Implementation of a secure system for calculating and supervising the energy consumption of electrical equipment

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ABSTRACT

With the advent of smart grids and the growing challenges associated with the production and consumption of electrical energy, it is crucial to deploy reliable systems to monitor production and consumption, as well as to improve energy efficiency. To ensure optimal decision-making in energy management and control systems, it is essential to have both efficient measurement systems for data collection and acquisition and secure information exchange. These elements are fundamental to ensuring the smooth operation of energy systems and enabling precise supervision of energy flows, thus contributing to more efficient use of available electrical resources. This article focuses on the implementation of a complete electrical energy calculation and management system for energy consumers. To achieve this, devices such as integrated digital control units and current and voltage sensors are used. The system architecture guarantees precise measurement and calculation of electrical energy and other important parameters, such as power factor in the case of inductive and capacitive loads, which have an effect on reactive energy. The data collected is stored in a secure database.

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1. INTRODUCTION

The advent of smart grid technologies, the integration of renewable energy sources, and the distribution of generation units have created considerable challenges in the field of electrical energy management [1]-[3]. These include the management and reduction of electricity demand. Power grids must be able to adapt to fluctuations in demand, particularly during peak periods. In addition, accurate measurement of electricity consumption is essential for efficient power management. Load fluctuations also require immediate detection to ensure that the power grid is not overloaded [4]. Optimizing energy consumption is another major challenge in electrical energy management. Another challenge is data transfer security, which is crucial to protecting the information exchanged between the various players on the power grid. These security concerns are the confidentiality, integrity, and availability of the data exchanged. Security measures must be put in place to protect against attacks, data leaks, and service interruptions [5], [6].

To overcome these challenges, the implementation of a secure energy consumption calculation, management, and supervision system for electrical consumers can provide an effective solution. This system enables precise measurement of energy consumption, detection of load fluctuations, optimization of energy consumption, and guarantees the security and quality of the power supply. This paper proposes a secure electrical energy calculation solution for consumers, using advanced technologies such as the internet of things (IoT) and embedded systems. The system is based on ESP32 cards equipped with current and voltage sensors to precisely measure the energy consumption of individual pieces of equipment. The data is then transmitted via a secure connection to a Raspberry Pi (Data center). Within this data center, remote monitoring and data analysis are used to improve the energy efficiency of the energy system. Decisions can be taken in real time to optimize energy consumption and reduce energy losses.

This work is divided into two main parts: The first part provides a detailed presentation of the system architecture and its main components. This part also presents the strategy, the steps, and the equipment required to implement the energy computing and supervision system developed. The second part is devoted to the presentation and discussion of the various results obtained. This section evaluates the effectiveness of the system and analyzes the data collected. Finally, a conclusion summarises all the work carried out, highlighting the main results and prospects for future research in this field.

2. STUDIED SYSTEM AND METHOD

2.1. Studied system

The system described in this section is part of a hybrid energy system incorporating an energy management model developed using artificial neural networks [7], [8]. This hybrid system combines several elements: a photovoltaic panel, a connection to the public electricity grid, a local energy storage device, electrical consumers, and an energy management model based on artificial neural networks. Figure 1 illustrates the system under study, which consists of a number of electrical appliances (consumers), each connected to an ESP32 card. The ESP32 plays a central role in collecting and transmitting energy data. The Raspberry Pi, with its computing power and storage capacity, can process, analyse, and store the information collected by the ESP32 cards. In the rest of this section, we will describe the various components used in the system, highlighting their specific roles and functions.

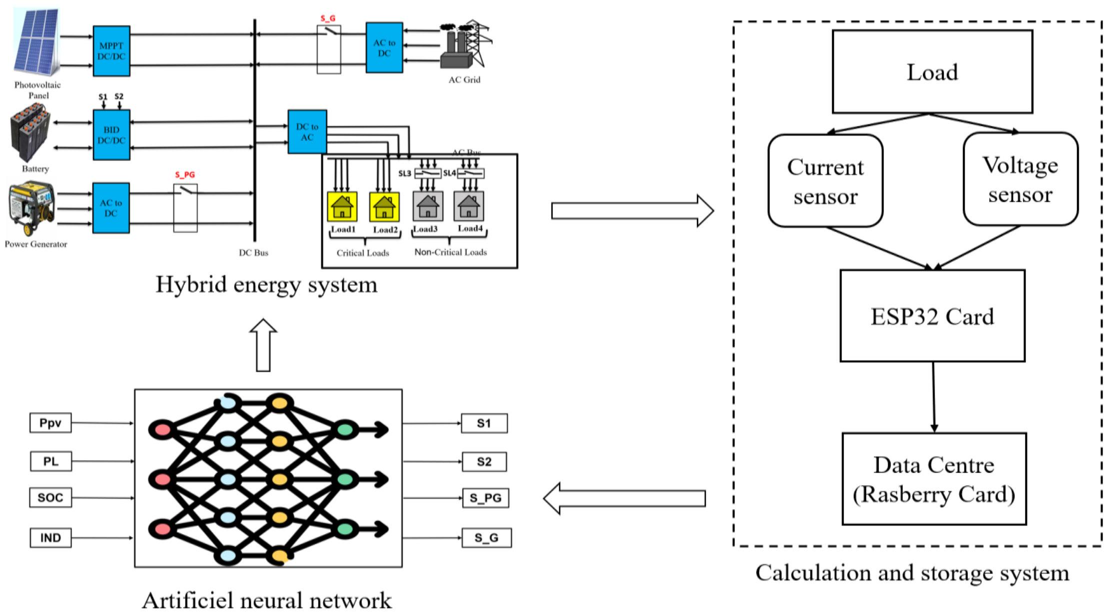

Figure 1. Architecture of the studied system

2.1.1. Loads

Electrical loads are devices that consume electrical energy to operate, such as household appliances, electronic equipment, lighting and heating systems, etc. There are two types of load: critical and non-critical. Critical load refers to an electrical load that is essential for the proper operation of a system or process.

This may include equipment such as security systems, data backup systems, and cooling systems. Loss of power to these critical loads can lead to serious consequences, such as data loss, property damage or endangerment of human life. On the other hand, non-critical loads refer to electrical loads that are not essential to the immediate operation or safety of a system.

2.1.2. Sensors

Figure 2 shows voltage and current sensors, the latter being key components of power measurement systems. Current sensors are used to measure the current flowing through an electrical load, while voltage sensors are used to measure the voltage across the load. In our case, we have adopted the ZMPT101B sensor in Figure 2(a) as the voltage sensor and the ACS712 sensor as the current sensor in Figure 2(b).

(a) (b)

Figure 2. Sensors used (a) voltage sensor and (b) current sensor

2.1.3. ESP cards

ESP32 cards play a central role in the collection of energy consumption data. They are equipped with current and voltage sensors that enable precise measurement of the equipment's electrical quantities. With their wireless connectivity, ESP32 cards transmit the collected data to our Raspberry Pi server, creating a distributed and efficient energy data collection network. The advantages of ESP boards are their low cost, ease of use, high flexibility, and compatibility with a wide range of programming languages [9], [10]. In addition, ESP boards offer a wide range of input/output ports for connecting different types of peripherals (Figure 3).

2.1.4. The rasberry card

The Raspberry Pi plays a central role as the data center of our system. It collects, processes and stores energy consumption data from connected equipment. The Raspberry Pi enables data to be easily accessed and visualized, making it easier to detect areas of waste and optimize energy consumption. In our case, we chose to use the Raspberry Pi 4 (Figure 4), which is an upgraded version of the Raspberry Pi and offers several advantages [11]-[14].

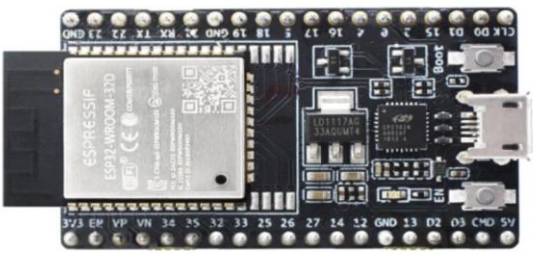

Figure 3. The ESP32 development card

Figure 4. Raspberry PI 4

2.1.5. System and protocol used

In our project, the Raspberry Pi pilots the system, integrating Apache, PHP, MariaDB, Node-RED and MQTT to collect, store, analyze and visualize energy data in real time [15]-[18]. Security is a high priority in our project to ensure the protection of our data and the integrity of the system. By using SSL/TLS rotocols, we ensure that data is encrypted during transmission from the ESP32 card to the Raspberry card, preventing any malicious interception or reading [19]-[22].

2.1.6. Phase-shift calculation technique

In order to calculate power consumption (active, reactive, and apparent) accurately, we need, in the first instance, to determine the phase shift between current and voltage. Our algorithm, shown in Figure 5, detects when voltage (t1) and current (t2) reach their maximum values. Using the difference between t1 and t2, the phase shift can be precisely calculated. These calculations are crucial for a reliable measurement of different power forms [23]-[25].

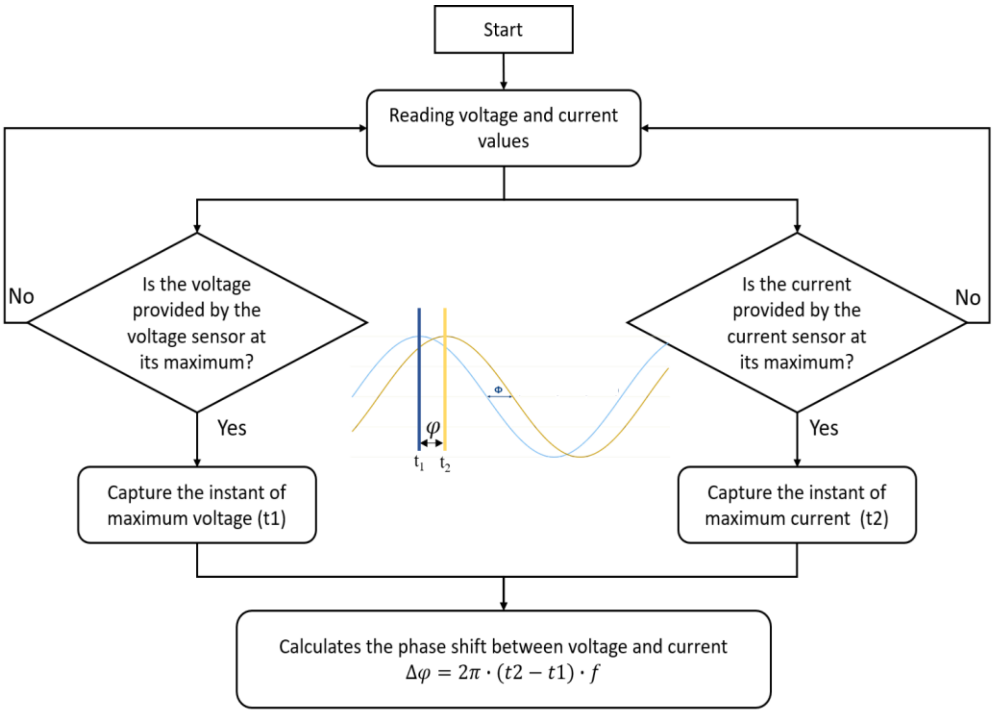

Figure 5. Algorithm for calculating the phase shift between current and voltage.

3. RESULTS DISCUSSION

In this section, we present and discuss the experimental results of real-time power consumption calculations for two types of loads: resistive and inductive. We also analyze the developed system’s ability to read current and voltage measurements, detect phase shift, calculate power, store data, and visualize them. Figure 6 shows the architecture of the system under study. In these experiments, current and voltage sensors are used to measure the corresponding values, which are then transmitted to the ESP cards. These cards ensure secure data transfer to the Raspberry Pi board using SSL/TLS protocols. On the Raspberry Pi board, phase shift detection, calculation of different power types, data storage, and visualisation are carried out.

Figure 6. Architicture of the system studied

3.1. Resistive load

In this section, the energy consumption data (voltage, current, active power, reactive power, and apparent power) of a resistive load during one hour of operation are presented. Figures 7-9 illustrate the system's capability to display and measure current and voltage and to calculate active, apparent, and reactive power. In this case, the resistive load has no reactive power, resulting in a zero-phase shift between current and voltage. Figures 7-9 show that voltage measurements stabilise at 239 volts, while current measurements stabilise at 507 mA. Active power measurements also stabilise at 121 W, while reactive power remains zero, as there is no reactive power present.

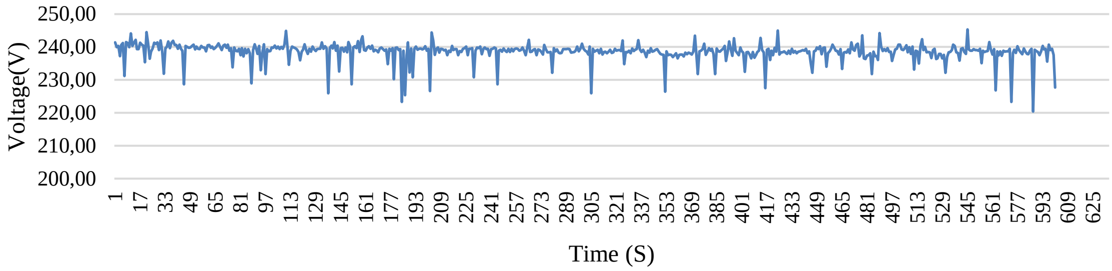

Figure 7. Voltage measurements of a resistive load

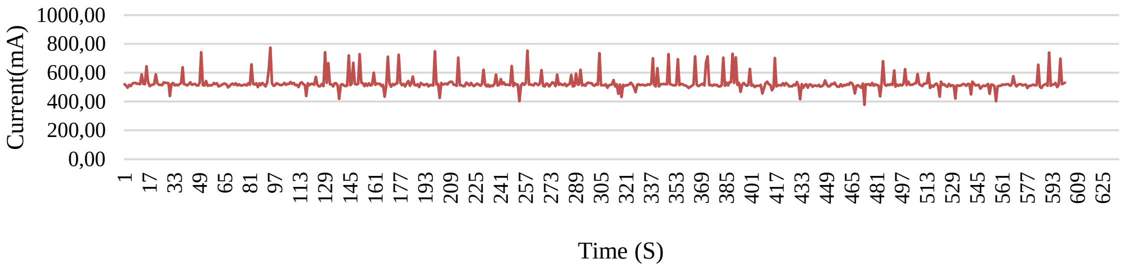

Figure 8. Current measurements of a resistive load

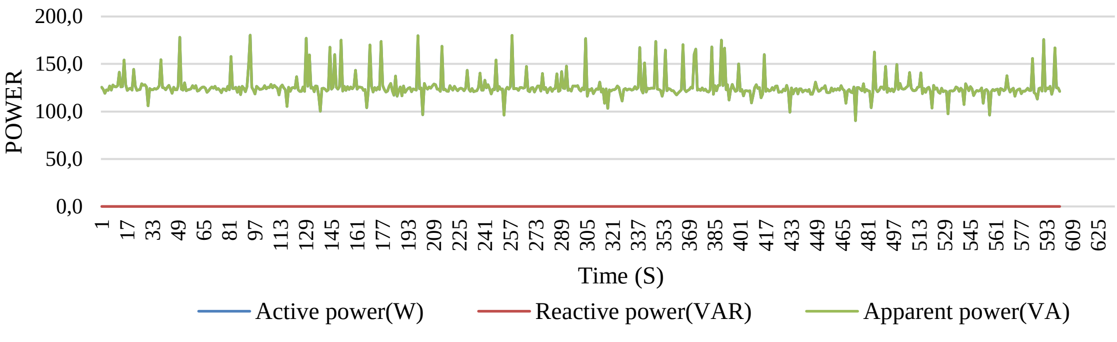

Figure 9. Active reactive load, and apparent power measurements of a resistive load

3.2. Inductive load

In this section, the energy consumption data (voltage, current, active power, reactive power, and apparent power) of a submersible water pump (indective load) during one hour of operation are presented. Figures 10-12 demonstrate the system's capability to display and measure current and voltage, as well as to calculate active and apparent power, including reactive power. In this case, the system effectively detected the phase between current and voltage, resulting in non-zero reactive power, as illustrated in Figure 12.

Figures 10-12 show that voltage measurements stabilise at 232 volts, while current measurements stabilise at 6.6 A. Active power measurements stabilise at 794 W, apparent power at 1,074 VA, and reactive power at 722 VAR.

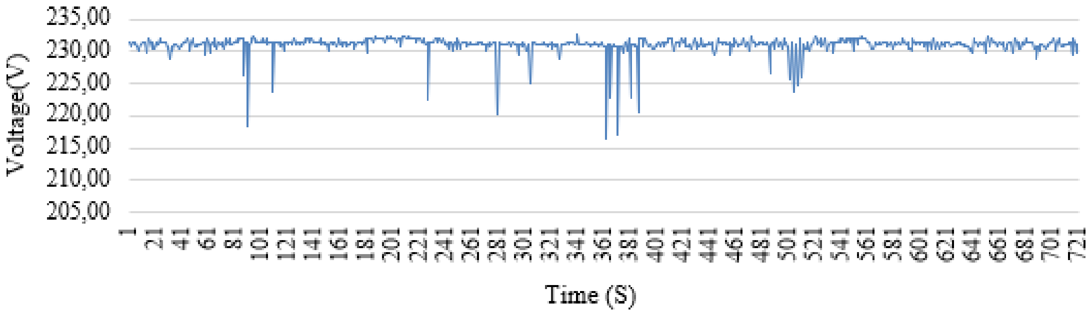

Figure 10. Voltage measurements of an Inductive load

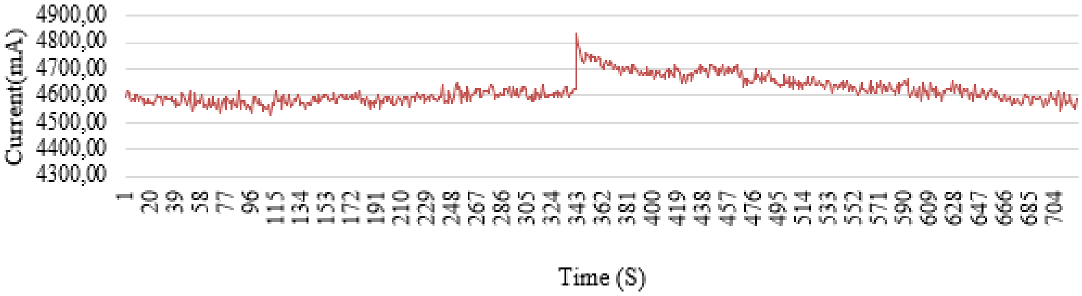

Figure 11. Current measurements of an Inductive load

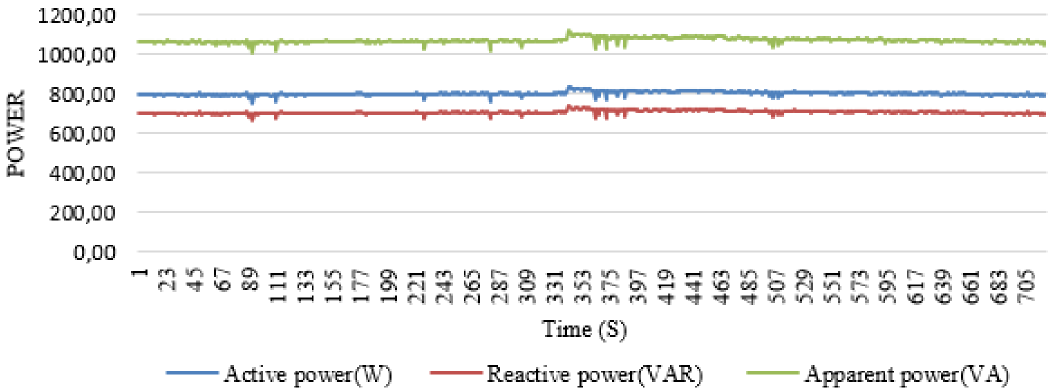

Figure 12. Active, reactive and apparent power measurements of an inductive load

Table 1 shows a comparison of real values and readings obtained with the developed measurement system. It compares the characteristics of real loads with experimental values for voltage, current, power factor, and active, reactive, and apparent power.

In the case of a resistive load, where current and voltage are theoretically in phase, our calculation system demonstrated high performance. Measured values for current (0.507 A compared with 0.50 A real) and voltage (239.2 V compared with 240 V real) show minimal deviations, resulting in efficiencies of 98.62% and 99.67% respectively. More significantly, the measured power factor is 1, perfectly matching the actual value and representing 100% efficiency.

This precision is also reflected in the power ratings: the measured active power (121.2 W) is very close to the real value (120 W, 99.01% efficiency), while the measured reactive power (0 VAR) coincides perfectly with the actual value (0 VAR, 100% efficiency). Consequently, the measured apparent power (121.2 VA) is also very close to the actual value (120 VA, 99.01% efficiency). These results demonstrate the high reliability of our calculation system for resistive loads, validating its ability to perform accurate measurements.

In the case of the inductive load, which is characterised by a phase shift between current and voltage (real power factor of 0.8), this reveals an increased complexity in the performance of our calculation system. The table shows that current (4.63 A for a real value of 4.7 A, with 97.55% efficiency) and voltage (232 V for a real value of 230 V, with 99.14% efficiency) measurements demonstrate high-quality the measurement. Although the processing of associated parameters such as power factor (measured at 0.74 for a real value of 0.8, 92.5% efficiency), active power (794.87 W for real 864 W, 92% efficiency) and reactive power (722.42 VAR for real 648 VAR, 89.7% efficiency) reveals the increased complexity associated with the inductive nature of the load, the measured apparent power (1074.16 VA for real 1081 VA, 99.37% efficiency) demonstrates the overall consistency of the measurements.

Table 1. Performance of the implemented system

	Parameters	Real values	Experimental values	Efficiency (%)
Resistive load	Current (A)	0,50	0,507	98,62
	Voltage (V)	240	239,2	99,67
	Power factor	1	1	100
	Active power (W)	120	121,2	99,01
	Reactive power (VAR)	0	0	100
	Apparent power (VA)	120	121,2	99,01
Inductive load	Current (A)	4,7	4,63	97,55
	Voltage (V)	230	232	99,14
	Power factor	0,8	0,74	92,5
	Active power (W)	864	794,87	92
	Reactive power (VAR)	648	722,42	89,7
	Apparent power (VA)	1081	1074,16	99,37

4. CONCLUSION

This article presents a secure system for measuring and calculating the electrical energy consumed or produced by various types of loads and generators. Using ESP32, Raspberry Pi, sensors, and appropriate protocols, we have developed a system for collecting, calculating, and analysing consumption data. As shown in the discussion section, the system implemented enables highly accurate measurement of electrical quantities such as current, voltage, active, reactive, and apparent power, as well as other important parameters such as power factor. The data collected is fed into a management model based on a neural network, which provides the appropriate decision-making tools to manage energy sources and secure the transfer of information. At the same time, the data is stored in a database for later analysis. Considerable emphasis has been placed on security, with the integration of SSL/TLS protocols to guarantee the confidentiality and integrity of exchanges between the various components of the system.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C	:	**C**onceptualization	I	: **I**nvestigation	Vi	:	**Vi**sualization
M	:	**M**ethodology	R	: **R**esources	Su	:	**Su**pervision
So	:	**So**ftware	D	: **D**ata Curation	P	:	**P**roject administration
Va	:	**Va**lidation	O	: Writing - **O**riginal Draft	Fu	:	**Fu**nding acquisition
Fo	:	**Fo**rmal analysis	E	: Writing - Review & **E**diting			

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

Informed consent was obtained from all participants involved in this research.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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