Design and Implementation of an IoT-Enabled Smart Plug Socket for Home Energy Management

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***Abstract*—This paper proposes an Internet of Thing (IoT)-enabled smart plug socket (SPS) to monitor and control energy consumption in a home/building energy management system. The device can wirelessly transmit data to a home energy management (HEM) controller. Additionally, the transmitted data can visualize, store, and analyze through the connected web server and smartphone. A customized android application is developed to interface the proposed SPS with the webserver and smartphone. According to experimental results, the proposed SPS can correctly interpret the power usage of wirelessly attached devices from anywhere without data loss. The proposed system has experimented with for 40-minute in the laboratory. The experiment shows an energy consumption of 0.124 kWh with an electricity bill of 0.697 RM. As a result, with the correct scheduling algorithm, the suggested smart socket framework can be utilized entirely in a home energy management system.**

Keywords*—*home energy management system (HEMS), smart plug, smart socket, internet of things (IoT), ESP32

I. Introduction

A smart plug (SP) is becoming more relevant to smarten daily life, reducing energy consumption. It is an electronic device that allows consumers to interface with their electrical appliances and control them remotely [1]–[3]. Furthermore, the SP monitors the power usage of electrical appliances. Several smart plug systems have been introduced in recent years, such as the OMG and Wi-Fi kamkunit. SP's can enable/disable an electrical appliance via 3G/Wi-Fi. They are also compliant with Android and iOS [4]. However, these SPs cannot calculate the power usage of the electrical appliance and can automatically detach a smartphone from electricity when completely charged [5]. As a result, several researchers attempt to include this function as a primary criterion. Authors [6] suggested an Arduino-based smart plug for monitoring electrical appliances power usage. In the SP design, the current transformer (CT) is a vital instrument in data acquisition since it measures current. The Ethernet module (ENC28J60) is often used to link the smart plug to the node. Users can gain access to such data on the server by utilizing a particular Android program. In a nutshell, SP can send data to a server. On the Arduino-Android network [7], it can be used to control and track power usage remotely. Reference [8] introduces smart plugs for building energy control systems (BEMs) that can sense the various type of appliances, their capabilities and assess energy usage.

It provides a mechanism used to manage at home systems by monitoring and controlling energy consumption effectively. Consequently, it has a beneficial impact when regulating the potential of energy use [9]. Their study suggests an SP that communicates using the ZigBee protocol. It can track an electric appliances voltage, current, water, and power usage record. Their smart plug transmits data to the HEM device. It manages and reduces peak demand at home using info. Author [1] presents wireless sockets and central control systems regulated by the Zigbee protocol to monitor energy consumption. According to experimental findings, the proposed smart socket interprets the power usage of wirelessly attached devices from up to 18 m away without data loss. As a result, with the correct scheduling algorithm, the suggested smart socket framework can be completely utilized in a home energy management system.

The authors in [10] suggest the smart socket, which employs a hardware and software arrangement in an automotive module. Their plug module connects to each injector and electronically monitor them from the Engine Control Unit (ECU). To connect and monitor their GUI, they use a serial port. On a laptop or desktop, the user will control RPM (Frequency) and issue commands for acceleration enrichment, among other things. All relevant studies have established smart plugs that are practical in usability for each study [11]–[13]. This paper would recommend a Wi-Fi smart plug socket with simplified components that can track and control power usage on WebApp smartphones (i.e. smartphone, iPad, laptop, etc.). The smart plug is driven by the ESP32 microcontroller, which includes a Wi-Fi module and a microcontroller [14]. The remainder of the paper is organized as follows. Section 2 of the paper presents the proposed system design. Section 3 discusses the prototype of the smart plugs

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with the experimental setup. Section 4 discusses the results are found from the experiments. Finally, the article is concluded in Section 5.

II. Proposed System Design

The smart plug socket (SPS) is intended to be connected to a home access point or Wi-Fi network. Fig. 1 shows the schematic diagram of the proposed SPS. Wires are connected with three distinct colors. The red color wire indicates the line voltage of 220 V. The light blue color indicates the 5 V DC voltage. The purple color line indicates the data communication lines; double arrow means double way communication. Line voltage is directly connected to the 10 A, 250 VAC relay modules, followed by a 30 W incandescent light bulb. The Wi-Fi module ESP32 is powering by the 5 V DC from the relay and can communicate both ways to the ZMPT101B voltage source (VS) and the ACS712 current source (CS).

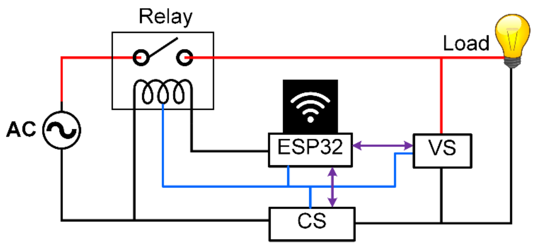


Fig. 1. Schematic diagram of the proposed smart plug socket.

III. Prototype and Experimental Setup

The proposed framework of the SPS comprises two main components: hardware and software—all the steps, equipment used in the SPS, and the experimental setup is shown in Fig. 2. There are three essential parts to this process: the relay module, a Wi-Fi unit, the voltage sensor, and the current sensor, each of which plays a vital role in carrying out its tasks. The software part includes coding at the microcontroller and developed a customized android application to set up the IoT connection.

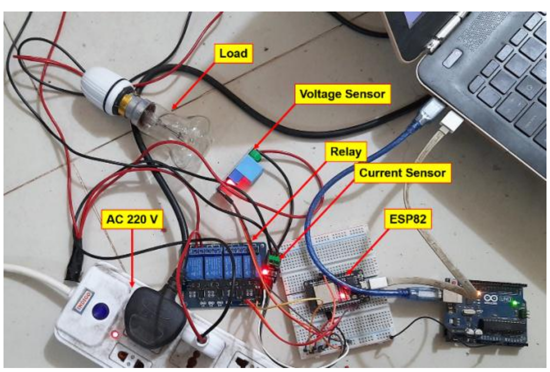


Fig. 2. Experimental setup of the proposed SPS prototype testing.

A. *Hardware Part*

The 220 V AC line voltage is connected to the relay. A relay is an electromechanical system that uses an electric current to open or close switch contacts. It includes modules that simplify the switching process, connects and serve as markers for the modules power status and whether the relay is active. In this experiment, a relay breakout board with 4-channels of 5V is used. The activation of this relay is capable controlling of 250 V AC line voltage at 10 A current. An optocoupler provides extra isolation at the controls front end, and the triggering logic for each channel is configurable by a mini jumper. Each relay may be set to activate at a high voltage of 5 V or a low voltage of 0 V. The ESP32 will act as a stand-alone machine or a slave computer to a host microcontroller unit (MCU), reducing connectivity stack overhead on the main application processor. This device can communicate with other systems to provide Wi-Fi and Bluetooth capabilities via the SPI/SDIO or I2C/UART interfaces. It operates safely in manufacturing conditions with a temperature range of –40°C to +125°C. ESP32 is equipped with specialized calibration circuitries, can automatically eliminate external circuit imperfections and adapt to changing external circumstances. ESP32 is a low-power microcontroller designed for handheld devices, portable electronics, and Internet of Things (IoT) applications [15]. It manages this low power usage by a mixture of many forms of proprietary software. The ESP32 incorporates cutting-edge technologies such as fine-grained clock gating, several power modes, and progressive power scaling. The ZMPT101B voltage sensor is an ideal device for measuring alternating current voltage. It has high precision and durability for measuring voltage and strength up to 250V AC. It is simple to use and includes a multi-turn trim potentiometer for tuning the ADC performance. The ACS712 current sensor [16] is a completely designed linear current sensor built on the hall effect with 2.1 kV RMS isolation and an integrated low-resistance current conductor. Current flows via the onboard hall sensor circuit contained inside its integrated circuit. The hall effect sensor senses incoming current by generating a magnetic field. As a hall effect sensor is sensed, it produces a voltage equal to the magnetic field, which is then used to determine the current.

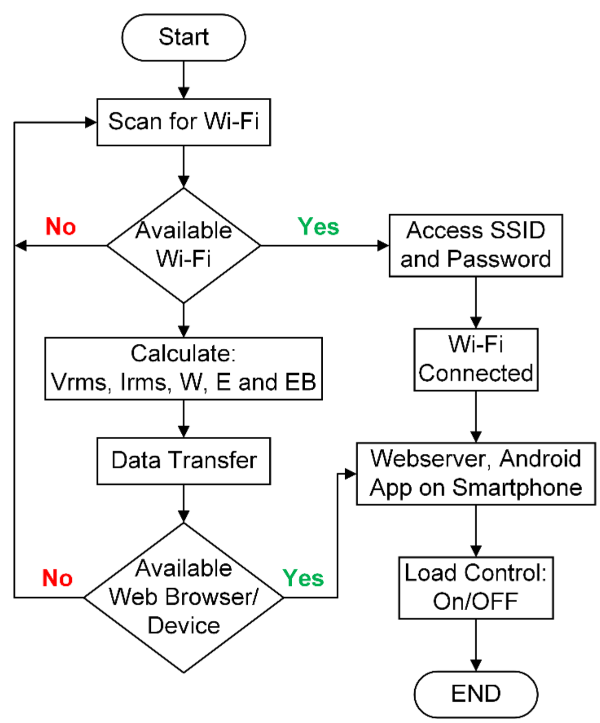


Fig. 3. Flowchart of the proposed SPS data processing steps.

B. Software Part

The software part is divided into two sections, (i) coding for electrical parameters and (ii) coding for IoT connection. Section (i) includes the coding to measure the electrical parameters of AC voltage (V), current (A), Power (W), Energy (kWh) and the electricity bill (unit/RM). The complete process of the software part can be presented by the flowchart shown in Fig. 3. Once the plug is connected to the line voltage, it will start to work. First, the system initializes and start to scan the available Wi-Fi network. If the desired Wi-Fi network is found, the owner has to use the required SSID and Password. Thus the SP will be connected to the Wi-Fi network. Now the webserver and smartphone App will be interfaced with the system. In the meantime, the system will start to calculate the voltage (Vrms), current (Irms), Power (W), Energy (kWh) and Electricity bill (EB) per unit in Malaysian Ringgit (RM) across a respective load.

The RMS value is measured by the equation (1) [17], where sensitivity is the variation in sensor output in reaction to 1A current change across the primary conductor,

$$I_{rms} = \frac{\sqrt{measured\ current\ sample} \times Sensitivity}{Analog\ to\ Digital\ Conversion \times V_{ref}} \tag{1}$$

The power is calculated by equation (2), where V is the operating voltage.

$$P = V \times I_{rms} \tag{2}$$

Total energy (kWh) is calculated by the equation (3),

$$kWh = \frac{Power\ (W) \times Hours\ of\ Operation \times 30\ days}{1000} \tag{3}$$

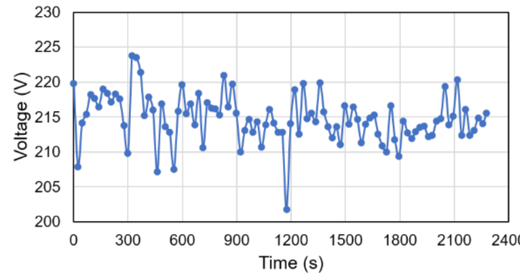
The electricity bill is calculated by the equation below,

$$EB = Energy\ (kWh) \times rate\ per\ unit\ (RM) \tag{4}$$

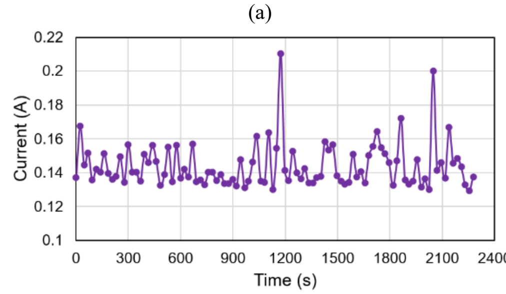
Once the measurements are complete, the system will search for an available device or web browser to transfer the data. If any connected device is available, the data will be transferred to that device or web browser. Finally, the connected loads can be controlled by smartphone apps.

IV. Result and Discussions

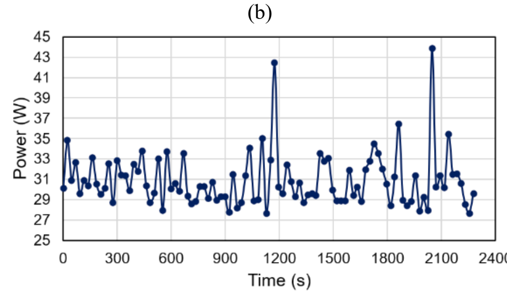
The designed prototype of the SPS is evaluated on a 220 V AC line voltage and 50 Hz frequency. A total of 2,400 s time has experimented with the prototype. Fig. 4 shows the graphs of different characteristics curves of the electrical parameters captured from the ThingSpeak channel through IoT connected webserver. In Fig. 4a, the voltage vs time relationship is shown. At the beginning of the experiment, the voltage-controlled relays ON/OFF moment, the voltage was 220 Volts. Since then, the voltage has been expanding over time, and the reported lowest voltage is 201 V AC, and the highest voltage is 223.81 V. Fig. 4b demonstrates the current vs time characteristics plot. Currents with a minimum of 0.129 A and a maximum of 0.21 A are measured. Maximum power of 43.85 W and a minimum power of 27.67 W is registered. Fig. 4c depicts the strength vs time curve. Fig. 4d depicts total energy vs time. In about 2400 seconds, the energy bill is registered as 0.70 RM. Fig. 4e depicts the bill vs period relationship. The bill seems to be growing linearly over time. Fig. 4a-c shows the opposite nature of the waveforms as we are taking the AC 220 V as a source. In the proposed circuit, no filter is used to reduce the noises in the signals. However, the inverse characteristics do not affect the energy consumption graph shown in Fig. 4d because as long the load is ON, the amount of energy consumption will be increased.



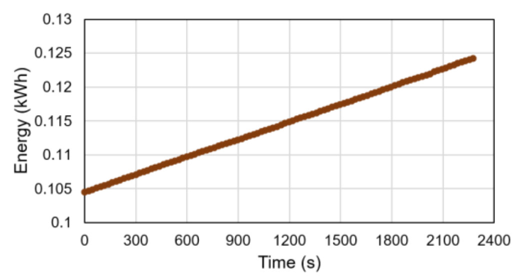
(a)



(b)



(c)



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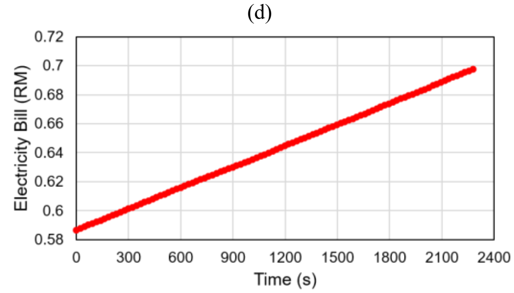
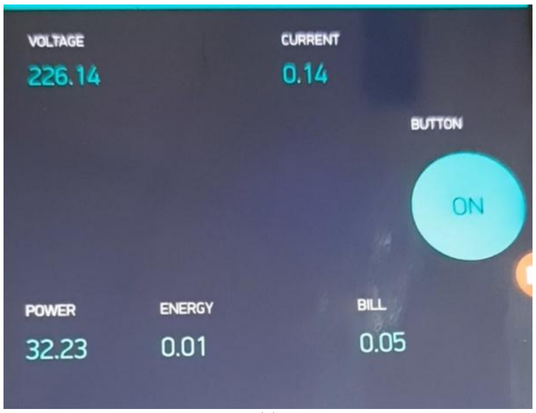


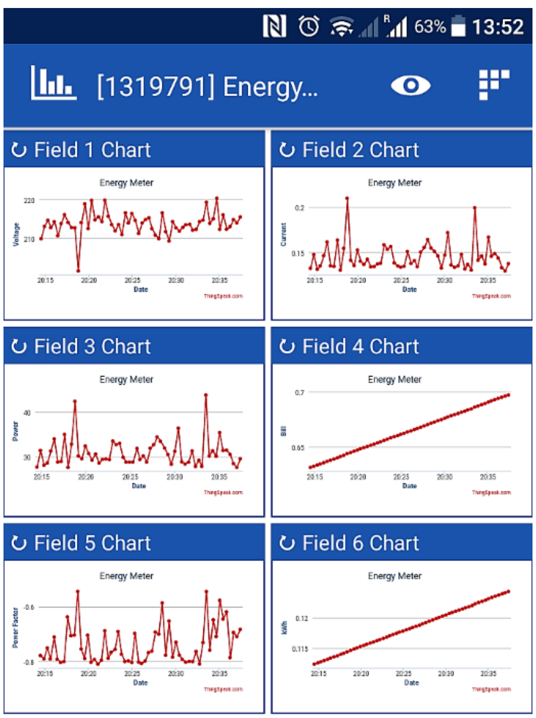
(e)

Fig. 4. Different characteristics curve depicting by ThingSpeak channel (a) Voltage vs time, (b) Current vs time, (c) Power vs time, (d) Energy consumption vs time, and (e) Electricity bill vs time.

Fig. 5 illustrates the IoT functionality of the smart socket. A dashboard for monitoring and managing loads is shown in Fig. 5a. The loads would be regulated by the owner from the dashboard based on the energy bill or other variables. The owner can ON\OFF the loads based on his desire. Here no logics are used to select the ON/OFF timing of the connected load across the SPS. Fig. 5b depicts how the data strings obtained by the Android apps are shown on the mobile screen together. Thingspeak.com is used for cloud service.



(a)



(b)

Fig. 5. (a) Developed customized dashboard on android application, (b) Energy management monitoring on a smartphone through IoT.

V. Conclusion

In this article, the design and implementation of an ESP32 Wi-Fi module based smart plug-socket is presented. Various hardware and software specifications are well clarified. A hardware prototype is designed to monitor and analyze the voltage, current, consumed power, and electricity bills. The proposed device shows the total energy consumption of 0.124 kWh and the total electricity bill of 0.697 RM in a 40-minute laboratory experiment. The experiment demonstrates successful bidirectional connectivity capabilities. The IoT features control the attached electrical appliances remotely from anywhere through the developed customized Android application and web browser. By considering the tested features of the proposed device, the proposed smart plug socket can be easily adopted with home energy management applications.

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