



**AUMENTANDO A EFICIÊNCIA ENERGÉTICA POR MEIO DO MONITORAMENTO EM
TEMPO REAL BASEADO EM IOT EM SISTEMAS DE BAIXA TENSÃO
ENHANCING ENERGY EFFICIENCY THROUGH IOT-BASED REAL-TIME MONITORING
IN LOW-VOLTAGE SYSTEMS**

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RESUMO

Este artigo apresenta o desenvolvimento de um sistema inteligente de monitoramento de energia baseado em tecnologias de Internet das Coisas (IoT), projetado para aumentar a eficiência energética, reduzir custos operacionais e apoiar a gestão sustentável de energia. A solução proposta visa aplicações de baixa tensão e utiliza um microcontrolador PIC18F4520 para aquisição de dados de tensão e corrente em tempo real. O hardware inclui um circuito de detecção dedicado com um sensor de corrente de efeito Hall e um divisor de tensão baseado em transformador. Os dados são transmitidos sem fio usando um módulo Wi-Fi ESP-01 e visualizados por meio de uma aplicação web personalizada desenvolvida com Django. Para avaliar o desempenho e a potencial redução de custos, uma análise comparativa também foi realizada utilizando a plataforma Arduino. O protótipo foi testado em condições de carga resistiva e indutiva, incluindo eletrodomésticos, e obteve erros de medição abaixo de 1% para tensão e abaixo de 2% para corrente na maioria dos casos. O sistema também calcula o fator de potência com base na análise de sinais sincronizados. Os resultados demonstram a precisão, a escalabilidade e o potencial de integração da plataforma em sistemas de energia descentralizados. Este trabalho contribui para a otimização do uso de energia, promovendo práticas de consumo mais inteligentes e sustentáveis, alinhadas à transição energética global.

Palavras-chave: Eficiência Energética; IoT; Monitoramento Inteligente; Sistemas Microcontrolados; Sustentabilidade

ABSTRACT

This article presents the development of a smart energy monitoring system based on Internet of Things (IoT) technologies, designed to enhance energy efficiency, reduce operational costs, and support sustainable energy management. The proposed solution targets low-voltage applications and uses a PIC18F4520 microcontroller for real-time data acquisition of voltage and current. The hardware includes a dedicated sensing circuit with a Hall-effect current sensor and a transformer-based voltage divider. Data are transmitted wirelessly using an ESP-01 Wi-Fi module and visualized through a custom web application developed with Django. To assess performance and potential cost reduction, a comparative analysis was also conducted using the Arduino platform. The prototype was tested under resistive and inductive load conditions, including household appliances, and achieved measurement errors below 1% for voltage and under 2% for current in most cases. The system also calculates the power factor based on synchronized signal analysis. Results demonstrate the platform's accuracy, scalability, and potential integration into decentralized energy systems. This work contributes to the optimization of energy usage, promoting smarter and more sustainable consumption practices aligned with the global energy transition.



Keywords: Energy Efficiency; IoT; Smart Monitoring; Microcontroller Systems; Sustainability

1 INTRODUCTION

Interest in monitoring the quality of electrical energy in transmission and distribution systems or industrial installations has grown significantly in recent decades [1]. The increasing demand for energy efficiency and sustainability drives the search for innovative solutions for energy consumption monitoring and control. Conscious energy consumption has become a pressing topic, with various modern technologies employed to address this issue [2]. In this context, the Internet of Things (IoT) emerges as a promising technology, enabling remote monitoring and automation.

IoT refers to a network of physical objects, such as appliances and vehicles, connected to the internet via sensors and software. This technology offers significant opportunities to enhance energy efficiency across homes, businesses, and industries, contributing to energy conservation and reducing operational costs [3].

Aligned with these trends, this project proposes an energy monitoring device using a PIC microcontroller to analyze voltage and current values. The system integrates with the ESP-01 module, a common IoT component, to transmit collected data to a web page. Initially built on a protoboard to validate the concept, the device revealed limitations such as measurement instability, contact failures, and lack of robustness, making it unsuitable for real-world applications.

To address these issues, the project transitions the device to a printed circuit board (PCB) for the final build. Additionally, comparative analyses between the PIC microcontroller and Arduino are conducted to explore a potential shift to the Arduino platform. This evaluation considers technical aspects, error reduction, enhanced system compactness, and cost efficiency.

This system, by enabling precise and real-time consumption analysis, can be a valuable tool for increasing awareness and control over energy use, especially in residential or small industrial setups. By leveraging IoT, it supports decentralized energy management strategies, contributing to the overall optimization of electricity systems — a key aspect of sustainable energy practices.

2 METHODOLOGY

2.1 ARCHITECTURE

The hardware architecture, illustrated in Fig. 1, integrates components for voltage and current measurement and data processing. The voltage measurement system comprises a step-down transformer (1 in Fig. 1) and a circuit for attenuation and half-wave rectification (4 in Fig. 1), generating proportional signals from a 220V input. A 5V power supply (2 in Fig. 1) powers the ACS712 current sensor (6 in Fig. 1), the PIC18F4520 microcontroller (8 in Fig. 1), and the AMS1117 regulator (5 in Fig. 1), which provides 3.3V for the ESP-01 module (7 in Fig. 1).

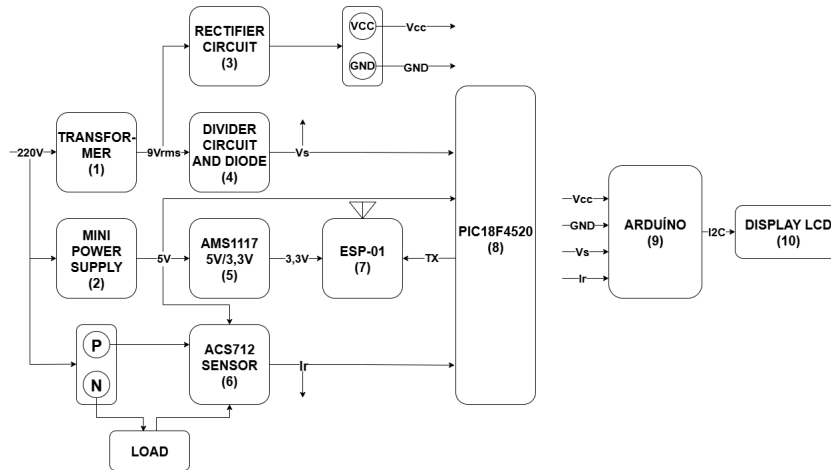
The ACS712 sensor, placed in series with the load, measures current, while the PIC18F4520 processes data from the voltage and current sensors and sends results to the ESP-01 for display on a web page. For comparative purposes, the Arduino (9 in Fig. 1) processes voltage and current signals, along with rectified circuit outputs (Vcc and GND), while an LCD display (10 in Fig. 1) shows the monitored data.



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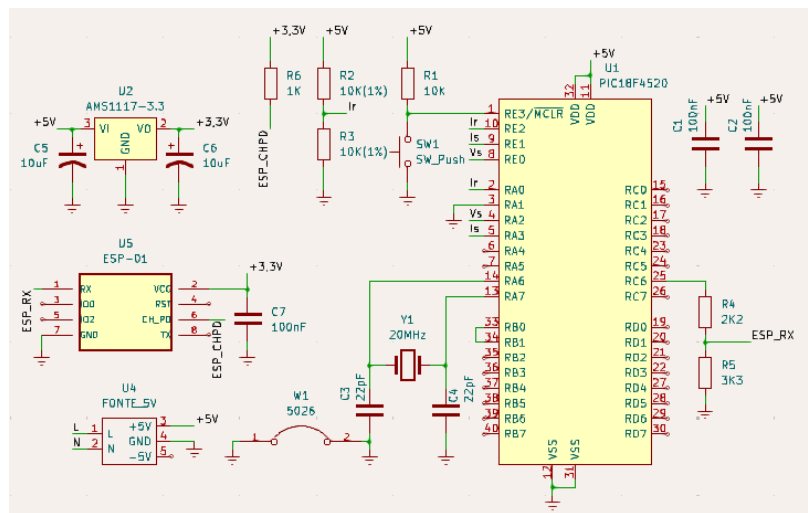
Fig. 1 - General Project Architecture.



2.2 HARDWARE

The hardware design integrates the PIC18F4520 microcontroller with circuits for voltage and current measurement. In the PIC circuit (Fig. 2), current signals from the ACS712 sensor are fed to pins 5 and 9, while pins 2 and 10 receive a reference voltage derived from a precision resistor divider (R2 and R3). Voltage signals from the measurement circuit reach pins 4 and 8, with GND as their reference, ensuring consistent potential. The system is powered by a 220VAC/5VDC source, with the AMS1117 regulator providing 3.3V for the ESP-01 module. Communication with the ESP-01 occurs via pin 25, using a voltage divider to match the module's 3.3V operating level.

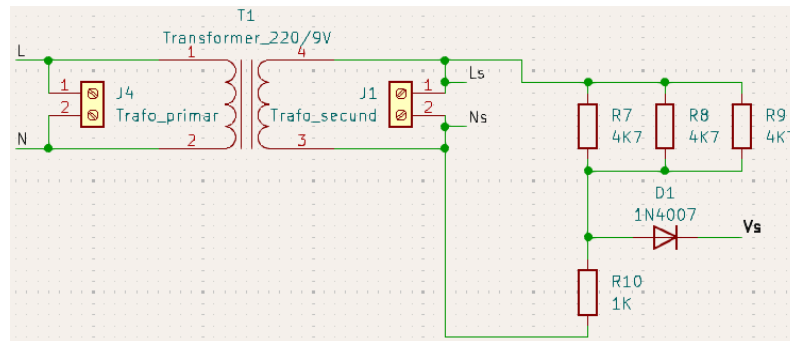
Fig. 2 - Electrical diagram of circuits related to the PIC.





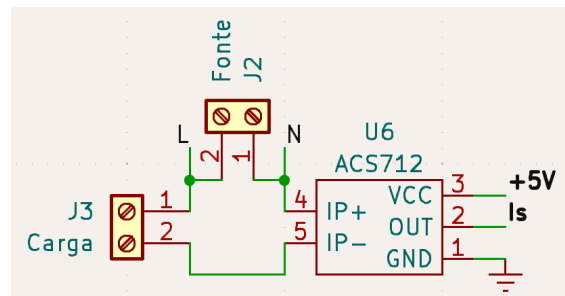
Voltage measurement is achieved through a half-wave rectified signal from a resistive divider (4 in Fig. 1) connected to the secondary of a 220V/9V transformer (Fig. 3), ensuring isolation from the mains. The divider uses a parallel configuration of three $4.7\text{k}\Omega$ resistors ($R1$) and a $1\text{k}\Omega$ resistor ($R2$), producing a maximum output voltage of 4.96V .

Fig. 3 - Electrical diagram of the voltage meter circuit.



For current measurement, the ACS712 sensor, based on the Hall effect (Fig. 4), generates a voltage signal proportional to the current flowing through its load terminals. The model used (5A) provides a sensitivity of 185mV/A . The sensor's reference voltage, equal to half the supply voltage (2.5V for a 5V supply), indicates the current direction: values above 2.5V represent positive current, and values below 2.5V represent negative current.

Fig. 4 - Electrical diagram of the current meter circuit.



2.3 FIRMWARE

The firmware of the project was structured into four key functionalities: sample timing, voltage measurement, current measurement, and synchronization wave generation.

2.3.1 Sample Timing

The PIC18F4520's TIMER0 was configured to synchronize sample collection, allowing for 48 samples per 60 Hz waveform cycle. This configuration achieved a sampling interval of approximately 3.456 ms . Interrupts were used to manage the timing and sampling process efficiently.

2.3.2 Voltage Measurement

Voltage readings were taken from the AN5 analog port (pin 8 in Fig. 2), collecting 48 samples per cycle. The RMS voltage was calculated by summing the squares of the samples, dividing by the total, and taking the square root. This process was repeated



10 times, averaging the results for greater accuracy. As the values of the negative half cycle are discarded, the result of the sum in the RMS calculation is multiplied by 2.

2.3.3 Current Measurement

The algorithm for calculating the current is similar to the one used for calculating the voltage; however, two signals are collected through the analog ports. The reference voltage of the current sensor is measured through analog port AN7, and the sensor's output signal is measured through port AN6 (pins 9 and 10, respectively, in Fig. 2). The results are multiplied by a proportionality factor that takes into account the 10-bit ADC resolution and the sensor's sensitivity (185 mV/A), and the difference is stored in an array. No information is discarded since this waveform is rectified.

2.3.4 Synchronization Waves

Square waves proportional to the voltage and current waveforms' half-cycles were generated using the PIC's internal comparators. These waves were used to calculate the power factor by measuring the phase difference. TIMER1 and external interrupts synchronized the process, with the RB1 port (pin 34 in Fig. 2 configured as output) generating a square wave proportional to the phase shift between voltage and current. The phase angle was calculated using a predefined formula that considered the timer's prescaler and system frequency.

The firmware code, including the configuration of timers, ADCs, and comparators, as well as the algorithms for RMS and power factor calculations, is detailed in the project's GitHub repository [5], ensuring replicability and further exploration.

2.4 SOFTWARE

The software bridges the data processing performed by the PIC microcontroller to the web visualization interface. This communication is facilitated by the ESP-01 Wi-Fi module, which uses UART to receive data and make it available on a web page via the HTTP protocol, utilizing its integrated server. The module was programmed using the Arduino IDE (version 1.8.19), with network credentials configured to establish a connection within the same local network as the web system.

The web interface was developed using the Django framework, which follows the Model-View-Template (MVT) architecture and uses Python (version 3.10, although earlier versions down to 3.6 were also tested successfully). The visual customization was achieved using Bootstrap, providing a modern and intuitive interface. In test mode, the software simulates random data, while in real operation, the measured values are displayed once the "IP Address" field is updated with the ESP-01's address.

The system delivers a user-friendly interface for real-time monitoring of voltage, current, and power, with the complete source code available in the project's GitHub repository [5], including scripts and libraries for system replication and customization.

2.4 PCB DEVELOPMENT

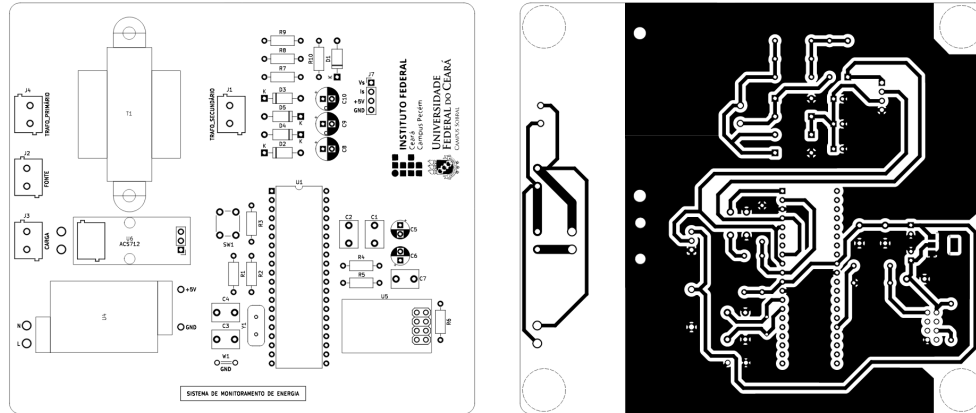
The Printed Circuit Board (PCB) design process, from the schematic to the layout, was executed using the open-source software KiCad version 8.0. Once the schematic was finalized, the PCB layout was developed. During this stage, connection traces between components were routed, carefully considering the current levels each conductor would carry. Fig. 5 showcases the PCB layout, illustrating the top and bottom views of the board.

Fig. 5 - PCB layout. On the left, the top view of the board and on the right, the bottom view.



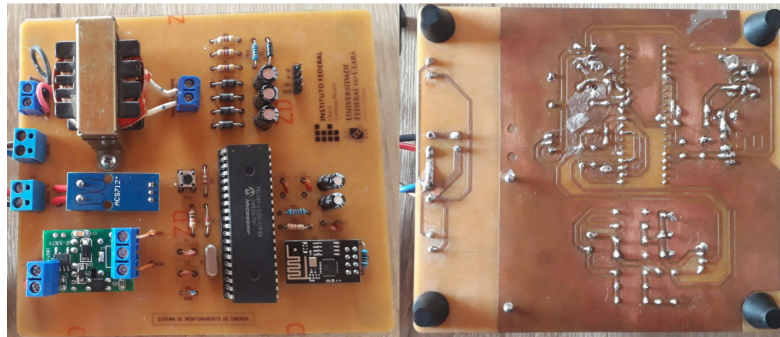
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For manufacturing the PCB, an LPKF M60 prototyping machine was used. A transparent adhesive sheet containing all the component footprints and graphical elements was applied to the top of the board, facilitating component placement. Subsequently, components were soldered and secured in their designated positions. The completed PCB, with top and bottom views, is displayed in Fig. 6, highlighting the successful implementation of the circuit design.

Fig. 6 - PCB finished. On the left, the top view of the board and on the right, the bottom view.



3 RESULTS AND DISCUSSION

The developed prototype was tested on devices connected to a low-voltage electrical network to verify its functionality. A module with seven incandescent lamps and various household appliances was used to evaluate the system's performance under purely resistive loads and more realistic operating conditions. The system's measured values were compared with those obtained from a multimeter and another Arduino-based system, which was considered as a potential replacement for the PIC18F4520 in future projects. The Arduino code is available in the GitHub repository [6].

3.1 TESTING WITH INCANDESCENT LAMPS

The incandescent lamp module consisted of seven 120 W lamps connected in parallel. The power was supplied via the prototype's input terminal linked to a 220 VRMS power source.

For each measurement, one switch was turned on until all seven lamps were powered. The results are presented in Table 1, where N represents the number of active lamps. Subscripts t , m , p , and a refer to values obtained from theoretical calculations, the multimeter, the prototype (with PIC), and the Arduino system, respectively, with V for voltage and I for current.



Table 1 - Results of the test with incandescent lamps

<i>N</i>	<i>V_t</i>	<i>V_m</i>	<i>V_p</i>	<i>V_a</i>	<i>I_t</i>	<i>I_m</i>	<i>I_p</i>	<i>I_a</i>
1	220	220,3	220,10	221,30	0,55	0,53	0,58	0,872
2	220	220,1	219,30	219,71	1,09	1,08	1,15	1,321
3	220	219,3	219,01	218,30	1,64	1,62	1,70	1,876
4	220	219,2	218,40	217,87	2,18	2,15	2,22	2,370
5	220	218,6	217,56	215,81	2,73	2,71	2,79	2,959
6	220	219,2	217,10	216,40	3,27	3,25	3,30	3,540
7	220	218,8	216,80	214,43	3,82	3,81	3,86	4,148

3.2 TESTING WITH HOUSEHOLD APPLIANCES

The prototype was further evaluated with common household devices, including a sandwich maker (750 W), a coffee maker (550 W), a vacuum cleaner (1000 W), and a blender (550 W). The results are summarized in Table 2, following a similar structure to Table 1.

Table 2 - Results of the test with household appliances

<i>DEVICE</i>	<i>V_t</i>	<i>V_m</i>	<i>V_p</i>	<i>V_a</i>	<i>I_t</i>	<i>I_p</i>	<i>I_a</i>
Sandwich Maker	220	225	219,84	216,09	3,40	3,40	3,48
Coffee Maker	220	219	215,16	217,22	2,50	2,45	2,56
Vacuum Cleaner	220	222	221,04	217,52	4,54	2,19	2,24
Blender	220	223	215,70	219,91	2,50	1,37	1,47

The tests revealed significant deviations in the measured current values for the vacuum cleaner and blender compared to theoretical values. This discrepancy is attributed to the motor-driven nature of these appliances, which were not operating at full capacity. For instance, during the blender test, it was run at its lowest speed with 1 liter of water (about 66.6% of its maximum capacity).

4 CONCLUSION

In this work, a platform was developed to measure voltage and electric current, analyzing the energy consumption of devices connected to a low-voltage network. Using a microcontroller for data acquisition and a web application for visualization, the system communicates via a Wi-Fi module. The chosen method was the root mean square (RMS) value for alternating electrical quantities, with a transformer and rectifier diode generating the voltage signal and a Hall-effect-based current sensor measuring the current. Power factor calculation was integrated into the project, utilizing the microcontroller's comparator module.



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Practical tests validated the measurement accuracy, with average errors below 1% for voltage and, in most cases, below 2% for current, except for currents below 1 A. The system also calculated the power factor angle, achieving maximum errors around 2%. The developed platform demonstrated its operational capability in trials with different loads, comparing favorably with other devices and theoretical calculations. Furthermore, the alternative Arduino-controlled system proved viable, with errors around 5% in this initial version, showing potential for improvements in future projects.

Beyond its technical performance, this solution contributes to the optimization of energy systems by enabling real-time monitoring, accurate consumption analysis, and improved energy awareness. Such tools are essential for promoting energy efficiency and sustainability, especially in decentralized or small-scale applications. This approach aligns with the global movement towards smarter and more resilient energy infrastructures, reinforcing the importance of integrating IoT technologies into the energy transition.

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