uploads/2018/01/PZEM-004T-Datasheet.pdf. [Accessed 30 July 2021].
[48] ESP. ESP32 series datasheet. Espressif Systems 2021:1–65 [Online]. Available: https://www.espressif.com/sites/default/files/documentation/esp32_datasheet_en.pdf. [Accessed 30 July 2021].
[49] BERC. Electricity retail tariff 2020. 2020. Dhaka, Bangladesh, https://dpdc.org.bd/public/media/siteassets/docs/retail_tariff_2020.pdf. [Accessed 25 June 2021] [Online]. Available:.
[50] Fluke. 5502A multi-product calibrator. 2013. Everett, USA, http://download.flukecal.com/pub/literature/4225366C_w.pdf. [Accessed 25 May 2021] [Online]. Available:.
[51] EVERFINE. DPS series AC power supply. 2018. Hangzhou, China, http://www.everfine.net/en/productsinfo.php?cid=112&id=580. [Accessed 25 May 2021] [Online]. Available:.
[52] LILYGO. TTGO T-call ESP32 SIM800L specification. 2020 [Online]. Available: http://www.lilygo.cn/prod_view.aspx?TypeId=50033&Id=1127&FId=t3:50033:3. [Accessed 5 July 2021].
[53] SSGSHOP. Single phase postpaid meter. SSGSHOP; 2017. https://ssgeshop.com/product/single-phase-postpaid-energy-meter/. [Accessed 5 July 2021].
[54] Hexing. User manual single phase energy meter. 2013 [Online]. Available: http://www.inogate.org/documents/10.1_User_manual_of_Single_HXE12-KP.pdf. [Accessed 5 July 2021].
[55] Emanuel AE, McNeill JA. Electric power quality. Annu Rev Energy Environ 1997;22:263–303. https://doi.org/10.1146/annurev.energy.22.1.263.
[56] Majeed Butt O, Zulqarnain M, Majeed Butt T. Recent advancement in smart grid technology: future prospects in the electrical power network. Ain Shams Eng J 2021;12:687–95. https://doi.org/10.1016/j.asej.2020.05.004.
[57] Chawdhury MA. Smart grid status in Bangladesh. Islamabad: SAARC EnergyCentre; 2019. p. 1–26 [Online]. Available: https://www.saarcenergy.org/wp-content/uploads/2019/11/Country-Presentation-Bangladesh.pdf.
[58] Khan I. Household factors and electrical peak demand: a review for further assessment. Adv Build Energy Res 2021;15(4):409–41. https://doi.org/10.1080/17512549.2019.1575770.
[59] Khan I. Temporal carbon intensity analysis: renewable versus fossil fuel dominated electricity systems," Energy Sources, Part A Recover. Util. Environ. Eff. 2019;41(3):309–23. https://doi.org/10.1080/15567036.2018.1516013.
[60] Muralidhara S, Hegde N, Pm R. An internet of things-based smart energy meter for monitoring device-level consumption of energy. Comput Electr Eng 2020;87(106772):1–10. https://doi.org/10.1016/j.compeleceng.2020.106772.
[61] Abate F, Carratù M, Liguori C, Paciello V. A low cost smart power meter for IoT. Measurement 2019;136:59–66. https://doi.org/10.1016/j.measurement.2018.12.069.
[62] Karthick T, Charles Raja S, Jeslin Drusila Nesamalar J, Chandrasekaran K. Design of IoT based smart compact energy meter for monitoring and controlling the usage of energy and power quality issues with demand side management for a commercial building. Sustain. Energy, Grids Networks 2021;26(100454):1–15. https://doi.org/10.1016/j.segan.2021.100454.
[63] Pawar P, VittalK P. Design and development of advanced smart energy management system integrated with IoT framework in smart grid environment. J Energy Storage 2019;25(100846):1–13. https://doi.org/10.1016/j.est.2019.100846.
[64] Labib L, Billah M, Sultan Mahmud Rana GM, Sadat MN, Kibria MG, Islam MR. Design and implementation of low-cost universal smart energy meter with demand side load management. IET Gener Transm Distrib 2017;11(16): 3938–45. https://doi.org/10.1049/iet-gtd.2016.1852.
[65] Al-Oudat N, Aljaafreh A, Saleh M, Alaqtash M. Iot-based home and community energy management system in Jordan. Procedia Comput Sci 2019;160:142–8. https://doi.org/10.1016/j.procs.2019.09.454.
[66] Santhosh C, Aswin Kumer SV, Gopi Krishna J, Vaishnavi M, Sairam P, Kasulu P. IoT based smart energy meter using GSM. Mater Today Proc 2021;49(9): 4122–4. https://doi.org/10.1016/j.matpr.2021.02.641. In Press.
[67] Pocero L, Amaxilatis D, Mylonas G, Chatzigiannakis I. Open source IoT meter devices for smart and energy-efficient school buildings. HardwareX 2017;1: 54–67. https://doi.org/10.1016/j.ohx.2017.02.002.
[68] Avancini DB, Rodrigues JJPC, Rabelo RAL, Das AK, Kozlov S, Solic P. A new IoT-based smart energy meter for smart grids. Int J Energy Res 2020;45:189–202. https://doi.org/10.1002/er.5177.
[69] Okino A, Wazir M, Masood R. Smart grids security challenges : classification by sources of threats. J. Electr. Syst. Inf. Technol. 2018;5:468–83. https://doi.org/10.1016/j.jesit.2018.01.001.