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A Low-Cost Wireless Sensor System for Power Quality Management in Single-Phase Domestic Networks

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***Abstract*—This article presents a novel low-cost hardware and software tool for monitoring power quality in single-phase domestic networks using an ESP32 microcontroller. The proposed embedded system allows remote evaluation and monitoring of electrical energy consumption behavior through non-invasive current measurement parameters. Based on these measurements, power, power factor, total harmonic distortion, and energy consumption are calculated. The collected data is then published and visualized on a free and open IoT application in the cloud. The tool was designed to be both cost-effective and high-quality. During laboratory testing, the equipment demonstrated a high level of precision, as compared to a network analyzer. Additionally, the design utilized the smallest number of components possible, while still maintaining quality performance. The ESP32 microcontroller enables wireless data transmission, making remote monitoring and management of energy consumption more accessible and efficient. Moreover, the non-invasive measurement method makes the tool safer and more user-friendly, as it does not require any interruption of power supply. The proposed tool can help identify and address power quality issues that arise in domestic networks, which can have a significant impact on energy consumption and costs. The IoT application enables users to access their power consumption data remotely, facilitating better energy management and reducing wastage.**

Keywords*—*Cost-effective; current measurement; energy consumption; ESP32 microcontroller; non-invasive; power quality; remote monitoring

I. INTRODUCTION

As the world population continues to grow, so does the demand for energy. Unfortunately, this increase in demand is accompanied by a decline in natural resources and an increase in environmental pollution, leading to climate change. It is crucial to raise awareness among people about the importance of energy usage and to bridge the gaps in accessibility and culture [1], to create a better environment for all.

However, the current home energy measurement technology falls short of achieving this goal. The technology is primarily used to charge users for the service provided, without giving them the means to measure, verify, or control the amount charged. Furthermore, most users do not understand or have access to information provided by their energy meter [2], as it typically displays only a set of numbers on a counter located outside their homes.

Modern and innovative technologies such as embedded systems with high-capacity microcontrollers and IoT information technologies can provide more efficient, compact, and cost-effective solutions for domestic energy measurement [3]. These technologies have the potential to optimize energy measurement, enabling more precise remote monitoring and control from anywhere in the world, and providing the user with easily accessible and understandable information [4]. By creating a more precise and accessible energy measurement tool, users can plan their energy consumption more intelligently and responsibly. This can help mitigate the effects of global warming and promote energy efficiency [5], thus contributing to the conservation of the environment.

The aim of this research is to design and implement a robust IoT meter prototype capable of measuring electrical energy consumption and providing the average user with accurate real-time information about their energy usage at home. This information will enable the user to manage their energy consumption with an innovative and cost-effective solution, contributing to energy efficiency and promoting sustainability [6].

The proposed tool provides a high-quality and efficient solution for domestic networks, enabling users to be more aware of their energy consumption and manage it more intelligently and responsibly. By creating a robust and user-friendly IoT meter, this research aims to address the issues of accessibility and awareness in the use of energy. The use of innovative technologies such as embedded systems and microcontrollers has the potential to revolutionize the field of power quality monitoring and management [7], contributing to the sustainable development of modern society.

A. Issues in Existing Work

In recent years, power quality management in single-phase domestic networks has witnessed significant advancements. However, there remain certain inherent challenges. The majority of existing systems fall into one of the following categories:

1) Systems that prioritize advanced functionalities but, as a result, become too complex and expensive for regular household users [8], [9].
2) Systems that are affordable but compromise on the depth of data and the quality of measurements they provide. This often leads to a lack of complete understanding of energy usage patterns, reducing the efficacy of management efforts [10].
3) Devices that focus solely on energy consumption, overlooking the broader aspect of power quality which is crucial given the increased presence of non-linear loads in contemporary households [11].

4) Systems that although being technologically advanced, aren't user-friendly or accessible for an average user. Such systems, despite their potential, have limited real-world application due to the steep learning curve they present [12].

These issues represent significant barriers for users who wish to adopt sustainable energy consumption practices in their homes.

In addition to its simplicity and cost-effectiveness, the prototype was designed to maintain quality in both hardware and software, while keeping in mind the experience and prices of the market. The hardware and software were designed to ensure flexibility and openness to the public. In fact, there is no need for subscription to IoT platform Adafruit.io, which allows data to be uploaded at a rate of one data per second and stored at no cost.

The ESP32 Dev Kit v1 microcontroller [13] serves as the brain of the circuit and has an integrated Wi-Fi capability, which is a significant advantage for sending data directly to the cloud without additional devices. Wi-Fi enables the data to be sent in real-time to the internet or a local network if required. In this case, it is connected to the cloud platform dashboard Adafruit.io. The SCT 013030 [14] current sensor is used for signal conditioning, which has a ratio of 30A/1Vac, is ideal for its low cost and suitability for many households that do not exceed a power consumption value of 7200 W. One of its main features is its non-invasive type, which allows the installation to be safer by avoiding the need to cut parts of the wiring. The current conditioning is carried out through a precision full-wave rectification circuit to obtain a reliable signal at the ADC input and with minimal voltage loss in the diodes. An operational amplifier, the LM324, is used for this purpose. With these materials, the prototype can be constructed. The rest of the design is software-based and is programmed in the Arduino IDE environment, which is widely known and easily programmable using the C++ language.

Upon analyzing various studies related to energy meters, it was observed that the technologies used do not meet the characteristics of simplicity in their design. This means that more than one board must be used to fulfill the same functions that can be provided by an ESP32 microcontroller, which has greater processing capabilities and is more integrated and cheaper than an Arduino solution with an additional IoT communication card. Additionally, many of the designs do not consider the price, which can be a significant barrier to the acquisition of an energy meter by the user. Although some functions, such as bidirectional measurement, may seem important, most people currently do not have access to this type of technology due to their low-income status, so it would not make sense to include this function [15]. Other technologies are based on conditioning additional circuits to the energy meter. However, if the energy meter makes a mistake in the measurement, the additional device will also be incorrect, which does not provide reliability to the readings. Many designs also include functions of an incorporated power analyzer, which seems relevant given the increase of non-linear loads in homes and which can shed light on their impact on the distribution network. However, the contemplated design is not compact, and the solution is not cheap.

B. Overcoming the Challenges with the Proposed Approach

Our research aims to bridge the aforementioned gaps in power quality management for single-phase domestic networks. The proposed wireless sensor system addresses the need for a balance between advanced functionalities and user accessibility. Leveraging the capabilities of the ESP32 microcontroller, the system offers a comprehensive suite of measurements, from active power to total harmonic distortion, while ensuring that the data is readily accessible through an intuitive IoT interface [16]. Furthermore, our commitment to a cost-effective design ensures that our solution remains affordable, promoting widespread adoption and contributing substantially to the global energy efficiency movement.

Over recent years, the significance of monitoring energy consumption has grown considerably, especially in the wake of rising energy demands and the increased focus on sustainable living. As a response to these trends, this work introduces a comprehensive IoT-based current meter, designed to provide real-time insights into energy consumption patterns, thus facilitating better energy management. Our endeavor is rooted in the following main contributions:

- Development of an IoT-based current meter firmware that harnesses the power of the Fast Fourier Transform (FFT) for precise and efficient current monitoring.
- Configuration of the Analog-to-Digital Converter (ADC) tailored to ensure a detailed representation of the current waveform, enhancing energy monitoring capabilities.
- Adoption of Robin Scheibler's FFT library for high fidelity signal decomposition.
- Empirical derivation of an amplitude correction factor, thereby refining energy consumption measurements.
- Comprehensive power and energy calculations, offering real-time energy consumption insights.
- Incorporation of Total Harmonic Distortion of Current (THDi) calculations, revealing the system's performance metrics and potential energy consumption anomalies.
- Rigorous prototype testing and validation against industry-standard measurement tools, ensuring the reliability and accuracy of the developed system.

The ensuing sections detail the methods employed, the design considerations, and the empirical findings that validate the contributions outlined above.

II. RELATED WORKS

The efficient use of electrical energy is becoming increasingly important in the face of rising demand and limited resources [17]. Energy providers charge customers for the energy delivered to their homes or businesses, but not all of this energy is utilized efficiently; a portion is wasted. The energy demand of a system is known as the *apparent power* or *absorbed power*, which can be further broken down into the *active power* that is actually used and the *reactive power* that is wasted. In practice, active power should be as close as possible to apparent power, but this is not always the case. The difference between the two can be measured by the power factor [18]. With the growing number of electronic devices in homes, the situation is different, as loads have increased their nonlinear components, increasing the harmonic content and the power factor, which can significantly affect the network and loads [11]. Therefore, it is essential to begin measuring these variables in homes to facilitate future studies on the impact of harmonics in the distribution network. The proposed tool can help identify and address power quality issues that arise in domestic networks, which can have a significant impact on energy consumption and costs.

In recent years, several studies and devices have been developed to measure power consumption and other parameters in order to determine the quality of energy in homes. Trujillo and Lorenzo [8] proposed an electric power consumption analyzer using Arduino and MATLAB to study various household loads. Benalcazar et al. [9] analyzed the generation and correction of the main sources of harmonic distortion commonly found in household and some industrial electrical networks, using LabVIEW and the National Instruments DAQ 6008 acquisition card. Garcia-Granados et al. [19] designed and implemented a single-phase power analyzer for domestic use using voltage, current, and power waveforms.

In the same vein, Mathew [10] aimed to optimize energy consumption by implementing intelligent control of household appliances using a smart meter and IoT. The system analyzed usage patterns, collected physical variables through an Arduino Uno, and featured a switching mechanism. Furthermore, the system was parametrized based on peak demand hours to reduce the electricity bill.

The disadvantages of the prototypes compared to the one proposed are mainly related to their limitations in terms of functionality, precision, and cost-effectiveness. For instance, the prototype developed in [8] only measures the active power consumption, whereas the proposed system using an ESP32 can measure not only the active power but also other parameters such as power factor, total harmonic distortion, and energy consumption. Similarly, the prototype presented in [9] focuses on the analysis of harmonic distortion in household and industrial networks but lacks the capability to provide real-time energy consumption information to users. The system presented in [19] is a single-phase power analyzer that can measure voltage, current, and power, but it does not have wireless data transmission capabilities and requires additional hardware for data visualization. Additionally, the prototypes mentioned in the paragraph do not take advantage of modern and innovative technologies such as IoT, which can facilitate remote monitoring and management of energy consumption in a cost-effective and user-friendly way.

Several prototypes and devices have been developed to monitor and control energy consumption in households using IoT technology. Ramani et al. [12] propose a prototype that combines IoT with solar energy monitoring and household energy consumption control using an Arduino and an ESP8266. The aim of the prototype is to improve energy efficiency by controlling the use of generated and consumed energy in parallel. However, the use of an ESP8266 may limit the range of the system due to its lower wireless transmission capability compared to the ESP32.

Another prototype proposed by Sheeba et al. [20] improves the conventional digital energy meter by converting it into an IoT-enabled device using an optocoupler circuit to capture LED pulses and a system that sends data to a cloud-based platform called Firebase. This design reduces the number of components required and improves the efficiency of the existing infrastructure.

Although several commercial energy meters are available in the market, they have limitations. For example, eMon energy [21] is an energy monitoring system in Indonesia that can measure up to 14 circuits accurately, store and upload real-time information to cloud services such as InfluxDB & Grafana, Emon CMS, or Mango Automation. However, it may not be suitable for all households as it may not measure voltage in all phases or may not be configurable for both residential and industrial sectors.

The use of intelligent meters for measuring energy consumption has gained significant attention in recent years. One such example is the Engage smart meter [22], which can measure instantaneous values with power factor in four quadrants. It operates as a bidirectional energy meter for both consumption and generation, with a cost of approximately 141.99 Euros. Another example is the Wibeee Box [23], a WiFi-enabled electricity meter that monitors data on electricity consumption and allows users to view it from their smartphones, tablets, or computers. This device has a cost of 181.75 Euros. These devices provide valuable information on energy consumption and can help users make informed decisions about their energy usage, leading to energy savings and a reduction in greenhouse gas emissions. However, they often come with a high price tag, which can be a barrier to their widespread adoption.

To address this issue, we propose a novel low-cost hardware and software tool for monitoring power quality in single-phase domestic networks using an ESP32 microcontroller [16]. Our embedded system enables remote evaluation and monitoring of electrical energy consumption behavior through non-invasive current measurement parameters. Based on these measurements, power, power factor, total harmonic distortion, and energy consumption are calculated. The collected data is then published and visualized on a free and open IoT application in the cloud.

Our tool was designed to be both cost-effective and high-quality, utilizing the smallest number of components possible while still maintaining quality performance. The ESP32 microcontroller enables wireless data transmission, making remote monitoring and management of energy consumption more accessible and efficient. Moreover, the non-invasive measurement method makes the tool safer and more user-friendly, as it does not require any interruption of power supply. Our proposed tool can help identify and address power quality issues that arise in domestic networks, which can have a significant impact on energy consumption and costs. The IoT application enables users to access their power consumption data remotely, facilitating better energy management and reducing wastage.

III. METHODS

In this section, we outline the materials utilized for the hardware design, as well as the software employed in the development and implementation of the prototype. Our goal is to provide a step-by-step account of the prototype's creation, emphasizing IoT technology and energy savings as the focus of our innovation.

The main components in our prototype's development were an SCT013-030 current sensor and an ESP32 dev kit V1 module. For the programming of the module, the Arduino IDE development environment was used, in which we configured the relevant libraries for the ESP32 module and Adafruit platform libraries (Adafruit MQTT Library) to facilitate the web publication of the results.

A. Material Description

1) ESP32: The ESP32 module from Espressif Systems is a System on Chip (SoC) that incorporates a dual-core 32-bit Tensilica Xtensa LX6 microprocessor (Fig. 1). This microprocessor typically operates at 160 MHz, but it is capable of achieving a clock speed of up to 240 MHz. The module integrates both a Wi-Fi communication stack and a Bluetooth Low Energy (BLE 4.1) communication stack, underlining its capacity for seamless integration into IoT applications.

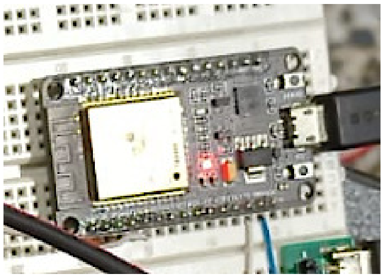

Fig. 1. Development board Dev kit V1 ESP32.

The programming of the ESP32 is achieved using the Arduino IDE and the C language, reinforcing its accessibility to developers across varying skill levels. The module employs a Reduced Instruction Set Computer (RISC) architecture, making it optimal for executing instructions at a high speed, thereby supporting more efficient energy use.

Featuring 30 pins, the module is flexible and adaptable for various inputs and outputs. The power supply voltage is 5 Vdc via the micro USB port or the Vin port, while all input and output pins operate at 3.3 Vdc. With 25 digital pins, the board can connect with a range of devices including sensors, LEDs, buttons, and other peripherals.

In addition, the ESP32 module includes two 12-bit ADC converters with 18 channels, expanding its interfacing capabilities. At an approximate cost of $8 USD, the ESP32 provides a cost-effective solution for developing IoT devices with an emphasis on energy efficiency.

2) SCT013-030 Current Sensor: The SCT013-030 is a split-core current transformer typically used to measure alternating current (Fig. 2). One of the major advantages of this sensor is that it does not require cutting of wires for operation, thereby enhancing the safety of its usage. The sensor is relatively affordable, with a market price of approximately $9 USD.

Fig. 2. SCT013-030 current sensor.

Key features of the SCT013-030 current sensor are outlined below:

- Input current: The sensor can accurately measure AC in the range of 0-30A with a 1Vac output. This broad range accommodates a variety of applications, underscoring the sensor's versatility.
- Non-linearity: It exhibits a non-linearity of ±1%, implying that the output is a highly accurate representation of the input. This characteristic is crucial for precise control and measurement tasks.
- Bandwidth: With a bandwidth of 1000Hz, the sensor is capable of handling fast-changing current levels, making it suitable for monitoring harmonic distortion.
- Resistance grade: The sensor has a B-grade resistance level, indicating its ability to withstand moderate current flows without performance degradation.
- Working temperature: The sensor can operate efficiently in a wide temperature range, from -25°C to 70°C, which ensures its performance under diverse environmental conditions.
- Dielectric strength: The sensor exhibits a dielectric strength of 1000Vac/1 min 5mA between its shell and output. This feature implies a high level of insulation, reducing the risk of electric shock.
- Cable length and Size: The sensor comes with a 1-meter long cable and has a compact size of 13mm x 13mm. This makes it convenient to integrate the sensor into various system configurations.

B. Signal Conditioning for the SCT013 Sensor

1) Voltage signal conditioning: At the outset of this project, the operating parameters of the current sensor were duly identified, verifying its ability to measure up to the 11th harmonic, courtesy of its 1 kHz bandwidth. The signal fed into the current sensor or current transformer is an AC signal ranging from 0 to 30 A ac. The sensor then transforms this into a voltage level between 0-1 Vrms due to the presence of an internal burden resistor.

If the incoming current signal is in a sinusoidal mode, the output of the current transformer is a sinusoidal signal with an amplitude between 0 and 1 Vrms. Consequently, the maximum peak-to-peak voltage this signal can achieve is given by Eq. (1):

$$V_{pp} = V_{rms} \times 2\sqrt{2} = 2.82842 \tag{1}$$

Considering that the Analog to Digital Converter (ADC) of the ESP32 module only receives positive values between 0 and the reference voltage (in this case 3.3 VDC), it is necessary to condition the signal from the current sensor to fit within this operational window (Fig. 3). To achieve this, we decided to add a DC voltage of 1.56 V to the sensor's input signal. Therefore, the maximum and minimum peak voltages at the ADC input will be Eq. (2) and (3):

$$V_{p_{max}} = 1.56V_{dc} + \sqrt{2} = 2.97V_p \tag{2}$$

and

$$V_{p_{min}} = 1.56V_{dc} - \sqrt{2} = 0.1458V_p \tag{3}$$

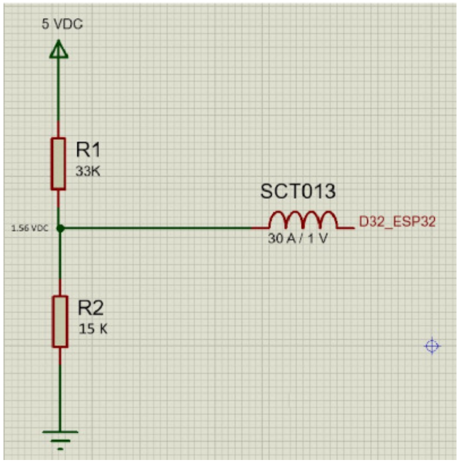

Fig. 3. Voltage divider on the analog input of the ESP32.

Through this voltage signal conditioning process, we ensure that the ADC of the ESP32 module operates within its specified range, optimizing the accuracy of our current measurements and contributing to the overall energy efficiency of the prototype.

C. *Characterization Test for the SCT 013-030 Sensor Curve*

To validate if the SCT013-030 sensor aligns with the manufacturer's linearity specifications, a characterization test was conducted. A resistive load was used alongside a stepwise variable voltage source that incremented by 0.5 V until an output current of 27A was achieved. This test's purpose was twofold: firstly, to ensure the performance of the sensor under various operating conditions, and secondly, to formulate an associated equation reflecting the sensor's response, which would be instrumental in the prototype's implementation.

The test's resultant curve depicting the sensor's behavior is presented in the Fig. 4. It should be noted that this characterization is crucial not only for validation against the manufacturer's specifications but also as an input to the development of the control algorithm that drives the IoT device's energy savings.

The equation that describes the sensor's behavior, derived from the curve, is crucial in determining the precise measurements of current. This data is used to calibrate the signal conditioning process and to feed accurate current values into the system's control algorithm, ensuring the IoT device operates at optimal energy efficiency.

D. *Software Development*

The development of the firmware for the current meter encompassed several stages, each contributing to the comprehensive functionality of the IoT device. The process began with the generation of a vector comprised of 1024 twelve-bit values, corresponding to the samples of the current signal emanating from the sensor. This data acquisition is essential in capturing the intricate details of the current waveform and provides a robust base for the subsequent Fast Fourier Transform (FFT) algorithm implementation Eq. (4).

$$\text{Vectorcurrent} = [I_1, I_2, \ldots, I_{1024}] \tag{4}$$

where I_i are the twelve-bit samples of the current signal.

After data collection, the selection and testing of the FFT algorithm were carried out. FFT is a powerful computational tool used to transform the acquired time-domain current samples into the frequency domain. The frequency domain representation of the current signal provides a more detailed understanding of the signal components, which aids in accurate and efficient current monitoring Eq. (5).

$$\text{FFT}(\text{Vector}_{\text{current}}) = [\text{Amp}_1, \text{Amp}_2, \ldots, \text{Amp}_{1024}] \tag{5}$$

Subsequent to the FFT process, the final stage involved integrating the firmware with the Adafruit.io platform for data publication. This stage is of paramount importance in the IoT application, as it provides a way to share, visualize, and analyze the data generated by the IoT device in a user-friendly manner. This step bridges the gap between raw data collection and actionable insights, contributing significantly to the overall energy savings facilitated by the IoT device.

E. *ADC Configuration and Sampling Time*

The Analog-to-Digital Converter (ADC) was configured with a resolution of 12 bits and an internal reference voltage of 3.3 VDC, the default setting. This provided an operating voltage window from 0 to 3.3 VDC, corresponding to output values ranging from 0 to 4096. For ease of operation, a mapping function, `mapf()`, was implemented to convert the ADC output values to input values expressed in millivolts. The

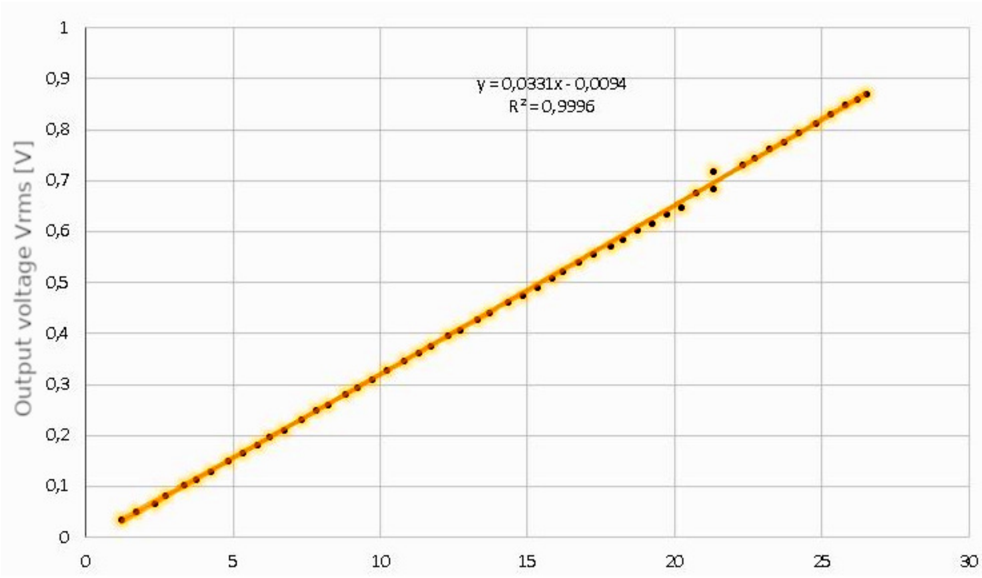

Fig. 4. Experimental characterization curve sensor SCT 013-030.

`mapf()` function accepts the maximum and minimum values of the ADC as parameters and returns a floating-point value between 0 and 3300 mV Eq. (6).

$$\begin{aligned}&\text{Mapped Value (mV)} = \\ &\qquad \text{mapf(ADC Value, ADC Minimum,} \\ &\qquad\qquad \text{ADC Maximum}, 0, 3300) \end{aligned} \tag{6}$$

To sample the current waveform accurately, it was determined that data should be collected over ten periods of the fundamental grid frequency. Given that the grid frequency for Colombia is 60 Hz, this corresponds to a sampling period of approximately 166.66 ms. The sampling time and frequency can therefore be calculated as Eq. (7) and (8):

$$t_s = \frac{0.166666}{1024} = 0.00016275 \text{ s} \tag{7}$$

and

$$f_s = \frac{1}{t_s} = \frac{1}{0.00016275} = 6144 \text{ Hz} \tag{8}$$

This sampling frequency is more than sufficient for measuring up to the 15th harmonic (900 Hz), ensuring that the device captures a detailed picture of the current waveform for efficient energy monitoring and control.

F. Implementation of Fast Fourier Transform Algorithm

We utilized the Fast Fourier Transform (FFT) computation library authored by Robin Scheibler, which offers a comprehensive description on FFT On The ESP32. This particular library algorithmically decomposes a discrete signal into its spectral constituents through a Radix-2 Decimation in Frequency method. It employs the Bit-reversal technique to reorder the output vector, starting from the DC component (zero frequency at position zero of the output array) up to the sampling frequency divided by two for a unilateral transform or up to the sampling frequency for a bilateral transform.

The output vector of the algorithm contains complex values corresponding to each frequency in the measurement range. Hence, post-FFT, the amplitude calculations for each frequency are performed on the input vector. The fundamental frequency and its corresponding amplitude are identified as the maximum of the computed magnitudes Eq. (9).

$$A_f = \sqrt{Real^2 + Imag^2} \tag{9}$$

Here, A_f denotes the magnitude at a specific frequency, and this value should coincide with the amplitude at that frequency. Based on our practical observations, we found a need to correct these values. Thus, we introduced a correction factor for the amplitude of each frequency component, which we denoted as $I_{error} = 0.662946429$. This value was derived empirically using laboratory measurements and curve fitting techniques Eq. (10).

$$A_f = 0.662946429\sqrt{Real^2 + Imag^2} \tag{10}$$

These corrective steps ensured the precision of the signal decomposition, thereby enabling more accurate energy consumption measurements and contributing to the broader goal of enhancing energy efficiency through IoT technologies.

G. Calculation of Power and Energy

The SCT013 sensor's current measurement range (0 to 30A) is mapped once the amplitude of the fundamental frequency is obtained. This mapping is accomplished through the function *Calculate_Irms()*. Assuming a sinusoidal input voltage regime of 120 Vrms amplitude, the instantaneous power P_0 in kilowatts is defined as follows Eq. (11):

$$P_0 = \frac{V_{rms} \times I_{rms}}{1000} \tag{11}$$

The energy calculation used a base time of 1.04 seconds, the time it takes for the program to complete all computations, from sampling to THDi calculation, six times over. Hence, energy, E, is calculated as Eq. (12):

$$E = P(W) \times T_{(1040)} ms[h] = P(W) \times 1040[ms] \times \frac{1h}{3600 \times 10^3 ms} \tag{12}$$

Given that energy accumulation should not exceed 24 hours, the accumulation timer and energy counter reset every 24 hours (86400 seconds).

H. Calculation of Current Harmonic Distortion

Once the FFT of the current signal and the corresponding harmonic amplitudes are obtained, the Total Harmonic Distortion of Current (THDi), caused by the presence of nonlinear loads in the system, is determined Eq. (13):

$$THD_i = \frac{\sqrt{\sum_{n=2}^{n_{max}} I_n^2}}{I_1} = \frac{I_H}{I_1} \tag{13}$$

Here, I_H denotes the root mean square (rms) value of the harmonic current, and I_1 represents the rms value of the fundamental current. This calculation offers an important insight into the system's performance, specifically concerning the influence of nonlinear loads, which directly impacts energy consumption and system stability. Thus, it provides a key factor for implementing energy-saving solutions in IoT environments (Fig. 5).

I. Prototype Testing

In order to comprehensively evaluate the performance of the prototype, a specialized testing setup was designed and implemented. This process required a current source capable of supplying current to a biphasic load. In this instance, the load was represented by four infrared lamps, typically used in automotive paint-drying ovens. This testbed, under normal operation, is capable of delivering 380V line-to-line (VLL). However, the load can withstand up to 220VLL.

The testing process started from a zero-baseline voltage, which was progressively increased. Simultaneously, the current values were measured using the SCT013 current sensor, an Extech clamp meter, and an AEMC 8220 power quality analyzer. This procedure was done to cross-verify and confirm the accuracy of the measurements taken by the developed prototype. The Fig. 6 illustrates the high voltage laboratory setup, which was utilized for performing these tests on the prototype.

Fig. 7 provides a comprehensive illustration of the intricate connection or measurement schema adopted in this study. At the core of this configuration are the three principal devices, which are pivotal to the research:

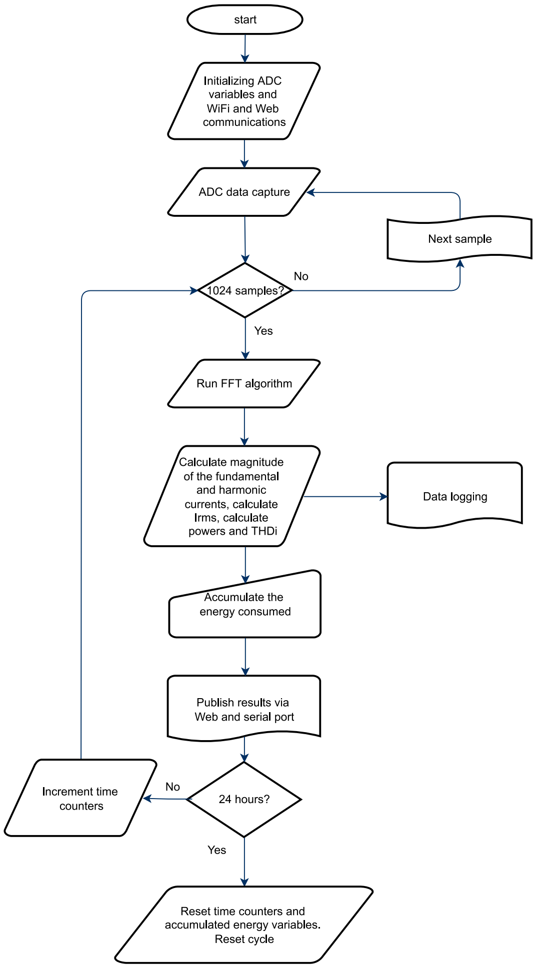

Fig. 5. Flowchart of the processing algorithm.

- SCT013 Current Sensor: This sensor is designed to measure the current flowing through a conductor without the need to interrupt the circuit. It uses a magnetic core to detect changes in current and convert it into a voltage, which can then be read by our prototype. Its non-invasive nature allows for safer and more convenient monitoring, especially in scenarios where continuous power supply is paramount.
- Extech Clamp Meter: Acting as a supplementary tool, the Extech clamp meter aids in the measurement process by clamping onto the conductor to determine current values. Its utility is evident when one wishes to validate readings quickly without delving into intricate circuit connections, providing a quick yet reliable snapshot of the current scenario.
- AEMC 8220 Power Quality Analyzer: This device is considered the gold standard in our research. The AEMC 8220 is a versatile tool capable of measuring multiple parameters, including voltage, current, and power quality attributes. In our schema, it serves the dual purpose of providing reference measurements and validating the accuracy of our prototype's readings. By comparing results from the IoT-based energy sav-

Fig. 6. Test bench.

ing prototype with the AEMC 8220, we ensure the credibility and reliability of our device.

The strategic arrangement of these devices is essential to achieve two key objectives: firstly, to enable accurate and consistent data acquisition by our IoT-based energy saving prototype; and secondly, to ensure that the measurements from the prototype can be cross-verified against established and well-regarded instruments in the industry, thereby reinforcing the validity and reliability of our findings.

A comprehensive view of the entire setup employed for prototype testing with the infrared lamps is depicted in Fig. 8. This illustration provides a clear visual of the prototype, connected and functioning within the wider measurement system.

Moreover, as shown in Fig. 7, the infrared lamps can be seen reaching incandescence during the testing phase. This phenomenon is a result of the power supplied to the lamps, showcasing the operational flow of the overall system. The lamps glowing red-hot emphasize the real-time nature of the prototype testing, hinting at the authenticity and practical applicability of this IoT-focused energy-saving system.

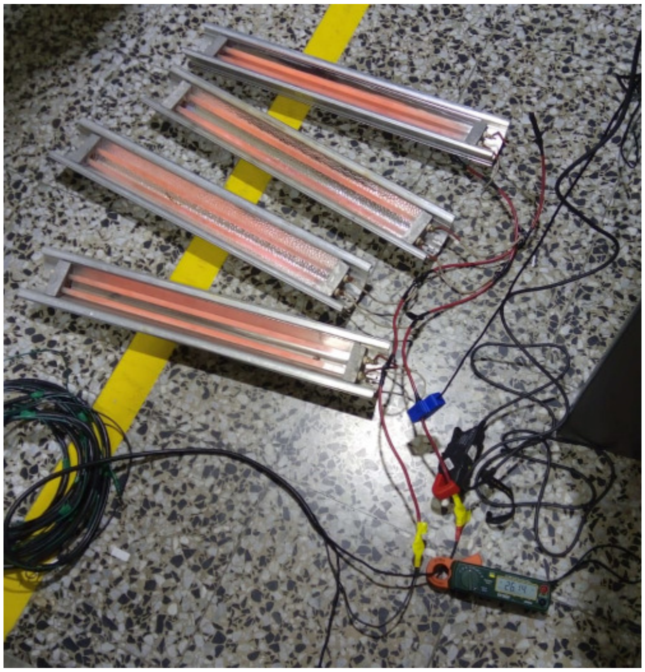

Fig. 7. Connection and operation of load and measuring instruments.

During the initial phase of testing, depicted in Fig. 9, the prototype exhibited behavior that deviated from the anticipated performance due to a confluence of factors. These variables are inherent in any experimental setup and include the accuracy of resistors, the measurement error introduced by the SCT013 current sensor, and the intrinsic variations in data acquired over time.

To account for these factors and to validate our prototype's performance, we compared the measurements obtained from our IoT-based energy-saving system with those acquired from two robust measurement tools: the Extech clamp meter and the AEMC 8220 power quality analyzer. This comparative approach allowed us to understand the performance nuances of the prototype and adjust the system to minimize the influence of external variables on the overall performance.

Following the preliminary testing phase and the insight gleaned from it, we made software adjustments to correct the discrepancies detected in the prototype's behavior. Our goal was to reduce the measurement error and improve the accuracy of the energy metrics provided by our IoT-based system.

During the subsequent testing phase, illustrated comprehensively in Fig. 10, we observed marked enhancements in the performance of our prototype. This phase of testing was crucial, as it allowed us to evaluate the modifications made after our initial tests.

- Data Points Alignment: The data points captured from our system were strikingly more aligned with those obtained from our reference measurement tools. Instead of a broad scatter or deviation, the points clustered around the readings from the AEMC 8220 and the Extech clamp meter. This closer alignment served as an early indication of the success of our recent tweaks and calibrations.

Fig. 8. Measurement and capture instruments during testing.

- Reference Measurement Tools: The choice of AEMC 8220 and Extech clamp meter as our reference tools was strategic. The AEMC 8220, being a renowned power quality analyzer, provided us with accurate and industry-accepted measurements. On the other hand, the Extech clamp meter gave us rapid and reliable snapshots of the current, serving as an essential tool for instant validation. Our prototype's readings moving closer to these reference tools' measurements was a significant achievement.

- Software Adjustments: The software adjustments we incorporated after the initial test phase were pivotal. These adjustments, a combination of algorithm tweaks and calibration methods, aimed at refining the measurement accuracy and eliminating any observed anomalies. The data from the subsequent testing phase strongly suggested that these software interventions played a major role in enhancing the prototype's performance.

Conclusively, the dataset from this testing phase clearly indicated that our prototype's behavior was now in tight congruence with the expected outcomes, grounded on the reference tools' readings. This not only solidified our confidence in the software changes we had implemented but also underscored the prototype's potential for reliable energy measurements in real-world applications.

IV. RESULTS

Examining the response portrayed in the various figure plots, it is evident that the devised energy meter's performance measures favorably with existing industry standard devices. Despite the intricate characteristics inherent in this prototype, it not only fulfils the capabilities of measuring active power and Total Harmonic Distortion of current (THDi) but accomplishes these tasks with significant cost advantages.

These characteristics are particularly vital for efficient energy management, and by having a solution that can provide such capabilities at a much lower cost, we are propelling ourselves towards improved energy savings. The insight from the experimental results suggest that integrating IoT technology with traditional electronics and control engineering principles can indeed form a basis for a high-performing, yet cost-effective solution for power and THDi measurement.

The overall performance of our device, as suggested by the curves depicted in the figures, confirms the robustness of the design and the success of our software adjustments in refining the meter's precision. These results provide substantial evidence that our approach to a more economical and compact energy meter can be invaluable in power quality and energy management systems where budget and space constraints are of importance.

While the prototype exhibited excellent performance with a precision rate of 91% compared to the AEMC 8220, it's worth noting that in scenarios with fluctuating loads, the device consistently measured active power within a margin of 2%. Moreover, the THDi measurements provided insights into the harmonics present, showcasing its capability to be a tool not just for energy measurement but also for preliminary power quality analysis in households. The low cost of approximately $24 USD makes this device particularly attractive for residential settings, especially in developing regions where budget constraints are paramount.

A. Limitations

Despite the evident success and promise of our IoT energy meter, it is crucial to acknowledge certain limitations of our study:

- Scope of Testing: The comparative testing was primarily performed against the AEMC 8220 energy meter. While it provides a benchmark, the results might differ when compared with a broader range of energy meters available in the market.
- Prototype Stage: The device is still in its prototype stage. Real-world application and longevity tests are required to ensure its robustness and durability over extended periods.

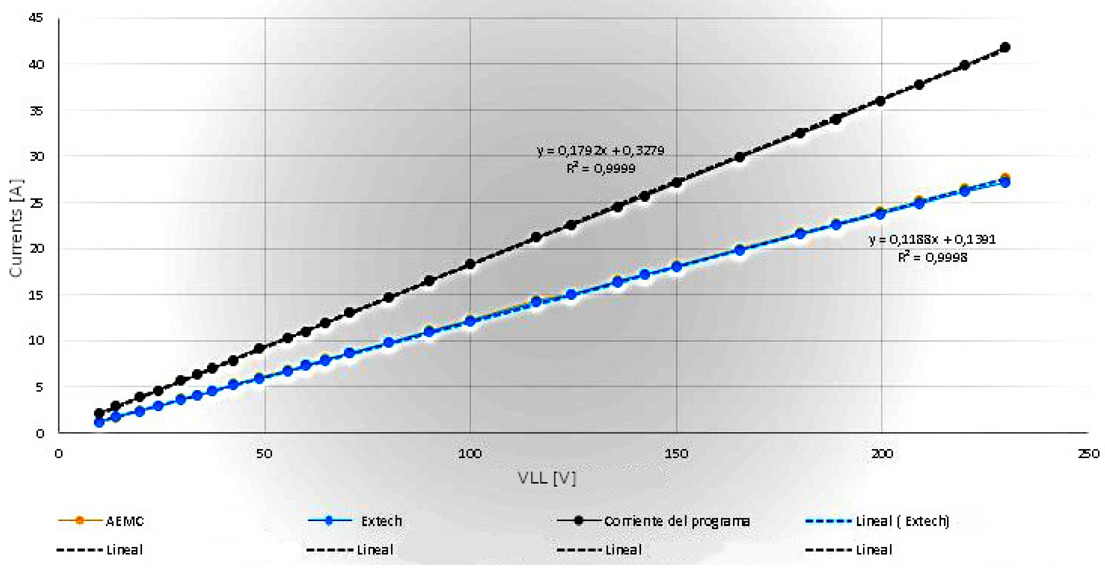

Fig. 9. Initial prototype testing.

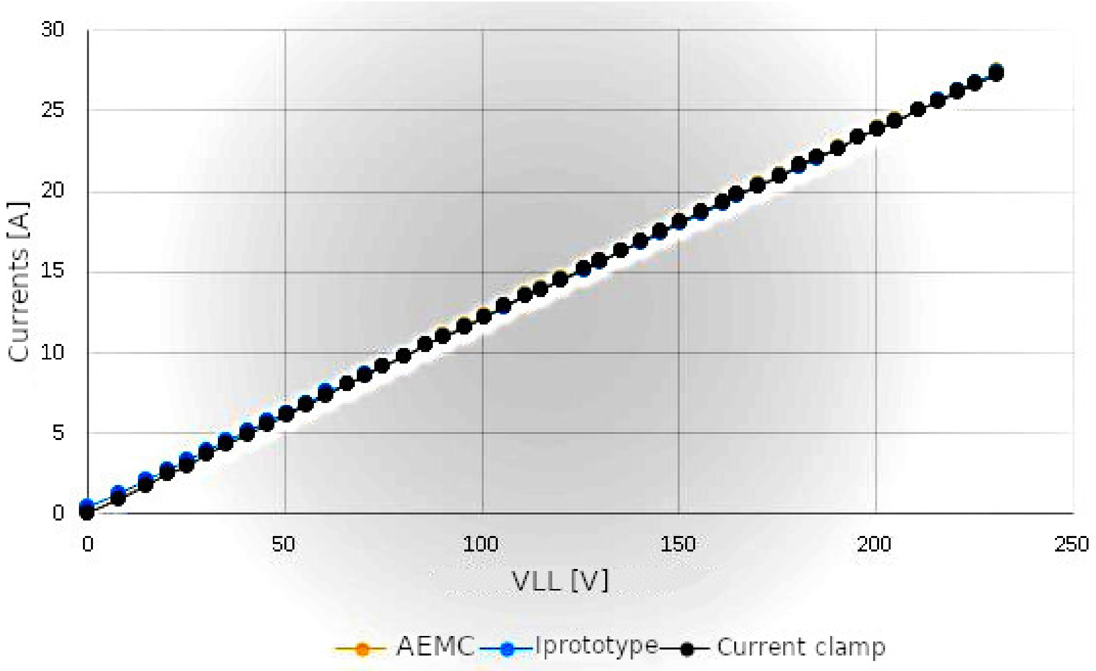

Fig. 10. Software-adjusted prototype testing.

- Potential Interferences: The prototype was tested in controlled environments. External factors like electromagnetic interferences or extreme environmental conditions, which can potentially affect the performance, were not extensively studied in this research.

- Software Limitations: While open-source software offers cost advantages and customizability, it might not be as optimized or stable as proprietary software solutions in certain scenarios. This might lead to performance or stability issues in some edge cases.

V. CONCLUSION

Throughout this study, we focused on the design and development of a cost-effective, user-friendly, and feature-rich IoT energy meter as an alternative to other market offerings. Our goal was to enable mass production of the meter to aid in critical global endeavors, including energy efficiency and optimization, especially considering the growing prevalence of nonlinear loads in residential settings.

The successful development of a prototype has been achieved using accessible and cost-effective materials, in conjunction with open-source software, costing approximately $24 USD. Comparative testing against a well-regarded AEMC 8220 energy meter yielded a precision of 91% in relation to key parameters such as active power and Total Harmonic Distortion of current (THDi).

The developed prototype's low cost and high quality offer substantial benefits to the realm of energy efficiency. It equips end-users with a simple, attainable tool for monitoring and managing their household energy consumption, thereby advancing residential energy optimization.

As we look to the future, it is feasible to extend the functionality of the device to include bidirectional energy measurement capabilities. This would enable the support of alternative energy sources for low-income users. Furthermore, the inclusion of THD measurements can assist in calculating the impact of harmonics on the distribution network, leading to improved power quality management at a residential level.

VI. FUTURE RESEARCH DIRECTIONS

While the current research and development have proven successful in designing an economical and precise IoT energy meter, there are several promising avenues for future research and enhancement of the device:

- Integration with Renewable Energy Sources: As the global shift towards green energy continues, integrating the energy meter with renewable energy sources such as solar and wind can be invaluable. It would be insightful to research how our meter could be enhanced to support not just traditional power sources but also renewable ones, offering users a comprehensive view of their energy consumption and generation.
- Advanced Harmonics Analysis: With the increasing use of nonlinear devices in homes, harmonics play a crucial role in power quality. Future research can delve deeper into advanced harmonic analysis techniques and provide users with detailed reports and insights into their energy consumption patterns, enabling them to make informed decisions on managing and reducing their harmonic footprint.
- Machine Learning and Predictive Analysis: By incorporating machine learning algorithms, the energy meter can offer predictive analytics on energy consumption, allowing users to anticipate their energy needs and adjust accordingly. This research could lead to the development of an intelligent system that not only monitors but also predicts and optimizes energy consumption based on historical data and user behavior.

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