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A Low Cost and Highly Parameterizable Energy Meter

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***Abstract*—The popularity of the Internet of Things (IoT) and demand for smart devices, particularly in the smart home industry, has increased in recent years. As a result, there is a growing need for affordable and functional energy meters to measure electric energy consumption, mainly due to the rise of electric vehicle (EV) sales and energy prices in Europe. In this paper, we present the development of an energy meter that accurately measures voltage, current, active power, frequency, and power factor. The energy meter is designed to provide information to an intelligent EVSE (Electric Vehicle Supply Equipment), allowing users to "plug and forget." We describe the hardware and software of the latest energy monitor version, including an ESP8266 microcontroller, a PZEM-004TV3 energy meter, an OLED display, and a power supply circuit board. We also present some results of the energy meter's use, highlighting its functionalities and benefits. The paper concludes with insights into a new version planned for the energy monitor. This paper will be of interest to researchers and industry professionals working in the IoT and smart device fields, as well as those interested in energy efficiency and EV charging infrastructure.**

***Index Terms*— IoT, Energy Meter, Microcontroller, Smart Metering.**

I. Introduction

In recent years, IoT is probably one of the most common fields targeted by industry, small, medium, and large companies, and even the general public with little or no knowledge of technology. According to [1], [2] it's possible to see that somewhere around late 2013, the search for the terms "IoT", "Internet of Things" and "Smart Home" exploded. The advent of Industry 4.0, the increase in the number of smart devices, the reduction in internet access prices, people's search for a more comfortable home, in which smart home appliances make a significant contribution, led to the massification of IoT. Nowadays, it is very rare to buy an appliance without smart functions or an application that allows you to control some of its functions, be it a robot vacuum cleaner or an air conditioning unit. Even today's washing machines or fryers have a Wi-Fi connection and an Android/IOS application that allows you to collect information on the operating progress or even allows to control them or load/upload new firmware. Lately, the increase of EV (Electric Vehicles) sales [3] and the increase in energy prices in Europe as lead people to acquire more knowledge of their electric energy consumption, which in turn has increased the search for devices that can measure the electric energy consumption. Some devices are present in the market [6], [7], however, either the functionalities are scarce or the price is high. This work presents the development and functionalities available on an energy meter developed by the authors. This device was designed to provide information to an intelligent EVSE (Electric Vehicle Supply Equipment) also developed by the authors [16], [17] designated as IEVCC (Intelligent Electric Vehicles Charge Controller), and since its first version has evolved into a more configurable and parameterizable device. The remaining of this document is divided into the following sections: section II describes some similar devices and work about energy meters; section III presents our device and explains its functionalities; section IV presents some results of the use of this device and section V presents the conclusions and future work directions.

II. Related Work and Devices

Probably the most known energy meter devices in the commercial world are the ones from Allterco - Shelly [6]. With products that have prices in the range of 17€ to 120€ (plus taxes), they provided a range of products that, beside measuring, are able to open the load circuit. However, this limits the maximum measurable current to 25A, and even though they provide information by HTTP/HTTPS, they don't have MQTT (Message Queuing Telemetry Transport) [15] or are unable to provide both MQTT and HTTP simultaneously and data transmission is limited to the shelly private cloud. Measurement of high power is provided by devices provided by smart-maic [7], which can measure up to 2000A and provide MQTT information, but have a price tag that starts at 60€ and goes up to 400€.

In [8], a comprehensive overview of the benefits and challenges of smart energy meters in intelligent energy networks, as well as an understanding of their impact on the future of energy management is provided. [9] gives an overview of the role of smart meter data in future energy systems and the opportunities and challenges associated with its use. A survey conducted by [9] shows that participants rated the ability to monitor real-time energy usage as the most crucial home energy display functionality. Other highly rated features included the ability to set energy usage targets and receive alerts when usage exceeds those targets, as well as the ability to view historical usage data. A study conducted over 12 months [10] where HEMs (Home Energy Monitors) were provided to the participants shows that using HEMs positively impacted household energy consumption and behavior over the medium term. Participants who used the HEMs were able to reduce their energy consumption by an average of 7.4%, with some participants achieving reductions of up to 20%.

III. Energy Meter Description

About three years ago, the authors felt the need to create an EVSE to fill a market gap. At the time, there was no EVSE on the market that the user could just ”plug & forget”. By ”plug & forget” we mean that the car could charge, taking full advantage of the contracted power, and the user can turn on any household appliances without fearing that the main circuit breaker would be triggered. In order to work like that, an energy meter was needed that could provide the house consumption at any time. Despite several products being present on the market, they lacked key features considered essential to the project: no customization, lack of MQTT or HTPP support or both, only sending the data to private clouds, the price tag too high, etc. This led to the development of the energy monitor described in this document and has evolved over time. This section describes the hardware and software of the latest version at the current time, and section V will provide insights into a new version planned.

A. Hardware

The energy monitor is built using an ESP8266 microcontroller [11], a PZEM-004TV3 [13], a 0.96” OLED display, and a power supply circuit board. The left side of Fig. 1 shows a front assembly of all used components. This PCB was created in such a way that the used ESP8266 can be replaced with an ESP32 [12] directly without any modifications to the hardware. The use of EPS32 allows the construction of a more powerful energy monitor that can be used to control/provide information to the designated mesh version of the IEVCC [5].

All circuit was assembled to fit inside a 3D printed box (right side of Fig. 1) with a design similar to a double circuit breaker that can be mounted on an electric board. The used PZEM-004TV3.0 allows the measurement of Voltage, Current, Active Power, and Frequency with an accuracy of 0.5% and Power Factor with an accuracy of 1% [14] and can measure up to 100A of current. It also provides an internal Active Energy counter that can measure up to 9999.99kWh, resetting to zero

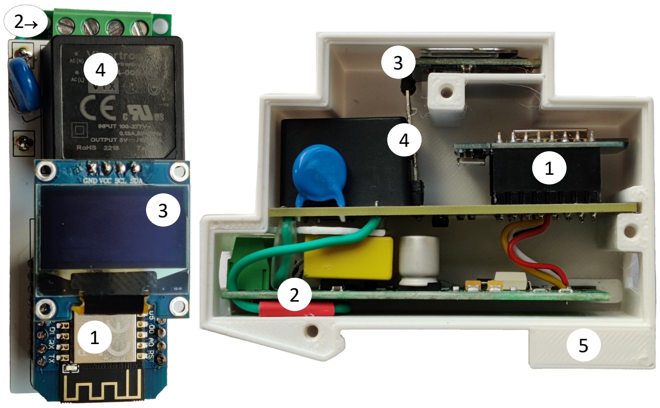

Fig. 1. Top view of Energy Monitor assembly (left) and inside the 3D printed box (right): 1-ESP8266; 2-PZEM-004V3.0; 3-OLED display; 4- PSU; 5-3D Printed enclosure

after this value or by software. The display offers the capability to show the current measurement of Voltage, Current and Active Power, cycling between values of other PZEM when installed. The total estimated cost for each energy monitor is about 20€. Up to 4 more PZEM can be added without needing hardware modifications (only a connecting cable must be soldered to the board by each PZEM added). A 3D-printed case was also designed to fit any new PZEM and uses the space on a single circuit breaker on an electrical installation board. Each additional PZEM allows the measurement of a new circuit and adds up to a cost of around 7.5€.

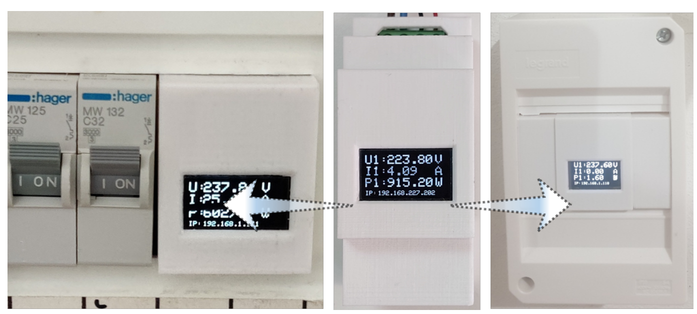

Fig. 2. A single phase energy monitor (left) and a three phase energy monitor (right)

Fig. 2 shows a single-phase energy monitor mounted on a main electric board and a three-phase energy monitor mounted on an external board due to the lack of space on the main board.

B. Software and Web Interface

The software was developed to function as an AP station for the first time the system is connected to power. The user can then connect to it with a mobile device and configure several options, including Wi-Fi credentials. In order to access it, the first step is to connect to the SSID emitted by the device at a specified IP address, where a webpage has the one shown in Fig. 3 is rendered. Here information about the current values being measured can be seen, and the device's IP address on the local network is also shown if the device is connected to the local network.

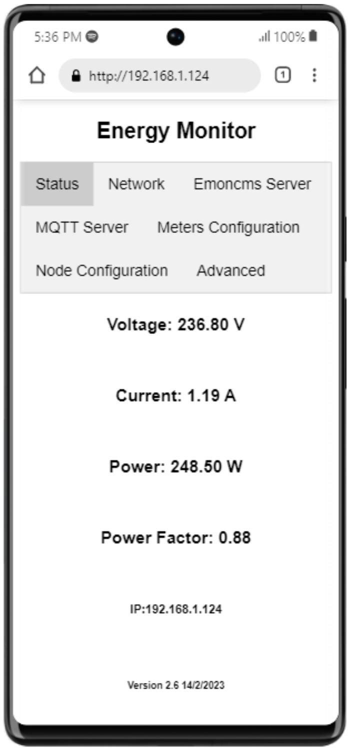

Fig. 3. Energy Monitor Status Web page

Input: Wi-Fi SSID and Password Textboxes
Output: Device with Wi-Fi Credentials
Read data from Wi-Fi SSID and Password Textboxes;
Store the read values into EEPROM;
Reboot device;
if *SSID and password are stored in EEPROM* **then**
    Read stored values in EEPROM;
    for *i* = *1 to 20* **do**
        Try to connect to Wi-Fi with stored credentials;
        if *Wi-Fi connection successful* **then**
            Break loop;
        end
    end
end
else
    Start AP Station Mode;
end

Algorithm 1: Connecting to Wi-Fi with Stored Credentials

The Network tab (Fig. 4) is where information about the local network can be entered so the device can connect to the local network. After the user enter the credentials and press the save button, Algorithm 1 is run.

Emoncms [14] is an open-source software that allows the user to keep track of the consumption of his devices and can calculate the user costs with energy, gains/savings with

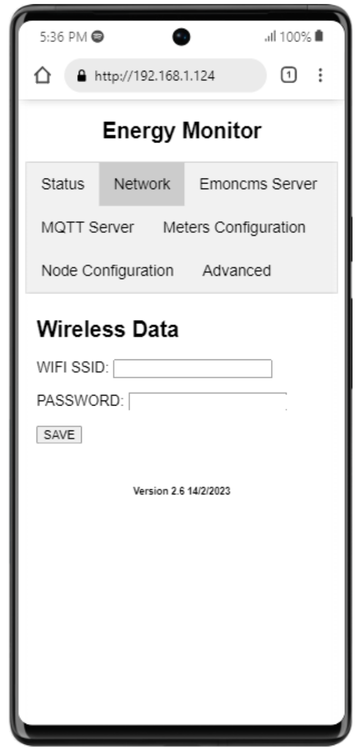

Fig. 4. Energy Monitor Network Settings tab

Input: MQTT Server, MQTT Port, Username and Password textboxes, DropDown on/off box
Output: Device with MQTT credentials
Read data from MQTT Server, MQTT Port, Username and Password textboxes and dropdown box selected option;
Store the read values into EEPROM;
Reboot device;
if *MQTT settings are stored in EEPROM and ON option was selected* **then**
    Read stored values in EEPROM;
    for *i* = *1 to 3* **do**
        Try to connect to MQTT Server with stored credentials;
        if *MQTT connection successful* **then**
            Break loop;
        end
    end
end
else
    Continue boot process;
end

Algorithm 2: Connecting to MQTT Server with Stored Credentials photovoltaic production, etc. It's possible to create an account on the emoncms website, but payment is required to have information stored. However, since emoncms is a web app, it's possible to install emoncms on almost any device with a web server. With this in mind, the possibility of sending information to emoncms was added to the energy meter (Fig. 5). After entering the required information, it is stored in the EEPROM to be available at the next boot.

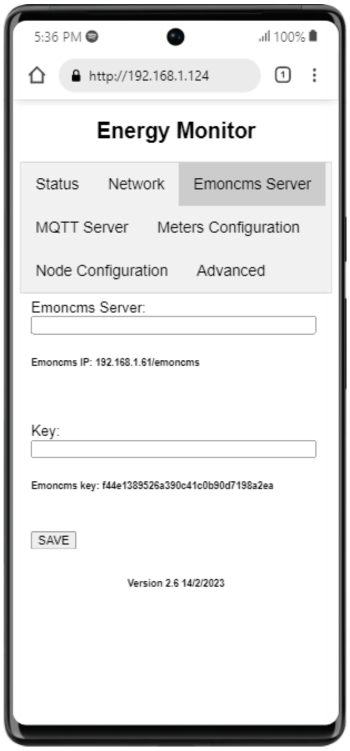

Fig. 5. Energy Monitor Emoncms Settings tab

The code created for the energy meter includes a simple MQTT broker. This protocol publishes the current values measured, and the IEVCC or any other client subscribes to that topic and uses the information to adjust the charging power. Due to the chip limitations (RAM and processing power), only messages with QoS 0 are supported, and no message is retained. Also, the number of clients connected to it is very limited. So, if necessary, it's possible to publish that information to an external MQTT broker, and that information is entered in the tab MQTT Server (Fig. 6). After entering the data, and pressing the save button, Algorithm 2 is run.

As stated before, the energy meter has the potential to connect to up to 4 PZEM, so it's necessary to configure the number o PZEM present. By default, this value is set to 1, so a Tab that allows configuring the number of PZEM is available (Fig. 7). Here options from 1 to 4 clamps are available, and also options for Solar and Triphasic are available. When option Solar is chosen, it's assumed that the first PZEM measures the house consumption and the second one measures the solar production. In this case, a second MQTT topic is created with the current measured from solar production. When a three-phase system powers the user house, the option Triphasic should be selected. Here it's assumed there are three clamps, one for phase, and only the highest current value is published to the MQTT topic.

Whenever an option is selected on this tab and the save button is pressed, that value is stored in the EEPROM. No reboot is performed, but every time the system boots, this value is read from the EEPROM and used.

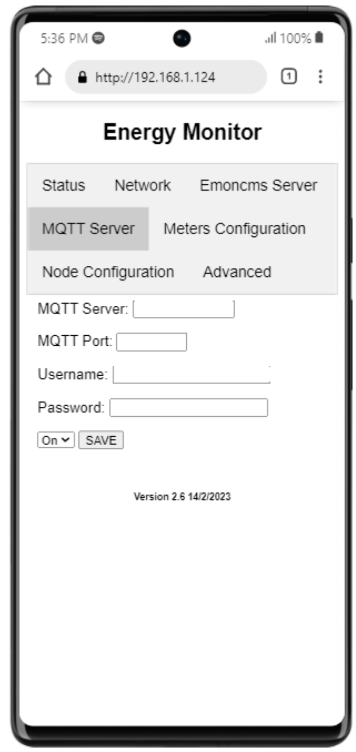

Fig. 6. Energy Monitor MQTT Settings tab

Sending data to emoncms is performed by an HTTP GET/POST method. On the request, the sending device must send a unique ID, an ID for each value, and the values. To define these IDs, the Node Configuration tab (Fig. 8) has a set of fields that allow defining the node name and each meter ID. Fig. 9 shows a screenshot of emoncms inputs where two energy meters send information. The first one, designed as ”Bastidor”, is a single clamp meter where the ”Meter 1 name” was also defined as ”Bastidor”, so the sent values - voltage, current, and power - appear designated as ”V_Bastidor”, ”I_Bastidor” and ”P_Bastidor”. The second energy meter is a three-clamp meter designed as ”Garagem”, and each clamp was designated as ”EV1”, ”EV2” and ”Tomadas”.

IV. Results

Several energy meters have been mounted over the last two years, working flawlessly since the beginning. They provide information on several house appliance consumption, sending data to a local emoncms system. A screenshot of a full cycle of a dishwasher is shown in Fig. 10. Here it's clear when the heating cycle begins/ends (the power rises to around 2000W

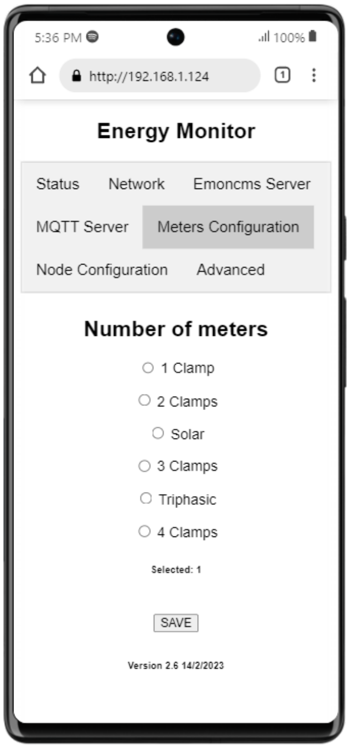

Fig. 7. Meters Configuration Tab

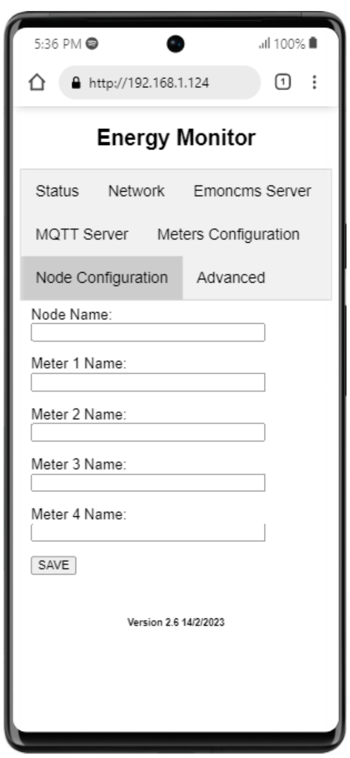

Fig. 8. Node Configuration Tab

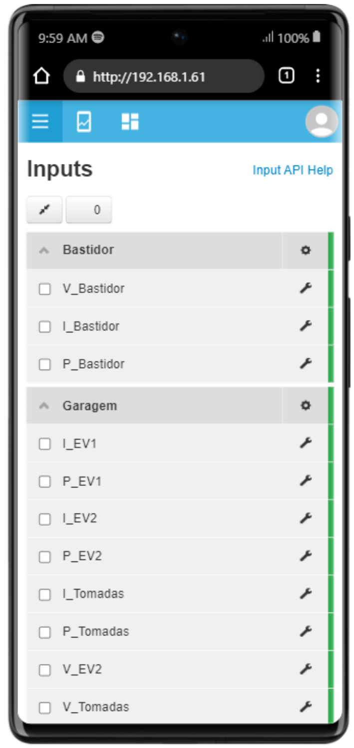

Fig. 9. Emoncms inputs screenshot example

and drops to 50W). Another example is the charging of an EV (Fig. 11). In this case, it's the charging of a 30kWh Nissan Leaf up to 100%. The charging was programmed to be complete at 8 AM with a constant power of 3400W (around 16A charging current). To fulfill that, it started at 3:50 AM, the Leaf charges at a constant current up to 98% and then enters a constant voltage charge cycle, which is visible in Fig. 11 when the power starts lowering (around 6:35 AM). Finally, Fig. 12 shows the measurement made in a photovoltaic production with a peak power of 2000W. The typical Gaussian curve associated with these productions is perceptible, and some power decay in production is related to small clouds passing by.

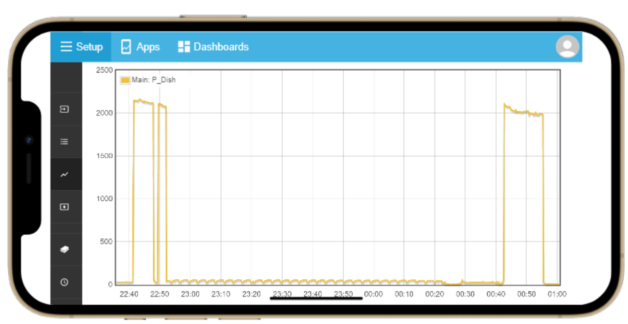

Fig. 10. A full cycle of a dishwasher

Fig. 11. A charging cycle of a Nissan Leaf to 100%

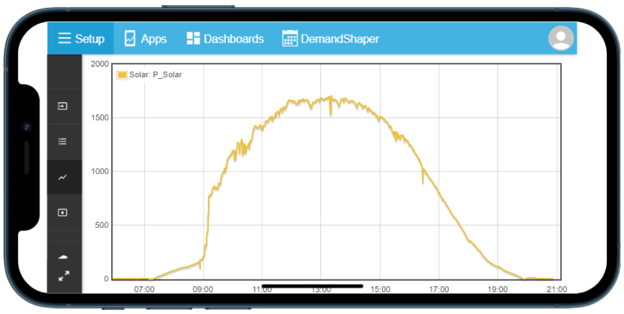

Fig. 12. Measurement from a photovoltaic production with 2000W peak

V. Conclusions

A low-cost and highly parametrizable energy monitor was presented in this work. It's built around a simple yet efficient and low-cost microcontroller and a board capable of high precision measuring Voltage, Current, and Active Power. The chosen microcontroller allows the integration of a web server, which in turn enables the construction of a web page that gives the possibility to configure a set of parameters related to the energy monitor and external servers for collecting data. The system also includes a simple MQTT broker, which periodically publishes some of the read values to a specific topic that other devices can subscribe to. The system allows the simple addition of more boards without any hardware modifications, and it is compatible pin by pin with a more powerful version (32 bits, dual-core) of the same microcontroller family, which in turn allows a more complex integration with external devices (*e.g.*, the mesh version of the IEVCC).

As future work, a more graphical web environment will be implemented to control the mesh version of the IEVCC. Also, it's on the plans for an even more powerful version using a Raspberry PI that integrates an emoncms system and a touch screen.

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