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RESEARCH ARTICLE

Smart Edge Device Utilizing Power Line Communication for Energy Management and Control of Electrical Appliances

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ABSTRACT The integration of intelligent systems in various industries has led to notable advancements in energy resource utilization. Power Line Communication (PLC) is widely used in the power industry for transmitting telemetry, speech, and protective tripping commands. While Wi-Fi has limitations in remote control and monitoring applications due to cost and power consumption, Wireless Sensor Networks (WSNs) face challenges like transmission errors and data losses. Developing a scalable WSN architecture is crucial, especially in the presence of excessive network coverage or non-line-of-sight situations. Challenges persist despite efforts to enhance WSN connectivity, and conflicts with wireless local area networks (WLANs) in the 2.4 GHz ISM band lead to issues like packet losses and interference. To address these issues, the proposal suggests integrating WSN with PLC technology to create a resilient utility network. The research introduces a Master-Slave system using frequency-shift keying (FSK) based PLC modules for effective management and supervision of the intelligent utility network, with scalability for diverse industrial intelligence applications.

INDEX TERMS Energy efficiency, power line communication (PLC), wireless sensor network (WSN), Wi-Fi, smart utility network, master-slave system, FSK modulation, industrial intelligence.

I. INTRODUCTION

Enhancing the energy efficiency of commercial devices is achievable through recent advancements in device management and electronic circuit chipset technologies [1]. However, the current energy crisis underscores the critical need to significantly improve energy management strategies. Industries face pressing challenges such as volatile energy prices, strict emission goals, and escalating operational expenses. Monitoring essential electrical factors like voltage, current, and power usage is crucial. Despite the scalability and flexibility of industries, obtaining precise real-time information on energy consumption remains deficient.

The conventional power consumption billing method faces challenges of inflexibility, unreliability, high costs, slow processing, and inefficiency. Typically, a manual process involves a designated individual reading the energy meter, transmitting data to the distribution unit, and issuing invoices based on consumed units during a billing period. This labor-intensive and time-consuming approach is prone to errors, compromising precision. Moreover, it requires significant time allocation for each client within the distribution network. Efforts are needed to address these inefficiencies and move towards more advanced and accurate energy management systems.

II. LITERATURE REVIEW

Intelligent technology introduces a transformative solution for enterprises to monitor real-time energy usage, especially

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TABLE 1. Comparison of various energy monitoring devices in the literature.

	AMMeter [5]	Acme-A [6]	YoMo [7]	Demo Board [8]	IoT Sensor [9]	MEDAL [10]	YoMoPie [11]	Proposed
Communication	x	ZigBee	Wi-Fi	UART	Wi-Fi	Wi-Fi, Ethernet	Wi-Fi, Ethernet, RF	Wi-Fi, PLC
Measurements	I	P,Q,S	P,Q,S,I,V	I, V	P,I,V	P, I, V, f	P,Q,S,I,V	P,Q,S,I,V
Sampling Frequency	1 Hz	1 Hz	1 Hz	14 kHz	x	50 kHz	10 Hz	10 Hz
Power Calculation	software	hardware	hardware	hardware	hardware	software	hardware	software
Open-Source	yes	yes	yes	yes	no	no	yes	no
Basis	Arduino	x	Arduino	ATmega328p	x	ATmega328PA	Raspberry Pi 3	Node MCU ESP 8266
Cost	Low	Moderate	High	Moderate	Moderate	High	Moderate	Low-Moderate
Integration	Limited	Limited	Moderate	Moderate	Limited	Extensive	Moderate	Extensive
Size	Small	Moderate	Large	Moderate	Small	Moderate	Large	Small
User Interface	Basic	Basic	Advanced	Basic	Basic	Advanced	Advanced	Advanced

during high-demand periods. The integration of the Internet of Things (IoT) enhances accuracy, efficiency, and response times, enabling proactive energy management, operational efficiency, and the adoption of sustainable practices [2], [3], [4].

Table 1 presents a comparison of various energy monitoring devices discussed in the literature. Each device is evaluated based on several criteria, including communication protocol, types of measurements, sampling frequency, power calculation method, open-source availability, and the underlying platform.

Among the communication protocols, ZigBee, Wi-Fi, UART, Ethernet, RF, and Power Line Communication (PLC) are mentioned. These protocols enable the devices to transmit energy-related data to a central monitoring system. Different devices offer varying types of measurements, including current (I), active/reactive/apparent power (P/Q/S), voltage (V), and frequency (f). The sampling frequency ranges from 1 Hz to 50 kHz, indicating the rate at which measurements are taken.

Smart meters utilizing power line connectivity offer remote access, streamlined planning, and reduced energy consumption for devices like radiators and air conditioners [12], [13], [14], [15]. This integration allows precise control over device energy usage during peak demand. Power line communication (PLC) forms the basis for data transmission between consumers and utility suppliers. PLC technology has evolved since the 1920s, now boasting data rates comparable to wired and wireless technologies. PLC classifications include broadband PLC (BB-PLC) and narrowband PLC (NB-PLC), with defined frequency ranges ensuring global compatibility. Based on the table 1 the key features of the proposed system is demonstrated as follows:

1) **Communication Flexibility:** Unlike some existing devices that are limited to specific communication protocols such as ZigBee or Wi-Fi, the proposed system integrates both Wi-Fi and Power Line Communication (PLC) capabilities. This dual communication approach enhances flexibility, ensuring reliable connectivity across diverse environments and offering redundancy in communication channels.
2) **Comprehensive Measurements:** While many existing devices offer a subset of energy-related measurements such as current, voltage, and power, the proposed system supports a comprehensive set of measurements including active power (P), reactive power (Q), apparent power (S), current (I), and voltage (V). This broad range of measurements provides users with detailed insights into energy consumption and power quality, facilitating more informed decision-making and effective energy management.
3) **Sampling Frequency:** The proposed system offers a sampling frequency of 10 Hz, which is comparable to or exceeds the sampling frequencies of existing devices. This high sampling rate ensures accurate and precise data capture, enabling users to capture transient events and fluctuations in energy consumption with greater granularity.
4) **Software-Based Power Calculation:** Unlike some existing devices that rely solely on hardware-based power calculation methods, the proposed system utilizes software-based power calculation algorithms. This software-based approach offers flexibility in algorithm implementation and allows for easier updates and modifications to accommodate evolving energy monitoring requirements and standards.
5) **Hardware Platform:** The proposed system is based on the Node MCU ESP 8266 platform, which offers advantages in terms of cost-effectiveness, low power consumption, and compatibility with a wide range of sensors and peripherals. This choice of hardware platform ensures scalability and ease of integration with existing infrastructure, making it suitable for various deployment scenarios and applications.

Frequency bands allocated for PLC include A-band (3-95 kHz) for low-voltage equipment, B-band (95-125 kHz) for diverse applications, C-band (125-140 kHz) for residential communication, and D-band (140-148.5 kHz) for alarm systems. Standards like X-10, Lon Works, PRIME, and G3-PLC demonstrate advancements, with data rates ranging from 120 bps to 300 kbps. PLC standards' global adoption is emphasized by frequency allocations in North America, Asia, Japan, and Europe, ensuring compatibility and efficient communication.

In the contemporary energy landscape, Intelligent Utility Management Systems (IUMS) integrate computing devices to manage energy consumption. Smart meters enhance data collection for informed decision-making, while non-intrusive load monitoring (NILM) aids load power profile analysis. Smart meters also enable adaptive tariff plans based on dynamic price signals. The incorporation of intelligent appliances with electricity usage understanding poses interoperability challenges in building management systems. Addressing mobility and volatility issues requires reliable service discovery procedures. Additionally, considerations for machine-readable descriptions of smart devices and network operations become crucial in the context of electric vehicles and Energy Management Systems (EMS) integrated into building infrastructures [16], [17], [18], [19], [20].

The utilization of a network of distributed sensing nodes results in the development of intelligent outlets and plugs. These devices not only facilitate remote load management by allowing for on/off control, but they also integrate sensors to monitor the consumption of the load. Nevertheless, it is crucial to acknowledge that current commercial solutions do not possess the ability to detect local loads for networked devices. In these solutions, all processing of consumption data takes place at the application level. The advancement of this technology has the potential to significantly alter the methods by which we regulate and preserve energy in domestic settings and beyond.

The primary contributions of this work encompass:

1) The system illustrated in Figure 1 caters to the essential requirement of effectively monitoring and controlling load profiles in different electrical appliances. This web application showcases an intuitive graphical interface (GUI) that offers up-to-date consumption data to both customers and utility companies. The network design has a central hub housing a Master device at the host location, along with several Slave devices that are interconnected with designated appliances. The Master device supervises and regulates load profiles, while each Slave device links to a specific appliance, enabling data collection and communication with the Master device.
2) The Master device utilizes a dedicated module to achieve efficient data storage, recording data at a high sampling frequency of 1 second. The data is transported using wireless technology, specifically Wi-Fi, to a secure cloud platform, guaranteeing quick access and storage. The system provides extensive analysis and advanced management features, such as power factor assessment, access to tariff data, and protection against low voltage, high current, and potential theft.
3) By incorporating an advanced control and monitoring system, users may effectively regulate the energy usage of individual devices via a user-friendly mobile application. By adopting this proactive strategy, not only will energy efficiency be improved, but there will also be noticeable cost reductions due to the availability of real-time data and control capabilities. The system prioritizes the significance of optimizing energy consumption, empowering users to make well-informed choices and advocate for energy conservation.

The structure of the paper is presented in the following manner: Section III provides an in-depth analysis of the approach employed in the proposed system, explaining its design and implementation. Section IV comprises a thorough presentation of the results and subsequent discussions, encompassing the outcomes and implications of the system's operation. Section V serves as the conclusion section of the study, providing a concise review of the findings and prospective areas for future research. It captures the important takeaways and implications derived from the study.

III. METHODOLOGY

The system architecture, depicted in Figure 1 and detailed in Figure 2 with master and slave devices, is meticulously crafted for the efficient monitoring and control of individual appliances, incorporating three key components: hardware, software, and communication [21]. The Master device, Slave device, and interconnected communication modules are illustrated in the overall system representation.

To optimize data transfer, a collaborative approach harnessing the strengths of both Wi-Fi and Power Line Communication (PLC) technologies is employed. Wi-Fi facilitates signal and data transmission between the primary device and the Cloud platform, ensuring users have unrestricted access to consumption data and analysis. Concurrently, Power Line Communication (PLC) technology ensures reliable communication between Slave devices and the Master device, establishing a robust pathway for accurate data transmission from individual appliances to the central hub. The synergy between Wi-Fi and PLC components enhances the system's effectiveness in comprehensive monitoring and control of appliance usage.

The subsequent sections delve into detailed analyses of the unique features and components within the software and hardware aspects. These explanations aim to provide readers with a thorough understanding of how these elements collaboratively contribute to the overall structure of the system

A. HARDWARE

Figure 2 outlines a schematic representation of a power line communication system involving multiple devices. The central component, referred to as the "Master Device," serves as the core controller. The diagram illustrates the connectivity of various components, including AC-DC converters, relay modules, voltage and current sensors, and a Power Line Communication (PLC) module. Each slave device, designated as the "nth slave device," is connected to the power line and communicates with the master through existing power lines as the medium of communication.

The communication protocol involves data transmission through the power lines, with a dedicated Web portal facilitating interactions. The HTTP request-response mechanism suggests a web-based control interface for managing and controlling the devices. The microcontroller serves as the brain of the system, coordinating data flow and power supply. This

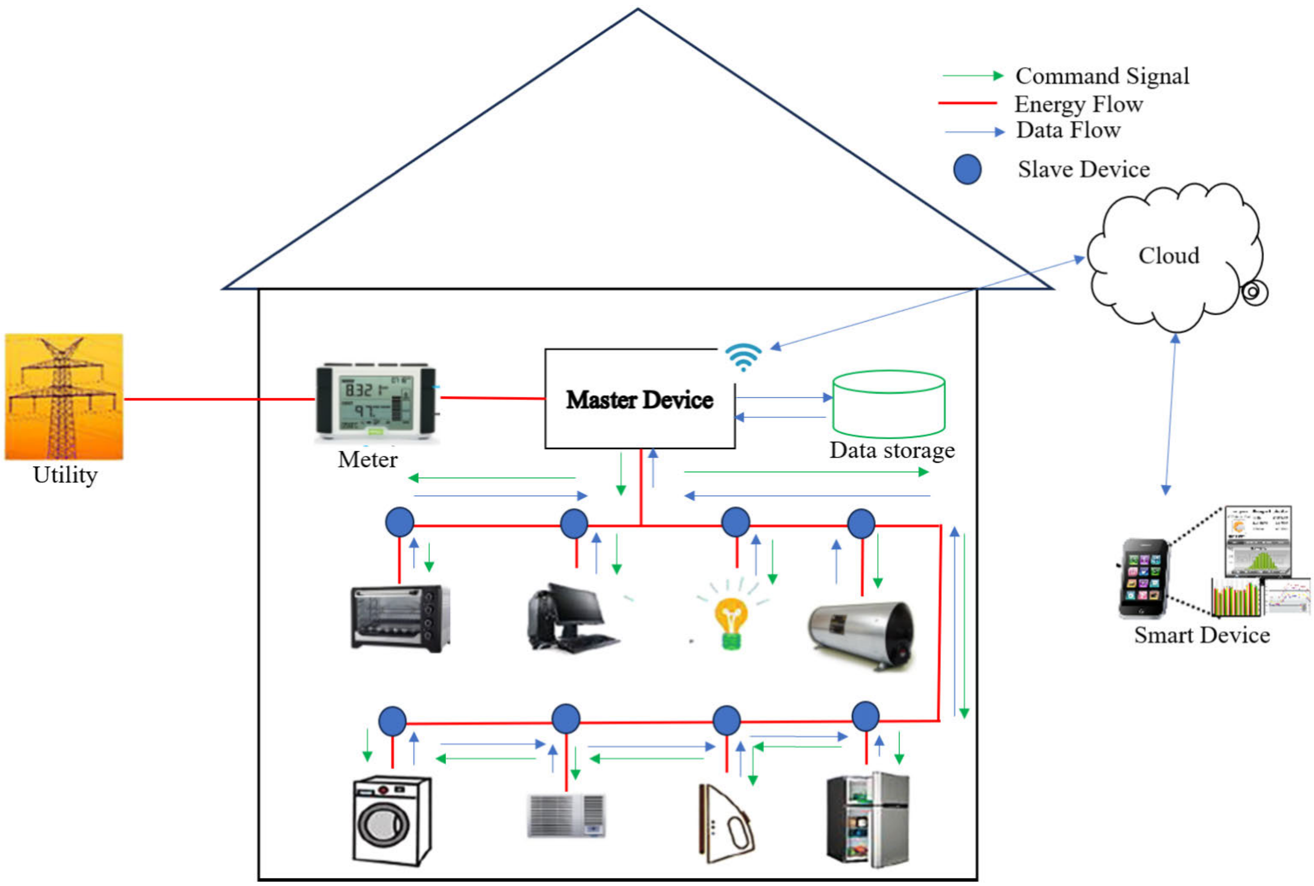


FIGURE 1. Architecture of the proposed home energy management system.

configuration enables effective communication, control, and monitoring of devices through a power line communication network, providing a scalable and interconnected solution for managing electrical devices in a networked environment.

1) MASTER DEVICE

The system initiates by utilising an AC-DC converter to transform the incoming alternating current (AC) into a direct current (DC) signal with a voltage of 5 volts. The power is allocated to various components, including the Power Line Communication module, ZMPT101B AC Voltage Sensor, Node MCU, and SD Card shield. The Node MCU oversees signal management, verifies internet connectivity, and handles data processing. The AC voltage sensor is responsible for supplying crucial data to the Node MCU calculations, which encompass power usage, power factor, and billing. The system's effective processing, utilising open-source programming, guarantees accurate monitoring and control, with a focus on adaptability and reliability. The ESP8266 WiFi module, ACS712 current sensor, and relay collaborate to provide efficient energy resource management.

2) SLAVE DEVICE

The system functions using a 5V direct current (DC) power source acquired by means of an alternating current (AC) to direct current (DC) converter. The ACS712 current sensor, Arduino microcontroller, and Power Line Communication module are supplied with power. The Power Line Communication module gathers command signals to provide effective communication across power lines. A strategically incorporated relay module enables the specific appliance connection or disconnection from the AC mains. The ACS712 sensor is utilized for current measurement, with its data being transmitted to the Arduino microcontroller. The microcontroller establishes communication with the master device via power lines. This architectural approach guarantees precise monitoring of load consumption, enabling accurate analysis and control techniques. The system's interconnected components improve the dependability of load consumption monitoring and analysis.

3) POWER LINE COMMUNICATION MODULE

The system effortlessly incorporates the KQ330f power line communication module, which is a highly recognised technology in the sector [22], [23]. By utilising single-carrier class modulation in the frequency range of 50 kHz to 350 kHz, this technology guarantees dependable transmission of data over power lines with low voltage. This integration improves operating capabilities by providing uninterrupted connectivity, excellent signal quality, and efficient data

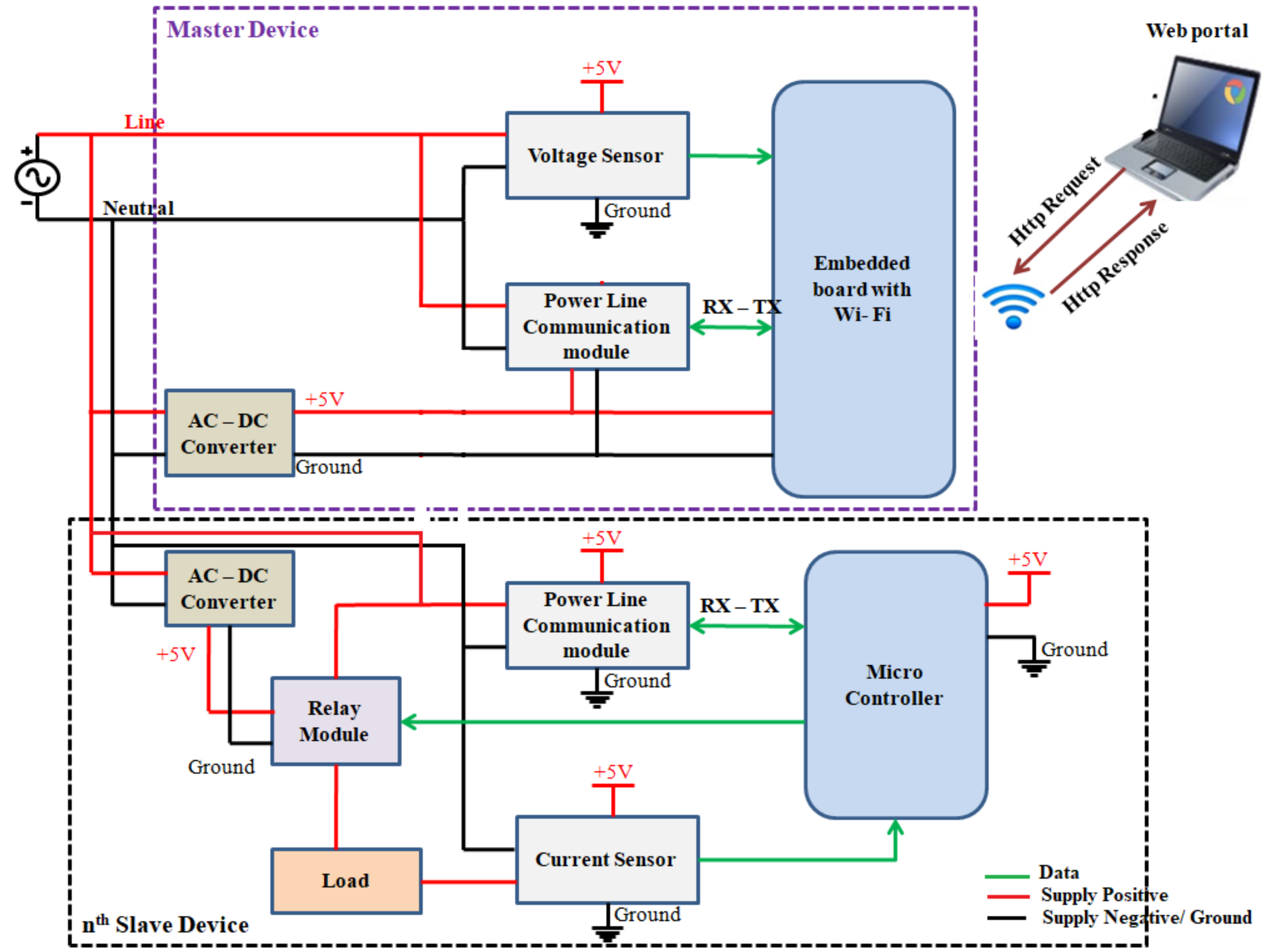


FIGURE 2. Architecture of the proposed system where master and slave are indicated with dotted lines. The power supply for all the sensors and PLC module is taken from AC -DC converter.

transfer at a reasonable cost. The KQ330f module enhances system efficiency and precision, obviating the necessity for a distinct communication infrastructure [24].

B. SOFTWARE

The software architecture can be effectively divided into two interconnected components: control flow and data flow. Figure 3 provides a simple process flow for remotely controlling an appliance through the internet. The sequence begins with the user activating the appliance by turning on the switch. The system checks for internet availability, and if the internet is accessible, it proceeds to check if the "ON Command" has been received. If the command is received, the system enables the GPIO (General Purpose Input/Output) pin, facilitating the transfer of the command from the master device to the slave device. Subsequently, the relay is enabled, triggering the switch to turn on the appliance. The process concludes with the appliance being operational. This structured flow demonstrates a basic yet effective mechanism for remotely controlling appliances based on internet availability and received commands, incorporating elements such as GPIO pins and relays for seamless communication and control. Figure 4 depicts a systematic process for monitoring and analysing electrical parameters in a power system. The sequence initiates with the system starting, followed by reading the current. The current value is then transmitted to the master device. The voltage at the master device is measured, and subsequent calculations include determining power (in kilowatts), power factor, energy consumption (in kilowatt-hours), and the associated billing amount (in Rupees). The system checks for internet availability, and if the internet is accessible, the data is sent to a web server for display. In the absence of internet connectivity, the data is stored locally. The process concludes with the data being transmitted to a mobile app, providing a comprehensive and real-time overview of the power system's performance and consumption metrics for user monitoring and analysis.

C. SYSTEM CONFIGURATION (WEB SERVER)

A web server serves as the foundation for an open-source Internet of Things (IoT) application, utilizing the HTTP

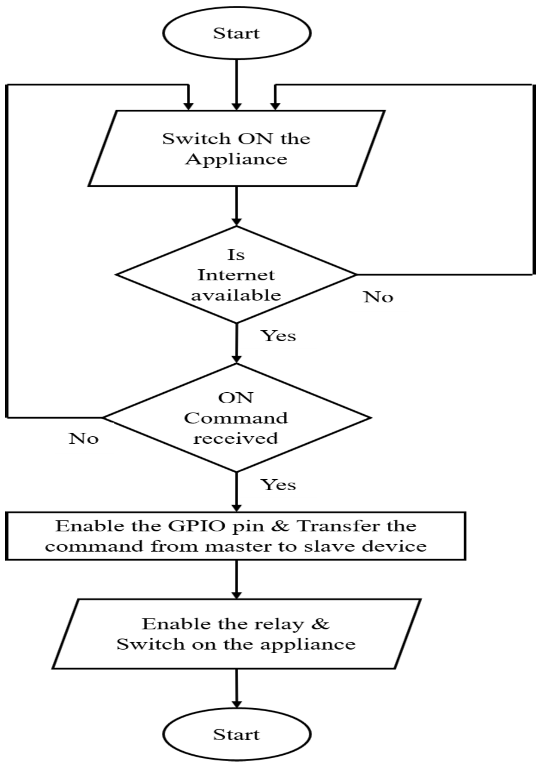


FIGURE 3. Controlling of the appliance flow chart.

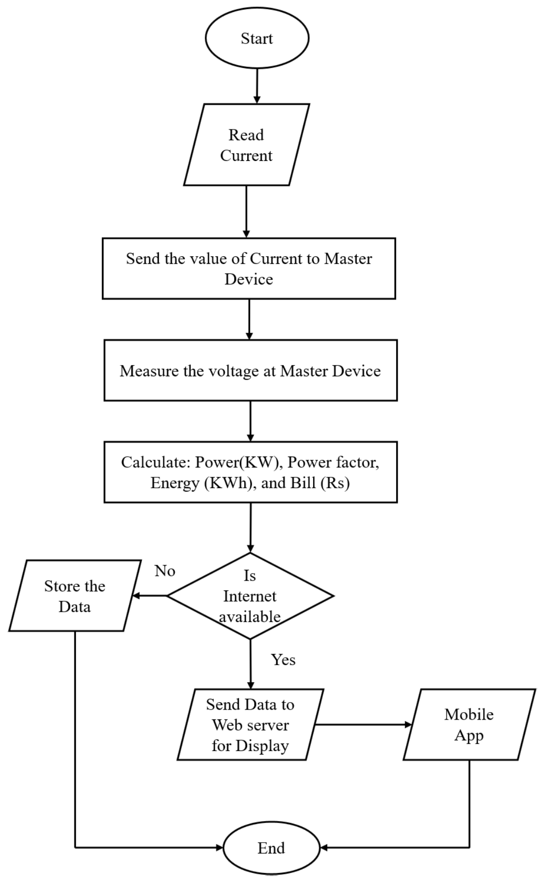


FIGURE 4. Monitoring of the appliance flow chart.

protocol to facilitate data storage and retrieval through either a local area network (LAN) or the Internet. This application is designed for displaying, interpreting, and calculating data, while also allowing for public data storage. It is specifically compatible with the ESP 8266 WiFi module. Within this project, data collected from an IoT-based sensor undergoes analysis and storage through the web server. The examination of this data is conducted seamlessly using both computers and mobile devices as long as a WiFi connection is established.

D. SYSTEM PARAMETERS

This section discusses the essential system variables that are taken into account while calculating performance. The system functions on a single-phase basis, with a housing voltage of 220 Vac. Significantly, the pivotal factor of household appliances resides on the current aspect, rather of the voltage element. Current, which refers to the movement of electric charge, is precisely defined as the amount of charge that is expended during a specific period of time. There are two forms of electric current: direct current (DC) and alternating current (AC). Unlike direct current (DC), which maintains a constant flow in one direction, alternating current (AC) periodically changes its direction. In order to account for the variability of alternating current (AC), calculations utilize the root mean square (RMS) current. RMS current is calculated as:

$$I_{rms} = \frac{I_{max}}{\sqrt{2}} \tag{1}$$

Power consumption is other crucial criterion in addition to the current. Power is a flow of electrical energy over a given period of time. It can also be described as the addition of the factors affecting voltage, current, and power. Equations (2) illustrate the power equation:

$$P = VICos\theta \tag{2}$$

where P = power in W, I = current in A, cosθ = power factor.

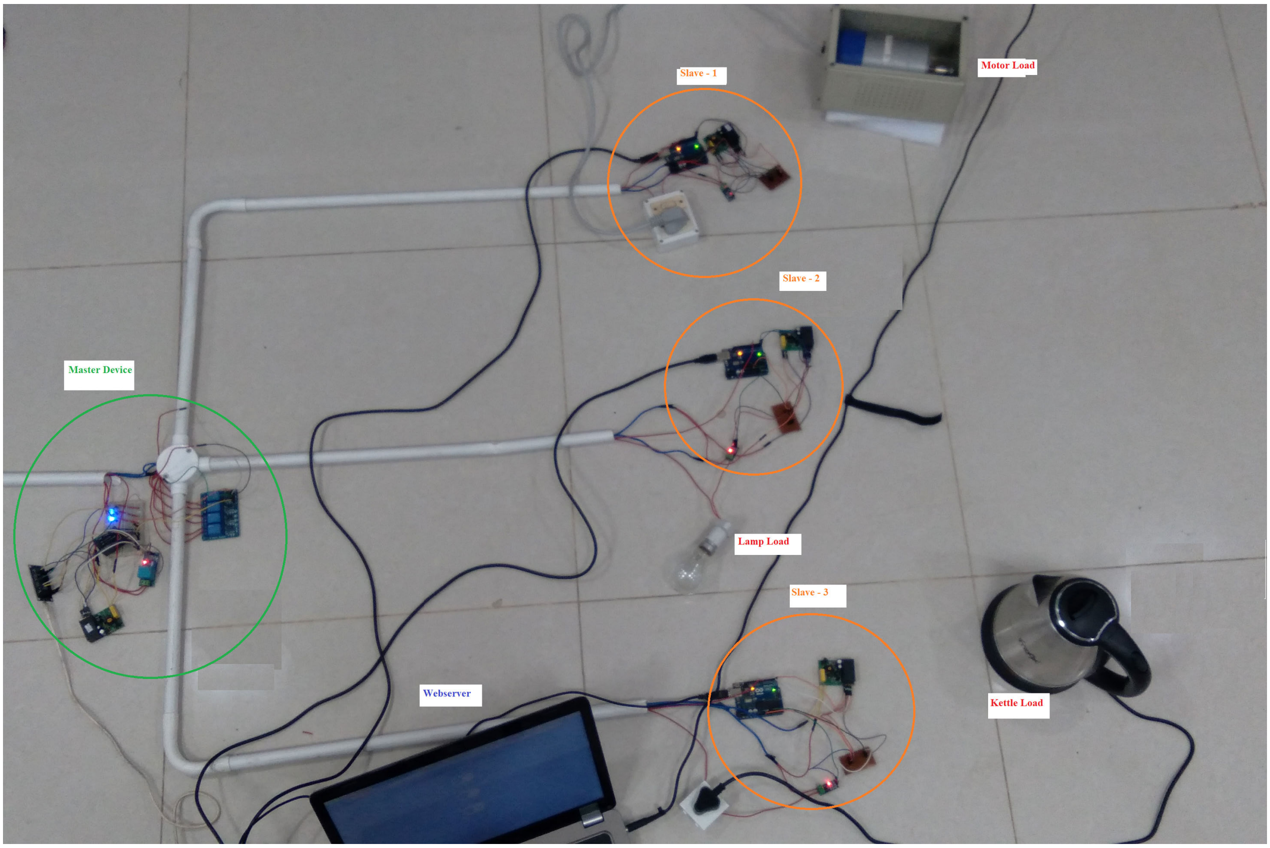
Power factor can be calculated by measuring the phase angle between voltage and current wave forms at a particular load. Equation (3) represent the phase angle measurement, equation (4) represent the power factor:

$$phase(\theta) = tan^{-1}\left(\frac{I}{V}\right) \tag{3}$$

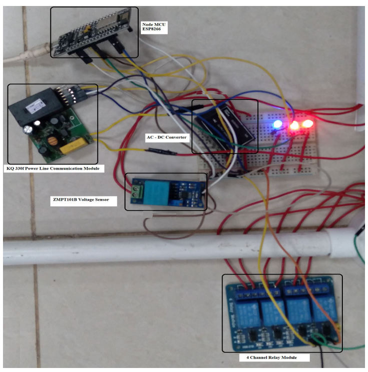
$$powerfactor = cos\left(\frac{phase * \pi}{180}\right) \tag{4}$$

where tan^{-1} represent four-quadrant inverse tangent of current I and the voltage V.

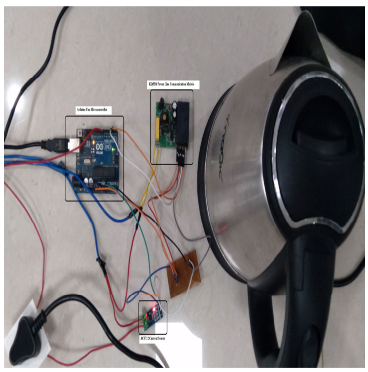
Table 2 outlines the measured and calculated quantities in the context of the described energy management system. The table serves as a comprehensive reference for understanding the various parameters involved in monitoring and controlling electrical appliances within the system. The measured quantities include voltage, current, and time, obtained through



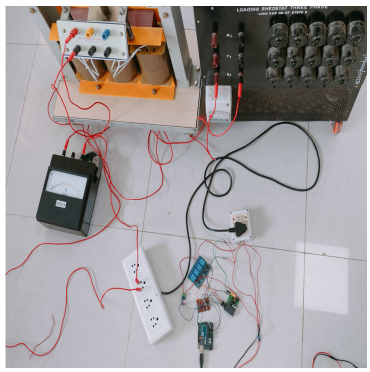
(a) Complete Setup



(b) Enlarged view of Master Device



(c) Enlarged view of Slave Device (Kettle)



(d) View of Resistive and Inductive Load

FIGURE 5. Experimental Setup of a Master and three Slave devices for various residential and industrial loads.

sensors such as ZMPT 101B for voltage and ACS712 for current, as well as the millis() function for time measurement. On the other hand, the calculated quantities encompass power in watts, energy in kilowatt-hours (KWh), power factor, and the bill amount in Rupees.

IV. RESULTS AND DISCUSSION

The hybridization of Power Line Communication (PLC) and Wi-Fi in our system yields superior performance compared to existing communication methods such as Wi-Fi, Zigbee, and Bluetooth. By integrating PLC, which utilizes the existing electrical wiring for data transmission, with Wi-Fi, the proposed system achieve enhanced reliability and stability in communication. This combination ensures a more robust and stable connection, minimizing susceptibility to interference and reducing data loss. Additionally, the hybrid approach extends the communication range, optimizes data transmission with reduced latency, and provides a cost-effective solution by leveraging the infrastructure already present in electrical wiring. In challenging environments, where

TABLE 2. Measured and calculated quantities in the energy management system.

S. No.	Measured Quantities	Calculated Quantities
1	Voltage (using ZMPT 101B Sensor at Master device)	Power in Watts (At Master device)
2	Current (using ACS712 sensor at each Slave device)	Energy in KWh (At Master device)
3	Time in msec (using millis() function at slave device)	Power factor (using phase angle delay of V and I at master device)
4		Bill in Rs. (using KWh and tariff at master device)

obstacles and physical barriers may impact wireless technologies, our hybrid system excels, offering improved robustness and efficiency in monitoring and controlling applications.

Wi-Fi technology is central to our system, facilitating seamless communication between primary devices, including Master and Slave devices, and the Cloud platform. Leveraging Wi-Fi ensures rapid and reliable transmission of energy consumption data in real-time, enabling timely monitoring and analysis for both end-users and utility companies. Wi-Fi's robustness ensures stable connections even in congested environments, preserving data integrity. Its scalability accommodates numerous devices and users, vital for diverse applications across residential, commercial, and industrial settings. Additionally, Wi-Fi's encryption capabilities safeguard sensitive data, ensuring compliance with privacy regulations and industry standards, bolstering the security and integrity of our energy monitoring solution.

Figure 5(a) describes the complete Master-Slave system where one master device and three slave devices are connected with various types of loads viz. Lamp load, Motor load, kettle. The enlarged view of master device along with a Relay control unit is shown in Figure 5(b), which consists NodeMCU ESP8266 microcontroller with Wi-Fi capability, KQ330f Power line communication module, ZMPT101B Voltage Sensor, 4 channel Relay control unit. The enlarged view of third slave device with kettle load is shown in figure 5(c). Each of the slave device consists of KQ330f Power line communication module, Arduino Uno microcontroller, ACS712 Current Sensor and a Load.

As the PLC module uses the existing power lines as the medium for communication the data loss and interruption is less. The system uses the serial asynchronous communication of the micro controller and FSK-KQ330 module to transmit data. Next, the transmission data is modulated by the FSK-KQ330 module. Through the external circuit (amplifier circuit and resonance detection circuit), the square-wave signal transforms into a sinusoidal signal. Finally, the signal is coupled to the power line after being isolated from the interfering signal.

A. CASE-1: RESIDENTIAL ENERGY MANAGEMENT

This section provides the results corresponding to the sensed current and power values for various appliances connected to a slave device. The appliances include a lamp, dryer, iron box, kettle, laptop charger, and printer. The results are taken with the appliances operate individually, combination of two and three appliances operate simultaneously.

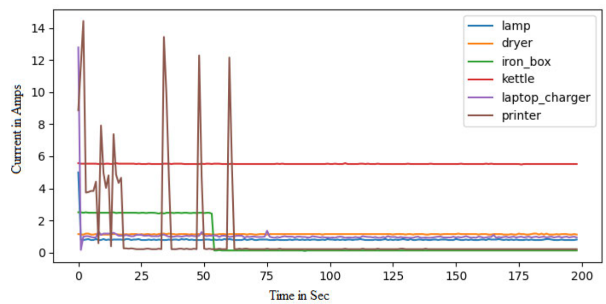


FIGURE 6. sensed current for various loads which are operated individually.

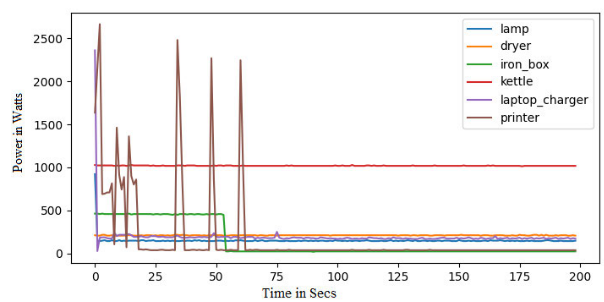


FIGURE 7. sensed power values for various loads which are operated individually.

figures 6 and 7 reveals varying power requirements among the appliances. The lamp, dryer, and iron box demonstrate relatively consistent current and power values, suggesting stable power consumption patterns. In contrast, the laptop charger and printer exhibit a broader range of values, indicating potential fluctuations in their power demands. Notably, the kettle consistently maintains a higher current draw, signaling its elevated power consumption compared to the other appliances.

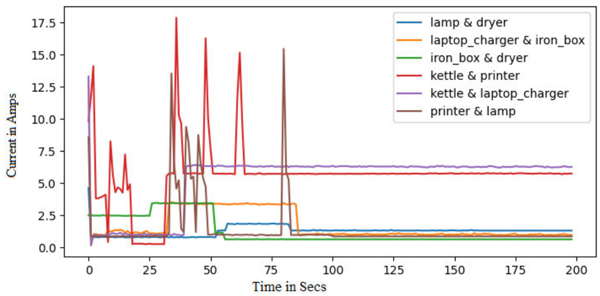


FIGURE 8. **sensed current for various loads when combination of loads operate simultaneously.**

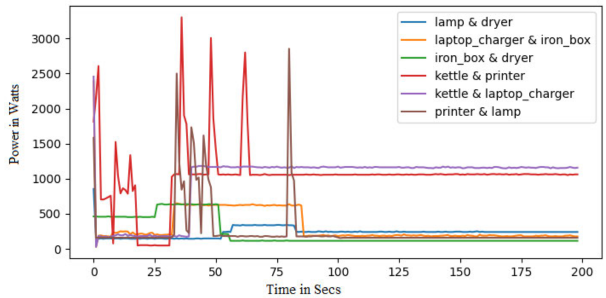


FIGURE 9. **sensed power values for various loads when combination of loads operate simultaneously.**

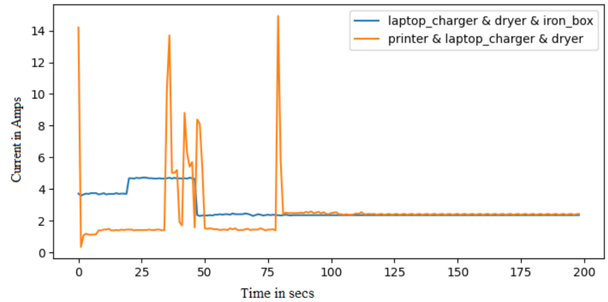


FIGURE 10. **sensed current for various loads when all are operated simultaneously.**

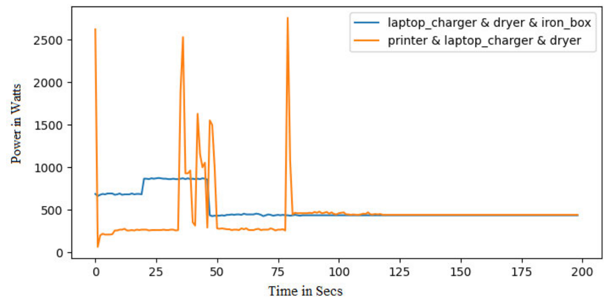


FIGURE 11. **sensed power values for various loads when all are operated simultaneously.**

Figures 8 and 9 display clear variations in power usage for various load combinations. For example, when a lamp and a dryer are used together, they require a total of 854 watts. Similarly, combining a laptop charger with an iron box results in a usage of 2389 watts. These findings emphasise the varying amounts of power consumption linked to different load combinations. The knowledge obtained from this data is helpful for understanding the power requirements when various combinations of loads are running simultaneously. These insights can be directly applied in many activities, such as the creation of electrical circuits, the estimation of energy consumption, and the optimisation of power distribution in residential or commercial structures.

Figures 10 and 11 depict the fluctuating power consumption levels resulting from different load combinations. For example, when a laptop charger, dryer, and iron box are used together, they consume a total of 685 watts. In contrast, when a printer, laptop charger, and dryer are used together, they consume a total of 2621 watts. These findings emphasise the variation in power usage linked to various load combinations. The information obtained from this data is helpful for evaluating the overall power demands while all loads are functioning concurrently. This information is valuable for comprehending the combined energy requirement in a system or infrastructure, such as a household or workspace. It has a vital function in optimising the distribution of power, making well-informed choices on energy management, and adopting measures to enhance efficiency.

B. CASE-2: INDUSTRIAL ENERGY MANAGEMENT SYSTEM

This section provides the results corresponding to the sensed current and power values for resistive, inductive and combination of both loads connected to a slave device. Here the industrial scenario is replicated by connecting resistive and inductive loads in a laboratory environment.

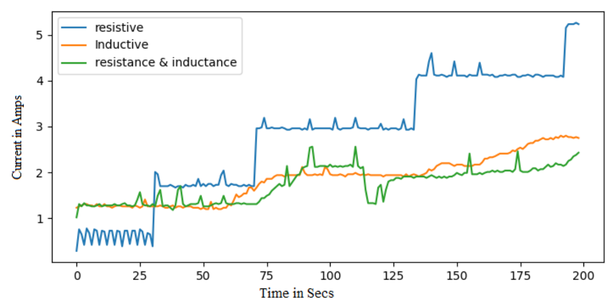


FIGURE 12. **sensed current for R, L, and RL loads.**

Figures 12 and 13 demonstrate the different behaviours displayed by different types of loads and their impact on power usage. The data highlights the disparity in power requirements between resistive and inductive loads, with the latter typically necessitating a greater amount of power. This information is important for designing electrical systems,

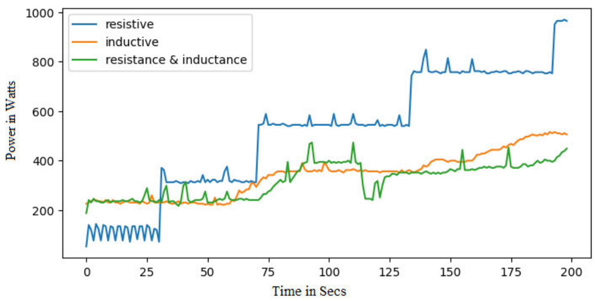


FIGURE 13. sensed power values for R, L, and RL loads.

calculating energy costs, and implementing initiatives to improve energy efficiency.

Furthermore, the discoveries provide valuable understanding on load characteristics, power factor, and energy usage trends. Having this comprehension can be crucial in managing loads, planning capacities, and optimising power distribution, hence guaranteeing the efficient and dependable functioning of electrical systems. The extensive knowledge acquired from this study enhances decision-making for enhancing overall energy efficiency and system performance.

C. ACCESSING ESP8266 WIFI MODULE IN WEB SERVER

The proposed system was tested using an Arduino UNO, a web server, and a WiFi + PLC module to send and receive data from sensors. The system was tested for three different loads of 40W bulb, Motor and Kettle. These loads are connected at the slave devices through ACS 712 current sensor. The command signal is passed through the webserver using various buttons. If the load was on the command is send to the microcontroller at the respective slave device through Power lines. After switching on the load the current will be sensed by the microcontroller and calculate the power and energy consumed. The data will be transmitted again to the master device via power lines and the ESP8266 Wi-Fi module at the master device will post the data on the webserver for display.

The setup also displays the webserver represented in figure 14 for control and monitor the load via a hybrid communication channel of Wi-Fi and PLC.

D. MONITOR AND CONTROL OF LOAD USING SMART POWER LINE COMMUNICATION

The control signal (command) signal is given through the webserver by using three toggle switches.The command signal is then transfered to the master device via wireless communication medium. Here the Wi-Fi communication uses Http protocol to get and post the information on to the webserver. At master device the micro controller ESP8266 receives the command signal from webserver. The same signal then modulated using Frequency Shift Keying (FSK) technique inside the KQ330f power line communication module. The modulated command signal is transmitted by the PLC module via power lines to the slave device.

At slave devices the received command signal via power lines is again demodulated by KQ330f module and send to the Arduino micro controller. This command signal is then transferred to the Relay control unit such that the corresponding relay will operate and the load was switched on/off. After switching on of the load, current passing through the load was measured using ACS 712 current sensor module. The sensed current was read by the analog pin of Arduino micro controller at slave device.

The current value sensed by the Arduino micro controller is again transmitted to the master device using power line communication. The ESP8266 micro controller at master device sense the voltage value using ZMPT101B voltage sensor. Finally by using the voltage and current readings ESP8266 estimates the power and energy consumed by the corresponding load using arduino programming. The calculated values are uploaded to the webserver for display.

Figure 14 represents the basic view of the webserver which has a title "Monitor and Control of Electrical Appliances using Smart Power Line Communication", where the data from the ESP8266 is uploaded with the date and time stamp. Webserver consists of different tabs for different loads, admin controls for security purpose. The data from the ESP8266 is uploaded and available for display. Each data point consists of time, voltage, current, PF, and Power consumed by that load. The data uploaded to the webserver can be downloaded as Comma Separated Values (CSV) file for further analysis of data.

E. LIMITATIONS

The proposed approach, although it has notable benefits, is nevertheless characterized by inherent limits that require careful evaluation. First and foremost, the system's reliance on current electrical infrastructure raises questions over its suitability in areas typified by obsolete or unreliable power grids. The efficacy of the hybridized Power Line Communication (PLC) and Wi-Fi strategy relies on the dependability of the existing electrical infrastructure. Additionally, the system is susceptible to electrical noise on power lines, which could result in signal interference. Despite efforts to mitigate this problem via filtering systems, the vulnerability to excessive noise situations can affect the overall dependability of communication.

In addition, although the hybrid approach increases the distance over which communication can occur, the Wi-Fi component of the system is still limited by its inherent constraints, particularly in installations of a large scale. Moreover, the incorporation of PLC and Wi-Fi technologies brings about intricacy in relation to system installation and upkeep, requiring specialized expertise for optimal arrangement and problem-solving. These limits emphasize the importance of thoughtful evaluation when determining if the system is appropriate for particular applications and circumstances. They also offer opportunities for future research to tackle and alleviate these restrictions.

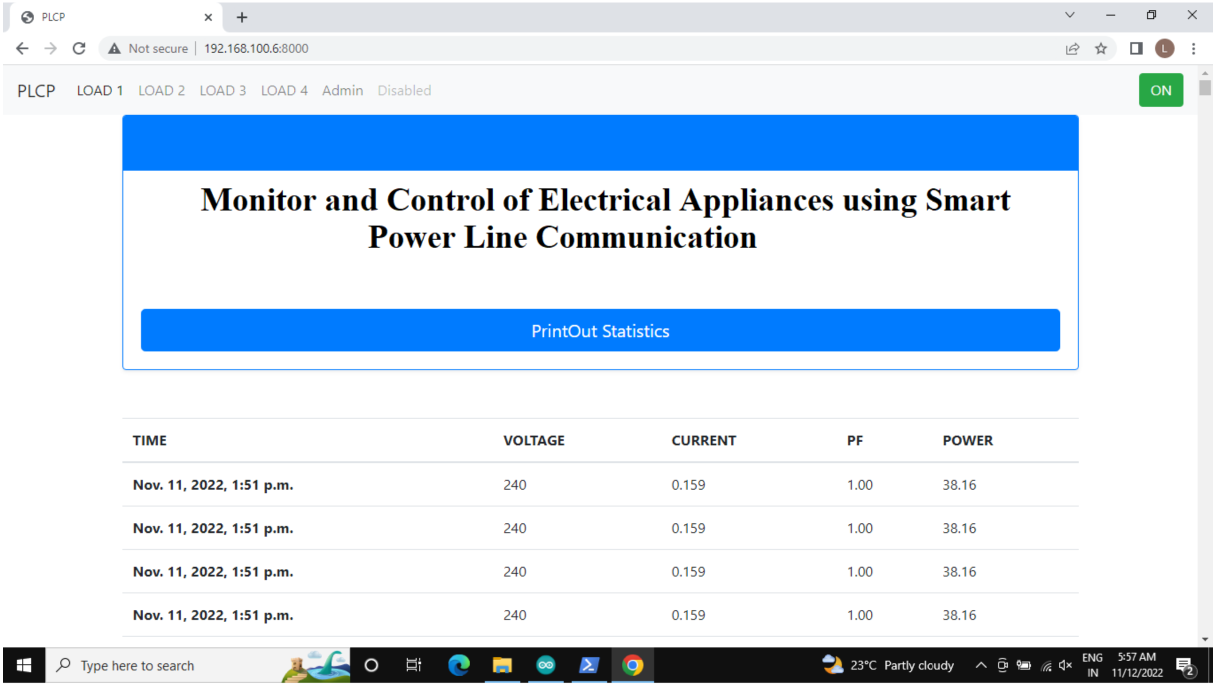


FIGURE 14. Monitoring of the appliance in a webportal.

V. CONCLUSION

Smart Edge Device Utilizing Power Line Communication for Energy Management and Control of Electrical Appliances represent a significant step toward enhancing energy efficiency and providing intelligent control solutions in residential and commercial settings. The utilization of Power Line Communication (PLC) technology has proven effective in establishing a reliable and efficient communication network, allowing seamless integration for energy management and appliance control.

Through our research and experimentation, we have demonstrated the feasibility of using a smart edge device to monitor and control electrical appliances over existing power lines. The incorporation of PLC ensures robust communication, eliminating the need for additional wiring or complex installations. The energy management features enable users to monitor power consumption, optimize usage patterns, and contribute to a more sustainable and cost-effective energy profile.

Future developments could focus on integrating advanced analytics and machine learning algorithms for predictive energy optimization, ensuring compatibility with an extended array of appliances and interoperability with diverse smart home ecosystems. Strengthening cybersecurity measures will be imperative to protect user data and maintain the integrity of the system. Exploring grid integration possibilities and enabling bidirectional communication can contribute to demand response initiatives and enhance grid stability. Scalability, both in terms of device expansion and system capabilities, should be a priority, and user education programs can be implemented to promote sustainable energy practices. This holistic approach aims to position the smart edge device as a pivotal component in the evolution of smart homes, fostering energy efficiency, user convenience, and a more interconnected and sustainable living environment.

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