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A novel low-cost smart energy meter based on IoT for developing countries' micro grids

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Summary

The increasing demand for energy calls for traditional power grids to become smarter. In developing countries, the challenge is to build smart grids by integrating renewable energy sources into the existing power systems with the help of micro grids. In this paper, a novel low-cost smart energy meter (SEM) is proposed for online energy measurement and billing. The proposed SEM is based on the Internet of things with LoRa-WiFi, which increases the connectivity range and reduces dependence on Internet access. A dedicated Android application provides a friendly communication between the user and the utility company. The proposed measurement system enables the user to get real-time supply voltage, current, and power consumption directly into their smart phones. The proposed SEM also helps energy companies become aware of possible thefts and faults and to provide reliable service to their customers.

KEYWORDS

Internet of Things (IoT), LoRa-WiFi, low-cost energy meter, micro grids (MGs), renewable energy sources (RES), smart energy meters (SEMs), smart grids (SGs)

1 | INTRODUCTION

The demand for energy has grown exponentially all over the world. The world is witnessing accelerated growth in energy consumption compared to population growth. This is very evident in developing countries where the challenge is to provide reliable energy at affordable rates.[1,2] Although improvements have been made to increase usage of electricity, there is still a huge part of the population without access to electricity.[3] For instance, grid connectivity in Asia is about 58%, which is very low compared to Africa, which has 65% grid connectivity.[4,5] Even if there is grid connectivity, the service is often too expensive and not reliable. It is critical to address this issue and to increase these numbers in order to bring opportunity and prosperity to developing countries.

Developing countries confront several barriers as they seek to industrialize using fossil fuels.[6] However, China, with India being the fast follower, shows that the use of renewable energy sources (RES) is a successful alternative in the industrialization process.[7,8] Other industrializing countries should learn from this example. Since RES are clean, the countries that adopt RES are free from payment burdens. Therefore, by moving forward with RES, countries generate employment, enhance energy security, and can address the economic impediments that affect growth.

Enabling energy access to isolated rural areas presents a big issue in developing and emerging countries.[4,5,9] Grid connectivity in rural areas, islands, or remote locations is extremely challenging due to technical and financial issues. To address this problem, micro grids (MGs) have been proposed, as they provide flexibility and adaptability.[4,10,11] An MG is an interconnection of local sources and loads, which operate in synchronization with the main grid. An MG can operate in two modes, namely, grid connected mode and islanded mode. In addition, MGs allow larger penetration of RES into the electric grid. Therefore, MGs provide cost-effective green energy for isolated rural areas and islands.

The need for RES penetration in the power grids calls for more responsibility and security in electricity management. In addition, the increasing demand for energy has already increased non-negligible waste of energy due to inefficient consumer appliances, outdated networks, inefficient routing, poor storage capacity, and, most significantly these days, energy theft.[12-14] In fact, power theft is the main problem in developing countries, causing significant loss to electricity boards.[15] It is crucial to prevent power thefts and unnecessary waste to save power. Smart grids (SGs) can

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address these problems, empowering traditional grids by improving information and communication capabilities.[11-14,16] Implementing such a technology requires analysis, management, and high-speed two-way digital communications. Researchers agree that the Internet of things (IoT) is the adequate technology to address these requirements.[13,14,16-18] IoT represents the interconnection of physical devices with embedded technology, able to interact with the environment and connected to the Internet. The idea of IoT is that the high-speed two-way digital communication technology allows the physical elements to act individually or in collaboration based on the sensing, analyzing, and controlling they perform. In addition, this can be implemented both in distributed and autonomous systems. Therefore, IoT can help SGs in many aspects, such as generation, storage, transmission, distribution, and consumption.[19]

Although several advances toward shifting the energy paradigm in developing countries have been made, there is still much work to be done.[1,2,4-9] In India, most of the existing power systems use traditional energy meters that can only record kilowatt-hours, and the recorded measurement is collected (on foot) monthly by meter readers and then processed by the energy company.[4,15] The traditional billing system is laborious and time consuming. In addition, it is not only slow and not flexible but also often not reliable. India has been an emerging country that has earmarked itself in enhancing the energy sector through renewable energy production and SG technology, but as long as this kind of energy meters, and billing system, is in place, the technology innovation from RES being integrated into SGs will not be achieved.

A developing country like India needs strong growth in the energy sector, and this can be achieved through smart technologies. A step forward in this direction would be to convert traditional meter reading into smart energy meters (SEMs). SEMs allow to monitor energy consumption through mobile application, to fix the pricing on a real-time basis, to ensure self-healing, and to optimize power consumption. This provides important improvements regarding theft detection and billing. Moreover, an efficient communication offers the user an easy-to-use and friendly customer interface. Hopefully, SEMs could also provide a framework to stop the current monopoly in the energy sector and its abusive tariffs.

In this paper, a novel low-cost SEM based on IoT through LoRa-WiFi is proposed. It is designed for energy measurement, power quality improvement, and online billing for developing countries in Africa and Asia. The SEM is built using Arduino Uno, together with WiFi-LoRa as the chosen protocol for providing Internet access to the system. Arduino sends, by means of WiFi-LoRa, real-time power consumption to an online database that contains all the useful information about the user, power consumption details, bills, etc. In particular, LoRa-WiFi has been chosen for implementing the IoT, since it reduces dependence on the Internet access, allowing users with no individual WiFi connection in areas of 10-15 km. This provides consumer access to consumption and billing data, thereby rendering the SEM more flexible, affordable, and inclusive. In addition, LoRa-WiFi is not an expensive technology, neither is Arduino, making the whole system truly feasible and affordable for performing real-time consumption monitoring and online billing management. This is a fundamental aspect of the proposed SEM, since its design is fully oriented to care about the users. Finally, a dedicated Android app is designed to provide an easy, friendly, and seamless communication between the user and the energy companies. The app receives all the information from the online server with the integrated database and updates the user on power failures, payments, etc.

2 | SEMs FOR SGS

Accuracy in electrical billing is highly needed, especially in developing countries where power theft is a major issue and concern. Together with the widespread use of home appliances in daily life, the need for improving the existing method for power consumption collecting and billing management increased significantly. In an attempt to address this, the automatic meter reading (AMR) technology was developed. This was a milestone for the power industry since it avoids the need for a person to visit the physical location for meter reading and consequently reduces the reading error. In addition, the billing can be based on real-time consumption instead of on the past or predicted consumption.

The incredible advances in technology have opened new horizons for automatic metering. The trend now is to consider automatic metering infrastructure (AMI) to improve communication and information flow, by enabling bidirectional communication between users and power providers.[15,19] In such a system, the meter is an SEM, which includes not only an energy meter chip for measuring the consumed electrical energy but also a protocol for data communication. Indeed, the embedded communication protocol enabling bidirectional high-speed communication is a principal advantage of the SEMs.[15] Researchers have proposed different platforms for AMIs.[13,15,19-22] Generally speaking, SEMs can connect to the network through fixed power line carriers or through wireless communication. Some of the wireless communications are GSM, GPRS, Zigbee, and WiFi Technology.

Selecting a proper communication protocol is crucial in SEM implementation. In general, wired connections (like PLCs) are implemented in areas where people have access to a fixed telephone network. Such areas are usually only residential areas. Bluetooth-based SEMs are designed for low-power consumption and are often implemented in areas where it is possible to install the meters close to each other, in order to establish a wireless communication with a master computer. This technique is not very efficient since the power class depends on the number of meters operating within the network. In addition, this technology can only be implemented in areas with high population density. In an attempt to address the unresolved issues, a new approach based on GMS/GPRS technologies has been developed.

The GSM/GPRS networks help provide coverage not only in developed countries but also in developing countries. These technologies currently incite tremendous interest since they can be implemented in rural areas, where the population density is very low, and there is no fixed telephone network. In the work of Bao and Jiang,[23] the authors proposed to use GPRS to build an SEM for long-distance data information transmission. The results in the aforementioned work[23] show that the proposed system not only raises the efficiency of the proposed SEM regarding data acquisition and transmission but also improves the energy management. The paper is based on countries in Africa and South Asia where the use of GPRS is still not widespread among the common population. Therefore, the implementation of the proposed system is not feasible. In the works of Vijayaraj and Saravanan[24] and Kanthimathi et al,[25] GSM technology was used to build an automated billing system. In such systems, the problem may arise when having to deal with missing SMS that would result in decrease of accuracy and overall performance.

3 | PROPOSED LOW-COST SEM

In this paper, we propose a novel low-cost SEM based on IoT through the use of the WiFi-LoRa protocol. The proposed SEM is built using Arduino Uno, which is an open-source technology that allows to sense and control objects in the physical and digital world. Since cost is one of the key factors in the selection and successful implementation of any technology in developing countries, the proposed model is well suited to meet this important objective.

As already discussed in Section 2, the communication protocol selection is a crucial step in the design of the SEM. The proposed SEM is intended to be implemented in countries such as Africa and Asia where rural areas are common. Therefore, to choose the proper communication protocol, it is necessary to take into account the restrictions imposed by the implementation. Among others, the communication protocol has to address the following features:

i. to be independent from fixed telephone lines and low Internet coverage;
ii. to work in areas with low population density;
iii. to be of low cost.

According to these restrictions and the discussion made in Section 2, neither fixed telephone lines (little or no telephone lines in rural areas) nor Bluetooth (only in areas with high population density) or GPRS/GSM (usually expensive) technologies would be the right choice for the cases contemplated. In the case of using cellular technologies, in addition to being expensive, they have the disadvantage of dealing with SMS losses, making the system not reliable enough. In this paper, a communication protocol that can efficiently manage the data, even in cases where loss of packages happens, is proposed on the basis of IoT through the WiFi-LoRa technology. The idea is to ensure a reliable (capable of dealing with losses of packages) and low-cost (people should be able to afford it) communication. WiFi-LoRa is a low-power network (LPN) designed to allow long-range communications among the objects connected to the network. The main advantage of this technology is that it allows connectivity without relying on individual WiFi connections in covering areas that can reach 10-15 km around, ie, within a neighborhood. WiFi-LoRa can be used to create a private wireless sensor network and be a third-party service, allowing the owners of sensors to deploy them in the field without the need of investing in gateway technology. In this way, a local network can be built in a neighborhood connecting several meters with WiFi-LoRa to a single gateway (due to the covering area of the technology), without the need for each household to own a gateway and, more importantly, without the need to have their own WiFi connection.

The communication flow is as follows. Each of the installed meters sends the measured data to a single gateway through WiFi-LoRa. This gateway provides Internet access to allow the data from each meter to be stored and processed by the energy providers. The energy provider then computes the bills and does online visualization, together with the billing, payment status, and other features. Note that the whole communication process is done without the need for each individual householder to have their own access to the Internet. In remote locations, individual householders may not have WiFi connectivity, and the idea of a meter being connected to the Internet without depending on individual Internet access is highly advantageous.

Figure 1 shows the proposed network architecture. In this figure, three SGs, namely, WAN (wide area network), NAN (neighborhood area network), and HAN (home area network), are interconnected using IoT through WiFi-LoRa. The SEMs installed at each home collect periodically the power consumption data of the home appliances. Then, the energy consumption data corresponding to each consumer (measured by each of the SEMs in the HANs) are collected by a gateway in the NAN and transmitted to the energy providers through WANs. The WiFi-LoRa technology has the advantage of allowing a NAN gateway to connect various HANs.

On one hand, in the forward communication direction, the SEM transmits, by means of home WiFi-LoRa, the power consumption data corresponding to each home appliance, which is connected to IoT devices from the householder side (HAN) to the NAN. This information is then sent forward to the online server. On the other hand, in the backward communication direction, the home WiFi-LoRa receives the information from the NAN about power pricing, which is then provided to the SEMs for taking the required actions to correct possible consumption issues in each home appliance.

The described architecture reduces the dependence on Internet access, allowing users with no individual WiFi connection within the neighborhood to benefit from the SG and allowing them to have access to all the information regarding their power consumption and the billing status. In this way, together with the low-cost technology for acquisition and control used in the proposed meter (Arduino Uno), the whole proposed SEM system is highly

i. flexible, ie, the used technology provides flexibility of functions;
ii. scalable, ie, since in the NAN network a single gateway can provide access to the Internet and send data to the power providers, when having to add a house (HAN) to the NAN network, the insertion is simple, straightforward, and, most importantly, not expensive; and

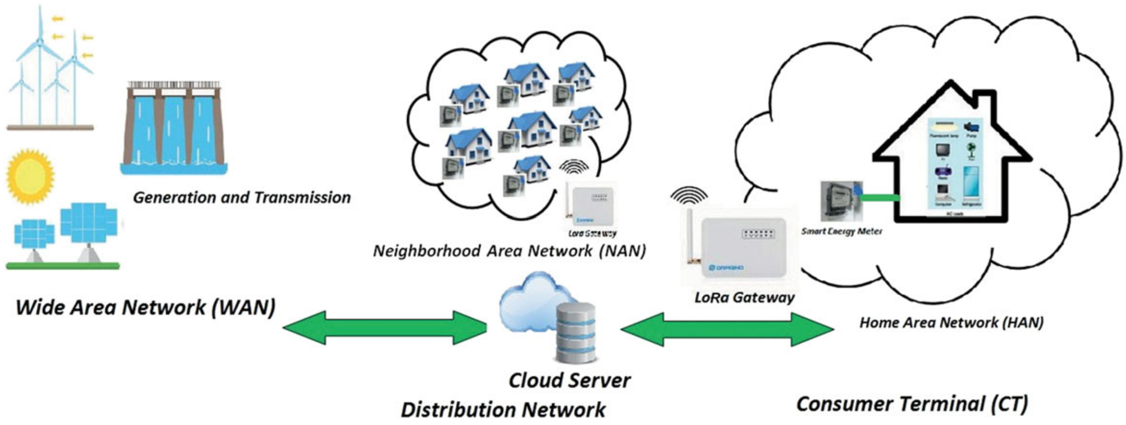

FIGURE 1 Network architecture

iii. affordable and inclusive, ie, using open-source technologies (Arduino Uno) and the fact that no individual WiFi connections are needed to access the bidirectional communication and online power consumption and billing management.

These are the fundamental aspects of the proposed SEM, since its design is fully oriented to care about the users.

In this paper, a dedicated Android app is designed to provide an easy, friendly, and seamless communication between the user and the energy companies. The Android app receives all the information from the online IoT server with the integrated database and keeps the user updated about power failures, payments, etc. In such a way, consumers have in their cell phones all the relevant information about their energy consumption just in time to troubleshoot effectively if needed.

4 | DESIGN AND IMPLEMENTATION OF THE PROPOSED SEM

The design of the proposed SEM involves a hardware module design (sensors that measure the power consumption and communicate with a control support) and a software module design (online signal processing, communication management). In addition, in this paper, a dedicated Android app is included to the proposed SEM system to fulfill the users' needs for billing and consumption information in real time and in an easy, friendly, and fluent way. The Android app is designed by using the Android Studio technology, and PHP is used as the server-side language for communication between the IoT online database and the mobile app.

4.1 | Hardware module design

The hardware module involves integration of the sensors with Arduino to measure the required parameters (see Figure 2). As already mentioned, Arduino is chosen due to its open-source electronic platform with easy-to-use software. Arduino has a great ability to process instructions with high accuracy, providing reliable communication with good hardware support. In addition, it offers flexibility in communicating through Bluetooth, RF communication, Ethernet, and WiFi. As already mentioned, in this paper, communication will be done via WiFi-LoRa.

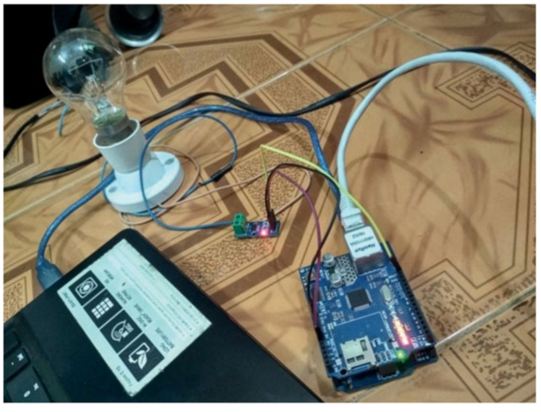

FIGURE 2 Hardware module

To actually measure the power consumption, voltage and current have to be acquired via the corresponding sensors. For the proposed SEM, voltage is measured using standard circuits consisting of transformers and rectifiers, whereas current is measured using an ACS712 current sensor. In Figure 3, the chosen AC712 sensor is shown. This particular selection of the current sensor responds to the low cost requirement of the whole system and, in addition, provides accuracy on the level of the traditional current sensors. In addition, the shunt resistors usually used can be ineffective for large currents and prolonged usage.

The actual calculation of the electrical energy consumption by the user has to be computed. The energy consumed by a user can be expressed as $E = P \cdot t$, where E is the energy expressed in kilowatt-hours, P is the power expressed in kilowatts, and t is the time expressed in hours. The calculation of P involves the voltage, the current, and the power factor. To compute the power factor, a zero-crossing detector circuit designed to detect the zero-crossing of voltage and current waveforms is proposed.

In Figure 4, the used zero-crossing detector is shown. The zero-crossing detector is built on the basis of a pulse train at the input of an XOR gate to detect which output has to be used to compute the power factor. In this paper, an LM324 is used to implement the zero-crossing detector. The LM324 series is of low cost and provides true differential inputs.

Figure 5 shows the power module. Once the physical parameters such as voltage and current are measured, the corresponding digital signals have to be computed, in order to perform the power calculation. This is done by means of Arduino. In this paper, a 1 second interval is considered for the voltage calculation, whereas the maximum value of the analog-to-digital converter (ADC) output gives the peak value of the voltage waveform. In the case of the current calculation, the peak value is also obtained. As Arduino gives an offset value of voltage in no-load conditions, this has to be taken into account and subtracted when computing the root mean square (RMS) using the current sensor ACS712.

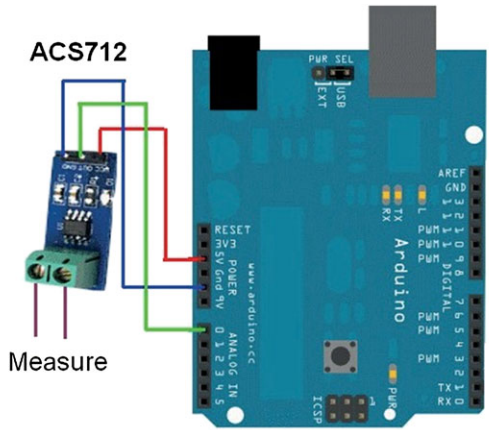

FIGURE 3 AC712 sensor

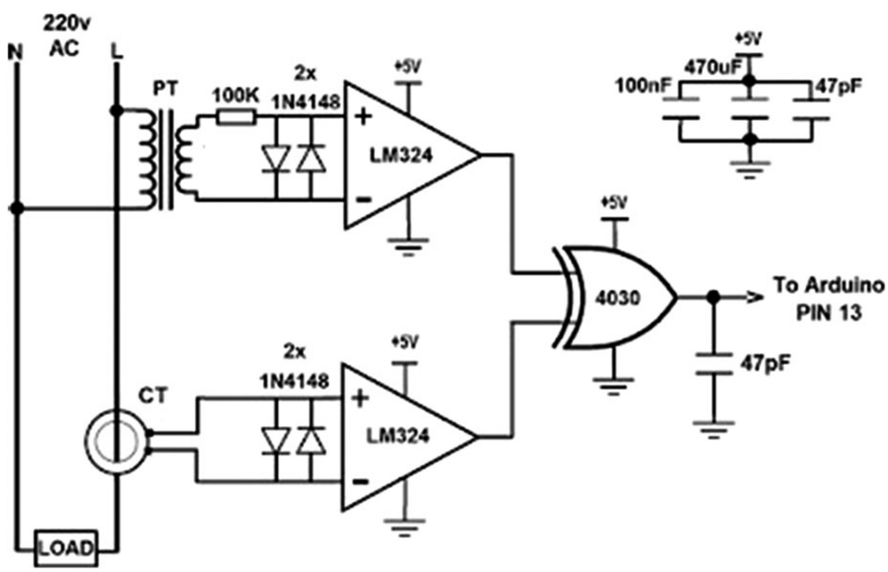

FIGURE 4 Zero-crossing detector

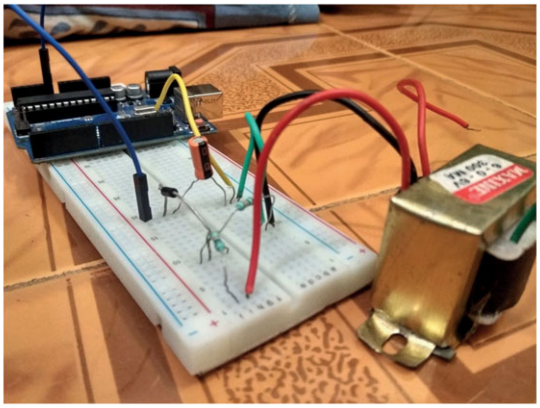

FIGURE 5 Power module

4.2 | Software module design

The software module involves the online information management. The IoT software design proposed in this paper is shown in Figure 6. The (single) IP gateway operating with LoRa-WiFi establishes the connection between the connected IoT devices and the server via an IP link. This communication provides data flow to and from the sensor nodes (physical meters) and the IoT server through the LoRa-WiFi gateway.

The IoT server consists of a message sender, a database management unit and storage, and an access manager. The message dispatcher provides bidirectional communication between gateways and the entire system. It decrypts or encrypts the data packets received from every element and stores the data in DMU. Each module in the DMU extracts the payload of each received message and decides on the storing mechanisms depending on the extracted payload. The processes of data collection, processing, and visualization are decoupled by the database. The network points and nodes are configured in the configuration unit (CU). The CU stores system status in the database, as well as inputs from the applications and the users. Finally, all communications are coordinated by a secure access manager, which provides privacy and data security. The access manager allows only authorized users to access the stored data. Users have also access to the network configuration, based on particular permissions for each network resource. On the other hand, the network owners have administrative permissions.

User interface (UI) management is a crucial aspect for the success of the proposed system. The UI allows clients, application engineers, and specialists to collaborate with an IoT server. The UI offers distinctive functionalities between standard and authoritative clients. Standard clients can just have access to the vital information relating to their HAN. On the other hand, authoritative clients have higher access benefits, being allowed to see the design and status of the IoT gadgets. The UI is in charge of three main interfaces, namely, the visualization, configuration, and web service

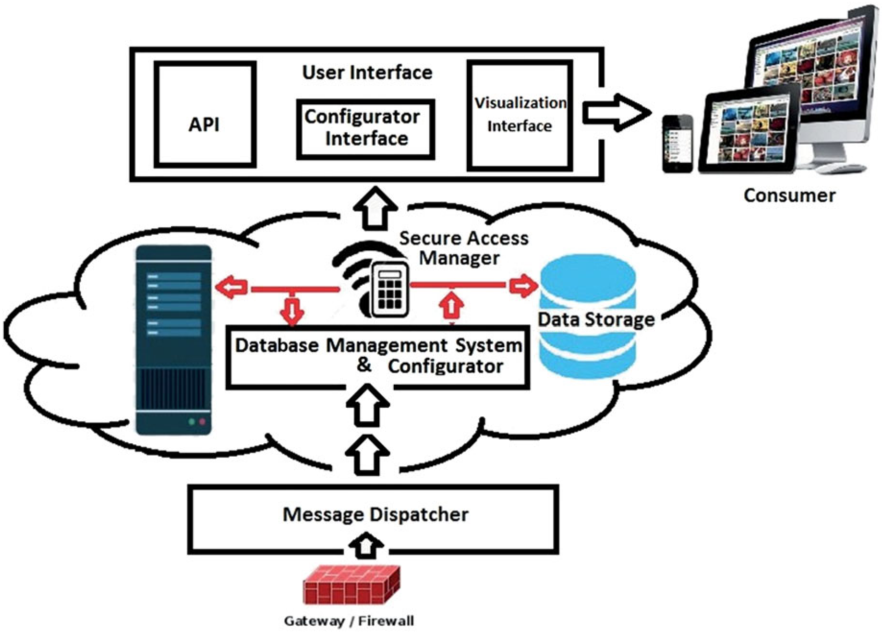

FIGURE 6 The proposed IoT software design

application programming interfaces. The visualization interface displays the energy utilization information. In addition, it allows authorized users to correct the energy consumption in smart home appliances.

The configuration interface provides visibility of the energy consumption of various devices and allows remote location management by the users as well as the registered network administrators. Finally, the web service application interface connects the IoT server to the utility service provider. This interface allows an efficient way of retrieving the collected data from different sources, so that energy companies have access to single or multiple measurement data, and notifies users about dynamic changes in tariffs and threshold alarms. Of course, only registered and authorized users should have access to the consumption data from the database through this web service interface, in order to ensure security and privacy.

5 | EXPERIMENTAL RESULTS

Figure 7A shows the login screen of the developed Android application. The user creates a profile using the profile section. The profile is registered after verification and approval. Figure 7B shows the profile view. Through this feature, the user will be able to view, update, and modify the profile. Once the user is registered and authorized, consumption data will be updated in the server.

Figure 8 shows the user's database management. The above interface provides management of the user database and consumption pattern as well as protection of user data.

In Figure 9A, the data consumption of a registered user can be seen as it is seen by the user. The registered user is allowed to see the consumption data, status, and charges and to pay for the billing through the Android app. The app also provides notifications related to the power failure and periodical maintenance schedule. In Figure 9B, a notification to the user can be seen, where a power failure is reported between 10:00 am and 12:30 pm on the date 06/04/2018. To display this notification, the whole process has to be properly working from the first step of actually measuring the physical parameters as well as computation of power and energy consumption.

This was followed by the second step of sending these data through the LoRa-WiFi HAN to the LoRa-WiFi NAN gateway, enabling the connection with the WAN. The data is stored in the IoT online database for the power providers to analyze as well as helps in the computation of billing, and report failures. The final step is in displaying this information via a notification message in the user cell phone through the designed Android application.

5.1 | Result comparison

The comparison between the proposed model and the existing work is shown in Table 1. Table 1 clearly highlights the salient features, advantages, and results of the low-cost SEM using the IoT technology.

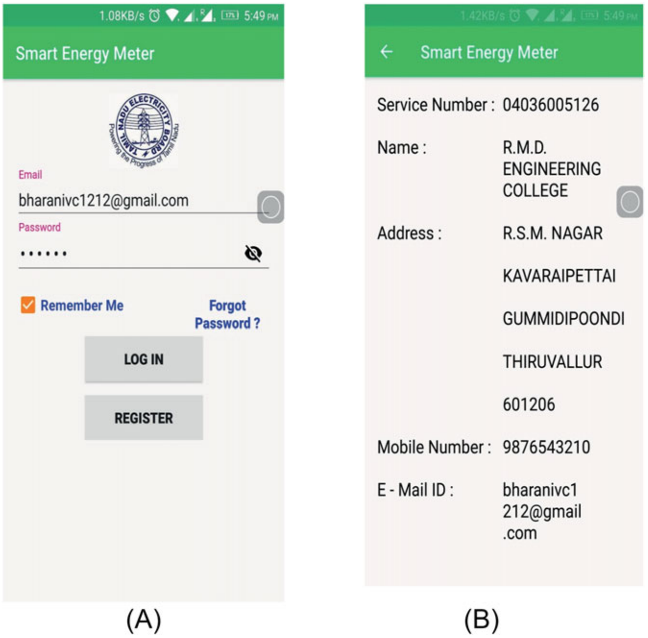

FIGURE 7 Developed Android application. A, Login screen; B, Profile screen

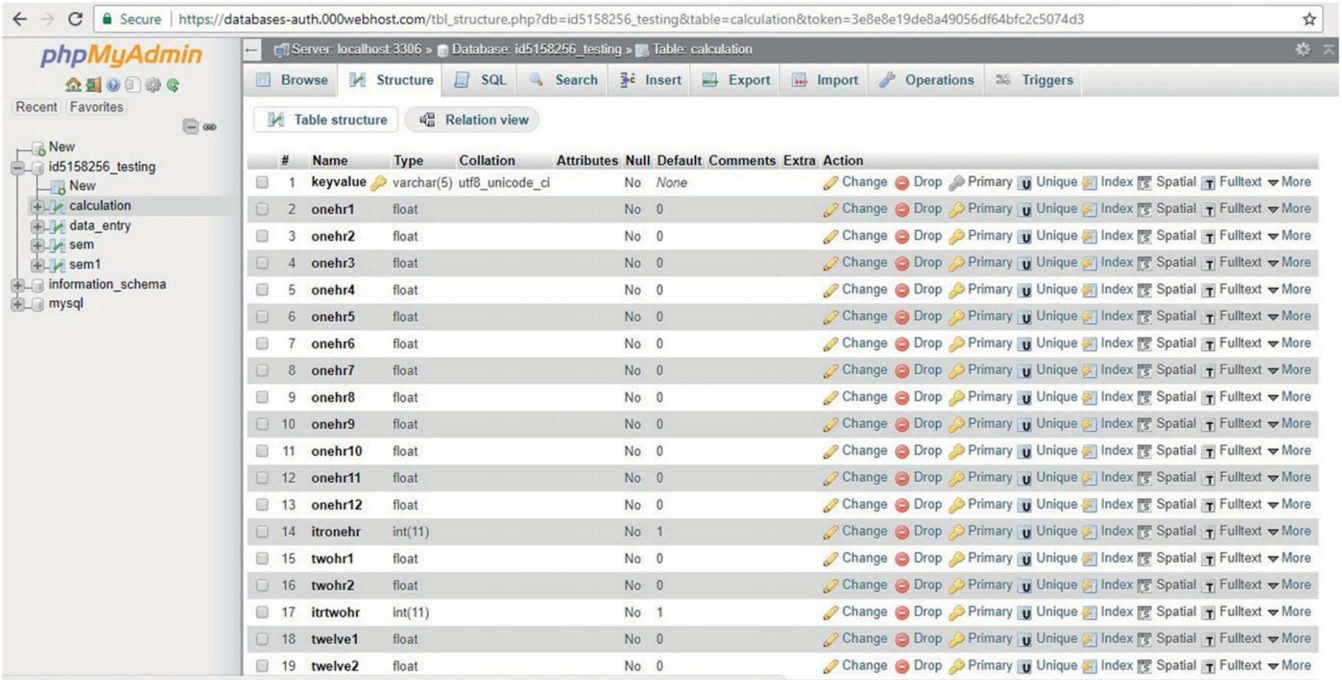

FIGURE 8 Management of users database

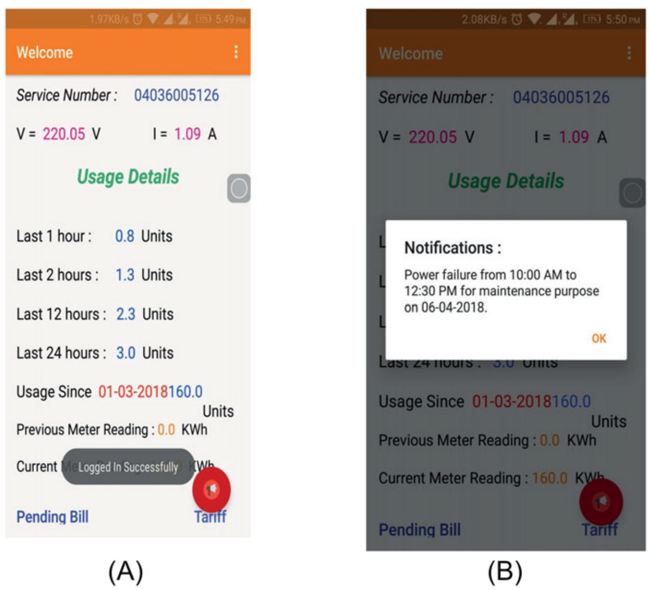

FIGURE 9 Android app. A, Billing screen; B, Notification screen

TABLE 1 Comparison between the proposed method and previous work

S.No	Description	Proposed Model	Existing Model
1	Accuracy	High Accuracy, 99.9%	Accuracy is 95.9%
2	Monitoring	Online (Real time)	Off-line
3	Communication	Two-way	One-way
4	Connectivity	Internet/WiFi	Not accessible
5	Alerts/Notification	User gets information	Not available
6	Bill Payment	Can be paid through app	Not available

The accuracy of the implemented SEM along with real-time connectivity can revolutionize the energy sector (penetration of MGs) in developing countries and bring a unique market for advanced metering infrastructure.

6 | CONCLUSION AND FUTURE DIRECTIONS

In this paper, a novel low-cost SEM based on IoT through WiFi-LoRa has been proposed. It improves the quality of energy monitoring for theft detection and payment features. The proposed model includes a mobile application that allows users to receive power consumption, failure, and billing reports directly into their mobile phone. It also provides connectivity to a household that does not have Internet access. This is the key feature of the proposed work, and it makes the proposed system affordable to a wide population. Finally, the proposed system can enable MGs to scale greater heights in the energy sector through the penetration of RES. The work can be further extended to develop self-healing fault-free resilient MGs as well as improve the energy efficiency of IoT devices employed in remote locations. Further research can be conducted in enhancing the communication capability of smart devices, which would enhance the intelligence of two-way communication. Another focus area of research could be to enhance the security features of the SEMs in order to safeguard the user Privacy, Authentication, and Authorization features. These security measures and features could prevent cyberattacks on smart MGs. Thus, the current paper provides a solid base for future developments toward the full implementation of SEMs into MGs of developing countries.

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