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Cost-Effective Design of IoT-Based Smart Household Distribution System

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Abstract: The Internet of Things (IoT) plays an indispensable role in present-day household electricity management. Nevertheless, practical development of cost-effective intelligent condition monitoring, protection, and control techniques for household distribution systems is still a challenging task. This paper is taking one step forward into a practical implementation of such techniques by developing an IoT Smart Household Distribution Board (ISHDB) to monitor and control various household smart appliances. The main function of the developed ISHDB is collecting and storing voltage, current, and power data and presenting them in a user-friendly way. The performance of the developed system is investigated under various residential electrical loads of different energy consumption profiles. In this regard, an Arduino-based working prototype is employed to gather the collected data into the ThingSpeak cloud through a Wi-Fi medium. Blynk mobile application is also implemented to facilitate real-time monitoring by individual consumers. Microprocessor technology is adopted to automate the process, and reduce hardware size and cost. Experimental results show that the developed system can be used effectively for real-time home energy management. It can also be used to detect any abnormal performance of the electrical appliances in real-time through monitoring their individual current and voltage waveforms. A comparison of the developed system and other existing techniques reveals the superiority of the proposed method in terms of the implementation cost and execution time.

Keywords: internet of things; smart household distribution board; smart appliances; condition monitoring; energy management

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1. Introduction

Worldwide energy demand has been significantly augmented over the last few years due to the increased population and rapid industrial advancement. As such, renewable energy sources have been widely employed at both industry and residential levels [1,2]. As a result, the traditional consumer market has been changed into prosumer-oriented market [3,4]. Thus, developing smart home systems to monitor and manage electrical energy has become essential [5]. Although a number of scholarly articles on the development of smart home systems have been published in the literature, developing a cost-effective prototype for the distribution board has not been given much attention. For instance, renewable energy-based smart home energy management system (HEMS) is presented in [6] to optimize the power generation and consumption. In [7], an internet of things (IoT)-related smart meter is explored to support voltage control strategies within the low voltage distribution system of 30 smart homes. Although the simulation analysis shows good performance, the proposed methodology can be only used to improve the user-friendly conditions.

An HEMS is proposed in [8,9] using dint of Bluetooth low energy and MATLAB simulation tool. However, wireless network is highly recommended over Bluetooth for real-world applications. To decrease the influence of wireless interference and unnecessary energy consumption, a smart home control network is presented in [10]. Although wireless sensors and power line communication are developed in this study, the system is implemented to manage lighting load only with a relatively high cost.

The Internet of Things technology facilitates power networks to analyse collected data, monitor power consumption, and enhance the energy efficiency [11–13]. The artificial intelligence (AI) aided IoT-Edge data is analysed in [14] for node-computing algorithm and storage mechanism comprising of tight coupling computation. Moreover, internet aided intelligent things are presented in [15] as an application for Melanoma cancer. A low-cost long range (LoRa) method is presented for smart home indoor localization to acquaint the advantages of IoT systems [16]. However, the accuracy of the LoRa method is potentially uncertain. The reliability and security of home IoT components are discussed in [17] via machine learning procedures.

Moreover, a web-based smart meter has been introduced in [18] for a wide-range of smart home systems applications. A hardware prototype is designed with the Arduino interfacing ESP8266 Wi-Fi module. To automate the smart home systems, several individual components such as Arduino Uno, ESP8266, and XBee are utilized in [19]. An android mobile application is suggested for the industrialization despite the exploration of the high speedy ThingSpeak website. In this concern, IoT-based domestic appliances are denoted in [20] using the ThingSpeak cloud. Besides, the Blynk application is explored in [21,22] as a user-friendly segment by means of Wi-Fi scheme.

2. Related Work in the Literature

A practical study on system-level aspects of IoT along with its emerging applications have been presented in [23]. In this study, the architecture and system-level issues of IoT are summarized to advance more progressive real-life IoT applications. The IoT technology is used in [24] to monitor the battery health condition through measuring some parameters such as temperature, humidity, voltage, and current. The ESP8266 Wi-Fi module is employed to observe the status of the investigated battery in real-time. This condition-based monitoring technique is very useful to enhance the battery's efficiency and elongate its operational life. Advancement in smartphone technology has facilitated monitoring the performance of various smart appliances in real-time [25].

Based on IoT, a Self-Learning Home Management System (SHMS) is proposed in [26] to manage the energy consumption. Three management systems have been considered in this research including home energy, demand side, and supply side. However, the cost of the proposed working prototype is relatively high. Monitoring a smart home energy performance with the integration of IoT is presented in [27]. Towards incorporating a smart home energy management in the cloud-centric solution based on IoT, a holistic architecture is proposed in this study. A smart home system with the help of Web-of-Objects in addition to cloud architecture is presented in [28]. The proposed system can be controlled from anywhere and the collected data can be stored in the cloud. The designed system is performed in three individual steps. A water-tank and autonomous door security is controlled by the developed system to diminish the human interference and secure the access to home devices.

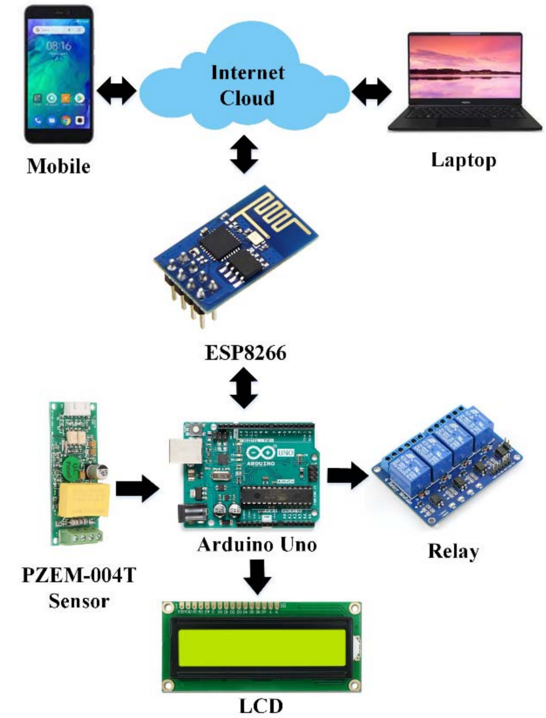
Table 1 summarizes the focus of the most recent papers in this area of research along with the focus of this paper. From the above discussion and Table 1, it can be concluded that a proper design of internet aided hardware prototype is crucial for individual users to effectively monitor the condition and performance of household appliances in real-time from anywhere. Hence, the main goal of this paper is to identify the characteristics of the smart household monitoring system associated with IoT facility. In this regard, a cost effective IoT smart household distribution board (ISHDB) is designed to visualize the consumption of the electricity and store the data into the ThingSpeak website. Additionally, the Blynk mobile application is employed to monitor the condition of various appliances by individual users in real-time.

Table 1. Survey on literature reviews.

Year	Reference	Focus
2016	[29]	Monitor indoor appliances by ZigBee without actual implementation
2016	[30]	Indoor energy management by Bluetooth of a short range coverage
2017	[31]	Monitor indoor appliances by Bluetooth of a short range coverage
2018	[32]	Monitor home temperature and humidity
2020	[33]	Monitor home appliances by IoT
2021	[34]	IoT-aided home energy management
2021	Proposed model	IoT-based smart household distribution board design

3. System Concept

Cost effectiveness and easy installation are essential features to make any model competitive in the global market for home applications. In this paper, a schematic overview of the proposed low cost ISHDB system as shown in Figure 1a is proposed to hold such features [35–37]. The system consists of two core modules, namely a) a hardware interface module and b) a software communication module. An Arduino Uno microcontroller is settled at the heart of the system to interface an IoT website and the hardware module. All of the communication and controls of this system are passing over the microcontroller. The IoT based system records various data including voltage (V), current (I), and power (P) from the definite segments. These data can be displayed on a liquid crystal display (LCD) screen, web server, and mobile application. The data restrained by the sensors are explored in the control system which perceives the consumption of the household loads and disconnects any load once the set limit current or power has been surpassed. The entire flowchart of the proposed system is revealed in Figure 1b. In the first step, the proposed IoT-based system receives the V, I, and P data from the measuring sensors. These data can be visualized through LCD display, web server, and mobile application. The calculated power is compared with a predefined value based on the rating of the monitored device. If the measured power exceeds the set limit, the associated relay is activated to disconnect this device; otherwise, the normal operating condition is maintained. The pseudocode of the proposed method is detailed in Figure 1c to understand the implementation of the intended model.



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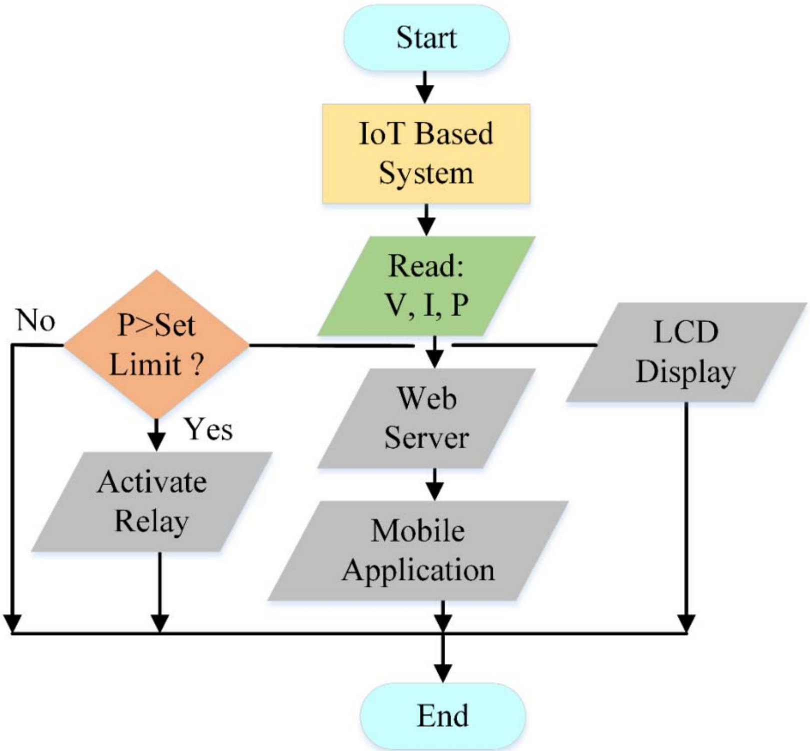


(**b**)

Figure 1. *Cont*.

```
Begin
    Input the IoT based System
    Read the collected data V, I and P from sensors
    Register internet aided web server and display data
    Register internet aided Blynk mobile application and display data
    Display data in LCD module
    If P is greater than set limit value, Then
        Relay is activated
    Else
        Relay is deactivated
    End If
End
```

(**c**)

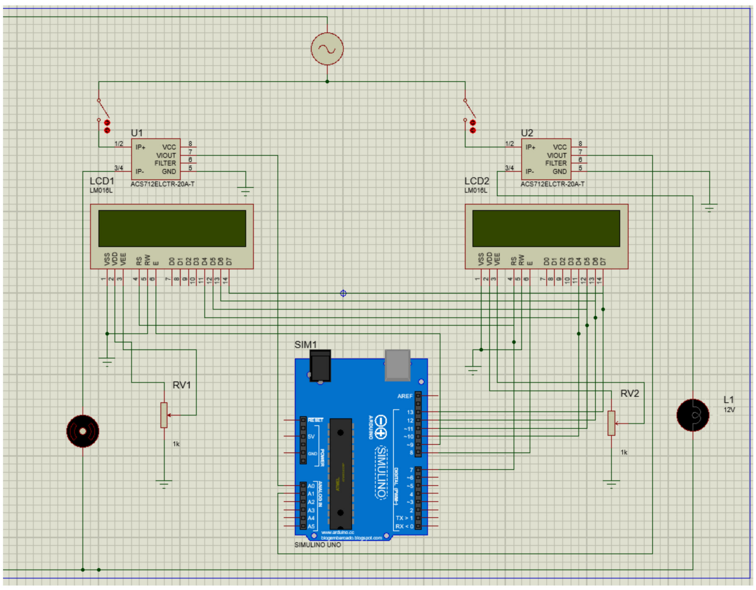
Figure 1. Proposed ISHDB system. (**a**) Schematic overview, (**b**) Flowchart, and (**c**) Pseudocode of the proposed method.

4. System Design

The performance of the proposed ISHDB system is assessed through simulation and experimental analyses. Various software tools such as Proteus, Fritzing, and MATLAB/SIMULINK are used to develop the proposed model.

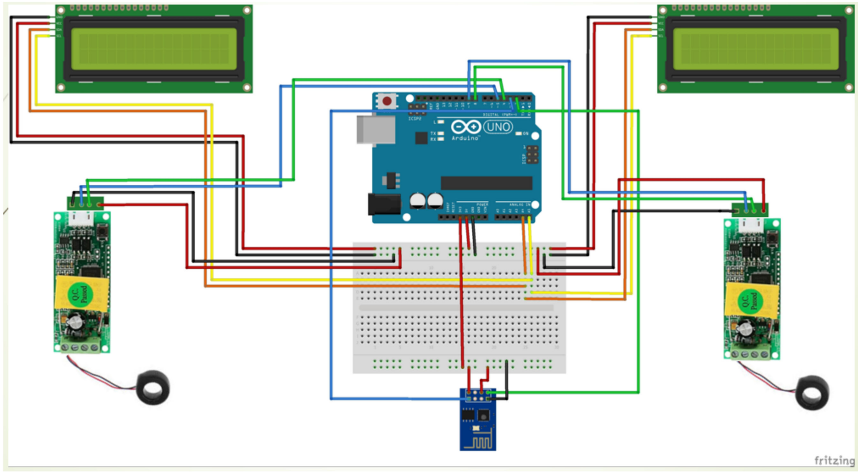
4.1. Simulation Model

The structure of the proposed ISHDB system is firstly developed using Proteus Professional Design Suite software, as shown in Figure 2a. The proposed model consists of AC power supply, Arduino Uno, sensors, two LCD screens, switches, and two different loads. The switches are assumed to mimic the operation of circuit breakers in real applications. The components are linked functionally so that they can operate according to the users' commands. Before developing the hardware prototype and to avoid circuit complexity, the intended model is simulated further using Fritzing software. To get a better realization about the hardware connection configuration, the electronic elements are assembled using a breadboard as shown in Figure 2b.



(**a**)

Figure 2. *Cont.*



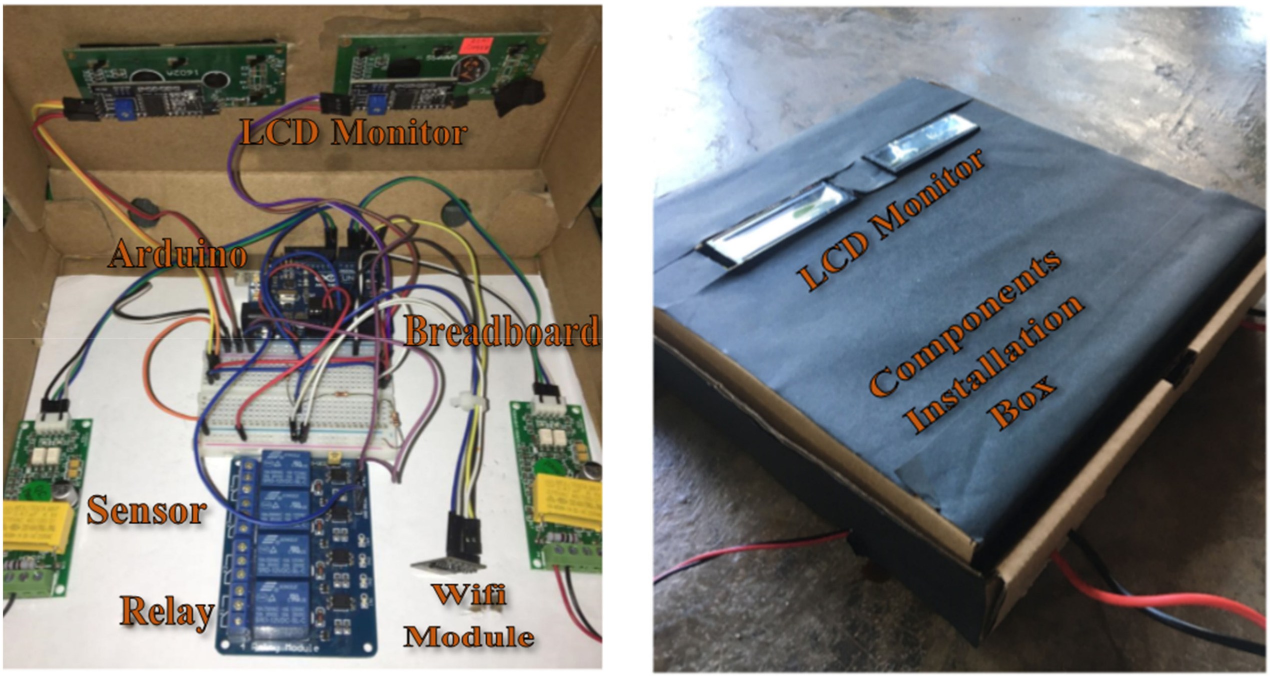
(**b**)

Figure 2. The simulation design of ISHDB in (**a**) Proteus and (**b**) Fritzing software.

4.2. Hardware Development

The hardware of the proposed ISHDB system is developed following the simulation design using Fritzing, Proteus, and Arduino IDE software tools. Figure 3a shows the developed hardware of the IoT-based smart household distribution board system inside a box while Figure 3b displays the outside part of the prototype. From Figure 3b, the consumer can monitor the voltage, current, and power consumption from the LCD screen. The block diagram of the developed hardware is shown in Figure 4. The designed distribution board comprises two lines associated to the house loads. An Arduino Uno is connected with two PZEM-004T sensors, an ESP8266 Wi-Fi module, a relay switch, and two I2C interfacing LCD monitors. To simplify the measurements and improve its accuracy, the method of definite sensor measurement (shunt type) was adopted as recommended by the manufacturers [38]. However, other measurement sensors of a better accuracy can be still used. Several precautions and safety schemes such as circuit breakers (CBs) and fuses are utilized while interfacing the AC power voltages and currents to low voltage electronic components. Although the loads are connected with the Arduino board through sensors, the commanding signal from Arduino switches turns the loads on or off to manage the power consumption.

In other words, the designed system acquaints a local controller which operates according to the power exceeding state. The value of 2 kW is assumed to be a threshold consumption limit in this hardware. As mentioned above, the measured voltage, current, and power data can be displayed on the LCD screen, ThingSpeak cloud, and Blynk mobile application. ThingSpeak cloud is employed in this paper as a medium to store and exhibit the data measured by various sensors. The ESP8266 Wi-Fi module is employed to receive and transmit the data from the sensors to the ThingSpeak web server that requires a sign in account. A channel is generated to visualise the data in the developed website. Albeit the internet speed can be an issue, this particular issue is avoided in this research using a short time span (15 s). In addition, the Blynk application is employed to monitor the usage wirelessly and remotely. The mobile app receives the sensors data through an ESP8266 Wi-fi module.



(a) (b)

Figure 3. Developed ISHDB hardware prototype; (**a**) inside a box and (**b**) outside view.

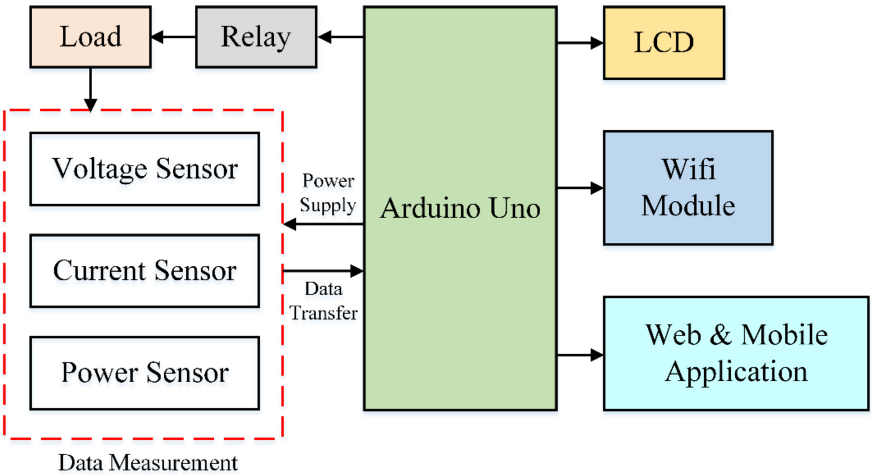


Figure 4. Block diagram of the developed ISHDB system.

4.3. Measurement Accuracy, Safety, and Protection Precautions

To comply with the safety regulations of the buildings equipped with ISHDB system, residual-current device (RCD) is recommended and is used in the experimental setup. RCD performs tasks similar to the conventional circuit breaker that is able to quickly interrupt the electrical circuit in case of overcurrent situation to prevent serious damages to the ISHDB system and other appliances. In addition to the protection of the experimental prototype using RCD, a 10-A fuse is installed to protect the electronic components such as sensors, LCD monitor, and relay switch. With regards to the measurement accuracy, the collected signals are measured following the manufacturing recommendations. Within the specifications of working voltage 80~260 VAC, current range 0–100 A, rated power 22 kW, and operating frequency 45–65 Hz, the measuring accuracy is 1.0 grade [39].

4.4. Cost Estimation

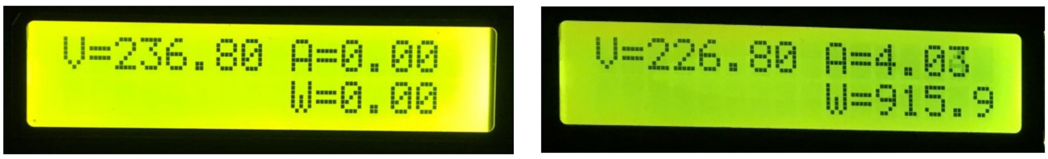
The proposed ISHDB system is not only technically sound, but it is also cost-effective for the household applications. Despite several research papers published in the literature on the IoT-based smart HEMS [6,7,26,40,41], a detailed investigation of ISHDB prototype accompanied by an estimation of the implementation cost is barely provided. To estimate the cost of the working prototype precisely, several factors such as features of the used components, number of the electricity lines, and the nature and number of loads that it can manage have to be considered. Considering these aspects, the estimation cost of the complete prototype developed in this paper is about US $100. This is a low-cost product when compared with conventional ISHDB systems. The technical performance of the developed ISHDB system is investigated under various domestic electrical loads of different energy consumption profiles, as will be elaborated below.

5. Results and Discussions

The records of the proposed ISHDB system can be visualized through LCD screen, ThingSpeak website, and Blynk mobile application displays. The obtained results are reckoned in two individual parts for without IoT and with IoT factors, as discussed below:

5.1. Performance of ISHDB with and without Loads

The proposed ISHDB model has been tested with several household electrical appliances including fan, television, garment steamer, iron, and toaster. The purpose of the testing was to evaluate the accuracy of the designed system. The selected household electrical appliances were tested for some periods during which the voltage, current, and power consumption were recorded. The operating voltage for all of the tested household appliances was kept within the range 220 V to 240 V. The measurement is displayed on the LCD as shown in Figure 5a without load in which there is no current and power consumption, and in Figure 5b with a 915.9 W connected load. The detailed results for various tested loads are presented below.



(**a**) (**b**)

Figure 5. Measured data (**a**) without and (**b**) with connected load.

The current and power profiles of a standing fan of a 55-W rated power are shown in Figure 6a for five minutes in which the current was being constant at 0.223 A. The speed of the fan was changed during the tested period which resulted in a change to the power consumption in the range of 50.1 W to 49.7 W. Figure 6b shows the results for a 105-W television (TV) with a 0.299-A constant current. The results reveal that the power consumption of the TV is within the range 65.80 W to 66.10 W. In the standby mode, the TV consumes about 0.5 W. Although the reading of the initial power consumed by the TV was about 99 W, it reduced after a few seconds to 66 W. The power consumed by a garment steamer was in the range 1780~1795 W as shown in Figure 6c. Moreover, the current fluctuated in the range 8.009 A to 8.069 A in two minutes. In this regard, the power was cut off for 10 s twice during this interval to maintain the temperature of the steamer following the change in the current profile.

The results for the 1000-W iron and 800-W toaster are shown in Figure 6d,e, respectively. In both cases, the power was automatically turned off for the last 10 s. For the tested iron, the power changed within the range 932 W to 915 W during the first 100 s. In contrast, the toaster took nearly 1 min and 50 s to toast two slices of bread with a power changing in the range 706.2 W and 698.6 W. The decreased reading may be attributed to an error within the appliance. The simulated AC voltage density is shown in Figure 7a while Figure 7b depicts the pure AC voltage signal. Nevertheless, for the low powered applications such as mobile phone or laptop charger and a small fan, the experimental result of the modified AC sine wave is as shown in Figure 7c.

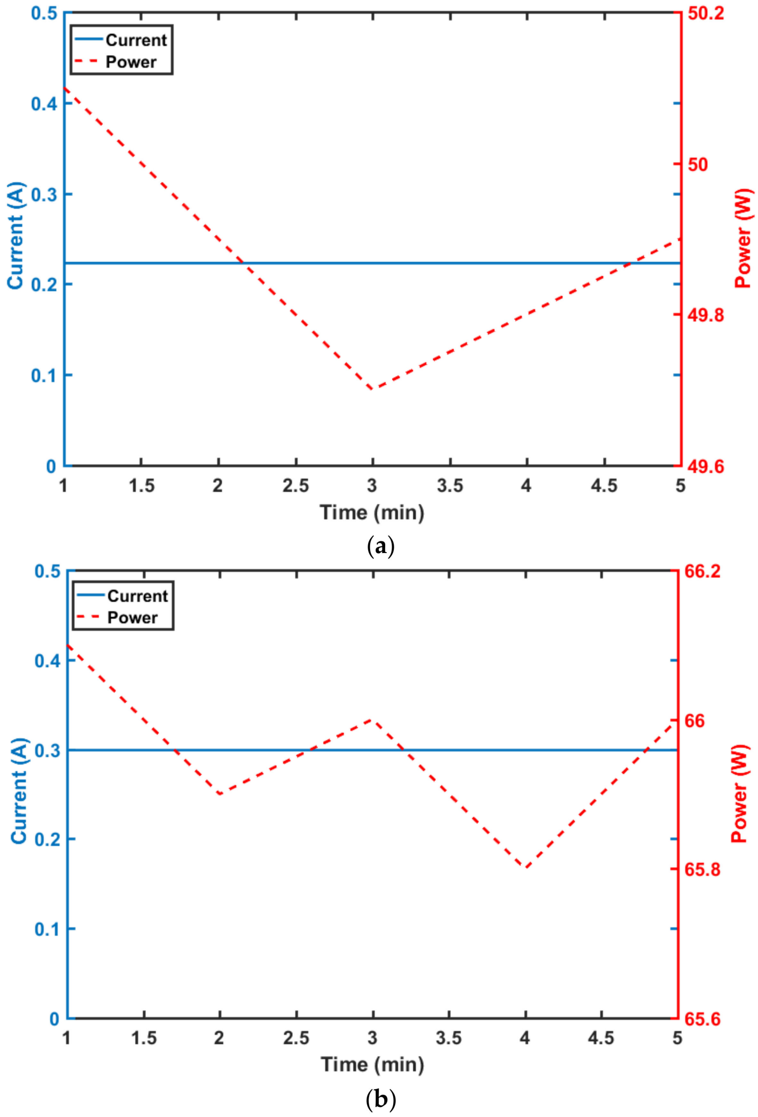
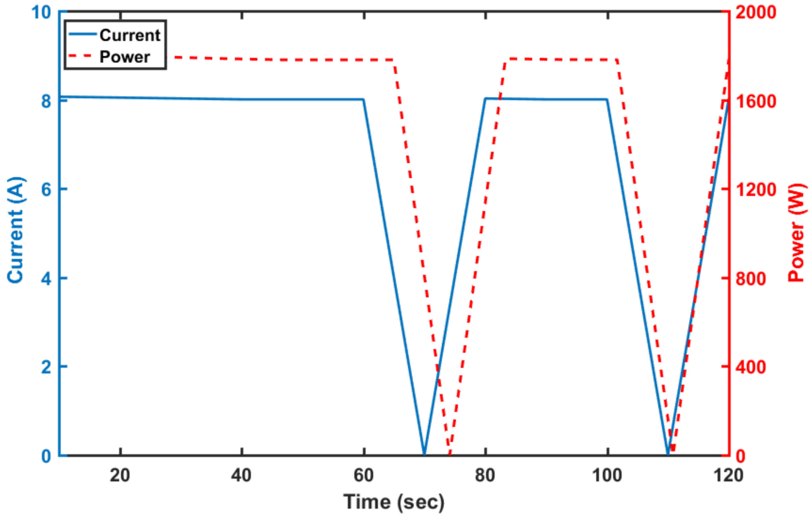


Figure 6. *Cont.*



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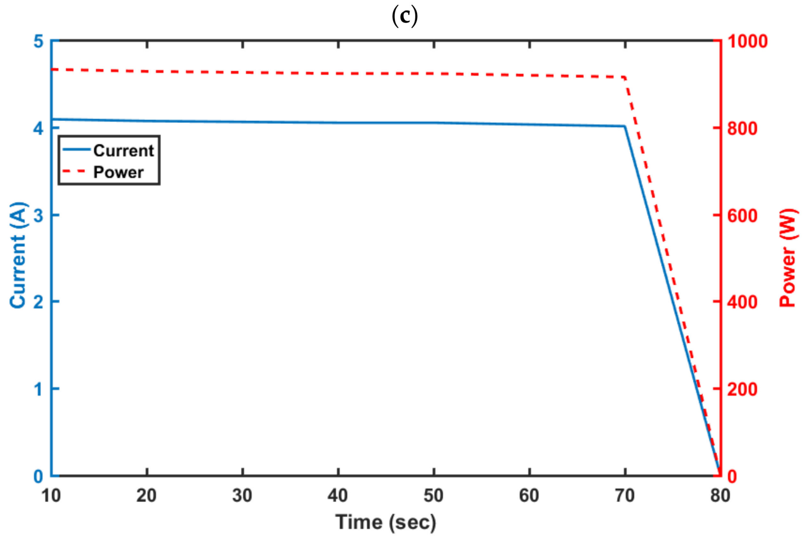

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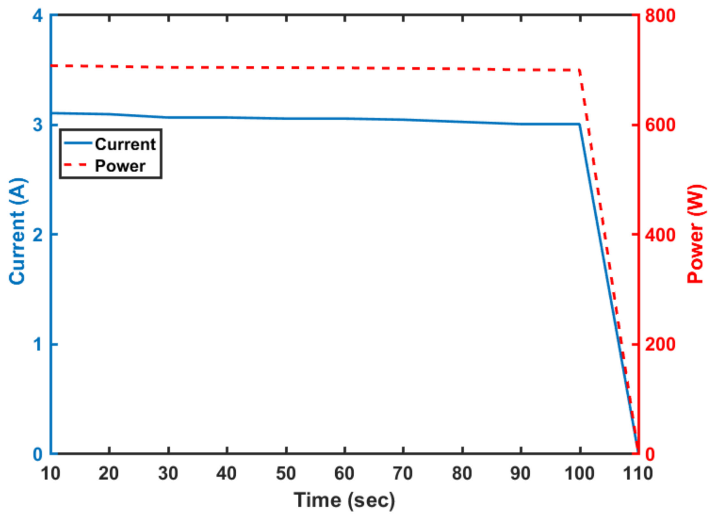
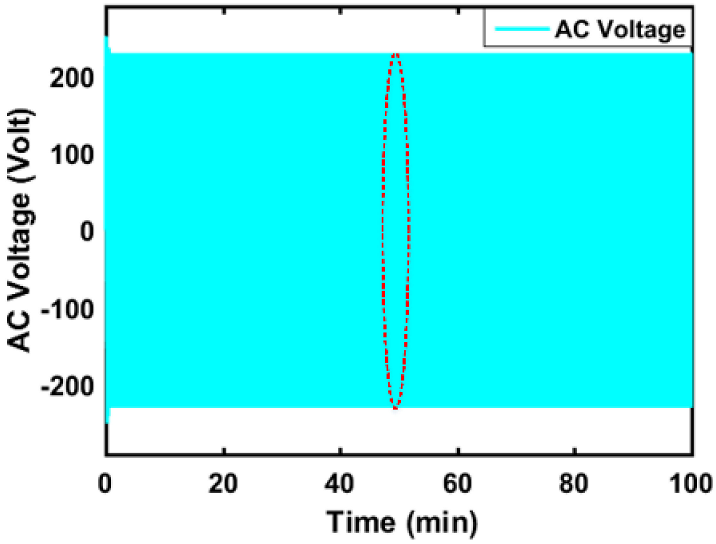


(**e**)

Figure 6. Experimental results for a (**a**) 55-W standing fan, (**b**) 105-W TV, (**c**) 1800-W garment steamer, (**d**) 1000-W iron, and (**e**) 800-W roaster.



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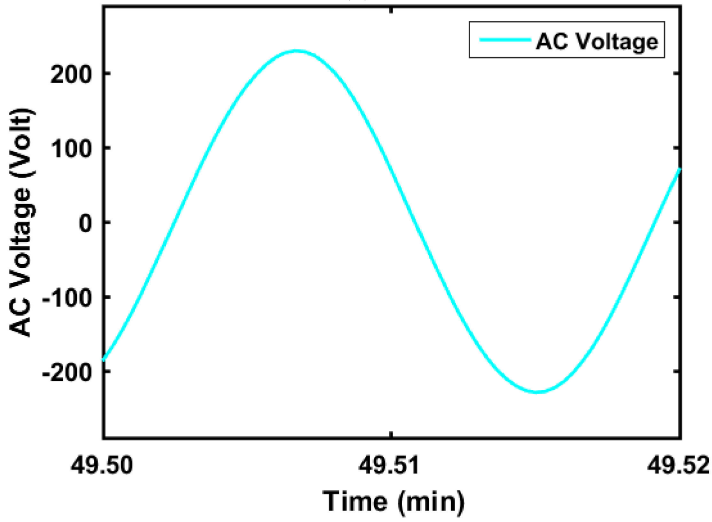

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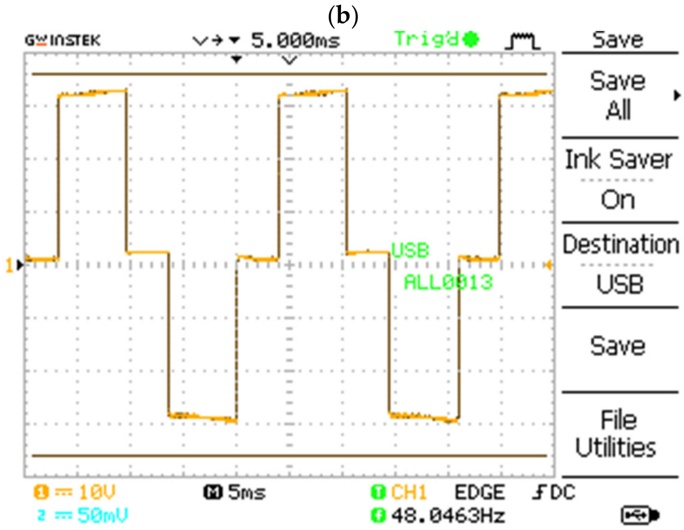


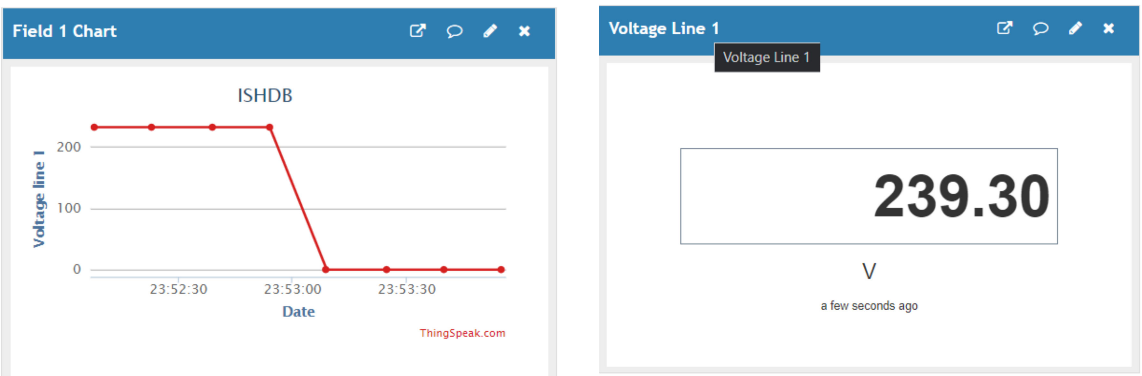
(**c**)

Figure 7. (**a**) AC voltage density, (**b**) Pure AC sine wave, and (**c**) Modified AC sine wave view on Oscilloscope.

5.2. ISHDB Tested with IoT Implementation

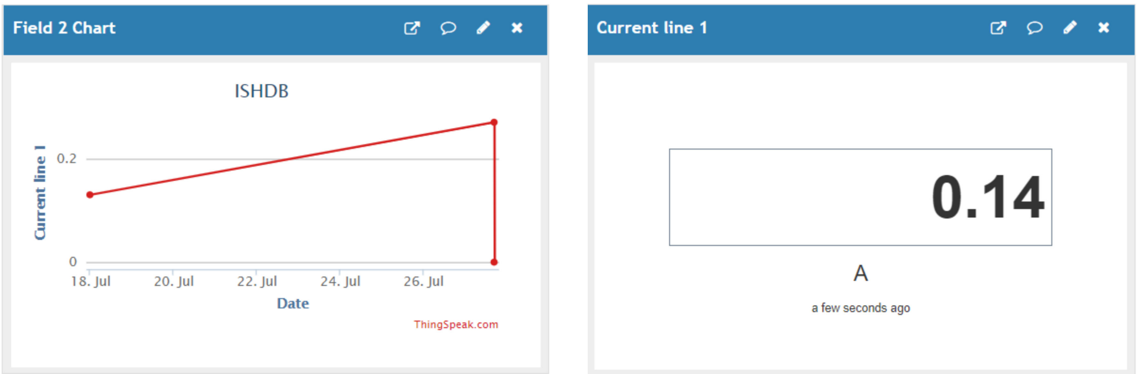
In the ThingSpeak-based web system, six field data have been proposed in the ThingSpeak channel. This includes: voltage line1 (field 1), current line 1 (field 2), power line 1 (field 3), voltage line 2 (field 4), current line 2 (field 5), and power line 2 (field 6). The channel status as shown in the web server was collected as revealed in Figure 8 and stored in the cloud. The channel was updated every minute to display each of the above six fields graphically and numerically as shown in Figure 8a–f. Additionally, in order to facilitate a user-friendly interface, a Blynk application has been developed. In this regard, Blynk project (ISHDB) accompanied by data screening (LCD) was created as shown in Figure 9a. Data of two fields (lines 1 and 2) are displayed in Figure 9b. These results demonstrate the effectiveness of the proposed method which is easy to implement for existing household systems. The proposed system was compared with other existing methods as shown in Table 2 to reveal the effectiveness of the developed ISHDB model. Compared to the several number of research papers on the IoT aided smart home applications, the proposed model in this paper shows superiority in terms of lowest cost and time-span.

The proposed method can also be used in renewable energy dependent devices as well as energy conversion systems [42–50]. It can also be adapted to monitor the condition of critical high voltage assets, power converters, and various flexible ac transmission system devices [51–54]. It is worth mentioning that the experimental measurements in this paper were conducted under ideal conditions in which signal noise and harmonic levels were not substantial. To facilitate the proposed system to function under highly polluted waveforms, a digital noise elimination technique such as the methods presented in [55–57] can be adopted. Moreover, the performance of the measurement sensors and other components involved in the system must be checked and calibrated regularly to detect any incipient malfunction and rectify it in a timely manner [58,59].



(a)

Figure 8. *Cont.*



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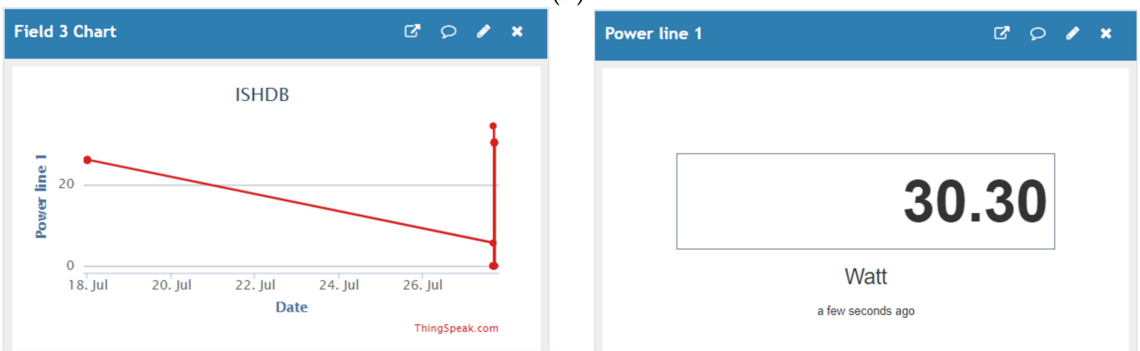

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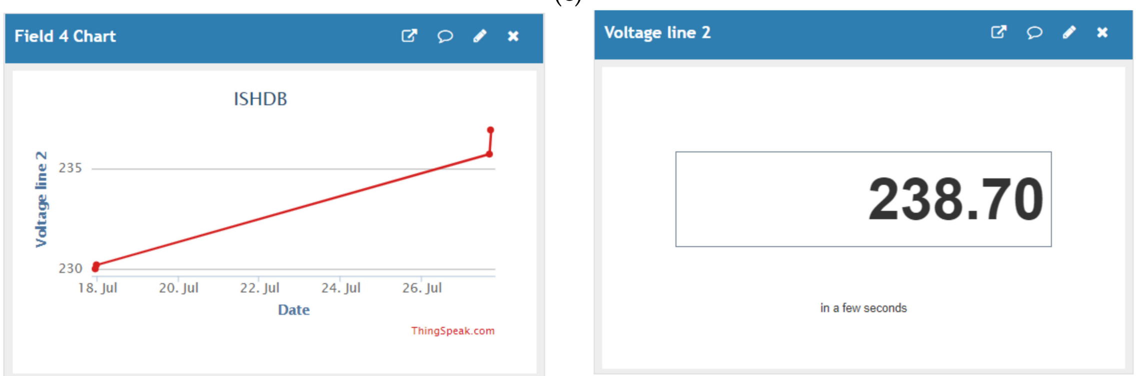

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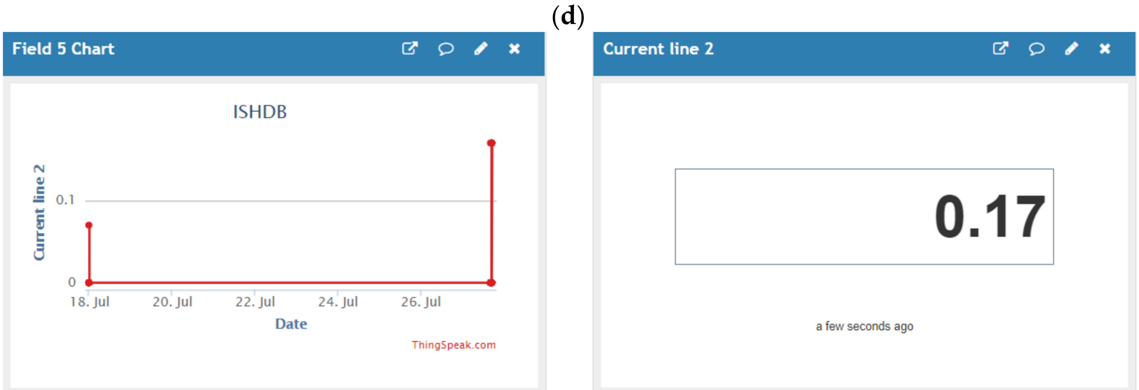
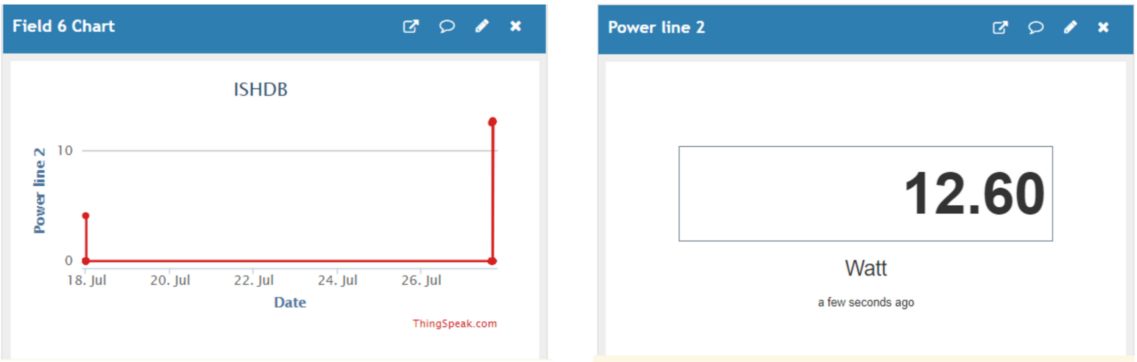


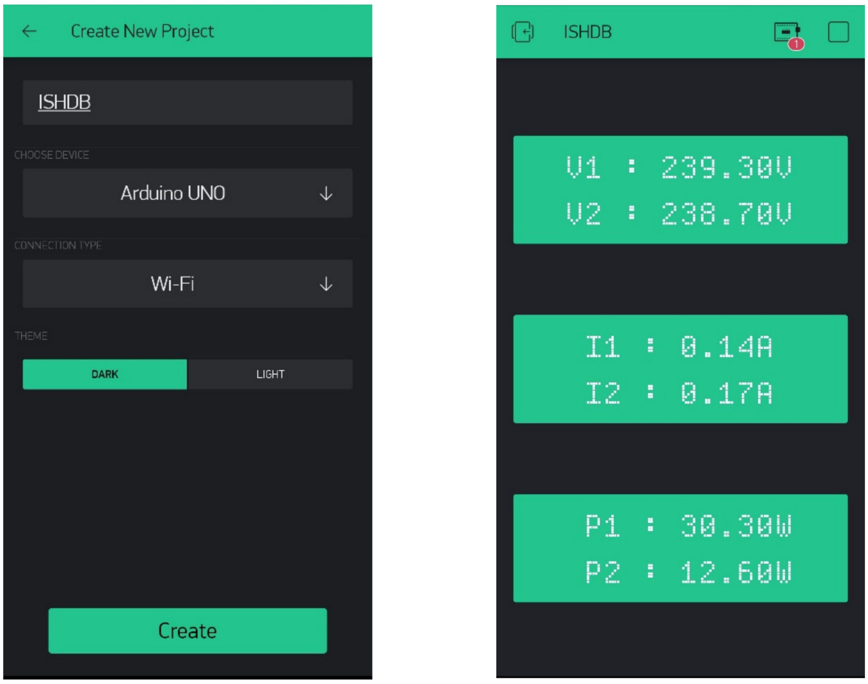
(**e**)

Figure 8. *Cont.*



(**f**)

Figure 8. (**a**) Voltage of line 1 in field 1, (**b**) Current of line 1 in field 2, (**c**) Power of line 1 in field 3, (**d**) Voltage of line 2 in field 4, (**e**) Current of line 2 in field 5, and (**f**) Power of line 2 in field 6.



(**a**) (**b**)

Figure 9. (**a**) Creating a new project in Blynk apps; (**b**) Complete visualisation of ISHDB parameters.

Table 2. Comparison of the proposed method with other existing techniques.

Reference	Year	Communication	Controller	User Interface	Applications	Time Span (s)	Cost (US $)
[60]	2018	Wi-Fi	NodeMCU	Web-Based, Mobile App	Home appliances monitoring	-	-
[61]	2019	Wi-Fi	NodeMCU	Web-Based	Control indoor appliances	-	-
[33]	2020	GSM	Raspberry PI, GSM Module	GUI-based, Mobile App	Home appliances monitoring	30	-
[34]	2021	Wi-Fi	Raspberry PI, ESP8266	Web-Based, Mobile App	Home security, energy management monitoring	15	140
Proposed Model in this paper	2021	Wi-Fi	Arduino, ESP8266	Web-Based, Mobile App	Home appliances monitoring, energy management	15	100

6. Conclusions

As the current residential homes are equipped with various smart appliances, energy management of such devices has become essential. An IoT-based smart household distribution board to monitor the performance of these appliances was developed in this study. The developed board can accurately monitor the current, voltage, and power consumption of several household appliances. Communication through Wi-Fi module has been presented where the measured data can be displayed on LCD, ThingSpeak web server, and Blynk mobile application. The complete prototype of the ISHDB was successfully developed and tested with some household appliances. The main conclusions of the experimental measurements can be summarized as below:

- The graphical view through the ThingSpeak web server and the numerical data displayed on the Blynk apps are identical. Thus, the results confirm that the proposed system satisfies crucial requirements of calibration, accuracy, and communication.
- The developed hardware can monitor the usage of electricity based on IoT and control the limit of power consumption. This feature enables users to monitor their appliances and promotes awareness on electricity consumption.
- The proposed ISHDB is cost effective and is of small time-span relevance that enables it to provide good technical performance.

Further research is required to extend the application of the proposed system for additional functionalities such as IoT-aided AI methods for security purposes.

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