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ORIGINAL ARTICLE

Intelligent Cloud-based Electrical Socket (iCESocket) for Smart Home Applications

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ABSTRACT - Domestic electricity consumption has been rising steadily in recent years as a result of rapid increase in population and economic development. This is a major cause for concern as the reliance on non-renewable energy sources have had a high carbon footprint on the environment. Furthermore, the occurrences of numerous electrical problems resulting in deaths and financial loss have posed a major safety concern. This paper proposes an Intelligent Cloud-Based Electrical Socket (iCESocket) to enhance energy efficiency and electrical fault protection. Electrical data acquired via sensors are transmitted to the server for storage, analysis, monitoring and control. The iCESocket demonstrates promising results of 1.48% mean average percentage error (MAPE) in measurement indicating good accuracy and consistency. The iCESocket is validated to be effective in monitoring and controlling electrical usage of appliances remotely while detecting electrical fault. For future work, data collected from the iCESocket can be analyzed for demand-side management (DSM) such as for the demand response mechanism of smart grid to improve grid stability, reduction of peak demand and other applications.

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INTRODUCTION

Nowadays, various electrical appliances are created for improved convenience and quality of life of end-users. For instance, fans, fridges, and air-conditioners provide a comfortable living environment. However, these electrical appliances contribute to rising electricity consumption, straining electricity generation to keep up with the demand. According to Our World In Data [1], there has been an escalating electricity usage trend in the decade. As shown in Figure 1, electricity consumption has seen a steady rapid rise from the 1980s till 2019 [2].

In a similar vein, electricity generation in many countries such as Malaysia relies heavily on burning fossil fuel resources such as coal, natural gas or oil, which are non-renewable [3]. In 2018 alone, the total electricity generated in Malaysia was 43% and 39% by coal and natural gas, respectively, as depicted in Figure 2. The burning of coal, natural gas and oil for power generations has severe consequences on the environment producing a tremendous amount of greenhouse gases and other pollutants, resulting in global warming and climate changes [4]. Besides, these non-renewable resources are also depleting over the years.

In a nutshell, the reliance on non-renewable energy sources with electrical appliances of the high carbon footprint as well as potential losses of lives and assets due to the safety concern of faulty appliances are the two key problems to be tackled. Therefore, there is an urgent need for an effective new solution to reduce electricity consumption and enhance energy efficiency.

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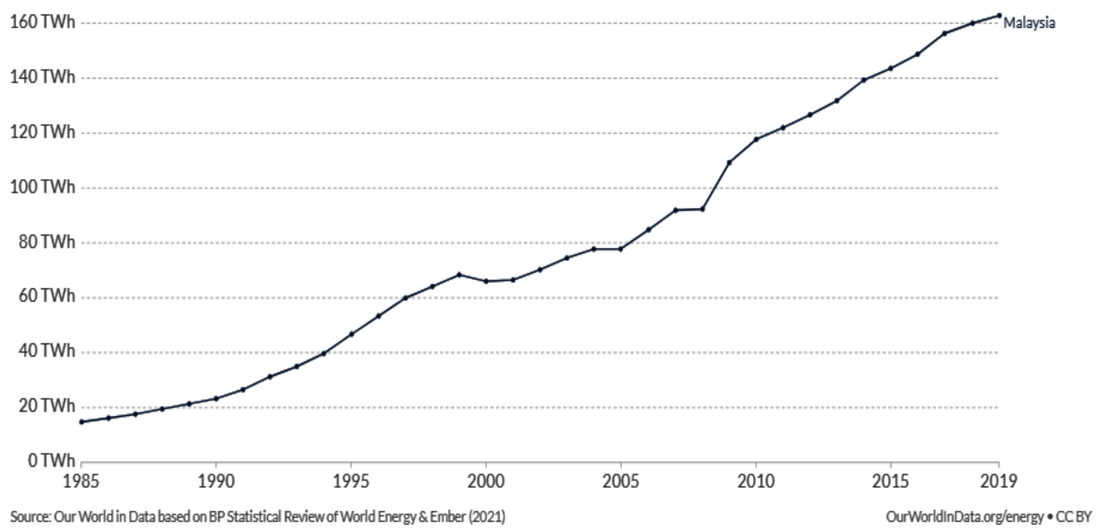


Figure 1. Malaysia's Electricity Consumption from 1985 to 2019 [2]

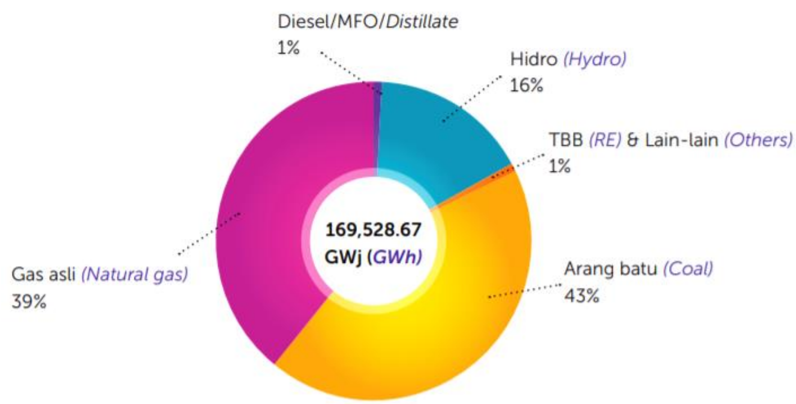


Figure 2. Electricity Generation By Fuel Type in Malaysia for 2018 [5]

In this paper, an energy-efficient, intelligent electrical socket solution is proposed. As an essential electrical power outlet device, an electrical socket plays an essential role in home electrical and electronic appliances [7]. The proposed Intelligent Cloud-based Electrical Socket (iCESocket) for Smart Home Applications improves domestic electricity consumption efficiency and improves safety protection against electrical faults with a cloud-based data-driven control mechanism built in. With the iCESocket, end-users can use smartphones, tablets, or computers with user interfaces (UIs) to monitor electrical operational conditions and energy consumption apart from controlling various electrical appliances connected to the network. The iCESocket has shown promising results in a residential setting.

LITERATURE REVIEW

Smart Sockets

To date, many existing household appliances are still not deemed "smart" or "intelligent," despite the fact that home automation systems have become more popular and accessible. The cost of replacing those electrical items with smart gadgets is usually quite high. The majority of them are developed in a proprietary manner, with no regard for open communication protocols or standards for open data connectivity [6]. A "smart" socket (or plug) has emerged in recent years as an intelligent power socket or adaptor for electrical appliances that may be integrated into a smart home network [7]. It allows customers to control the connected appliance via the Internet via wireless technology. Ordinary electrical appliances are effectively transformed into linked "smart devices" once connected to a smart socket. As a result, owners of smart appliances can control them remotely in real time or on a schedule.

As shown in Figure 3, there are a variety of off-the-shelf smart sockets on the market. For example, Belkin's Wemo Insight Smart Plug [8] comes with a plug-and-play feature that allows customers to turn on/off electrical appliances and monitor them from anywhere. It works with Android and iOS devices and can pair with Amazon Alexa or Google Home for hands-free voice control. TP-link [9] invented the Wi-Fi Smart Plug HS100, which allows remote access to smart devices. It can be used at home with a third-party cloud platform like Amazon Alexa or Google Home. Meanwhile, Mi Smart Power Plug Socket was introduced by Xiaomi [10] and launched the Mi Smart Power Plug Socket, which works with the Xiaomi smart home app on smartphones to control appliances switching remotely over a Wi-Fi network. The timing switch function allows appliances to be switched on and off automatically or on a schedule.

(a) Wemo Insight Smart Plug [8] (b) TP-link HS100 Plug [9] (c) Mi Smart Plug Socket [10]

Figure 3. Existing products of smart socket or plug

Current Sensors

The current sensor is the critical component in the smart sockets and is used to measure the connected electrical appliance's current consumption. It is typically connected to a microprocessor or microcontroller to pre-process and digitise the measured analogue current into digital time-stamped data before transmitting it to the cloud platform for storage, analytics, and control. Therefore, the users can monitor the connected appliances' energy consumption parameters through the cloud, with electrical parameters computed and visualised. Furthermore, the current sensor is also used to protect electrical faults by detecting and isolating faulty appliances. Once an overcurrent condition is detected, it immediately disconnects the socket from the power supply mains.

Scientifically, a current sensor is typically a transducer that measures the current based on converting the selected property into the output voltage proportional to the current in the designed path. As the current passes through a circuit, voltage drops across the path, and a magnetic field is induced near the current-carrying conductor [11]. Current sensors can be classified into different categories based on scientific principles or electrical characteristics for accurate measurement. A Rogowski coil current sensor operates with the principle of converting the measured current to a secondary current that is proportional to the turn ratio. A clamp power meter is a measuring apparatus that operates with the CT method [11], as depicted in Figure 4. As it measures a large current without undergoing magnetic saturation, there is no energy loss in the form of heat. Although it is thin and flexible, it can only measure AC current with difficulty measuring current less than 10A [11] [12].

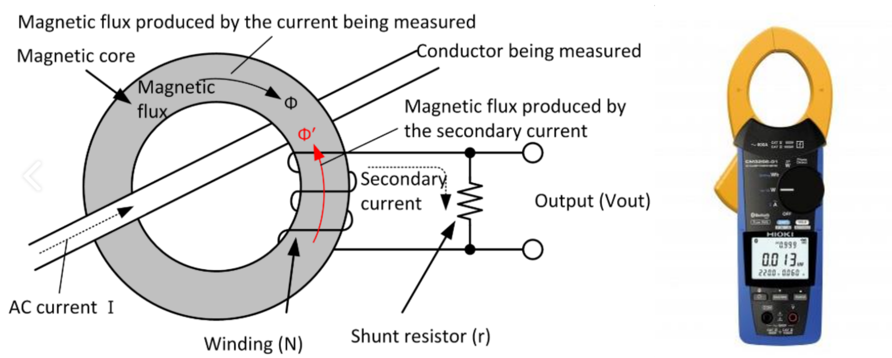


Figure 4. Principle of Rogowski Coil Current Sensor [11]–[13]

A Hall element current sensor converts the magnetic field induced around the measured current to voltage using the Hall Effect [14]. When current flows in a conductor, an induced magnetic field is measured in the form of Hall voltage through the Hall element. As the Hall voltage is relatively small, an amplifier needs to be magnified to produce an output signal proportional to the current value, as depicted in Figure 5. The Hall current sensor is cheap and can measure both AC and DC currents. One example of the Hall element sensor is the ACS712 current sensor, a micro-electromechanical system (MEMS) based sensor. Due to its high accuracy in sensing, controlling and actuating and producing output, MEMS are widely applied in various fields, such as automation, instrumentation, industrial and medical.

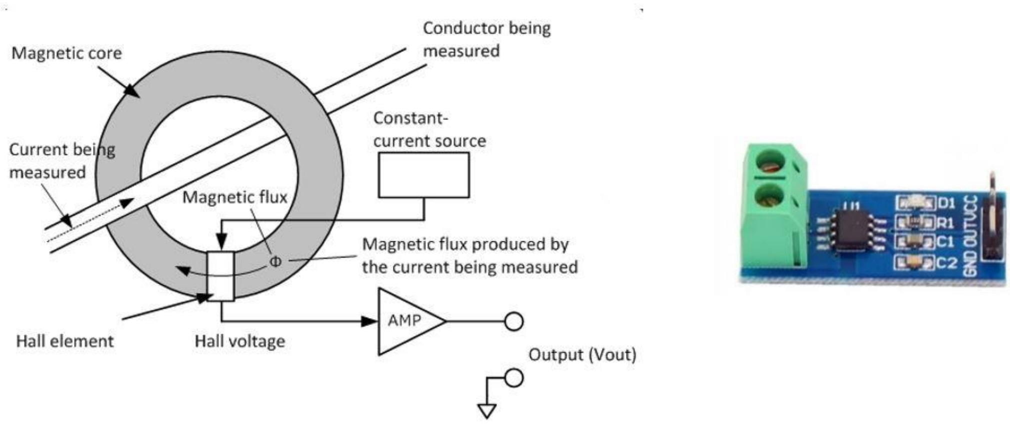


Figure 5. Principle of Hall Element Current Sensor [14][15]

To sum it up, smart features of existing smart sockets are embedded into ordinary electrical appliances to make them smarter while protecting an electrical overload condition. The differences of the state-of-the-arts are summarised in Table 1. Technical gaps exist in terms of the support of wireless mode in both Wi-Fi and mobile network, AI-enabled with data analytics, safety, multi-functional and cost-effective. Furthermore, ACS712 current sensor [15] based on the Hall Effect principle has numerous merits for measuring the current consumption of connected electrical appliances. AC712 can measure both AC and DC current and have numerous applications, including motor control, load detection and management, acting as a switched-mode power supply, and overcurrent fault protection.

Table 1. Comparison of Existing Smart Sockets

Features	Wemo Insight	TP-link HS100	Mi Power Plug
Ease of installation	Yes	Yes	Yes
Control function	Manual / Remote	Manual / Remote	Manual / Remote
Monitoring	Yes	No	No
Controlled power	AC only	AC only	AC only
Wireless Mode	Wi-Fi	Wi-Fi	Wi-Fi
Data trending/analytics	No	No	No
Safety function	Not stated	Not stated	Yes
AI-based fault detection	No	No	No
Multi-functional	No	No	No
Price	Medium	Medium	Medium

RESEARCH METHODOLOGY

The proposed architecture of the iCESocket system is shown in Figure 6. It is based on a three-tier layered architecture design: the acquisition, transport, and cloud layers. The target electrical appliance is plugged into the iCESocket client unit to acquire and upload the acquired data to the cloud servers through wireless connectivity, Wi-Fi, or mobile networks.

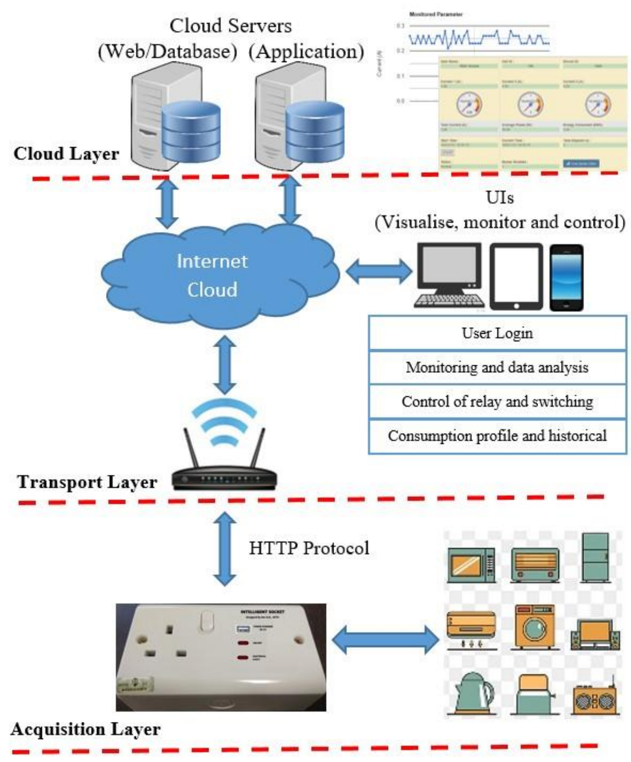


Figure 6. The proposed architecture of the iCESocket system

i. Acquisition Layer

The acquisition layer is essentially a microcontroller-based client unit coded in C with connected sensors and actuators to monitor, control, and detect faults with Wi-Fi or mobile network wireless connectivity and a current sensor to acquire electrical parameters. It is connected to the cloud for real-time monitoring and automated control. The ACS712 module [15] is used as the current sensor to measure the electricity consumption in terms of root-mean-square (RMS) AC current. Since the utilities highly regulate the supply voltage, it is set as 240V to calculate other power parameters. The acquired data is transmitted to the cloud platform using Secured HyperText Transfer Protocol (HTTPS). Besides, the client unit also performs actuating and switching the connected appliance based on the control signal received from the cloud platform via the HTTP protocol, either for optimisation, energy efficiency, or fault protection purposes.

ii. Transport Layer

The transport layer facilitates data transfer by open and standard network protocol on communication devices such as a router, Wi-Fi Access Point, Internet switches and mobile broadband modems. The connection between iCESocket and Cloud Platform is used to transmit the acquired electrical parameters from the client to the cloud or control signals from the cloud to the client unit. In this work, the ESP8266 module [16] connects with Wi-Fi infrastructure routed with an Ethernet network for reliable data connectivity between the iCESocket and cloud platform.

iii. Cloud Layer

The cloud layer consists of various cloud computing servers such as web servers, databases, and application servers. They have collectively named as the cloud platform, allowing authorised users to remote access for monitoring, controlling, and data analysis services. The collected data is stored and analysed for, for instance, anomaly and fault detection using machine learning (ML) algorithms. Once the fault is detected, the actionable information in the control signal will be delivered to the iCESocket client unit to remedy the identified fault.

Hardware Architecture

As shown in Figure 7, iCESocket hardware components consist of an ATMEL microcontroller unit (MCU), a wireless module, a power regulation unit, ACS712 current sensor and protective and switching relays.

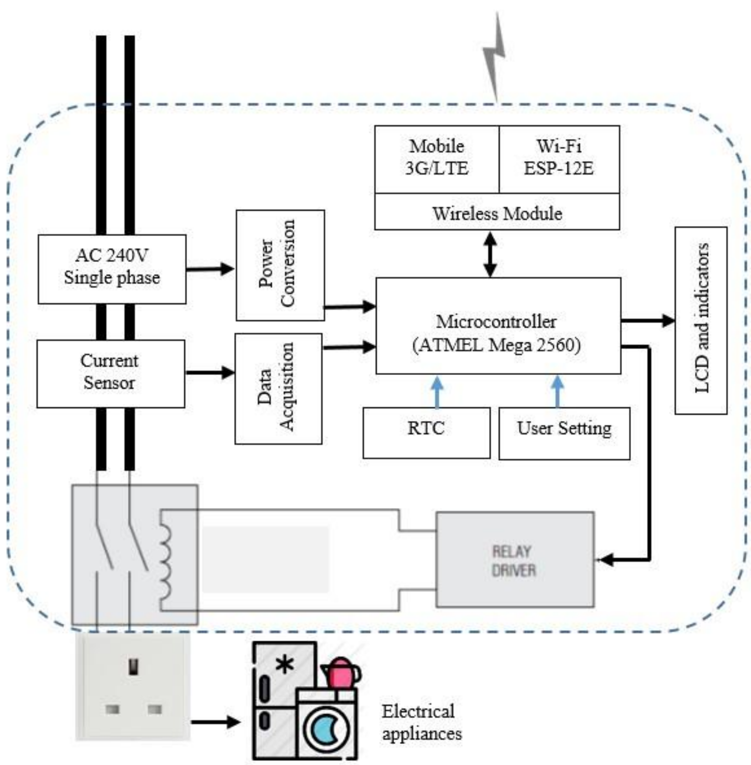


Figure 7. Block Diagram of iCESocket Client Unit

The ATMEL MCU serves as the "brain" of the iCESocket and the interface to ACS712 current sensor, ESP12E Wi-Fi module, 3G/LTE module and protective relays. Powered from direct connection to domestic AC 240V, the power conversion unit is used to convert and regulate the power supply to the iCESocket 's hardware circuit and phone charger socket use. The relays have a faster reaction time (in the range of 1~2ms) than the miniature circuit breaker (MCB) (typical trip time of 20ms). They are used in iCESocket with different roles, namely protective relay and switching relay. The protective relay is used as the primary control of the electricity supply for protection against electrical faults. In contrast, the switching relay is used for the switching function of the electrical appliance connected. Potential electrical faults are detected based on a cloud-based machine learning fault detection algorithm.

Based on Hall Effect, ACS712 current sensor is used to measure the current consumption of the connected appliance. Only authorised users can access and observe the acquired data of various electrical parameters via the cloud platform. A load curve is generated automatically together with other energy parameters of the connected appliance. In this regard, the consumption profile and pattern can be analysed to detect any anomalies in power consumption or appliance's operational failure. Figure 8 depicts the end prototype of iCESocket.

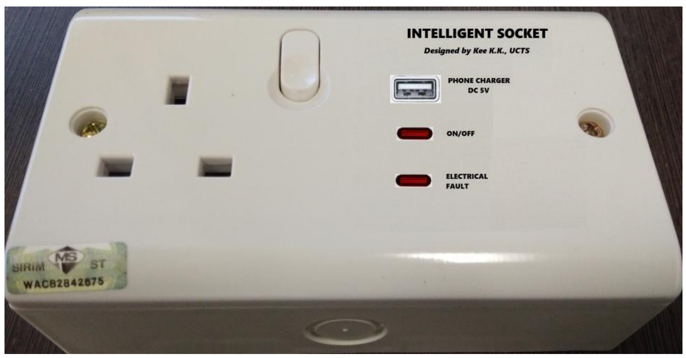


Figure 8. End prototype of iCESocket

Software Architecture

ATMEL MCU is coded with various control features with low-level C language at the hardware level. It is connected with ACS712 Current Sensor to acquire analogue electrical signals and convert them into digital form with timestamps for storage and data analytics of consumption profile and fault detection in the cloud. At the cloud level, the web server and application server are running with high-level Python Machine Learning programs. The platform comes equipped with various GUI dashboard tools which offer easy monitoring and control of connected appliances.

i. Performance Measurement

Precision and accuracy are two important performance metrics used in scientific measurement [17]. Accuracy measures how close an observed value is to the actual value. Precision is repeatability which refers to the closeness of the agreement between the results of successive measurements carried out under specific conditions. The results are usually reported in terms of standard deviation and coefficient of variation (CV) [16]. In this work, the electrical current measurement from the ACS712 current sensor is subject to a series of performance tests for precision and accuracy.

ii. Standard Deviation and Coefficient of Variation

Standard deviation is the degree of deviation of a set of samples from the average value calculated as follows:

$$\sigma = \sqrt{\sum_{n=1}^{N} \frac{(I_{S,n} - \overline{I_{avg}})^2}{N}} \quad (1)$$

Where: σ is Standard deviation, N is the number of samples, $I_{S,n}$ is the measured current value by ACS712 and $\overline{I_{avg}}$ is the average current value sensed by ACS712 (in A).

The coefficient of variation is defined as the standard deviation (σ) divided by the mean (μ). It is expressed by percentage (CV in %).

$$CV\ (\%) = \frac{\sigma}{\mu}\ x\ 100\% \quad (2)$$

Where: the lower of CV indicates good precision and repeatability of measurements [18].

Basically, CV (%) < 10 is very good, 10-20 is good, 20-30 is acceptable, and CV>30 is not acceptable [19] [20].

iii. Mean Absolute Percentage Error (MAPE)

MAPE evaluates the overall differences between the measured and reference values [21]. MAPE can be calculated with the formula shown in Equation (3).

$$MAPE = \left(\frac{1}{N} \sum \frac{|I_{ref} - \bar{I}|}{I_{ref}}\right) \times 100\% \quad (3)$$

Where: N is the number of observations, I_{ref} is the reference (or test) current value (in A), and $\bar{I}$ is the average current value measured by ACS712.

Since MAPE is a dimensionless index, a lower of MAPE indicates a better of its performance [22]. MAPE is a good measure of the accuracy of a sensor. Chang et al. [23] suggested that the measurement's performance is classified as excellent if MAPE is less than 10%, while MAPE between 10-20% is considered acceptable.

RESULTS AND DISCUSSION

For the precision test on ACS712, the measured current readings were repeatedly recorded for 100 samples with different test current settings ranging from 0 to 20.0A. The precision can be determined by statistical analysis of standard deviation. A lower standard deviation indicates good precision of measurement [22]. The coefficient of variation of the samples for each setting is 1.2%. It implies that the ACS712 has good precision.

Meanwhile, the accuracy test of ACS712 was conducted in a laboratory setup. A calibrated Lovato's DMG800 Energy Meter (as test measurement) was used for calibration and benchmarking between the readings of the calibrated instrument and the targeted ACS712 current sensor. The controllable resistive load bank is gradually varied with the known current. Both the measured and test current readings were recorded. Table 2 shows the highest percentage of errors was 4.44%, and MAPE was merely at 1.48%.

Table 2. Comparison of readings between the test current (Iref, A) and the measured current (I, A)

Load setting	Test Current, Iref (A)	Measured Current, I(A)	Error in %
1	0.18	0.17	4.44
2	3.00	3.03	1.00
3	6.00	6.03	0.50
4	8.00	8.08	1.00
5	10.00	10.11	1.10
6	12.00	12.09	0.75
7	14.00	14.12	0.86
8	16.00	16.09	0.56
9	18.00	18.21	1.17
10	20.00	20.68	3.40
		MAPE =	**1.48**

A Scatter plot with the trend line and R^2 (coefficient of correlation) is used for correlation analysis. In a perfectly calibrated instrument, the measured (y-axis) and test (actual, y-axis) values would be the same (i.e. $y = x$ and $R^2 = 1.0$). Based on the results shown in Figure 9 ($y = 1.0217x - 0.0891$, $R^2 = 1.0$ or 0.9996), the measured values differ from the actual values by a low constant percentage of error of 2.17%, which means they are highly correlated. These results further confirm the creditability of the ACS712 current sensor for measuring electrical parameters.

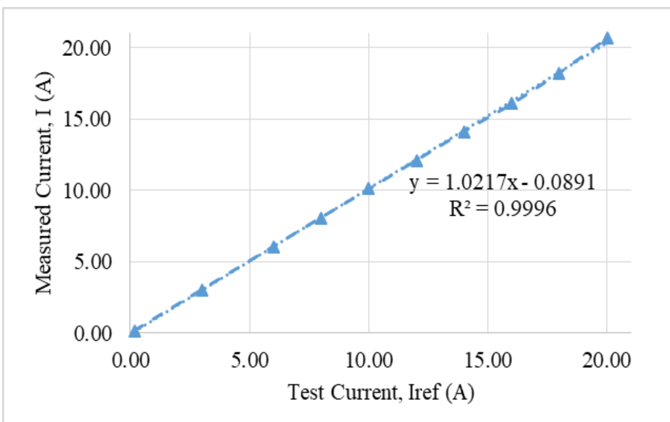


Figure 9. Result of accuracy test

i. Functionality Test

Figure 10 shows the GUI of the administration dashboard of iCESocket. The one-time configuration procedure allows information such as mobile phone number, email, and personal settings to be set before the system is operational.

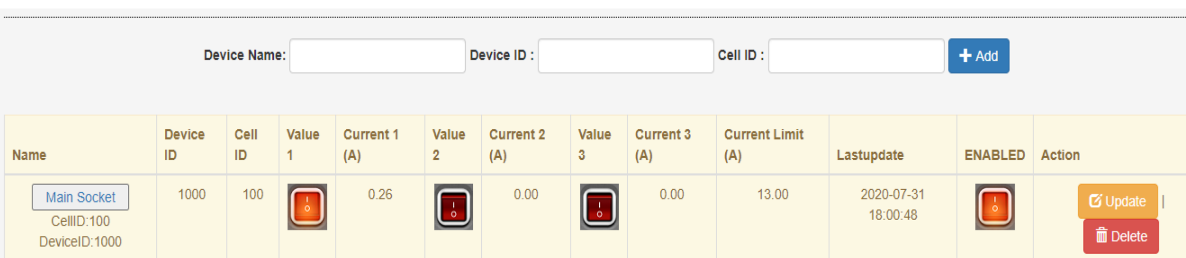


Figure 10. GUI of the administration dashboard

With the iCESocket cloud platform up and running, an authorised user can perform real-time monitoring of the electrical consumption parameters of the connected appliance from the dashboard. Real-time values of the essential electrical parameters measured are displayed and updated every 30 seconds, as shown in Figure 11.

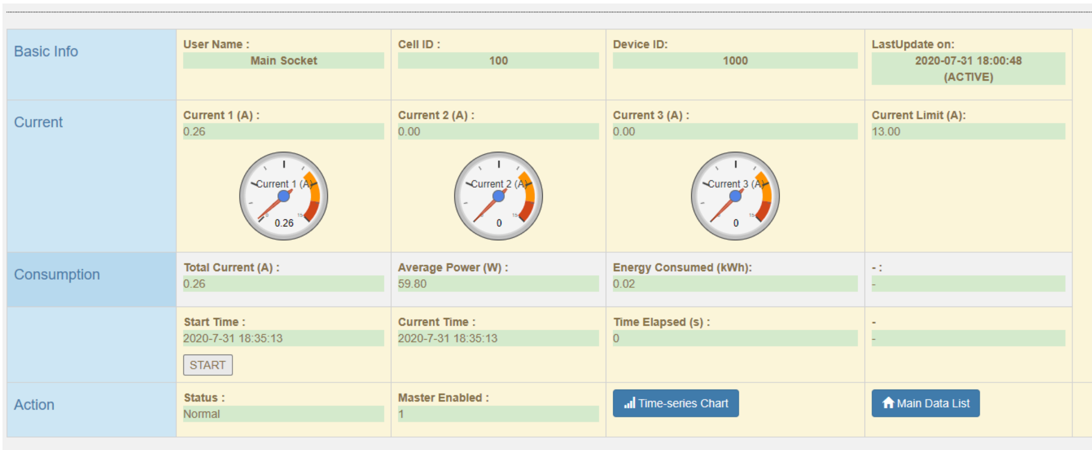


Figure 11. Monitoring Platform of iCESocket

Furthermore, real-time current usage trending data can be visualised as a time-series chart, as shown in Figure The chart serves as a tool for usage pattern analysis that can further improve energy efficiency and anomaly detection.

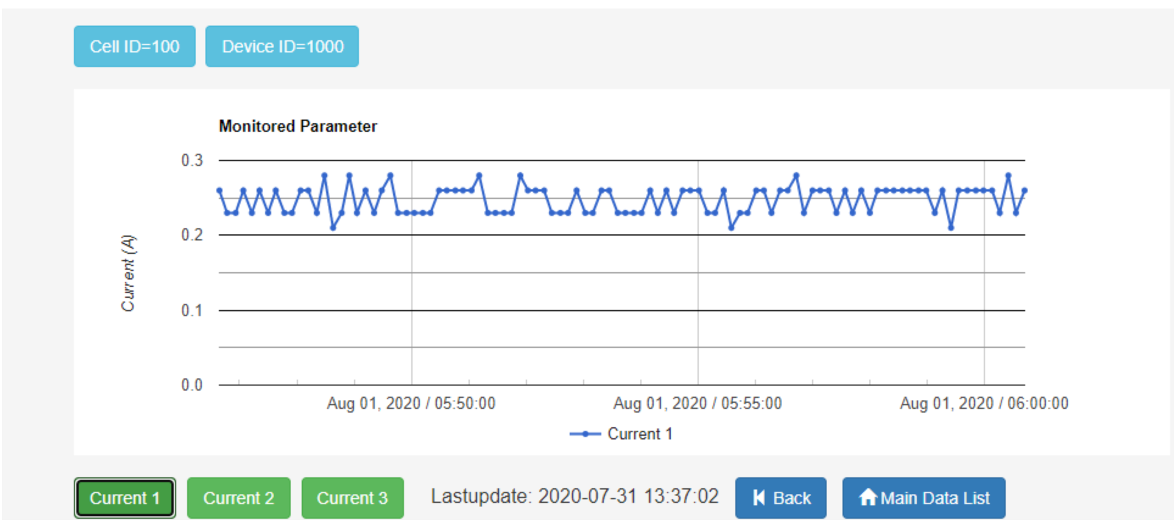
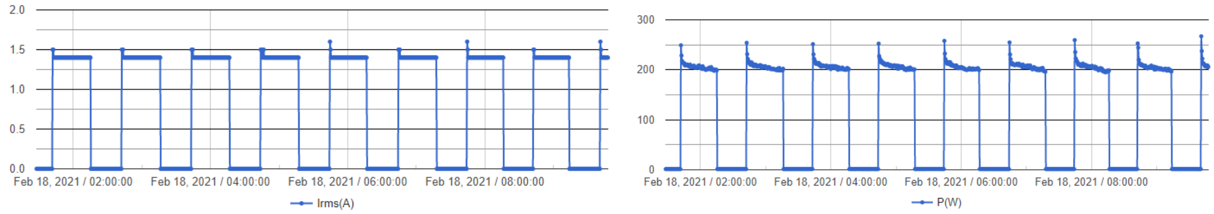


Figure 12. Real-time and historical data and trending

ii. Validation Case Study

For validation in an actual residential use case, iCESocket was installed in a residential terraced house with a single-phase supply from 10 Feb 2021 to 24 Feb 2021, for a duration of 14 days. Wi-Fi mode is adopted for real-time communication between the user and iCESocket. The electrical appliance of interest was a Sharp brand refrigerator with a 385-litre capacity. The experiment was to compile the refrigerator's consumption load curve for analysis and anomaly detection. The result is in line with a residential energy-saving use case. After six hours of operation, the refrigerator's load consumption load curve in periodic current and real power values is recorded, as shown in Figure 13. It is noteworthy that the periodic patterns are due to the cooling cycle of the refrigerator



(a) Load current (b) Power consumption

Figure 13. Load consumption curve of the refrigerator.

Figure 14 highlights the refrigerator's load curve with a suspected anomaly (red circled) occurring from 11:30 am to 1:30 pm. The suspected region shows a different load pattern. In this experiment, the trigger event for the anomaly is carried out by deliberately opening the refrigerator door in high frequency for meal preparation for lunch, or the door was not closed or sealed properly as a consequence of that. It can be deduced that anomaly was due to the unusually frequent opening of the door. Hence, users should be advised to decrease the frequency and period of opening a refrigerator's door to increase energy efficiency. Besides, the door seal may also need to be inspected at regular intervals for potential cost savings due to faulty seal. Notification to the user via SMS and email can automatically execute once the anomaly is detected.

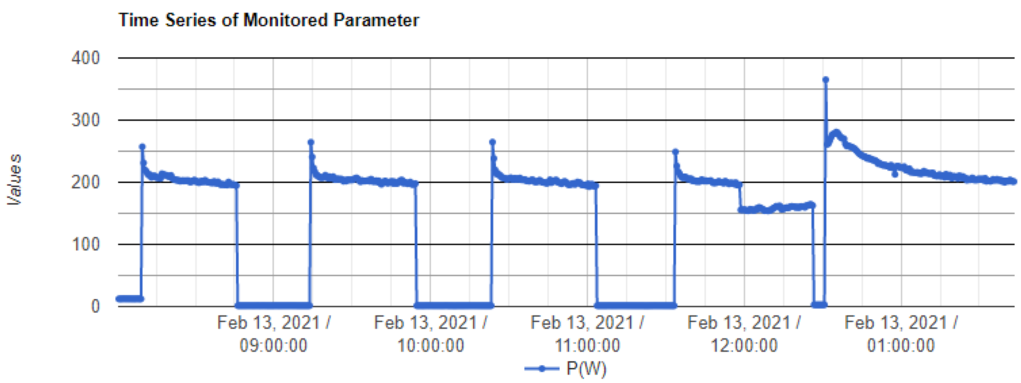


Figure 14. Abnormal load curve of the refrigerator.

In short, iCESocket possesses numerous merits in terms of the ubiquity of wireless technology, safety, cost, scalability and functionality. Due to the modularity of the hardware design, the wireless module can be switched between Wi-Fi and mobile networks (LTE/3G) modes. Essentially, iCESocket supports online monitoring and controlling, and smart analysis of electrical operation conditions using ML algorithms. For instance, electrical faults can be monitored, and anomalies in operational conditions detected. It is therefore useful for predictive maintenance of connected appliances.

CONCLUSION

One of the most significant advantages of Smart Home technology is intelligent and safe energy consumption. This paper presents the design, development, and testing of iCESocket, a smart socket. It is built with a microcontroller, connected to the cloud with Wi-Fi module, measures current consumption with a current sensor and controls electrical appliances on/off with relays. The "smart" feature of iCESocket is achieved by remotely controlling electrical appliance usage by real-time usage pattern data using machine learning algorithms.

Based on the field data collected, the iCESocket show promising results in connecting and monitoring electrical appliances for energy-saving and anomaly detection has been presented. Experimental results show that the smart iCESocket can measure current consumption with up to 93.02 % precision and 96.95 % accuracy. Energy efficiency can then be improved by optimisation based on energy consumption parameters and load curves accessible on a remote dashboard. We envisage this extension with AI can be built into the socket to interpret the load curve and adjust the operational parameters of electrical appliances based on the surrounding conditions such as temperature, brightness, humidity, et cetera, to increase the energy efficiency further. Apart from that, iCESocket enables protection against a faulty event like an overcurrent. Users can set the current limit from the control dashboard. Whenever there is an overcurrent, the socket will automatically disconnect from the power supply. Users would then be notified to check the physical condition of the appliances.

In conclusion, iCESocket is proven to function in the residential smart home application. The work can be extended to the commercial or industrial sectors as well.

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