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Application of IoT Device-based Electric Power Measurement on Multifan System

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In this study, we explore the use of IoT devices, specifically ESP32, to record current, voltage, and electrical power data in a multifan system. The data reading speed of ESP32 is sufficient to read both voltage and current sensors, enabling the acquisition of the waveform signal. From the waveform data, the magnitudes of current, voltage, and power can be accurately determined using a reliable calculation technique. This application still needs calibration to ensure accurate values. Calibration can be done by adjusting the root mean square value and phase of the measured signal. In a multifan system controlled by a dimmer, the current is not always a sine wave. The total power of four fans with the same total speed is lower than the power of one fan with the same speed. The measurement results indicate that the values for current, voltage, power, and power factor are highly accurate, with a correlation coefficient of 0.99.

1. Introduction

Power is a crucial quantity of electricity, and everything in the world relies on how much power keeps objects or equipment operating. It is important for users to know the electrical power of office, household, or laboratory equipment used for experiments. This will help in estimating usage levels and costs. This estimation helps detect power wastage, which in turn incurs losses. Increasing flexibility in electrical power measurements can be achieved, as Samir and Fatah demonstrated by combining a camera into the readings to avoid manual errors in determining the power factor, utilizing a Raspberry Pi.(1)

The need for measuring electrical power primarily targets AC equipment, which is slightly more challenging to measure than DC power. In general, the magnitudes of AC voltage and current do not change synchronously but include a phase shift.(2) As a result, the term power

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factor emerged to quantify real power use. Although the AC voltage and current waveforms can be expressed by a sine function[3] with well-defined properties, various methods, including microcontroller-based signal processing, have been developed to determine the power factor. The problem arises when the signals are not measured accurately in time and magnitude, and signal processing is slow, and thus choosing the right method becomes crucial for obtaining accurate values. As a solution, a method will be developed involving calibration and calculation to accurately determine electrical power. This method will be reliable, easy to implement, and flexible.

The application of IoT across various fields is unstoppable. This includes fields such as agriculture,[4] heating, ventilation, and air conditioning (HVAC),[5,6] plantations,[7,8] marketing,[9] and humanity.[10] Low-cost measurement systems are often associated with the use of IoT devices or the IoT itself. The use of IoT in measuring electrical quantities has been extensively studied for various needs. Many projects focused on similar systems, such as the one by Messaoudi *et al.*, which used an IoT-based low-cost system to measure river water.[10] A similar system was also employed in solar photovoltaic power plants. Demir developed a low-cost remote monitoring system for solar photovoltaic energy, featuring a machine-learning-based power estimator. This system enables the early identification of maintenance needs and potential issues.[12] Oberloier and Pearce presented an open-source low-cost power monitoring system to perform various measurements of both loads and supplies, including solar photovoltaic systems, constructed entirely with open-source software and hardware.[13] Then, Oukennou *et al.* presented a low-cost solar panel monitoring system that measures current, voltage, and power, and visualizes results using the free IoT application Node-RED.[14] A system capable of measuring high dynamic currents is also associated with IoT applications, as discussed by Tehrani and Atarodi.[15] They used capacitors and analog switches as new pass elements to measure current consumption.[15] A prototype for collecting electricity usage data was developed by Asmadi *et al.* with 92.22% accuracy on paid bills.[16] The use of computer vision to reduce errors in repeated readings was developed by Fan *et al.*, achieving a detection speed of 123 frames per second.[17]

However, the most crucial element is the microcontroller, which serves as the electrical power data reading component. Consequently, methods for accurate electrical power measurement are continuously being developed. In this paper, we discuss the development of a watt meter that displays sine waves of AC current and voltage, which is also equipped with power calculation by processing these current and voltage signals into a smooth signal. The developed device is a power measurement system comprising customized hardware and software. The system is supported by web-based application using HTML/JavaScript code, which can run in web browsers such as Internet Explorer or Safari. The developed power measurement system is tested and applied to multifan systems.

2. Microcontroller and Web Service

Wireless access and the implementation of IoT systems offer options for providing flexibility in operating equipment. The use of microcontrollers in equipment facilitates the easy connection of multiple devices without the need for cables. The ability of the microcontroller to function as a web server simplifies the development of wireless communication through web programming. ESP32 is an example of a microcontroller capable of functioning as a web server.

Activating the web server on the microcontroller simplifies data transfer between devices, such as data transfer to and from PCs, smartphones, and mini-PCs when these devices are used as web clients. To access, send, or receive data from a microcontroller that functions as a web service, other devices can act as clients by accessing a web page created on the server side. Another approach is to develop an application or web page using HTML/JavaScript code on the client side. This application can be executed in a client-side web browser.

3. Research Methodology

The methodology of this research was conducted in several stages, as follows:

1. Design a data acquisition system for measuring the electrical power of a multifan system.
2. Write the algorithm for a power measurement method.
3. Design the hardware and software of a power measurement system.
4. Test and calibrate the power measurement sensor.
5. Test and implement the designed method.
6. Test the power measurement device and application on the fan system.
7. Record and analyze the measurement data from the experiment.

Data collection is performed by ESP32, which is designed to sample one wave period, approximately 255 data points for both voltage and current. To record current and voltage data with flexible reading needs, the server is designed to run in ESP32 to broadcast the data. The server's task is to transmit data to multiple clients. The collected data is then displayed in a web browser. The program on the web browser side is designed to calculate the power of the voltage and current signals measured and sampled by ESP32. The data signal is then processed by applying signal smoothing. The power measurement system hardware was built with sensors with the ability to read voltage and current signals. A diagram of the entire system is depicted in Fig. 1.

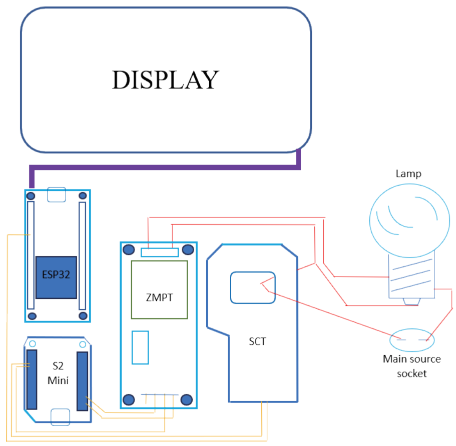

Fig. 1. (Color online) Power measurement system diagram.

Figure 1 shows that the voltage sensor used is the ZMPT, and the current sensor is the SCT 013 (1V/5A). The ESP32 S2 mini is programmed to capture voltage and current wave signals, which are then sent to a server built with Node.js. This server hosts a web page to display the measured voltage and current waveforms and processes the data to obtain values for voltage, current, and power. The other ESP32 is programmed to display the recorded waveforms. These measurements are applied to multifan control systems. Figure 2 shows the page of power measurements displayed on the web browser.

The measurement principle based on wave recording requires calibration through the following steps: (1) adjustment of the current reading values, (2) adjustment of the voltage reading values, and (3) power factor adjustment followed by the phase angle adjustment between the current and voltage signals. The results of the calibration of the designed power meter are shown in Table 1.

The calibrated current and voltage sensor waveforms are shown in Fig. 3. The waveform in blue is for the voltage sensor and the red wave is for the current sensor.

4. Results and Discussion

The power measurement hardware according to the design in Fig. 1 is shown in Fig. 4. In the power measurement hardware [Fig. 4(a)], one part of the sensor is connected to the ESP32 analog pin, which serves as a processing component in the device. The other parts are connected to the source terminals and load connectors.

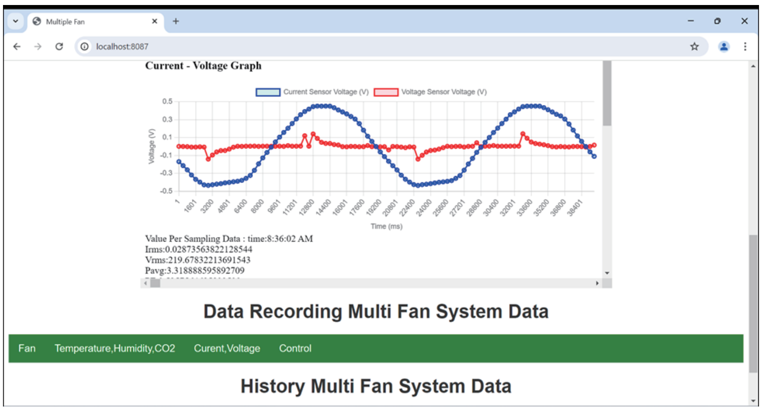

Fig. 2. (Color online) Web browser page of power measurement results.

Table 1
Results of calibration.

Calibration using 60 W lamp			Phase	Measurement using Lutron power meter			
Data size	Number of waves	Sampling	Shift	Current (A)	Voltage (V)	Power (W)	Power factor
1000	20	1000 ms	−3	0.26	226.3	59	1
Average using 15 data				Measurement using ESP-based power meter			
2024/7/26: 5:59:36 PM				Current (A)	Voltage (V)	Power (W)	Power factor
				0.259551	226.5356	58.56904	0.996105

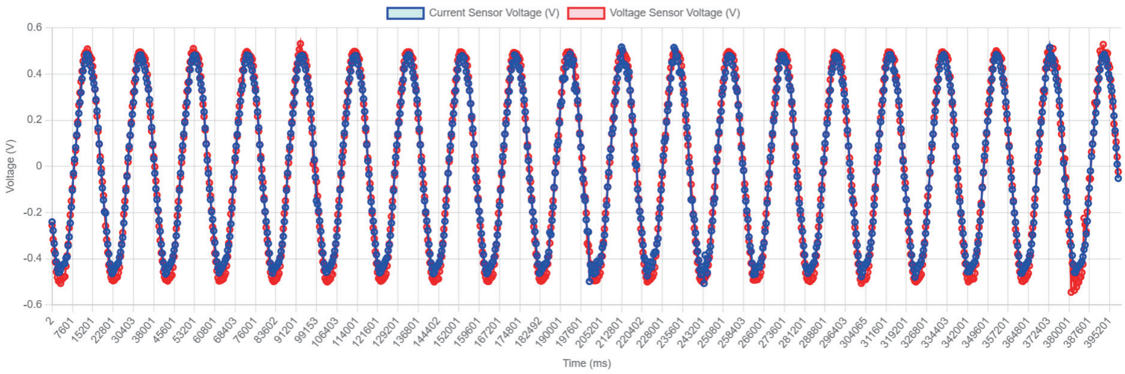

Fig. 3. (Color online) Waveforms of voltage for current sensor (red) and voltage sensor (blue) after calibration.

(a) (b)

Fig. 4. (Color online) (a) Power measurement hardware and (b) Lutron power meter for comparison.

The designed measurement device (ESP32-based power meter) was tested on one-fan and four-fan systems with the results presented in Tables 2 and 3. These results are compared with standard equipment (Lutron power meter) to determine the level of accuracy. The comparison data of the one-fan system is shown in Table 2.

Figure 5 shows the comparison graph of data obtained from Table 2. The graph shows the high suitability of the results, as indicated by the correlation coefficients (*R*) of 0.98, 0.86, 0.999, and 0.997 for each measurement of current, voltage, power, and power factor, respectively.

The applications of current, voltage, and power measurement devices for four fans are shown by the graph in Fig. 6 obtained from Table 3. In the four-fan system, the power meter also shows a high accuracy as demonstrated by the correlation coefficients (*R*) of 0.999, 0.918, 0.9998, and 0.9995 for each measurement of current, voltage, power, and power factor, respectively.

The results obtained from current, voltage, and power measurements using the ESP32-based device show excellent agreement with those obtained using the Lutron power meter as the standard power meter device.

Table 2
Implementation of hardware on one fan.

	Measurement using Lutron power meter						Measurement using ESP32-based power meter			
No.	RPM	Current (A)	Voltage (V)	Power (W)	Power factor	Time	Current (A)	Voltage (V)	Power (W)	Power factor
1	1177	0.15	223.2	33	0.97	10:25:23 AM	0.15	223.29	33.29	0.97
2	1125	0.15	223.7	32	0.97	10:30:16 AM	0.15	223.20	31.54	0.95
3	1065	0.14	223.7	30	0.91	10:33:55 AM	0.15	223.68	29.68	0.91
4	1012	0.14	223.2	27	0.84	10:36:43 AM	0.14	223.45	27.19	0.86
5	975	0.13	222.9	24	0.8	10:40:13 AM	0.13	222.60	23.54	0.79
7	697	0.11	223.9	15	0.6	11:01:01 AM	0.11	223.81	15.49	0.61
8	532	0.11	224	11	0.5	11:10:16 AM	0.10	224.27	11.38	0.53
9	315	0.08	223.4	7	0.41	11:14:49 AM	0.08	222.96	7.19	0.42
10	255	0.05	224.6	4	0.33	11:18:50 AM	0.05	224.68	4.17	0.34
11	142	0.03	224.5	2	0.25	11:23:04 AM	0.04	224.86	2.34	0.29

Table 3
Implementation of hardware on four fans.

	RPM setting				Measurement using Lutron power meter					Measurement using ESP32-based power meter			
Data no.	Fan 1	Fan 2	Fan 3	Fan 4	Current (A)	Voltage (V)	Power (W)	Power factor	Time	Current (A)	Voltage (V)	Power (W)	Power factor
1	142	255	315	532	0.25	226.50	22	0.38	6:29:56 PM	0.26	227.30	23.10	0.39
2	200	200	200	200	0.21	228.10	11	0.23	6:47:22 PM	0.21	227.42	12.13	0.26
3	0	0	800	0	0.12	228.50	19	0.65	6:54:48 PM	0.13	227.85	19.21	0.67
4	975	1012	1065	1125	0.57	228.00	114	0.88	7:04:19 PM	0.56	227.46	112.45	0.88
5	0	0	1177	0	0.15	224.70	34	0.97	9:45:36 AM	0.15	222.97	33.46	0.97
6	0	0	1177	1177	0.31	224.20	67	0.97	9:52:45 AM	0.30	222.94	65.94	0.97
7	0	1177	1177	1177	0.46	223.90	100	0.96	9:58:31 AM	0.46	222.97	98.30	0.97
8	1177	1177	1177	1177	0.61	223.10	132	0.97	10:02:37 AM	0.61	222.73	131.10	0.97
9	167	697	1056	1177	0.41	223.30	76	0.85	10:13:38 AM	0.40	223.02	75.89	0.85

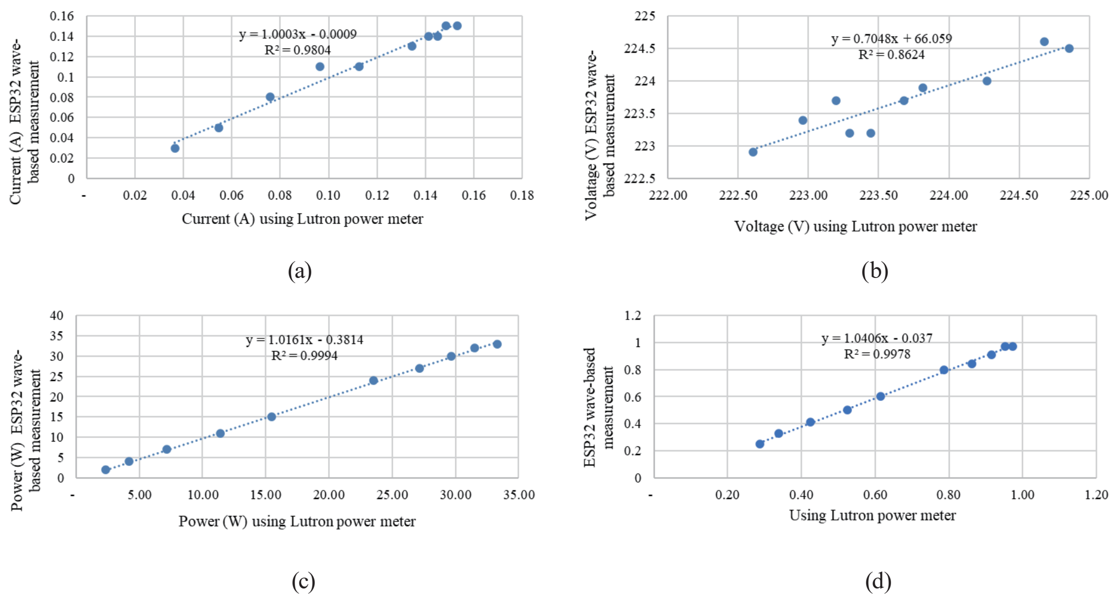

Fig. 5. (Color online) Graph of one-fan measurement: (a) current, (b) voltage, (c) power, and (d) power factor.

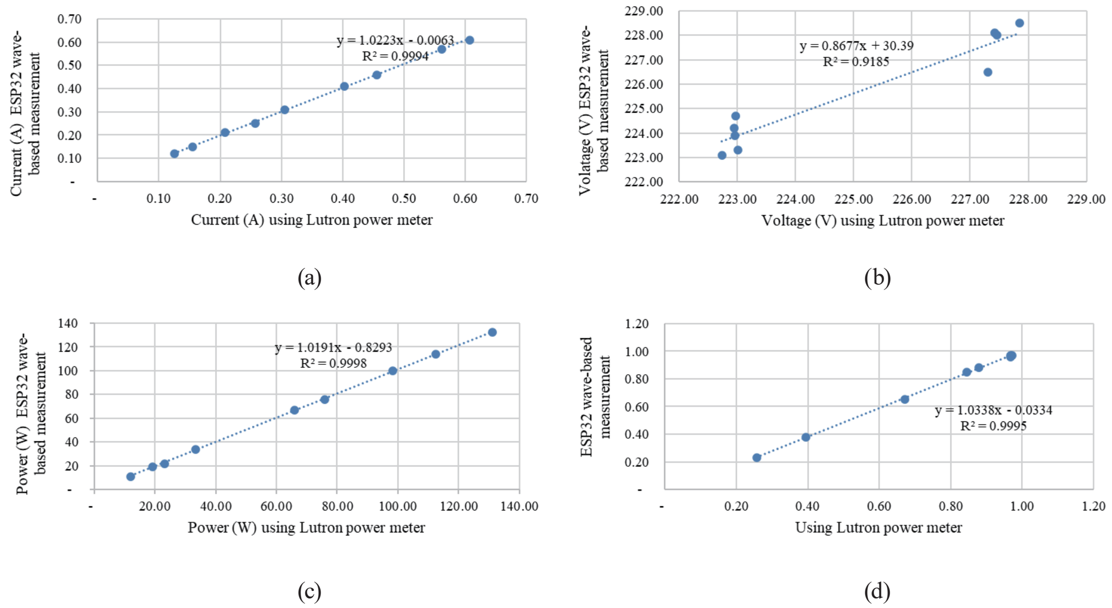

Fig. 6. (Color online) Graph of four-fan measurement: (a) current, (b) voltage, (c) power, and (d) power factor.

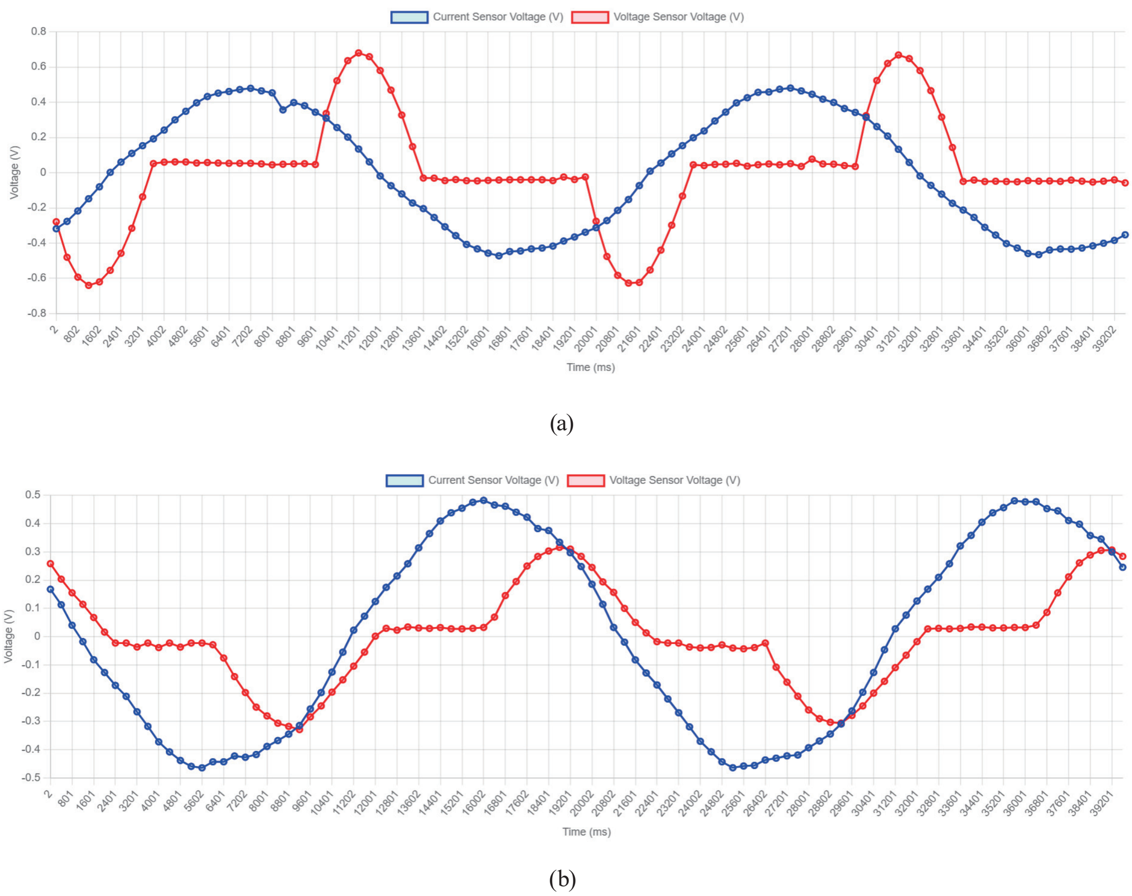

Fig. 7. (Color online) Current and voltage waveforms for four-fan experiment: (a) Table 3, data no. 2 and (b) Table 3, data no. 3.

The current and voltage sensor waveforms from the four-fan experiment (Table 3) are shown in Fig. 7. The current waveform (red wave) below the maximum fan speed is not completely sine-shaped in both figures. Figure 7(a) shows the current and voltage waveforms using data no. 2 from Table 3; four fans with an rpm setting of 200 each were used. Figure 7(b) used data no. 3 in which only one fan with an rpm setting of 800 was used, the same as the total rpm setting of all fans in data no. 2. From both plotted data, at the same total speed for four fans (data no. 2), the current is higher than when using only one fan (data no. 3). However, the total power consumption is lower for four fans than for one fan.

5. Conclusions

According to the results of the power measurement system, the conclusions that can be drawn are as follows:

1. Current, voltage, and power measurement devices based on waveform measurement using ESP32 produce values with very good conformity as compared with those obtained using the standard power meter device (Lutron).
2. Calibration can be done in one stage by adjusting the current, voltage, and phase values.
3. The designed device can visualize the shape of the measured signal.
4. The current wave on the fan is generally not in the form of a sine wave, whereas the voltage wave remains in the form of a sine wave.
5. The total power of four fans at a certain total speed will be lower than the power of one fan at the same speed.

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