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Design and Evaluation of Wireless Power Monitoring IoT System for AC Appliances †

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Abstract: The paper is aimed to develop a wireless alternating current (AC) power monitoring module which features the advantage of cost-effectiveness and sufficient reliability for the proposed AC power monitoring Internet of Things (IoT) system. The novel wireless AC power monitoring module consists of both ZMPT101B voltage sensor and ACS712-20 current sensor; a 16-bit analog-to-digital (ADC) ADS1114 with I^2C interface and WeMos D1 Mini Wi-Fi module were integrated for monitoring refrigerator and air conditioner appliances with the ratings of single-phase 110/220 V_{AC}, respectively. First, both analog readings of V/I sensors for AC appliances are converted into data streams in compliance with I^2C (inter-integrated circuit) protocol, and are forwarded to a WeMos D1 Mini Wi-Fi module for the corresponding values of instantaneous electric power and energy, power factor (pf), and frequency well programmed in the built-in ESP8266EX IoT-based microcontroller unit (MCU) based on the well-known AC power fundamentals. All of the important AC power parameters are sent to the ThingSpeak IoT platform through Wi-Fi network. The visualization of voltage, current, electric power and energy, pf, and frequency is illustrated in the ThingSpeak IoT platform. Both close agreement and confidence of the proposed AC power monitoring IoT system for both refrigerator and air conditioner are evaluated with two CM3286-1 AC Power Meters. Taking the commercialized CM3286-1 instrument as reference, the values of mean absolute percentage error (MAPE) for above six electrical parameter readings are all less than 2%. The evaluation results illustrate sufficient closeness of agreement and confidence for the proposed wireless AC power monitoring IoT system for in situ monitoring AC appliances with single-phase 110/220 V_{AC} ratings. Furthermore, the cost of the proposed AC power monitoring module is less than 100 USD, which makes the novel module more cost-effective than commercialized AC power meters which generally cost over 1000 USD. The novelties of the work are the following: (1) the introduction of ADS1114 provides I^2C interface directly for Wi-Fi module to reduce the capital cost of the proposed wireless AC power monitoring module; (2) the sufficient confidence of the proposed AC power monitoring IoT system has been validated with closeness of agreement as compared to the commercialized CM3286-1 AC Power Meters. These make the assessment action of environmental, social, and governance (EGS) for stakeholders much more feasible with the advantages of cost-effectiveness and sufficient confidence.

Keywords: wireless AC power monitoring module; WeMos D1 Mini; ThingSpeak IoT

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1. Introduction

1.1. Background

With the increasing importance of environmental, social, and governance (EGS), companies have been aware of carbon footprint for sustainable production to enact their corporate social responsibility. The annual report of BP pointed out that the global primary energy consumption and electric energy consumption annually increased by 1.51% and 2.52% from 2010 to 2019, respectively [1]. The imposition of lockdowns all over the world for the COVID-19 pandemic since 2020 made the transport-related energy inflict a significant decline, and this cascading effect made the global primary energy consumption decline by 4.5% individually. The effect of lockdowns drastically declines the energy consumption in transportation, industry and commercial sections, and electricity consumption is concurrently counterbalanced by residential section due to blockade effect. However, the abrupt decline in global electric energy consumption was relieved due to accumulated contribution of both promising emerging electricity from renewable energy and the shift toward electrification, especially electric vehicles, apparatus, and appliances, as the effect of the COVID-19 crisis. The statistical information of both global primary energy and electric energy consumption between 2010 and 2020 are drawn in Figure 1a. On the other hand, the annual changes in industrial production index of Taiwan were soaring up to 7.1% and 13.6% in 2020 and 2021 even in the face of the COVID-19 outbreak [2]. The industrial production in Taiwan contributed both the primary energy and electric energy consumption in the country with the increasing trend by 0.46% and 2.78%, respectively. Figure 1b shows both primary energy and electric energy consumption information in Taiwan between 2010 and 2020 [3,4]. Both the growing trend of electrification level for all energy sectors and the migration of renewable energy in electricity generation indicate that the electric power consumption can be a sustainable translation action to mitigate the thread of climate change. Therefore, efficient and cost-effective production and utilization methods of electricity are of increasing significance. These make the power monitoring technologies of electricity more important for monitoring the corresponding carbon footprint of electricity use to efficiently assess the ESG metrics for strategic and management purposes. However, the online electricity monitoring for appliances and production instruments in residential, commercial, and industrial sections is still inadequate. Using commercialized digital multimeter (DMM) and power meters for in situ continuous monitoring is neither cost-effective nor convenient in real practices. These facts motivate us to develop a cost-effective and sufficient reliability alternating current (AC) power monitoring Internet of Things (IoT) system for single-phase AC appliances.

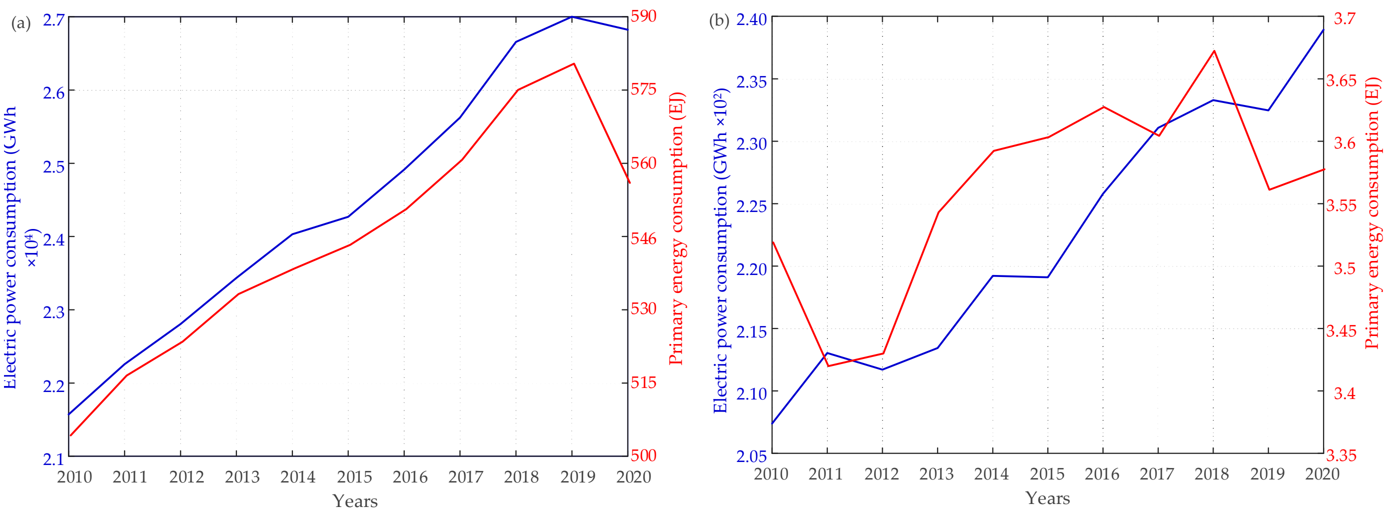

Figure 1. Primary energy and electrical power consumption: (**a**) Global; (**b**) In Taiwan. Source: [1–4].

1.2. Literature Review

To the best of our knowledge, only a few researches have paid much attention to monitoring the AC electric parameters for AC appliances. A Smart Energy Meter (SEM) was proposed by Preethi and Harish to measure the energy consumption and send the corresponding data to personal computer (PC), and deliver the billing through Short Message Service (SMS) of GSM network [5]. Patrono et al. punctually measured the voltage, current, and power parameters of home appliances through the smart plug for monitoring abnormal behavior of elders [6]. The Digital Universal Energy Logger (DUEL) integrating a 10 kΩ potentiometer and a CQ2334 current sensor with an ATtiny85 Microcontroller Unit (MCU) chip was originally proposed by Oberloier and Pearce [7]. Up to 127 DUEL nodes can be simultaneously monitored through an I^2C (inter-integrated circuit) interface and logged on a single SCL/SDA bus by an Arduino Uno. Nayyef and Husein proposed an IoT-based power monitoring and management system based on a Wireless Sensor Network (WSN) [8]. Firstly, both ZMPT101B voltage sensor and ACS712-20 current sensor were integrated with Arduino UNO for AC voltage and current readings, respectively. By programming algorithms, the corresponding electrical power and energy and power factor (pf) were obtained. Finally, all the parameters above were forwarded to the Blynk platform through a NodeMCU ESP8266 Wi-Fi module and Wi-Fi network. In addition, both Blynk- based Graphical User Interface (GUI) and APP were illustrated for smart monitoring. This work monitors most important electrical parameters of AC electricity and only the frequency is not available. Sookasame and Wu presented a real-time power consumption monitoring system in which both AC adaptor and Current Transformer (CT) were integrated with an Arduino Uno and an Ethernet shield to monitor the electrical parameters of voltage, current, electric power and energy [9]. The data were analyzed on the Online Transaction Processing (OLTP) and Online Analytical Processing (OLAP) platforms. Their work features the applications of Android Operating Systems developed to control utilities and to analyze energy consumption for the related electricity bill. Both pf and frequency were not available in their work. Sutisna et al. integrated both step-down voltage transformer and YHDC SCT-013 CT with Arduino Uno. The measured voltage and current readings were well validated with the instruments of Kyoritsu KEW 6315 and Hioki 328-20, and the results showed the error tolerance of $\leq$5% [10]. Finally, the measured results were illustrated in the self-development intranet through 3G mobile communication network. However, both voltage and current measurement instruments are not convenient and cheap for in situ observation. A smart wireless IoT-based energy metering system was addressed by Chowdary et al., which aggregated both ZMPT101B voltage sensor and STC013-30 current sensor, an Arduino Mega 2560 R3 and ZigBee S2, and simply delivered electric consumption for billing [11]. Ramelan et al. presented a wireless AC power monitoring module by integrating both ZMPT101B voltage sensor and STC013-30 current sensor with an Arduino Uno with a RoLa shield [12]. The visualization of voltage, current, and power readings was illustrated in the ThingSpeak IoT platform through the self-developed RoLa communication network. Therefore, the other AC electrical parameters such as pf, electric energy and frequency are not available in their work. Hasan et al. presented a wireless AC electricity monitoring system in which both step-down transformer and STC013-30 current sensor were first integrated with an Arduino Uno and an ESP8266 Wi-Fi module [13]. The visualization for the all readings of voltage, current, and electric energy was illustrated in the ThingSpeak IoT platform through a Wi-Fi communication network. However, the corresponding electric power, pf, and frequency parameters are not found in their work. With the increase in sensing devices, integration of multiple AC power monitoring devices with compact WiFi devices such as ESP32 or WeMos D1 Mini modules in compliance with series communication protocol is of increasing importance. A commercially available PZEM-004t power energy meter integrated with raspberry PI 3 to monitor and control electric loads for energy conversion was addressed by Limprapton et al., which offered the voltage, current, electric power and energy [14]. Varela-Aldás et al. used a M5Stack Core ESP32 IoT platform to integrate two PZEM-004t V3.0 power energy meters and developed a web-based and mobile APP applications for AC electric parameters monitoring system which was validated with the Gen 2 Vue Energy Monitor device with the accuracy in electric power and energy over 1.95% and 0.81%, respectively [15]. In the previous work, a compact and sufficient reliability AC power monitoring module with a ZMPT101B voltage sensor and an ACS712-20 current sensor were integrated with an ATMega328 MCU to monitor the electrical parameters of voltage, current, electric power and energy, and pf [16]. The finalized wireless monitoring AC power device was implemented by integrating the self-developed AC monitoring module with a WeMos D1 Mini module with the Tx/Rx interface of Universal Asynchronous Receiver/Transmitter (UART) communication protocol. However, the algorithm for both electric power and energy as well as pf were conducted by the ATMega328 MCU and the calculation of AC frequency was not developed in this work. In addition, the MCU in the WeMos D1 Mini was only in charge of data transmission and not used efficiently. Therefore, this work proposes a brand-new wireless AC power monitoring device by directly integrating WeMos D1 Mini module with an inter-integrated circuit (I^2C)-interface V/I sensing module in which 16-bit analog-to-digital converter (ADC) ADS1114 directly converts the analog readings of both ZMPT101B voltage sensor and ACS712-20 current sensor in compliance with I^2C protocol. With the introduction of the ADS1114 ADC device featuring I^2C interface, the WeMos D1 Mini module can read the observation of both AC voltage and current signals and conduct the calculation of the associated electric power and energy, pf and frequency. This design configuration will work without the ATMega328 MCU. The proposed configuration makes it more compact and cost-effective. The review results are summarized in Table 1. The wireless AC power monitoring module only using both voltage and current sensors, an ADS1114 ADC and an ESP8266EX IoT-based MCU, to provide the above AC electric parameters through the I^2C protocol is the novelty of the work. This makes the assessment action of ESG much more feasible and cost-effective.

1.3. Structure Organization

The remainder of this paper is organized as follows. First, the system design and the related AC power theory are described in Section 2. Section 3 illustrates the design and implementation of the novel wireless AC monitoring module in the proposed wireless AC monitoring IoT system and visualization of voltage, current, electric power and energy, pf, and frequency in the ThingSpeak IoT platform. The in situ evaluations are also illustrated in Section 3. Finally, brief conclusions and future works are presented in Section 4.

2. Materials and Methods

Figure 2 shows the proposed wireless AC power monitoring IoT system for AC appliances, consisting of an AC/DC rectifier, a WeMos D1 Mini Wi-Fi module and an I^2C-compatible AC power monitoring device by integrating both ZMPT101B voltage sensor and ACS712-20 current sensor with a two-channel 16-bit ADC ADS1114 module. First, an ADS1114 ADC module aggregates both analog readings of both voltage and current sensors and converts the sensing data into data streams complying with I^2C protocol. The live data are forwarded to WeMos D1 Mini through the I^2C interface. A built-in MCU in the WeMos D1 Mini Wi-Fi module performs the well-programmed algorithms for the corresponding electrical power and energy, pf, and frequency. The observation of all the above six electrical parameters is displayed in a 1.54" FTF display with SPI interface and further sent to the ThingSpeak IoT system via Wi-Fi network.

Table 1. Comparisons for AC power monitoring technologies.

Item	Electrical Parameters						Sensing Layer		Communication. Layer	Information/ App Layer	Ref.
	Voltage (V)	**Current (A)**	**Power (W)**	**Electricity (Wh)**	**pf**	**Freq. (Hz)**	**Sensors**	**Processor/ MCU**			
1	√	√	√	√	×	×	Smart Energy Meter	ARM7	ZigBee	PC/SMS	[5]
2	√	√	√	×	×	×	Voltage/Current sensors	Cloud Building Bolck (CBB)	WiFi, Bluetooth, GPRS, 3G/4G	Personal Data Capturing System	[6]
3	√ (0–300)	√ (0–50)	×	×	×	×	10 kΩ potentiometer CQ2334 current sensor	ATTiny 85 chip/ Arduino Uno	DUEL (I^2C)	×	[7]
4	√ (0–250)	√ (0–20)	×	×	×	×	ZMPT101B voltage sensor ACS712 current sensor	Arduino Uno NodeMCU	WiFi	Blynk GUI/ Blynk APP	[8]
5	√ (0–230)	√ (0–100)	√	√	×	×	AC adaptor Current transformer (CT)	Arduino Uno Ethernet sshield	Ethernet	OLTP/OLAP APP	[9]
6	√ (0–240)	√ (0–13)	√	√	√	×	Step-down transformer YHDC SCT-013 CT	Arduino Uno	3G Lan	Intranet	[10]
7	√ (0–250)	√ (0–30)	√	×	×	×	ZMPT101B voltage sensor ACS712 current sensor	Arduino Mega/ ZeeBee S2	ZeeBee	Intranet	[11]
8	√ (0–250)	√ (0–20)	√	×	×	×	ZMPT101B voltage sensor ACS712 current sensor	Arduino Uno/ LoRa Shield	RoLa	ThingSpeak IoT	[12]
9	√ (80–260)	√ (0–100)	√	√	×	×	PZEM-004t	Raspberry Pi3	WiFi	Intranet	[13]
10	√ (0–240)	√ (0–20)	×	√	×	×	Step-down transformer ACS712 current sensor	Arduino Uno/ ESP8266 WiFi	WiFi	ThingSpeak IoT	[14]
11	√ (80–260)	√ (0–100)	√	√	√	√	PZEM-004t V3.0	M5Stack Core2 ESP32	WiFi	ThingSpeak IoT Mobile APP	[15]
12	√ (0–250)	√ (0–5/20)	√	√	√	√	ZMPT101B voltage sensor ACS712 current sensor	ATMega 328 WeMos D1 Mini	WiFi	ThingSpeak IoT	[16]
13	√ (0–250)	√ (0–5/20)	√	√	√	√	**ZMPT101B voltage sensor ACS712 current sensor (ADS1114 ADC)**	**WeMos D1 Mini**	**WiFi**	ThingSpeak IoT	proposed

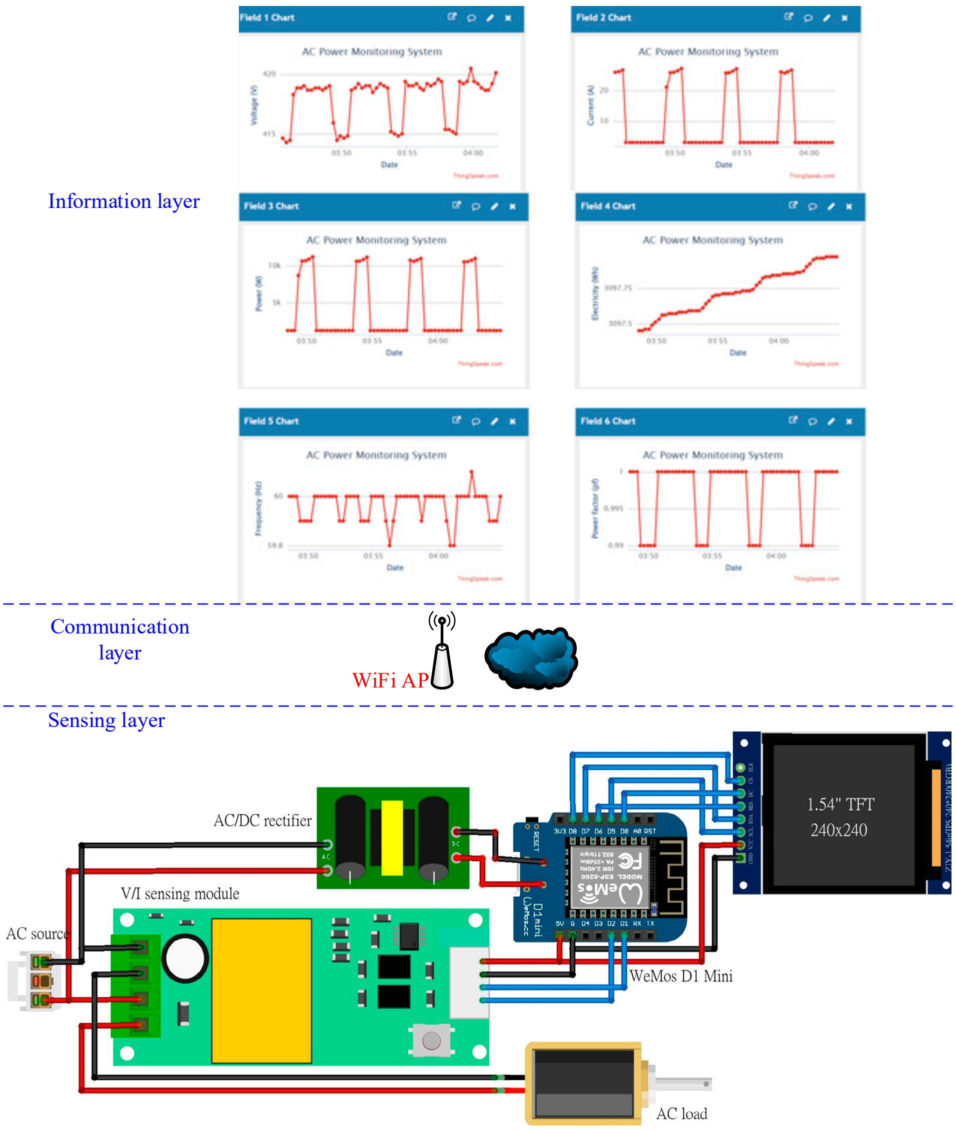

Figure 2. Schematic of proposed AC power monitoring IoT System.

2.1. Fundamental Principles of AC Power

Consider a linear electric circuit consists of an AC power supply with a branch voltage and current which are, respectively, expressed as

$$v_{\mathrm{AC}}(t) = V_{\max}\cos(\omega t + \theta_v) \tag{1}$$

and

$$i_{\mathrm{AC}}(t) = I_{\max}\cos(\omega t + \theta_i), \tag{2}$$

where $V_{\max}$ and $I_{\max}$ are the maximum amplitude of voltage and current signals in volt (V) and ampere (A), θ_v and θ_i are their corresponding phase angle in degree, and $\omega = 2\pi f$, in which f in hertz (Hz) is the frequency of AC electricity. The instantaneous power is defined as

$$p_{\mathrm{AC}}(t) = v_{\mathrm{AC}}(t)i_{\mathrm{AC}}(t) = \frac{V_{\max}I_{\max}}{2}[\cos(2\omega t + \theta_v + \theta_i) + \cos(\theta_v - \theta_i)]. \tag{3}$$

The corresponding average power is then obtained by

$$P_{\text{Ave}} = \frac{1}{T}\int_{t_0}^{t_0 + T} p_{\text{AC}}(t)dt = \frac{V_{\max}I_{\max}}{2}\cos(\theta_v - \theta_i), \quad (4)$$

where $T = 2\pi/\omega$ is the period of the voltage and current. The effective values of periodical AC voltage and current are defined in the form of root mean square (RMS) and are obtained as

$$V_{\text{RMS}} = \sqrt{\frac{1}{T}\int_{t_0}^{t_0 + T} v_{\text{AC}}^2(t)dt} = \frac{V_{\max}}{\sqrt{2}} \quad (5)$$

and

$$I_{\text{RMS}} = \sqrt{\frac{1}{T}\int_{t_0}^{t_0 + T} i_{\text{AC}}^2(t)dt} = \frac{I_{\max}}{\sqrt{2}}. \quad (6)$$

The average power through mathematical derivation is obtained as

$$P_{\text{Ave}} = V_{\text{RMS}}I_{\text{RMS}}\cos(\theta_v - \theta_i), \quad (7)$$

where $V_{\text{RMS}}I_{\text{RMS}}$ is the apparent power of AC electricity in volt-ampere (VA) or kilo VA (kVA). The power factor (pf) is defined as the ratio of the average power and the apparent power and is provided by

$$\text{pf} = \frac{P_{\text{Ave}}}{V_{\text{RMS}}I_{\text{RMS}}} = \cos(\theta_v - \theta_i), \quad (8)$$

where the angle $\theta_v - \theta_i$ is the angle shift between the voltage and the emerged current caused by the load impedance, i.e., the phase angle of the load impedance. Then, the electric energy is defined as

$$w_{\text{AC}}(t) = \int p_{\text{AC}}(t)dt. \quad (9)$$

Therefore, the corresponding electric parameters such as electric power and energy as well as pf can be simultaneously obtained as both voltages and current values are visualized. Finally, the frequency of AC electricity can be obtained by counting the number of the maximum amplitude of voltage signal in cycles per second [17].

2.2. Hardware Design for Wireless AC Power Monitoring Module

A novel AC power monitoring module with the I^2C series communication protocol, consisting of a ZMPT101B voltage sensor, a ACS712-20A current sensor, and an ADS1114 16-bit ADC module, is developed as shown in Figure 3a. The ZMPT101B voltage sensor is a current-type voltage transformer for AC voltage reading with high galvanic isolation and sufficient accuracy [18]. A current-limited resistor and a sampling resistor are designed to keep the input and output current rated ratio of 2:2 mA which the input current was set up by the limiting resistor R_1 in series and the sampling resistor of 100 Ω in parallel to acquire the output voltage. The analog output voltage is then converted by a two-stage inverting OP amplifier at the voltage rating of 0–5 V. The corresponding circuit schematic of voltage sensor module is drawn in Figure 3b. A commercially available ACS712 current sensor is an AC/DC current sensor which consists of a linear Hall sensor circuit with a copper conduction path to generate a magnetic field and the built-in Hall IC converted into a proportional voltage [19]. The related circuit of the current sensing module with a ACS712ELCTR-20A-T current sensor of ±20 A rating current is well designed and shown in Figure 3c. ADS1114 module is a 16-bit delta-sigma (ΔΣ) ADC featuring high-precision and low-power consumption, and series communication protocol of I^2C interface [20]. Both analog outputs of voltage and current sensor, respectively, are read by A_{IN0} and A_{IN1} inputs of ADS1114 module, and are then output in the I^2C interface protocol. The I^2C-compatible AC V/I sensing module is illustrated in Figure 3a. The main technical parameters of both ZMPT101B voltage sensor and ACS712 current sensor are tabulated in Table 2. In fact, Wi-Fi network is one of the most available communication platforms in the residential, commercial, and industrial sections. In real practices of application fields, Wi-Fi Access Point (AP) is more available than others without additional construction. Therefore, the acquired readings of instantaneous voltage and current are sent to the following WeMos D1 mini Wi-Fi module through I^2C communication protocol as shown in Figure 3d. The WeMos D1 mini module is a successor to the ESP8266EX-based IoT MCU featuring the integrated low-cost, low-power System on a Chip (SoC) microcontrollers integrating with 4M/16M-byte flash memory and Wi-Fi module [21]. According to the Nyquist–Shannon sampling theorem, the sampling frequency for instantaneous readings of both voltage and current should be at least twice greater than or equal to the frequency (50 or 60 Hz) of AC electricity. In practical applications, a ten times sampling rate is recommended for better resolution of signal readings. Therefore, the sampling period of 2 ms and 1.67 ms are suggested for 50 and 60 Hz AC power systems, respectively.

The sampling period for the voltage and current reading of the AC monitoring module is programmed in an interval of 1.67 ms with the sampling number of 167 for 60 Hz. Based on the above derivation of AC power basics, the corresponding RMS values of voltage and current, instantaneous and average power, accumulated consumption of electric energy, and pf are then calculated based the voltage and current readings. In addition, the frequency of AC electricity can be found in cycles per second by the code programming.

2.3. Firmware Design for Wireless AC Power Monitoring IoT System

A commercially available WeMos D1 Mini Wi-Fi module contains a built-in ESP8266EX IoT-based MCU and is programmable under the open-source Arduino Integrated Development Environment (IDE) which supports the languages C and C++ with specified rules of code structure. First, the readings of both ZMPT101B voltage sensor and ACS712 current sensor integrated with ADS1114 ADC module are developed under Arduino IDE environment. Based on the above derivation of AC power fundamentals, the corresponding RMS values of voltage and current, instantaneous and average power, accumulated consumption of electric energy, pf, and frequency are then calculated based on the voltage and current readings. In order to illustrate the observation period in per minute in the ThingSpeak IoT platform, the RMS values of voltage and current are defined as

$$X_{\mathrm{RMS}}(kT_{\mathrm{O}}) = \sqrt{\frac{1}{n}\sum_{j=1}^{n} x_j^2(jT_{\mathrm{S}})}, \tag{10}$$

where $X = V, I$, $X_{\mathrm{RMS}}(kT_{\mathrm{O}})$ is the k^{th} RMS values of voltage or current, T_{O} is the observation period in the ThingSpeak IoT platform, $x = v_{\mathrm{AC}}, i_{\mathrm{AC}}$, $x_j(jT_{\mathrm{S}})$ is the j^{th} values of voltage or current, T_{S} is the sampling period of ESP8266EX MCU which is 1.67 ms, i.e., 600 samples per second (SPS) for 60 Hz or 2 ms, i.e., 500 SPS for 50 Hz, and n is the sampling number for a sinusoidal signal, which is n = 3600 for 60 Hz or n = 3000 for 50 Hz. The ADS1114 ADC includes a Programmable Gain Amplifier (PGA) which allows DC voltage input ranging from ±256 mV to ±6.144 V with the advantage of precise large- and small-signal measurements. The ADS1114 performs A/D conversion rate up to 860 SPS. Having the k^{th}—minute RMS readings of voltage and current, electric power (in W) and energy (in Wh) are, respectively, obtained as

$$P_{\mathrm{Ave}}(kT_{\mathrm{O}}) = V_{\mathrm{RMS}}(kT_{\mathrm{O}}) I_{\mathrm{RMS}}(kT_{\mathrm{O}}) \mathrm{pf} \tag{11}$$

and

$$w_{\mathrm{AC}}(kT_{\mathrm{O}}) = \sum_{k=0}^{k} \frac{P_{\mathrm{Ave}}(kT_{\mathrm{O}})}{60} \tag{12}$$

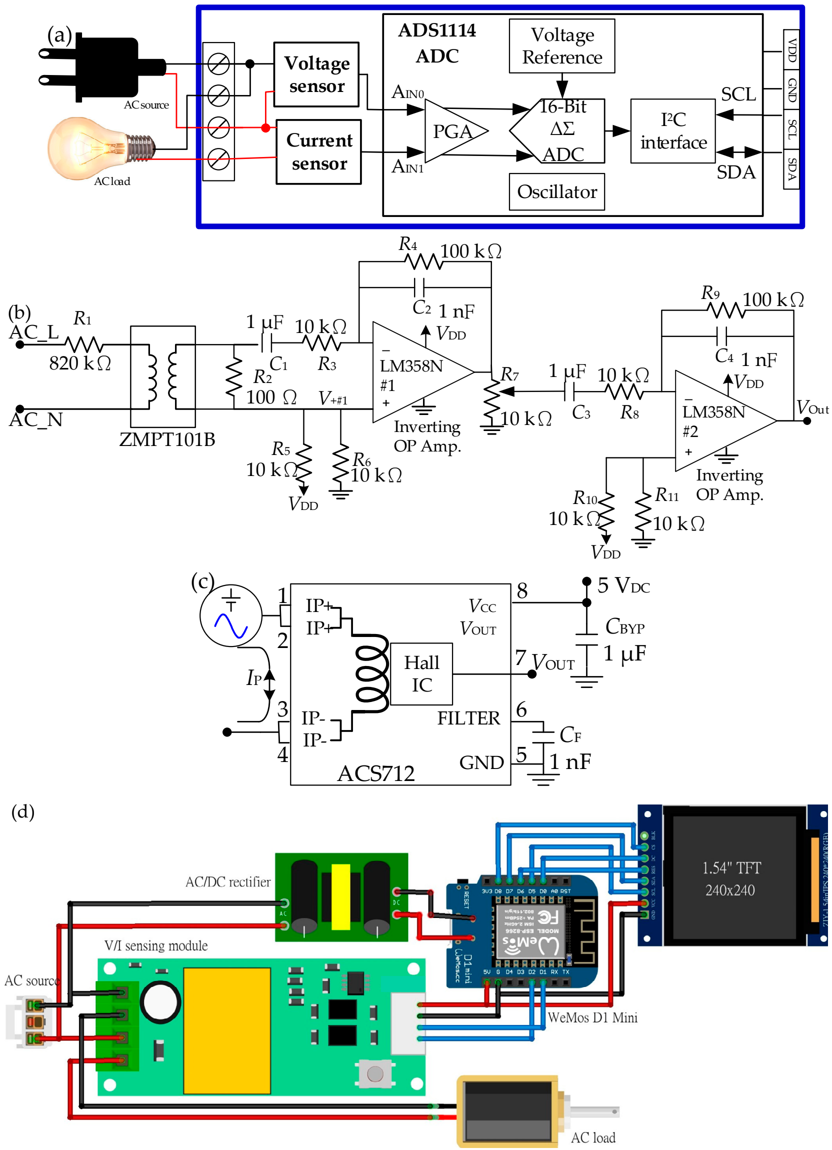

Figure 3. Circuit schematics: (**a**) AC V/I sensing module; (**b**) Voltage sensing module; (**c**) Current sensing module; (**d**) Wireless AC power monitoring module.

After the installation by entering the json file of ESP8266 core into the field of the "Additional Boards Manager URLs" and selecting an ESP8266 Boards version for the ESP8266-based board, the software for the proposed wireless AC power monitoring module was developed in the same coding configuration in the same Arduino IDE. All the data of online voltage, current, electric power and energy, pf, and frequency can be read through Wi-Fi network by WeMos D1 Mini module and Wi-Fi AP. Finally, all the observation data of electrical parameters including voltage, current, power, electric energy and pf are further sent to the ThingSpeak IoT platform through a Wi-Fi access point (AP) gateway on site, with its SSID and password checked in advance and coded in the software program later. The ThingSpeak IoT platform is an open-source IoT Application Program Interface (API) which conveniently provides an IoT platform to store and retrieve sensing data using the application layer Hypertext Transfer Protocol (HTTP) and the Message Queuing Telemetry Transport (MQTT) publish–subscribe network protocol over the Internet. Both HTTP and MQTT run over TCP (Transmission Control Protocol) connections and are both client–server in architecture. HTTP servers directly respond to requests from clients and MQTT allows messages to pass in both directions between clients and servers. HTTP deals with requests one at a time, with overhead such as authentication being carried out each time. ThingSpeak

IoT platform offers both HTTP and MQTT connection function for IoT systems to transmit data from sensor to back-end. The MQTT protocol features the message transmission in both directions between clients–severs and clients and the minimization of data overhead for each package. The proposed wireless AC power monitoring module serves a client and ThingSpeak IoT platform serves a server in charge of data storage and observation requests form the sensing client. Furthermore, the live data streams in the cloud can be directly visualized by the ThingView APP and further aggregated, visualized and analyzed using MATLAB software. The flowchart for the wireless AC power monitoring module is drawn in Figure 4.

Table 2. Main technical parameters of voltage and current sensors.

Sensor Type	Main Technical Parameters				
	Input Voltage (V)	Input Current (A)	Output Voltage (V)	Output Current (mA)	Operating Temperatur (°C)
ZMPT101B voltage sensor	0–1000	0–0.01	0–1	0–10	40–60
ACS712-20 current sensor	0–20	±20	0–1	0–50	−25–60

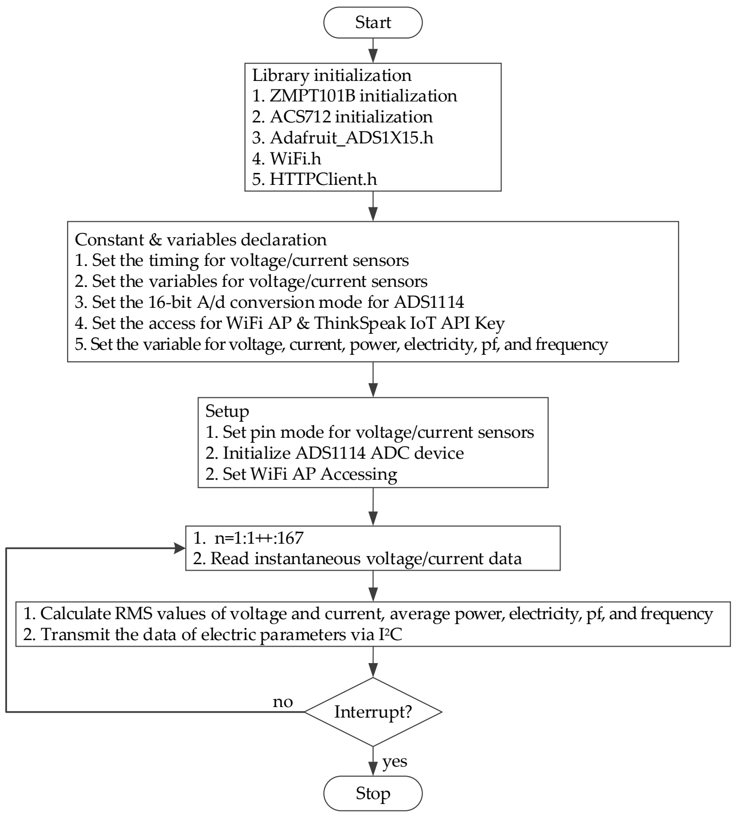

Figure 4. Programming flowchart for wireless AC power monitoring module.

3. Results

After integrating the novel wireless AC power monitoring module including ZMPT101B voltage sensor and ACS712 current sensor, an ADS1114 ADC device, and a WeMos D1 mini Wi-Fi module, the RMS readings of both voltage and current for the voltage and current sensors were calibrated with two sets of CM3286-01 AC Clamp Power Meter, which is a high-performance, true-RMS digital multimeter (DMM) for measuring AC voltage and current with the basic accuracy of (Voltage: ±0.7% rdg. ± 3 dgt.; current: ±1.3% rdg. ± 3 dgt.; Power: ±2.0% rdg. ± 7 dgt.) [22]. The observation of voltage, current, power, pf, and frequency from the CM3286-01 AC Clamp Power Meter can be logged to smartphone through Bluetooth and saved in CSV format. The recording data were further edited in Excel and the corresponding electric energy was accumulated with the multiplication of power and time. The evaluation processes were conducted in a 24 h continuous measurement for refrigerator and air conditioner in the office (H716) of the Computer Science and Information Engineering, Da-Yeh University in Taiwan and the results were forwarded to ThingSpeak IoT platform. Finally, the data were exported by clinking the "Data Import/Export" icon in the ThingSpeak IoT platform and analyzed on the MATLAB environment.

In order to double-check the close agreement, confidence, and reliability of the proposed AC power monitoring system compared to commercialized AC power meter, both voltage and current sensing readings as well as the calculated electrical power and energy, pf, and frequency were calibrated with two commercially available CM3286-01 AC Clamp Power Meter instruments for both refrigerator and air conditioner, respectively. The associate processes are described as follows.

3.1. In Situ Monitoring Results of Electrical Parameters for Refrigerator

The observation of the proposed wireless AC monitoring module and two CM3286-1 AC Clamp Power Meter instruments at a 1 min sampling period in a continuous 24 h measurement is depicted in Figure 5. Figure 5a illustrates that the sensing voltage values are generally lesser than the readings of those of CM3286-1 AC Clamp Power Meter instrument. However, the difference between them is less than $\pm$ 3 V. As shown in Figure 5b, both readings of ACS712 current sensor and CM3286-1 AC Clamp Power Meter instrument are in close agreement. This makes the calculated results of electric power and electricity for the proposed wireless AC power monitoring module in close agreement with these readings of CM3286-1 AC Clamp Power Meter instrument as shown in Figure 5c,d. In addition, the corresponding data of the calculated pf and the readings of measurement instrument are really in concurrence as shown in Figure 5e. Figure 5f illustrates that the frequency readings of CM3286-1 AC Clamp Power Meter instrument are more stable than the calculated ones of the proposed wireless AC power monitoring module. However, the difference between them is less than $\pm$1 Hz.

Taking the measurement results of CM3286-1 instruments as references, the relative difference between the proposed AC monitoring IoT system and CM3286-1 AC Clamp Power Meter instruments is defined as

$$e_j^n = x_j^n - \hat{x}_j^n \tag{13}$$

where x_j^n and $\hat{x}_j^n$ are the j^{th} measurement values of the proposed AC power monitoring module and two CM3286-1 AC Clamp Power Meter measurement instruments, $j = v_{\text{AC}}, i_{\text{AC}}, p_{\text{AC}}, w_{\text{AC}}, f_{\text{AC}}$, pf. The performance index of mean absolute error (MAE), mean absolute percentage error (MAPE), and root mean square error (RMSE) and for close-agreement analysis are defined as [23]

$$\text{MAE} = \frac{1}{N}\sum_{n=1}^{N}\left|x_j^n - \hat{x}_j^n\right|, \tag{14}$$

$$\text{MAPE} = \frac{100\%}{N}\sum_{n=1}^{N}\frac{\left|x_j^n - \hat{x}_j^n\right|}{\hat{x}_j^n} \tag{15}$$

and

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(x_j^n - \hat{x}_j^n\right)^2}, \tag{16}$$

where N is the observation number. As shown in Figure 6a, the reading voltage difference between ZMPT101B voltage sensor and CM3286-01 AC Clamp Power Meter ranges from −2.4140 V to 0.2434 V. Considering the basic accuracy voltage reading CM3286-1 AC meter with the full scale of 600 V_{AC}, the reading uncertainty is ±4.2 V, and the digit uncertainty ±3 dgt. is ±0.3 V; therefore, the total uncertainty of voltage measurement for CM3286-1 AC meter is ± 4.5 V. The voltage reading of the proposed AC power monitoring system is totally acceptable as compared with the commercially available CM3286-1 AC Power Meter. The corresponding MAE and RMSE values are 1.1295 V and 1.3498 V, respectively. The MAPE value is 0.9283%, which can be an effective measure of close agreement with the CM3286-1 AC Power Meter instrument. These results means that the ZMPT101B voltage sensor in the proposed AC power monitoring module has enough confidence, like the commercialized CM3286-1 AC Power Meter instrument in the practical operation environment with the close agreement of ≤ ±1%. Figure 6b illustrates the current readings of the ACS712-20 current sensor in the proposed AC power monitoring module and the CM3286-1 AC Power Meter instrument in close agreement, and the current difference between them as well. Taking the current measurement results of the CM3286-1 AC Power Meter instrument as references, the difference comparisons for the ACS712-20 current sensor are in the range of −0.0206–0.0093 A. Both MAE and RMSE values are 0.0030 A and 0.0059 A, respectively; furthermore, the corresponding MAPE value is 0.7453%. The basic accuracy of AC current for the CM3286-01 AC Clamp Power Meter is ±1.3% rdg. ±3 dgt., and the full scale is 600 A_{AC}; therefore, the reading uncertainty is ±7.8 A, and the digit uncertainty ±3 dgt. is ±0.3 A; therefore, the total uncertainty of current measurement for CM3286-1 AC meter is ± 8.1 A. From the above close agreement analysis for current measurement, the ACS712 current sensor has sufficient performance for current measurement such as the commercialized instrument of CM3286-01 AC Clamp Power Meter in the practical operation environment with close agreement of ≤ ±1%. As shown in the datasheet of CM3286-01 AC Clamp Power Meter, the basic power accuracy for single-phase AC power measurement is ±2.0% rdg. ±7dgt. for full scale range between 0.005 kW and 360.0 kW with reading uncertainty of ±7.2 kW, the digit uncertainty ±7 dgt. of ±0.7 kW and the total uncertainty of power measurement for CM3286-1 AC meter of ±7.9 kW. All the power observations and the corresponding power difference between the proposed AC power monitoring module and the CM3286-1 AC Power Meter instrument are depicted in Figure 6c, which shows a close agreement between them with the power difference in the range of −5.0695–0.8641 W. Therefore, the MAE and RMSE values are 0.6987 W and 1.3574 W, respectively. Moreover, the corresponding MAPE value for power observation is 1.4586%. From the above closeness of agreement analysis for electric power, the proposed AC power monitoring module has sufficient performance for power measurement such as the commercialized instrument of CM3286-01 AC Clamp Power Meter in the practical operation environment with close agreement of ≤ ±2%. In addition, the electrical energy observations of both proposed AC power monitoring module and the CM3286-1 AC Power Meter instrument as depicted in Figure 6d show the difference in the range of −0.8520–0.0942 Wh, which makes the corresponding MAE and RMSE values of electric energy 0.4274 Wh and 0.3339 Wh, respectively, and the corresponding MAPE value being 0.0807%. Figure 6e furthermore illustrates their power factor values, which shows the difference in the range of −0.0069–0.0071; the corresponding MAE, RMSE, and MAPE values of pf are 0.0025, 0.0030, and 0.4597%, respectively. As shown in Figure 6f, the frequency observations of both proposed AC power monitoring module and the CM3286-1 AC Power Meter instrument illustrate the frequency difference between them, ranging from −0.0600 Hz to 0.0600 Hz. The corresponding MAE, RMSE, and MAPE values of frequency readings are, respectively, 0.0302 Hz, 0.0348 Hz, and 0.0504%. The closeness of agreement analysis results between the proposed AC power monitoring system and the CM3286-1 AC Power Meter instrument for monitoring AC power of refrigerator are listed in Table 3. The results reveal that these relative differences are all acceptable as compared to the accuracy of commercialized AC power instruments. This illustrates the proposed AC power monitoring module with sufficient reliability and confidence.

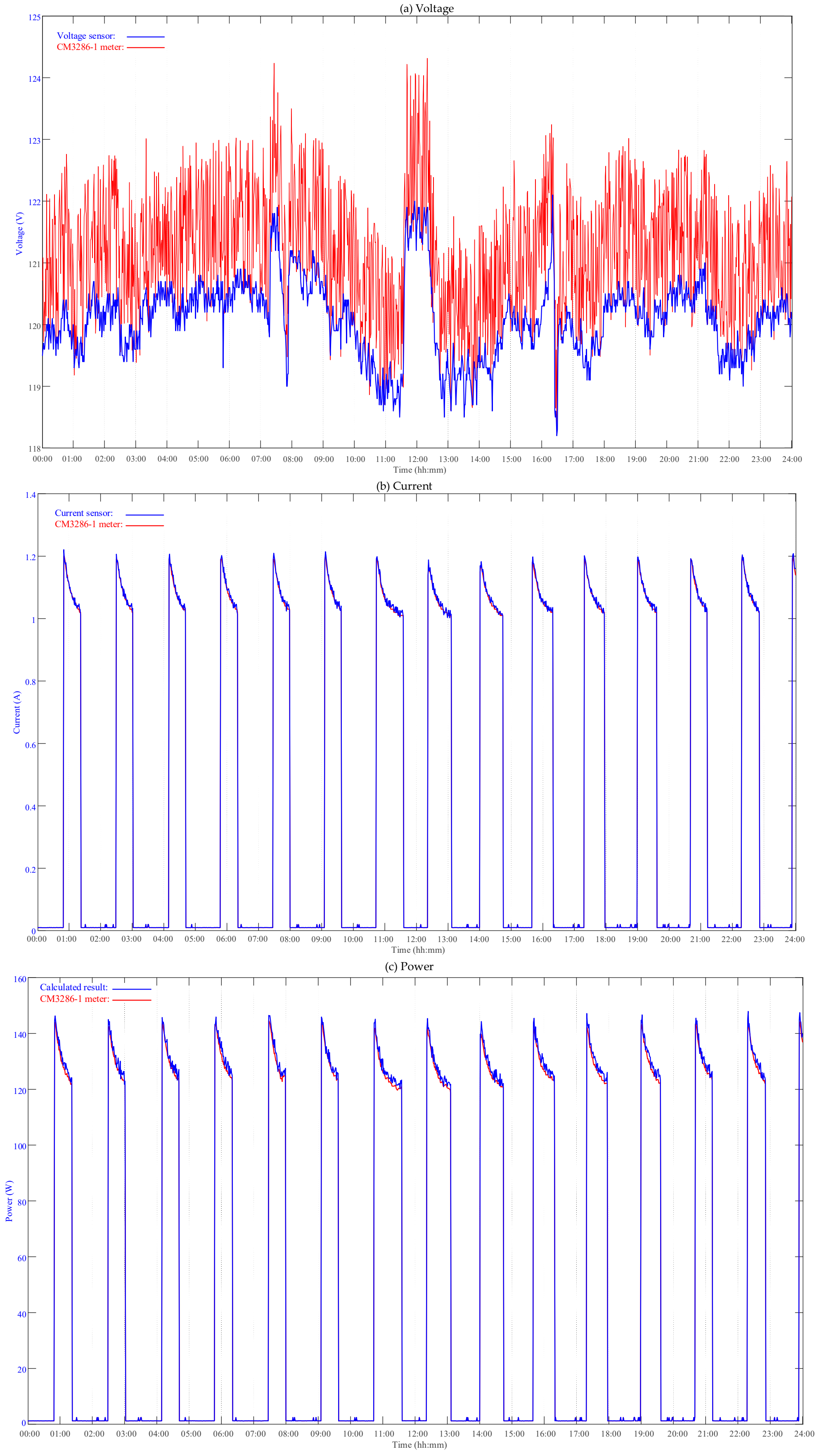

Figure 5. *Cont.*

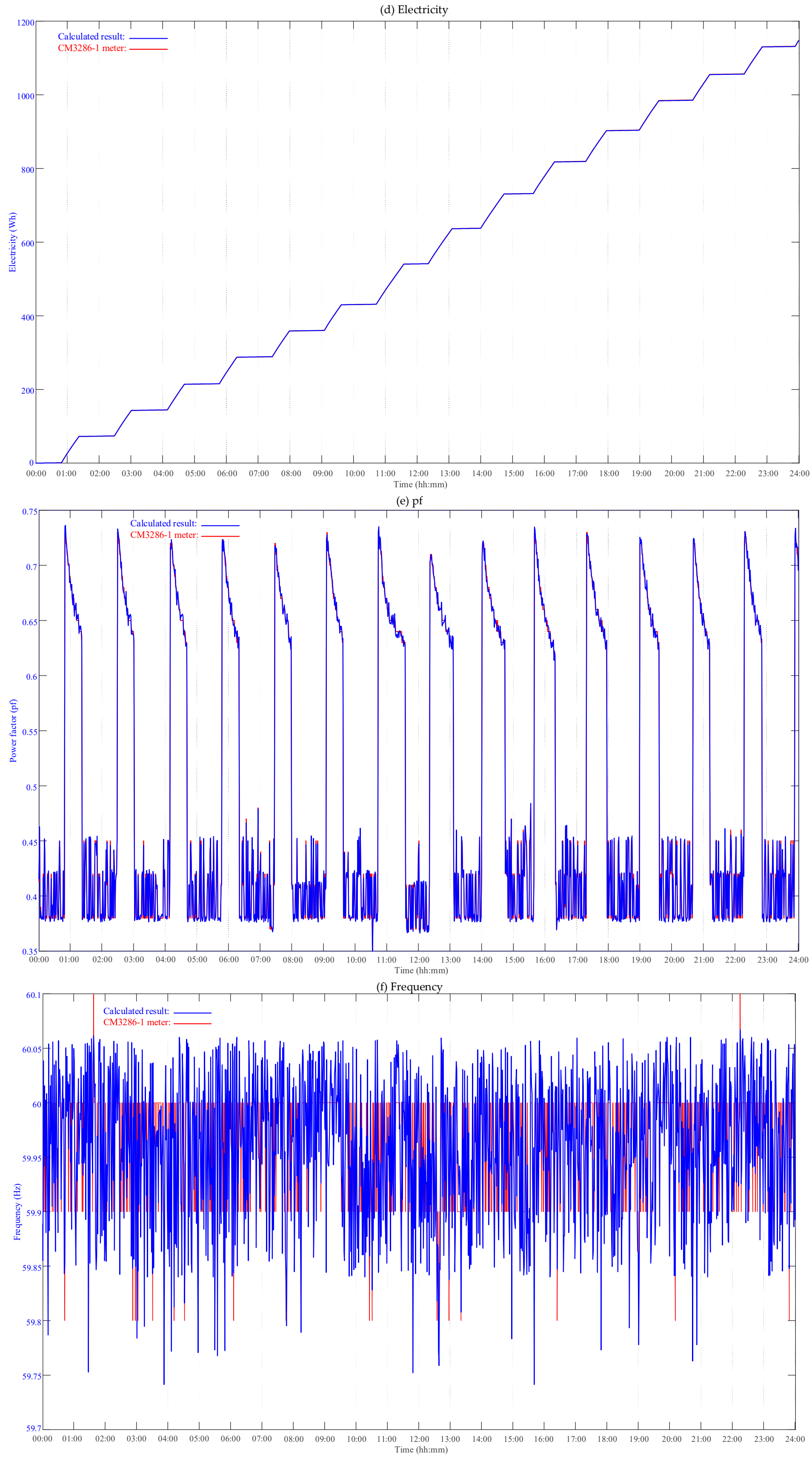

Figure 5. 24-hour measurement results of refrigerator: (**a**) Voltage; (**b**) Current; (**c**) Electric power; (**d**) Electric energy; (**e**) Power factor (pf); (**f**) Frequency (Hz).

3.2. In Situ Monitoring Results of Electrical Parameters for Air Conditioner

In order to further evaluate the performance of the proposed wireless AC monitoring module for single-phase 220 V_{AC} appliances, the observation of the proposed wireless AC monitoring module and two CM3286-1 AC Clamp Power Meter instruments for an air conditioner in the H716 office in a consecutive 24 h measurement with the sampling period of 1 min is depicted in Figure 7. Figure 7a illustrates that the sensing data are higher than the readings of CM3286-1 AC Clamp Power Meter instrument, and the maximum difference is not over 3.5 V. Similarly to Figure 5b, the sensing data of ACS712 current sensor are close to the readings of CM3286-1 AC Clamp Power Meter instrument with the difference of less than 0.3 A. The sensing results make the calculated electric power and electricity of the proposed wireless AC power monitoring module for monitoring air conditioner in good agreement with the readings of CM3286-1 AC Clamp Power Meter instrument as illustrated in Figure 7c,d. Figure 7e reveals that the calculated pf values of the wireless AC power monitoring module are lesser than the readings of CM3286-1 AC Clamp Power Meter instrument. The reason is caused by the phase shift of sensing voltage and current is larger than the one of the measurement instrument. Furthermore, the frequency readings of CM3286-1 AC Clamp Power Meter instrument are more stable than those calculated by the proposed wireless AC power monitoring module.

The close agreement analysis is conducted according to the same procedure as explained above. Taking the measurement results of CM3286-1 instruments as references, the relative difference of the voltage, current, electric power and electricity, pf, and frequency between the proposed AC monitoring IoT system and CM3286-1 AC Clamp Power Meter instruments is defined in Equation (9). As shown in Figure 8a, the reading voltage difference between ZMPT101B voltage sensor and CM3286-01 AC Power Meter ranges from −3.4128 to 0 V.

Considering the reading uncertainty ± 4.2 V for the CM3286-1 AC meter, the voltage reading of the proposed AC power monitoring system is totally acceptable as compared with the commercially available CM3286-1 AC Power Meter. The corresponding MAE and RMSE values are 1.6972 V and 1.9492 V, respectively. The MAPE value of 0.7908% reveals the sufficient closeness of agreement for voltage sensing in the proposed AC power monitoring module. The results of both Figures 5a and 6a illustrate that the ZMPT101B voltage sensor in the proposed AC power monitoring module has enough confidence, like the commercialized CM3286-1 AC Power Meter instrument in the practical operation environment with close agreement of $\leq \pm 1\%$. Being similar to Figure 5b, the current readings of the air conditioner using the ACS712-20 current sensor in the proposed AC power monitoring module and the CM3286-1 AC Power Meter instrument for an air conditioner with the rating of single-phase 220 V_{AC} are in close agreement as shown in Figure 6b, and the current difference between them is in the range of −0.0416–0.2047 A. The values of MAE, RMSE, and MAPE are 0.0368 A, 0.0645 A, and 0.8817%, respectively. Even the MAPE value of the ACS712-20 current sensor in the proposed AC power monitoring module slightly increases as compared to one for the current measurement of refrigerator; the ACS712 current sensor has sufficient performance for current measurement of single-phase 220 V_{AC} appliances like the commercialized instrument of CM3286-01 AC Clamp Power Meter in the practical operation environment with close agreement of $\leq \pm 1\%$. Furthermore, Figure 6c,d illustrates a close agreement between them for the measurement of both electrical power and energy. As shown in Table 4, the power difference is in the range of −41.0301–42.1660 W, and the corresponding MAE, RMSE, and MAPE values are 6.0745 W, 10.5090 W, and 0.7037%, respectively. In addition, the electricity consumption difference ranges from −3.6374 Wh to 2.9868 Wh, and the corresponding MAE, RMSE, and MAPE values are 1.1936 Wh, 1.4190 W, and 0.0216%, respectively.

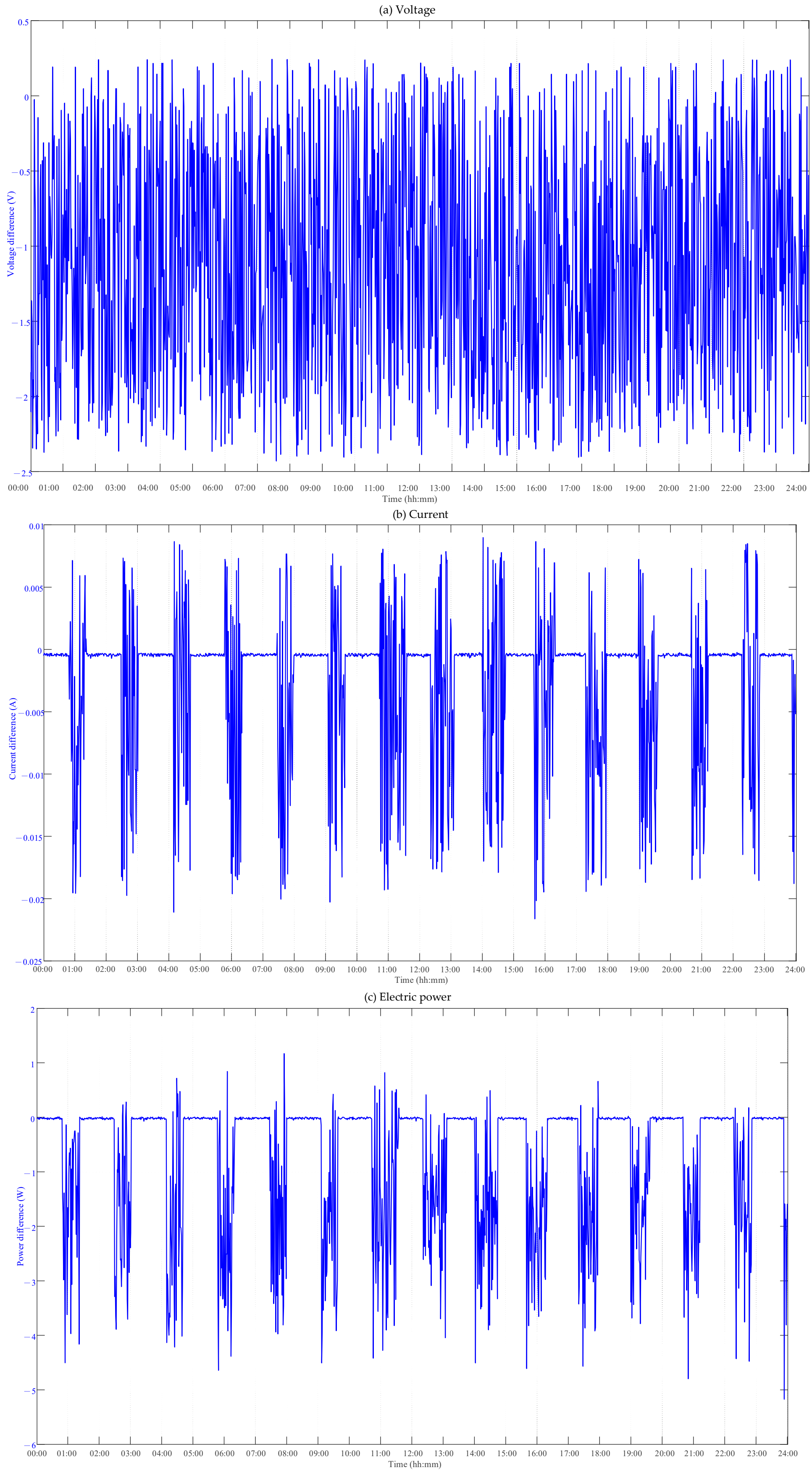

Figure 6. *Cont.*

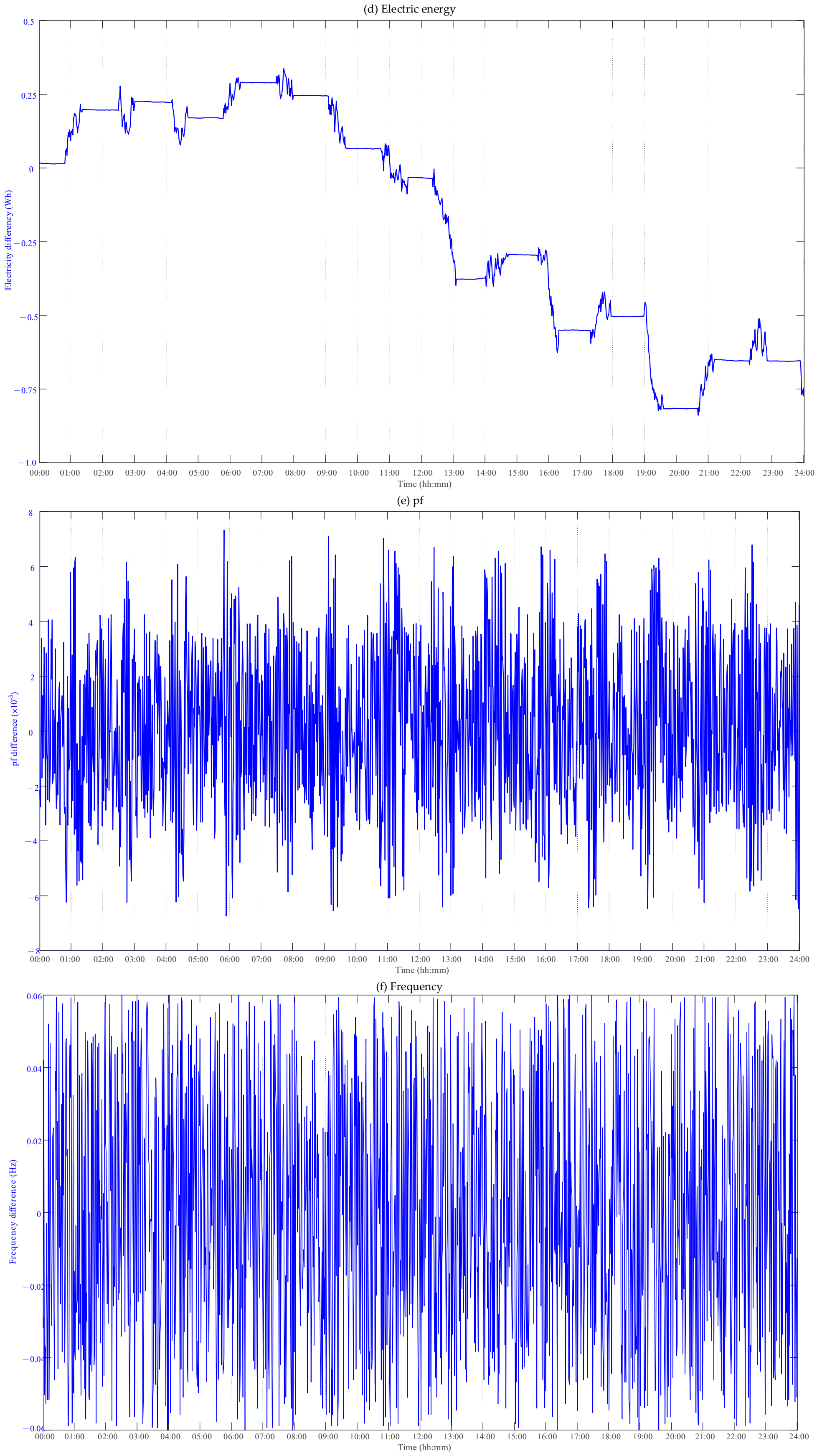

Figure 6. Close agreement analysis for 24 h measurement results for refrigerator: (**a**) Voltage; (**b**) Current; (**c**) Electric power; (**d**) Electric energy; (**e**) Power factor (pf); (**f**) Frequency (Hz).

Table 3. Close agreement analysis of proposed AC power monitoring system for refrigerator.

Items	Accuracy Analysis			
	Difference Range	**MAE**	**MAPE (%)**	**RMSE**
Voltage	−2.4140–0.2434 V	1.1295 V	0.9283	1.3498 V
Current	−0.0206–0.0093 A	0.0030 A	0.7453	0.0059 A
Power	−5.0695–0.8641 W	0.6987 W	1.4586	1.3574 W
Electrical energy	−0.8520–0.0942 Wh	0.3339 Wh	0.0807	0.4274 Wh
Power factor (pf)	−0.0069–0.0071	0.0025	0.4975	0.0030
Frequency	−0.0600–0.0600 Hz	0.0302 Hz	0.0504	0.0348 Hz

The close agreement analysis for both electrical power and energy for monitoring the electrical parameters of a single-phase 220 V_{AC} air conditioner further confirms that the proposed AC power monitoring module has sufficient performance for power and electricity measurement like the commercialized instrument of CM3286-01 AC Clamp Power Meter in the practical operation environment with close agreement of $\leq \pm 1\%$. Moreover, their associate pf values as shown in Figure 6e which illustrates the of difference ranging from −0.0001 to 0 and the corresponding MAE, RMSE, and MAPE values of 4.8620×10^4, 5.8034×10^4, and 0.0491%, respectively. As shown in Figure 6f, the frequency observations of both proposed AC power monitoring module and the CM3286-1 AC Power Meter instrument illustrate the frequency difference between them in the range of −0.0600–0.0600 Hz.

The corresponding MAE, RMSE, and MAPE values of frequency readings are, respectively, 0.0306 Hz, 0.0356 Hz, and 0.0510%. The MAPE of frequency increases a little as compared to the one in the refrigerator case. The close agreement analysis results between the proposed AC power monitoring system and the CM3286-1 AC Power Meter instruments for electrical measurement of air conditioner are presented in Table 4. The results show that these relative differences are all acceptable as compared to the accuracy of measurement instruments. These confirm the reading reliability and measurement confidence for the proposed AC power monitoring IoT system for single-phase 220 V_{AC} appliances.

Table 4. Close agreement analysis of proposed AC power monitoring system for air conditioner.

Items	Accuracy Analysis			
	Difference Range	**MAE**	**MAPE (%)**	**RMSE**
Voltage	−3.4128–0 V	1.6792 V	0.7908	1.9492 V
Current	−0.0416–0.2047 A	0.0368 A	0.8817	0.0645 A
Power	−41.0301–42.1660 W	6.0745 W	0.7037	10.5090 W
Electrical energy	−3.6374–2.9868 Wh	1.1936 Wh	0.0216	1.4190 Wh
Power factor (pf)	−0.0010–0	4.8620×10^{-4}	0.0491	5.8034×10^{-4}
Frequency	−0.0600–0.0600 Hz	0.0306 Hz	0.0510	0.0356 Hz

3.3. Display in ThingSpeak IoT Platform

ThingSpeak is an IoT analytics platform service in which all sensing data can be aggregated to send to private/public IoT platform using HTTP API or MQTT protocol for instant visualization of live data in the cloud [24,25]. Figure 9 illustrates the visualization of live data streams in the ThingSpeak IoT platform through the HTTP protocol for refrigerator and air conditioner, which are two public channels available online [24,25]. The observation data are exported and analyzed based on the MATLAB environment. The same information can be visualized by mobile devices such as phone and tablet through ThingView APP as shown in Figure 10.

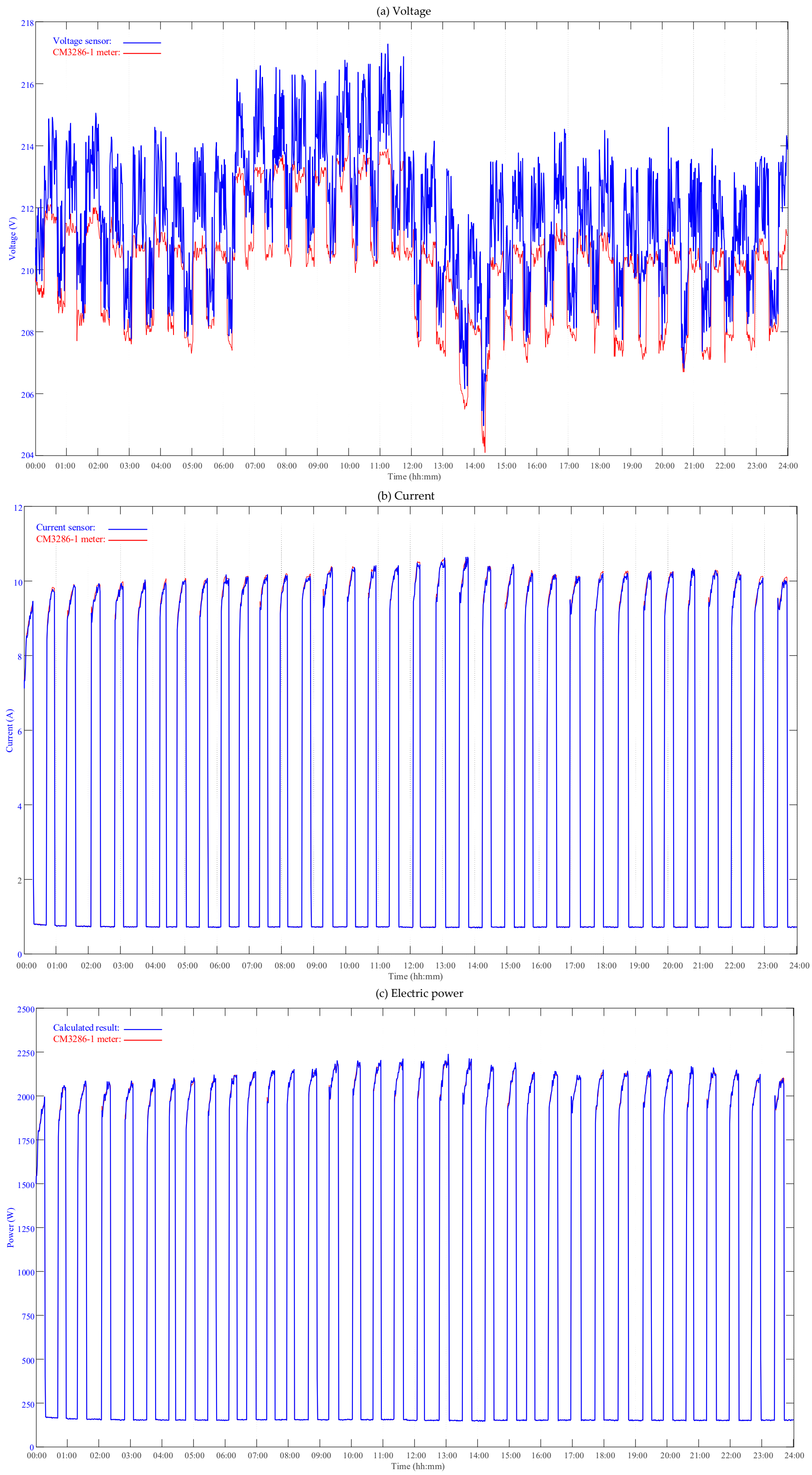

Figure 7. *Cont.*

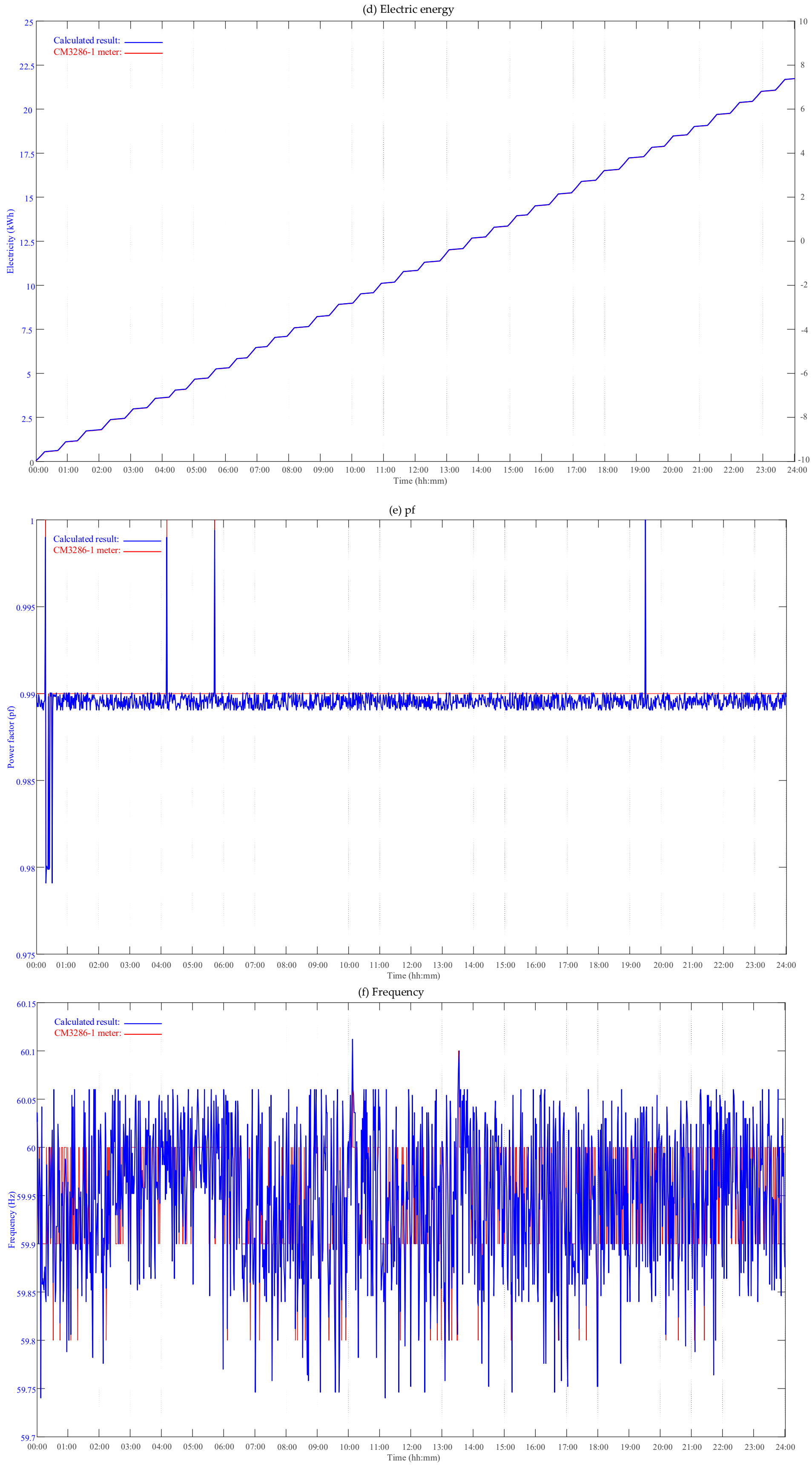

Figure 7. The 24 h measurement results of air conditioner: (**a**) Voltage; (**b**) Current; (**c**) Electric power; (**d**) Electric energy; (**e**) Power factor (pf); (**f**) Frequency (Hz).

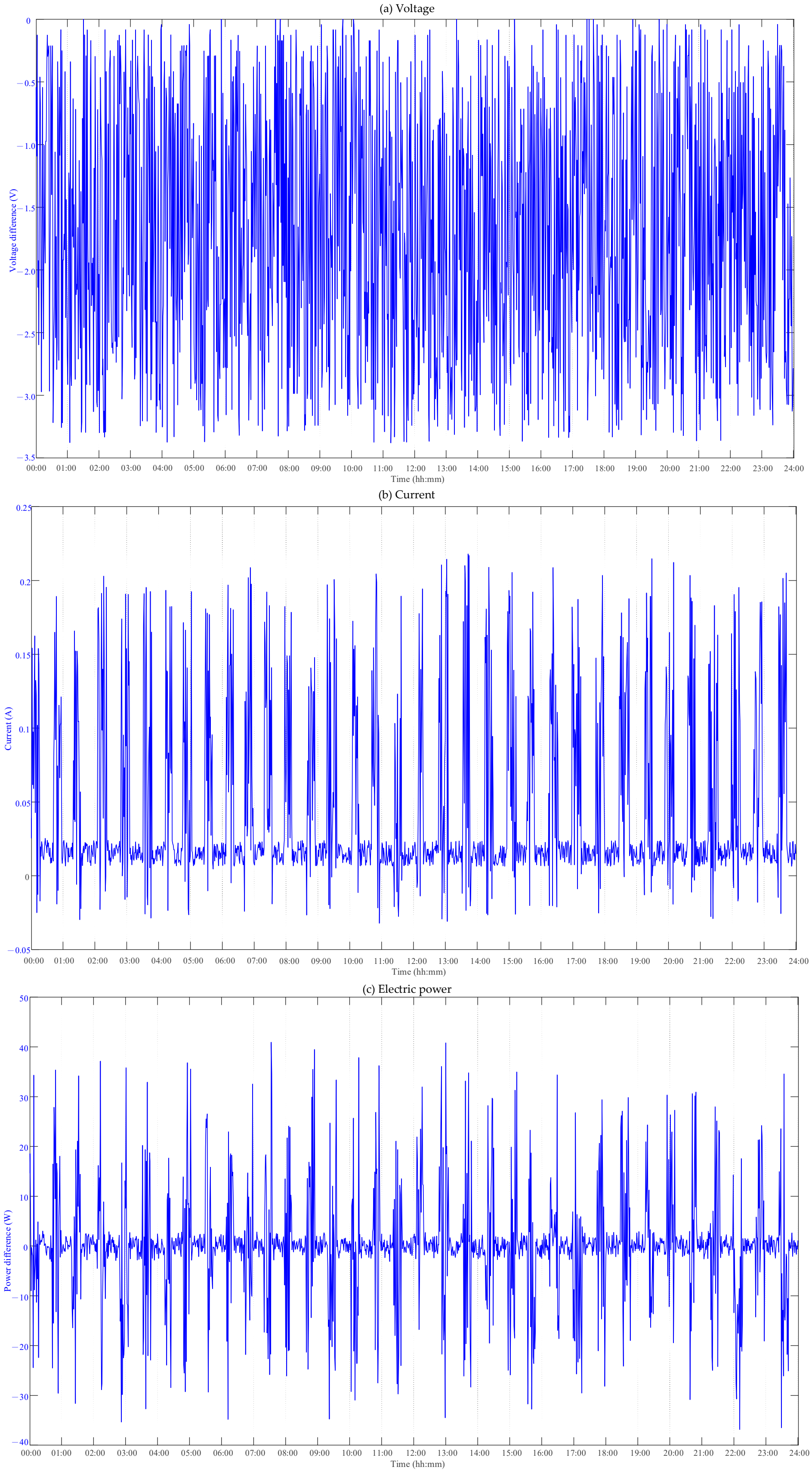

Figure 8. *Cont.*

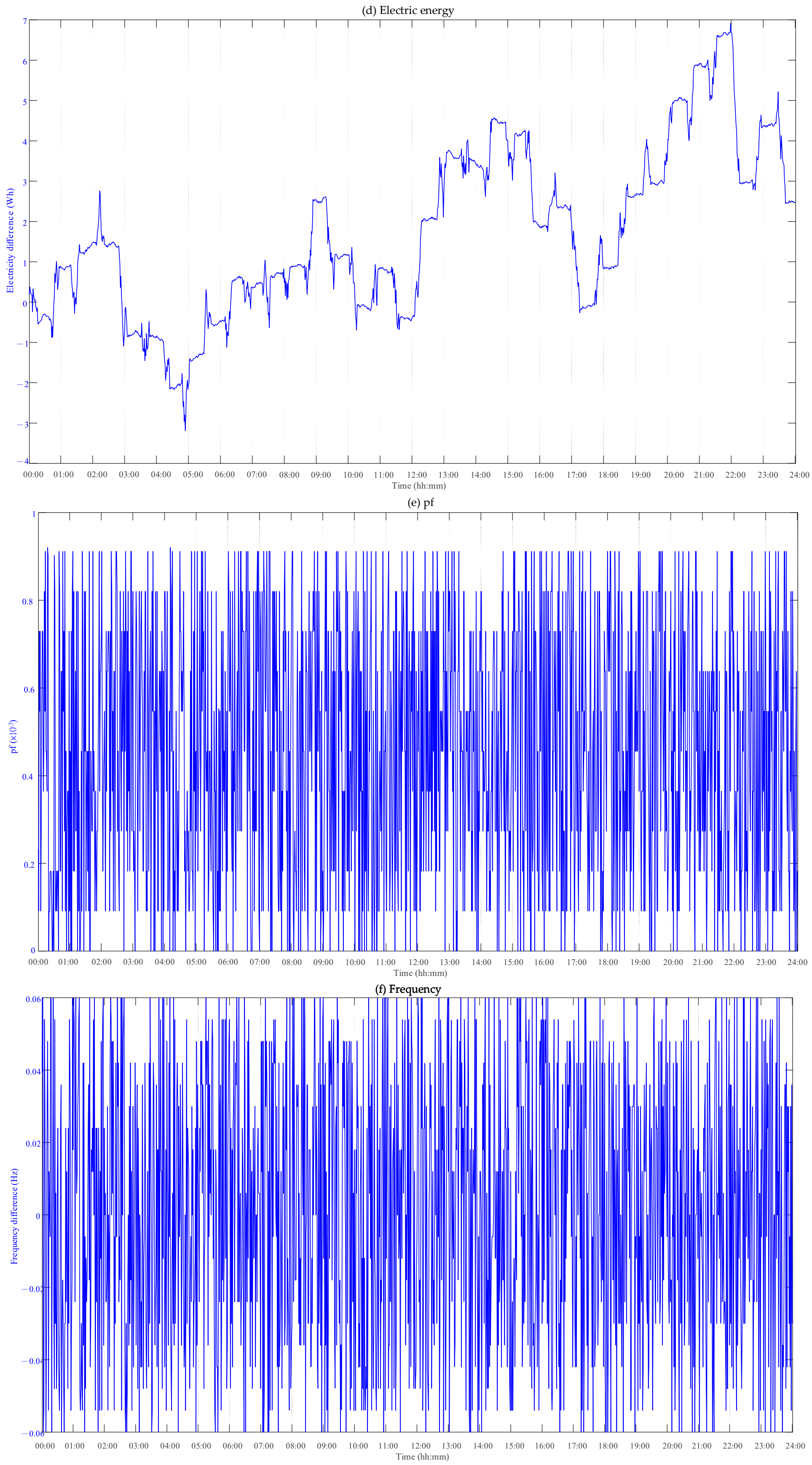

Figure 8. Close agreement analysis for 24 h measurement results of air conditioner: (**a**) Voltage; (**b**) Current; (**c**) Electric power; (**d**) Electric energy; (**e**) Power factor (pf); (**f**) Frequency (Hz).

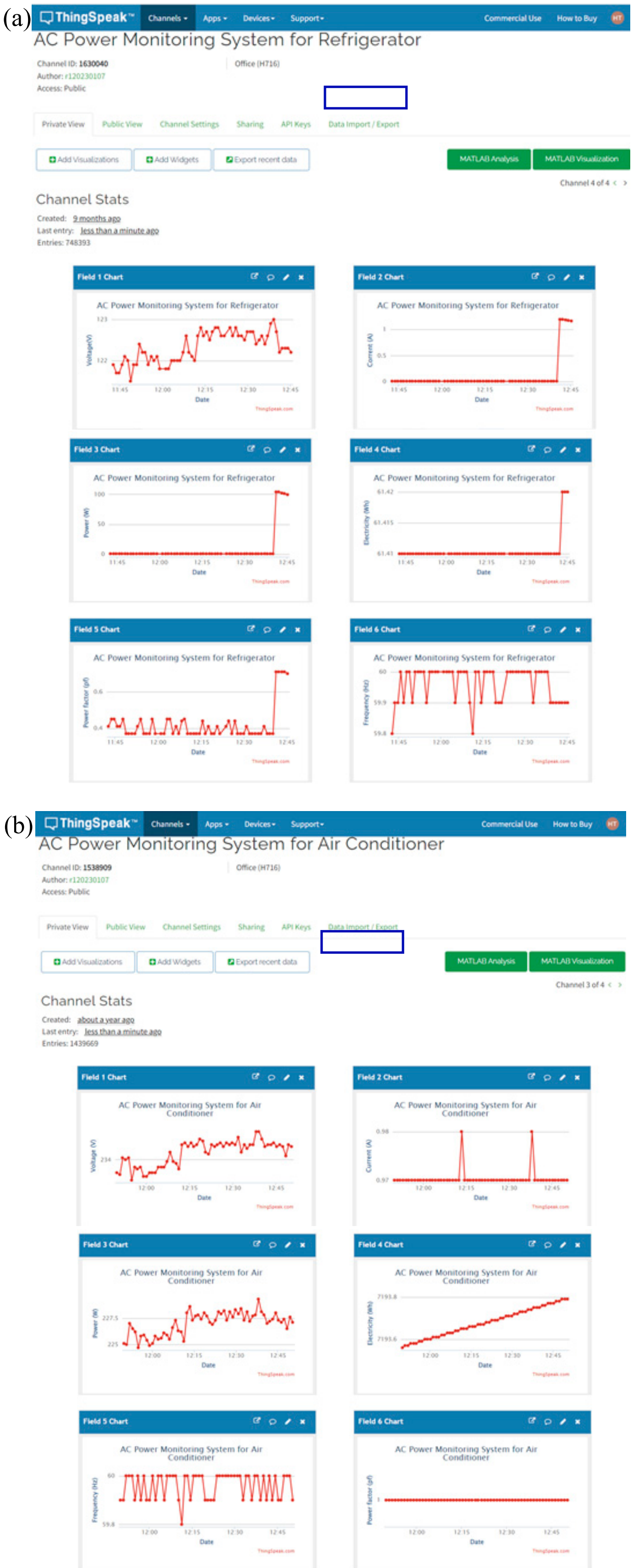

Figure 9. Parameter visualization of voltage, current, electrical power and energy, pf, and frequency in the ThingSpeak: (**a**) Refrigerator; (**b**) Air conditioner.

(a)
(b)


Figure 10. Parameter visualization of voltage, current, electrical power and energy, pf, and frequency in the ThingView: (**a**) Refrigerator; (**b**) Air conditioner.

4. Discussion

The proposed wireless AC power monitoring IoT system features the adoption of a two-channel 16-bit ADC ADS1114 module for the analog readings of both ZMPT101B voltage sensor and ACS712-20 current sensor, which directly provides for an ADC function in compliance with I^2C protocol for WeMos D1 Mini Wi-Fi module for monitoring all of the electric parameters for AC appliances. As compared with the previous work [13], the introduction of ADS1114 module not only saves the use of ATMega328 MCU, but also provides the more flexible I^2C interface. Therefore, the wireless AC power monitoring module in the proposed wireless AC power monitoring IoT system is more compact and cost-effective than the one in [13]. Furthermore, all of the important electrical parameters of voltage, current, electrical power and energy, power factor (pf), and frequency for single-phase 110/220 V_{AC} appliances are completely monitored with sufficient closeness of agreement and confidence through in situ evaluation with two commercially available CM3286-1 AC Power Meters. Moreover, the cost of the proposed wireless AC power monitoring module is less than 100 USD. Two CM3286-1 AC Power Meters are needed to measure the electrical parameters of voltage, current, electrical power and energy, pf, and frequency for the measurement application of single-phase 110/220 V_{AC} instruments. Each CM3286-1 AC Power Meter commercially available online costs over 1000 USD. This reveals the cost-effectiveness of the proposed wireless AC power monitoring module.

Furthermore, the close agreement analysis for electric power and energy between the proposed wireless AC power monitoring module and CM3286-1 AC Power Meters for single phase 110/220 V_{AC} appliances are 1.4586%/0.07037% and 0.0807%/0.0216%, respectively. In the literature review, the work of Varela-Aldás revealed that an AC electric parameter monitoring system consisting of two commercialized PZEM-004t V3.0 power energy meters integrated with a M5Stack Core ESP32 IoT platform was validated with the Gen 2 Vue Energy Monitor device with the accuracy in electric power and energy of over 1.95% and 0.81%, respectively [15]. The closeness of agreement of the proposed wireless AC power monitoring module illustrates better performance in the observations of both electric power and energy as compared to the integrated PZEM-004t V3.0 power energy meters and M5Stack Core ESP32 IoT platform.

Therefore, the novelties of the work are the following: (1) the introduction of ADS1114 provides I^2C interface directly for Wi-Fi module to reduce the capital cost of the proposed wireless AC power monitoring module; (2) the sufficient confidence of the proposed AC power monitoring IoT system has been validated with closeness of agreement as compared to the commercialized CM3286-1 AC Power Meters. The in situ monitoring applications for the proposed AC power monitoring IoT system at least include the smart socket for electric appliances and the in situ monitoring for power distribution panels in residential, commercial, and industrial sections.

Even displaying sufficient performance in the electrical characteristics, the possible Electromagnetic Interference (EMI) issue exists in the system-level integration for the proposed wireless AC power monitoring module. An AC/DC EMI filter for the DC power supply of all V/I sensors, an ADC device, and a WeMos D1 Mini Wi-Fi device will be designed for better performance. The aging issue of the proposed wireless AC power monitoring module could be further verified through continuous operation under in situ conditions.

5. Conclusions

The wireless Alternating Current (AC) power monitoring module in the proposed wireless AC power monitoring IoT system is originally addressed for in situ observation for the important electrical parameters of voltage, current, electrical power and energy, power factor (pf), and frequency for single-phase 110/220 V_{AC} appliances. The proposed wireless AC power monitoring module consists of both ZMPT101B voltage sensor and ACS712-20 current sensor, a two-channel, 16-bit analog-to-digital converter (ADC) ADS1114 module with I^2C interface for the conversion of the analog readings of V/I sensors, and a WeMos D1 Mini Wi-Fi module for instantaneous computation of the corresponding electrical power and energy, power factor (pf), and frequency parameters. The new module features more compact and cost-effective as compared to the ones in our previous work as well as those of commercialized Digital Multi-Meter (DMM) and AC power meters. Taking commercially available CM3286-1 AC Power Meters as reference, the in situ continuous measurement of both refrigerator and air conditioner with the rating of single phase 110/220 V_{AC} in the office (H716) of the Computer Science and Information Engineering Department, Da-Yeh University in Taiwan. The visualization is available online on the ThingSpeak IoT platform (refrigerator: [24]; air conditioner: [25]). The adoption of ADS1114 ADC directly integrating both voltage and current sensors as well as ESP8266EX IoT-based MCU significantly reduces the capital cost of the novel wireless AC power monitoring module. The in situ measurement of the proposed wireless AC power monitoring system further validated the sufficient confidence and convenience as compared to the commercialized CM3286-1 AC Power Meters. The above novelties make the assessment action of environmental, social, and governance (EGS) disclosures for stakeholders much more feasible, cost-effective, and user-friendly. The issues of EMI and device aging for the proposed wireless AC power monitoring module will be further considered for continuous measurement robustness.

Author Contributions: Conceptualization, H.-L.T. and L.P.T.; methodology, H.-L.T. and L.P.T.; software L.P.T. and W.-H.H.; validation, H.-L.T. and W.-H.H.; formal analysis, L.P.T. and W.-H.H. investigation, H.-L.T. and L.P.T.; resources, H.-L.T. and L.P.T.; data curation, H.-L.T. and L.P.T.; writing—original draft preparation, H.-L.T. and L.P.T.; writing—review and editing, H.-L.T.; visualization, L.P.T.; supervision, H.-L.T. and L.P.T.; project administration, L.P.T.; funding acquisition, H.-L.T. All authors have read and agreed to the published version of the manuscript.

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