

EnergID: Open-source smart system for monitoring electricity consumption in machining environments

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ABSTRACT:

EnergID is a system based on open-source hardware and software (Arduino, ESP32) designed to monitor electricity consumption in machining environments. The device measures key electrical variables in real time and transmits them via Wi-Fi to a server for graphical display on interactive panels and web pages.

The main innovation lies in its ability to determine the “Electrical Identity” of each machine, achieving complete traceability of each work cycle. Beyond measuring overall consumption, the system directly links energy expenditure to technical variables (material type, speed, cutting depth) and operational variables (each operator’s work style).

Analysis of this data enables the detection of malfunctions, downtime, or abnormal consumption, in addition to generating automatic alerts. Finally, EnergID helps identify efficiency patterns and best practices to optimize industrial processes without compromising quality.

Keywords: Electrical identity, Energy monitoring, Internet of Things (IoT), Traceability, Smart manufacturing

1. Introduction

EnergID is a system based on open-source hardware and software (Arduino, ESP32) designed to monitor electricity consumption in machining environments. The device measures key electrical variables in real time and transmits them via Wi-Fi to a server for graphical display on interactive panels and web pages.

The main innovation lies in its ability to determine the “Electrical Identity” of each machine, achieving complete traceability of each work cycle. Beyond measuring overall consumption, the system directly links energy expenditure to technical variables (material type, speed, cutting depth) and operational variables (each operator’s work style).

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2. Educational context and need

The EnergID project is part of the vocational training programs in Mechanical Manufacturing and Mechatronics, sectors deeply immersed in digitalization and Industry 4.0. The current educational framework requires equipping students with skills in sustainability and the Internet of Things (IoT). However, machining workshops operate in a traditional manner, without linking production to its energy impact in real time.

Need: There is a disconnect in the classroom between the manufacturing process and environmental management. Furthermore, commercial industrial telemetry systems are expensive and inaccessible to educational institutions and SMEs. EnergID bridges this gap using open-source hardware and software (Arduino, ESP32), measuring key electrical variables to determine the “Electrical Identity” of each machine. The system addresses the urgent need to link energy consumption with technical variables (material, cutting speed) and operational variables (operator style). Through interactive Wi-Fi-enabled panels, it allows students to analyse

data, detect malfunctions, implement predictive maintenance, and promote efficiency patterns and best practices without compromising the quality of the industrial process).

3. Objectives

The objective of this project is to design and implement a low-cost, modular, and scalable system within tooling processes that operates in real time, measuring the instantaneous power consumption of each work phase, thereby enabling the “Electrical Identity” of the machines to be determined and monitored.

This system will provide complete traceability for each machining cycle, directly linking consumption data to the technical and operational variables involved in the process. Thus, it does not merely measure energy consumption but analyzes how it varies depending on the type of part, the strategy used (number of passes, cutting depth, feed rate), the execution time, and the operator’s work style. Based on this analysis, efficiency patterns can be identified, best practices determined, and adjustments to work methods proposed to reduce consumption without compromising quality.

4. Methodology

4.1. Hardware Selection and Integration into the Machine

The system was designed to monitor the electrical panel of a machine tool (e.g., a universal milling machine with a three-phase main motor). To this end, three PZEM-004T v3.0 transducer modules (one per phase) were integrated.

- Galvanic Isolation: Split-core current transformers (CTs) were used. This allowed the main motor’s power phases to be tapped within the machine’s electrical panel without cutting wires or interrupting production, in compliance with electromechanical safety regulations.
- Bus Topology: The three PZEM modules were connected in parallel, sharing the ESP32’s UART communication pins (GPIO16 for RX2 and GPIO17 for TX2). Each module was pre-

configured via software with a unique Modbus-RTU address (0x01 for Phase R, 0x02 for Phase S, 0x03 for Phase T).

4.2. Algorithm and Connectivity (Arduino IDE) The program embedded in the ESP32 was structured under the following guidelines:

- Adaptive Sampling: The main loop performs a sequential scan (polling) of the three sensors every second, an optimal refresh rate to capture the transitions between the roughing, finishing, and stopping operations of the machine tool.
- Communication Protocol: The data is sent wirelessly (Wi-Fi 802.11 b/g/n) in JSON format to an Aply websocket service, which forwards it to the server hosting the Laravel webpage. Once the data is received, it is published in real-time and uploaded to a MySQL database.

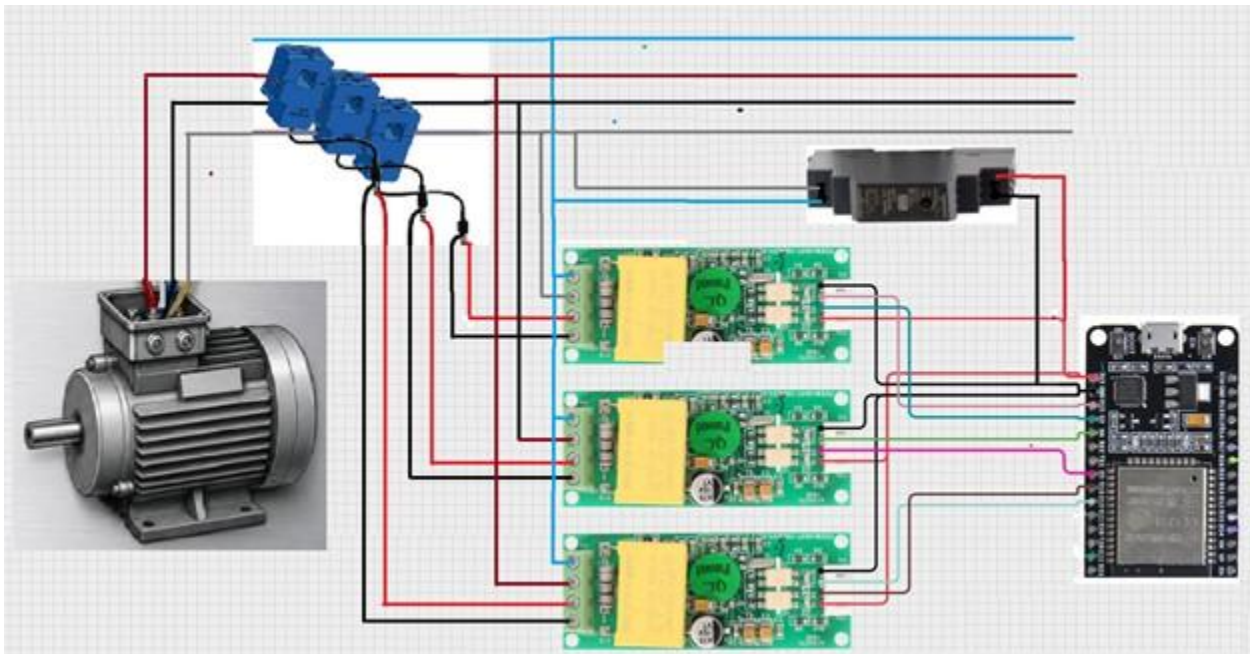


Figure 1 Electrical connection

4.3. Structured Storage (MySQL) A MySQL

Relational database server was deployed on the server using WAMP. The database features a table responsible for storing the data coming from the machine.

4.4. Graphical Interface (Dashboard)

For the visual environment on the computer, a web interface was created using the Laravel framework in PHP. A control panel was designed with an industrial focus, displaying:

- Triangle indicators for the instantaneous power consumption of the machine, alongside visualizations of currents and voltages in a phasor vector diagram.
- Line graphs plotting the power curve, allowing for visual identification of when the machine is turned off, idling, or in the middle of a machining process

4.5. Enclosure Design and Printing

- The enclosure is planned and dimensioned, taking the measurements of the various components: the board with the ESP32, the three PZEMs, the transformer and the terminal block.
- We will use Assembly Design to create the individual components as .par files and then assemble them.
- We design the base of the box, the access points and ventilation, and the lid
- The assembly is created.
- It is exported to .stl for printing.

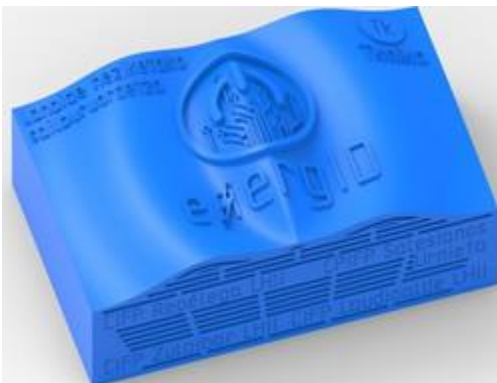


Figure 2 Box design and printing

5. Results and discussion

The prototype was tested on a star-delta starter model connected to a three-phase motor, yielding results nearly identical to those from commercial measuring devices (PEL103).

STAR	ENERGID			PEL103					
	LINEA1	LINEA2	LINEA3	LINEA1	LINEA2	LINEA3			
VOLTAGE	131,3	130,9	130,6	130,9	130,7	130,1	0%	0%	0%
CURRENT	0,383	0,386	0,376	0,3823	0,3868	0,374	0%	0%	1%
FREQUENCY	50	50	50	50	50	50	0%	0%	0%
ACTIVE POWER	0,0157	0,0144	0,0145	0,016	0,014	0,014	-2%	3%	4%
REACTIVE POWER	0,04781	0,0485	0,04684	0,048	0,049	0,048	0%	-1%	-2%
APPARENT POWER	0,050288	0,050527	0,0491	0,05	0,05	0,05	1%	1%	-2%
POWER FACTOR	0,31	0,28	0,3	0,324	0,277	0,291	-4%	1%	3%

Table 1 Electrical variable measurements of the EnergID prototype and the PEL103 network analyzer for the star motor connection.

TRIANGLE	ENERGID			PEL103					
	LINEA1	LINEA2	LINEA3	LINEA1	LINEA2	LINEA3			
VOLTAGE	132,4	132	131,6	132,2	131,3	132	0%	1%	0%
CURRENT	0,86	0,897	0,846	0,872	0,9	0,862	-1%	0%	-2%
FREQUENCY	50	49,9	49,9	50	50	50	0%	0%	0%
ACTIVE POWER	0,0751	0,0775	0,0736	0,075	0,076	0,072	0%	2%	2%
REACTIVE POWER	0,0855	0,0899	0,0855	0,087	0,092	0,088	-2%	-2%	-3%
APPARENT POWER	0,1139	0,1184	0,1133	0,115	0,119	0,113	-1%	-1%	0%
POWER FACTOR	0,66	0,65	0,66	0,668	0,652	0,66	-1%	0%	0%

Table 2 Measurements of electrical variables for the EnergID prototype and the PEL103 power analyzer with the motor connected in a delta configuration.

The system was tested on a milling machine while milling a metal workpiece. The technical and operational results demonstrated high accuracy.



Figure 3 Installation of the EnergID prototype and the PEL103 power quality analyzer in the electrical panel of a milling machine at the Arratiako Zulaibar vocational training center.

6. Limitations and safety

The energID prototype should be viewed as an advanced educational prototype, not as a finished industrial product. Functional tests have been conducted on various panels in different electrical installations and compared with power quality analysers such as the Chauvin Arnoux PEL 103 Power and Energy Logger, the Graphic Power Quality Analyzer PCE.GPA62, and the Ekion KI3P-Ct, yielding the same results in the early stages of the prototype.

Limitations

The sampling rate is not limited by the ESP32's processing power (which runs at 240 MHz), but rather by the PZEM-004T's hardware design itself, which only provides new data every 200 ms and communicates at a fixed rate of 9600 bps (baud). This is a slow speed by computer standards.

On the other hand, the time per transaction: sending the Modbus query from the ESP32 and receiving the 25-byte response from the PZEM at 9600 bps takes about 30 to 40 milliseconds. Multiplying this by 3 phases—to read Phase R, then S, and then T, the ESP32 will take about 100 to 120 ms of net data transmission time over the cable.

Finally, sending the data over Wi-Fi and inserting it into a MySQL database adds another delay.

In summary, the actual maximum rate for obtaining real-time data from all three phases simultaneously is every 250 to 300 ms, which means it would not be possible to observe the exact millisecond peak when a motor starts up; furthermore, if a tool breaks suddenly, the peak load lasts only a fraction of a second. The PZEM will likely skip that instant or average it out, preventing it from being used as a collision-based emergency stop system.

7. Methods and development process

General System Architecture and Data Flow

The architecture consists of three layers:

An initial layer for acquiring data on the physical parameters of the electrical network powering the lathe/milling machine, which are converted into low-voltage digital signals by the PZEM-004T modules. A processing layer in which the ESP32 reads these digital signals, encapsulates all this information and transmits it via TCP/IP sockets to the listening port of the MySQL server. The final layer, in which the industrial analytics software performs scheduled queries on the database to update the graphical elements of the dashboard.

8. Conclusions

This project demonstrates that vocational training students can design and implement complex industrial digitalization solutions on a limited budget, bridging the gap between traditional electromechanical maintenance and the demands of today's connected industry.

The results confirm that the combination of low-cost hardware (ESP32 and PZEM-004T) with industrial-grade open-source software (MySQL) is fully viable for secondary monitoring in plants and facilities.

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Data availability statement

No personal or sensitive student data were used in the preparation of this article. The examples and telemetry captures discussed correspond to educational tests carried out during the development of FP Robotik Interface. Project documentation selected generated examples and non-sensitive test materials can be made available by the corresponding author upon reasonable request.

Author contribution

Ekaitz Ortiz de Zarate, Iñigo Esnal Martiarena, Igor Bernas, Miguel Angel Gomez García and Iñigo Atxutegi contributed to project conceptualisation, technical documentation, testing and manuscript preparation. The final version was reviewed and approved by the authors.

Declaration of interests

The authors declare that they have no conflicts of interest related to this work.

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