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Desarrollo de una unidad de monitoreo remota (RMU) para sistemas de protección catódica en tuberías.

Development of a Remote Monitoring Unit (RMU) for cathodic protection systems in pipelines

Quito-2026

Approval of the Curriculum Integration Project Advisor

I, Mauricio Sebastian Tamayo Vegas, as the advisor for the Curricular Integration Project titled: *Desarrollo de una unidad de monitoreo remota (RMU) para sistemas de protección catódica en tuberías.*, prepared by Paúl Cabadiana, have guided and reviewed all parts of this project and consider it to meet the requirements established by the institution. Accordingly, I hereby give my approval to proceed with the corresponding academic process.

Mauricio Sebastian Tamayo Vegas

Curricular Integration Project Advisor

Statement of Authorship and Assignment of Rights

I, Paúl Cabadiana, declare under oath that the work described herein is my own; that it has not been previously submitted for any academic degree or professional certification; and that the detailed bibliography has been consulted.

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Dedicatoria

This thesis is the result of hard work, but also of the love of those around me. That is why I dedicate it with all my heart to my parents, my foundation and my driving force, for their example and unconditional support throughout my education. To my grandfathers, who light my path from heaven, and to my grandmothers, for their love and advice. To my brothers Vale and Mati, for being my team and my strength when I faltered, for the jokes that helped relieve my stress, and for always being there for me.

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Thank you all. This achievement belongs as much to you as it does to me.

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Resumen

El presente trabajo busca demostrar el desarrollo de una unidad de monitoreo remoto (RMU) para sistemas de protección catódica, dedicada la adquisición, el procesamiento y la visualización de parámetros eléctricos críticos, como el potencial ducto-suelo. El sistema propuesto posee un convertidor analógico-digital (ADS1115), un microcontrolador ESP32-C3 y comunicación inalámbrica mediante GSM y/o Wi-Fi, permitiendo la transmisión remota de datos y su visualización mediante una plataforma web. El diseño se basa en la metodología VDI 2206, siguiendo un enfoque estructurado de desarrollo mecatrónico. Se evaluaron diferentes alternativas de diseño para el sistema de adquisición, optando finalmente por una solución simplificada que reduce la complejidad sin comprometer la precisión. Las pruebas experimentales se realizaron mediante una estación de prueba que simula un sistema de protección catódica en condiciones controladas. Los resultados obtenidos muestran una alta concordancia entre las mediciones del sistema y un instrumento de referencia, con errores absolutos a nivel de milivoltios, incluyendo 0.6 ± 0.5 mV en estado ON y 1.6 ± 1.0 mV en estado OFF, lo que valida la precisión del sistema desarrollado. Adicionalmente, se verificó la correcta detección de los estados ON/OFF y la estabilidad de la señal. El análisis de consumo energético evidenció que el sistema es viable para aplicaciones en campo, considerando los requerimientos de potencia asociados a la transmisión de datos. Asimismo, el análisis de costos demuestra que el sistema representa una alternativa económicamente competitiva frente a soluciones comerciales. Finalmente, el sistema desarrollado constituye una solución funcional y adaptable para el monitoreo remoto de sistemas de protección catódica, con potencial para futuras mejoras como la incorporación de tecnologías de comunicación satelital

Keywords: Protección catódica, Monitoreo remoto, RMU, Adquisición de datos, ADS1115, ESP32, Comunicación GSM, IoT, Medición de potencial, Corrosión

Abstract

This paper aims to demonstrate the development of a remote monitoring unit (RMU) for cathodic protection systems, designed for the acquisition, processing, and visualization of critical electrical parameters, such as the pipeline-to-ground potential. The proposed system features an analog-to-digital converter (ADS1115), an ESP32-C3 microcontroller, and wireless communication through GSM and/or Wi-Fi, enabling remote data transmission and visualization via a web platform. The design is based on the VDI 2206 methodology, following a structured approach to mechatronic development. Various design alternatives for the data acquisition system were evaluated, and a simplified solution was ultimately chosen to reduce complexity without compromising accuracy. Experimental tests were conducted using a test station that simulates a cathodic protection system under controlled conditions. The results show a high degree of agreement between the system's measurements and those of a reference instrument, with millivolt-level absolute errors, including 0.6 ± 0.5 mV in the ON state and 1.6 ± 1.0 mV in the OFF state, validating the accuracy of the developed system. Additionally, the correct detection of ON/OFF states and signal stability were verified. The energy consumption analysis showed that the system is viable for field applications, considering the power requirements associated with data transmission. Likewise, the cost analysis demonstrates that the system represents an alternative economically competitive compared to commercial solutions. Ultimately, the system developed provides a functional and adaptable solution for the remote monitoring of cathodic protection systems, with potential for future improvements such as the incorporation of satellite communication technologies

Keywords: Cathodic protection, Remote monitoring, RMU, Data acquisition, ADS1115, ESP32, GSM communication, IoT, Potential measurement, Corrosion

TABLE 1
ABET Criteria / Thesis Cross Reference

Criterion	Outcome	Level of Mastery	Thesis Sections
1	Ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics.	Analysis, Comprehension, Apply	Introduction, Methodology, Results
2	Ability to apply engineering design to produce solutions that meet specified needs considering safety, environmental and economic factors.	Analysis, Evaluate, Create	Problem Statement, Methodology (VDI 2206), Design
3	Ability to communicate effectively with different audiences.	Comprehension, Apply	Entire document
4	Ability to recognize ethical and professional responsibilities and consider impacts of engineering solutions.	Analysis, Comprehension	Introduction, Discussion
5	Ability to function effectively as part of a team and manage tasks.	Analysis, Apply	Project Development (Methodology)
6	Ability to develop and conduct experiments, analyze and interpret data.	Analysis, Evaluate	Methodology, Results
7	Ability to acquire and apply new knowledge using appropriate strategies.	Analysis, Apply, Create	State of the Art, Methodology

Chapter I

Introduction

Corrosion is a natural electrochemical process that causes the progressive deterioration of metallic materials as they interact with their environment, tending to return to their thermodynamically most stable state. This phenomenon requires the presence of an anode, a cathode, and an electrolyte—conditions commonly found in metallic infrastructure that is buried or exposed to aggressive environments [2].

Figure 1 illustrates the general operation of an impressed-current cathodic protection system. In this system, an external power source supplies direct current to buried anodes, generating a current flow that polarizes the pipeline and reduces corrosion reactions. The protection potential is evaluated by measuring the potential difference between the pipeline and a reference electrode placed in the ground; this parameter is known as the pipeline-to-ground potential, which is essential for determining the effectiveness of the protection system.

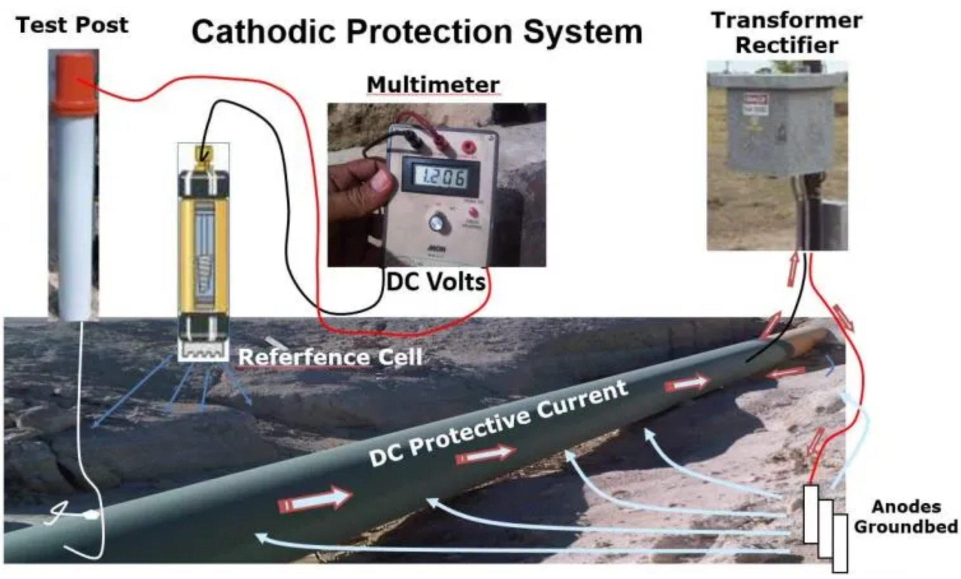


Fig. 1. Impressed-current cathodic protection system, showing the measurement of the pipe-to-ground potential using a reference electrode (adapted from AArav-international)

Problem Statement

In industrial settings, particularly in hydrocarbon and fluid transport systems, corrosion is one of the leading causes of structural failure, resulting in economic losses, environmental risks, and threats to operational safety [3], [4]. To mitigate this problem, cathodic protection has established itself as one of the most effective techniques, allowing for the control of the electrochemical potential of metal structures and significantly reducing their degradation.

However, the effectiveness of these systems depends on the continuous monitoring of critical electrical parameters, such as the pipeline-to-ground potential, which must be maintained within ranges established by international standards such as ISO 15589-1 and NACE SP0169 [5], [6]. Traditionally, these measurements are performed manually using test stations, which limits the frequency of inspections and hinders the timely detection of faults [7]. This involves the deployment of specialized personnel, high operating costs, and limitations on the frequency of data acquisition [8], [9]. Furthermore, the extensive geographic distribution of pipelines and difficult-to-access conditions make it challenging to conduct continuous inspections, affecting the ability to detect failures early [8], [10].

These limitations mean that traditional monitoring methods are generally reactive rather than preventive, leading to delays in identifying anomalies and increasing the risk of structural failures, spills, and significant economic losses [10], [11]. In response, the use of remote monitoring technologies has emerged as a viable alternative, enabling real-time data acquisition and transmission without the need for constant on-site inspection [9]. However, challenges remain regarding the implementation of reliable, energy-efficient systems adapted to real-world operating conditions.

In this context, there is a need to develop a remote monitoring unit (RMU) that improves the efficiency of cathodic protection system monitoring, facilitating decision-making and reducing the risks associated with corrosion in critical infrastructure.

Justification

The implementation of remote monitoring systems in cathodic protection addresses the need to overcome the limitations of traditional inspection methods, which have constraints in terms of measurement frequency, operating costs, and accessibility to remote areas [7], [12].

The adoption of technologies based on wireless communication and automatic data acquisition allows for optimized system monitoring, reducing operational risks and improving decision-making [13], [14].

Furthermore, the development of a remote monitoring unit (RMU) enables the integration of sensors, data acquisition systems, and communication systems into a compact and efficient solution capable of operating autonomously in the field [15], [16].

Furthermore, the incorporation of IoT technologies and wireless sensor networks opens up new possibilities for the intelligent management of industrial systems, enabling not only real-time monitoring but also the implementation of predictive strategies based on data analysis [17], [18].

In this context, the development of this project is justified as a technological solution aimed at improving the efficiency, reliability, and safety of monitoring cathodic protection systems in pipelines.

Objectives

General Objective: To develop a remote monitoring unit (RMU) for cathodic protection systems capable of acquiring, storing, and displaying electrical parameters, and to evaluate its performance in terms of accuracy and energy consumption.

Specific Objectives:

- Design and implement a data acquisition system for measuring cathodic protection potentials.
- Evaluate the system's accuracy by comparing it with reference instruments.
- Develop a web platform for remote data transmission.
- Analyze the system's energy consumption to assess its feasibility in field applications.

State of art

The monitoring of cathodic protection systems has evolved from manual methods to automated solutions based on remote communication technologies. Traditionally, these systems are monitored using test stations where periodic measurements of electrical potential are taken, which imposes limitations in terms of frequency, costs, and access to remote areas [7]. With technological advances, remote monitoring systems capable of acquiring and transmitting data in real time have been developed. Various studies have shown that the use of remote systems significantly improves operational efficiency, facilitating the early detection of anomalies and reducing the need for field inspections [13], [12]. In particular, the use of cellular communication technologies such as GSM and GPRS has been extensively researched for data transmission in cathodic protection systems. These technologies enable the implementation of remote monitoring units (RMUs) capable of sending information from geographically dispersed locations to control centers [14], [19]. Furthermore, current commercial solutions incorporate wireless communication modules, local data storage, and remote visualization platforms [15], [16]. In addition, recent research has explored the use of IoT-based architectures for monitoring corrosion in pipelines, integrating smart sensors and cloud platforms that enable real-time data management and analysis [17], [18]. These solutions offer advantages in terms of scalability, flexibility, and cost reduction, although they still present challenges related to energy consumption, communication reliability, and information security. Furthermore, the proper evaluation of cathodic protection system performance requires the precise measurement of parameters such as ON/OFF potentials, which make it possible to determine whether the structure meets the protection criteria established by international standards [20], [21]. These measurements are essential for validating system performance and ensuring the integrity of the infrastructure. Despite advances in remote monitoring technologies, significant challenges remain regarding the implementation of robust, energy-efficient systems capable of operating under adverse conditions. These aspects represent research opportunities for the development of new solutions that improve the reliability and efficiency of cathodic protection system monitoring.

Chapter II

Methodology

VDI 2206 Methodology Overview

The VDI 2206 methodology is a design guide for the development of mechatronic systems, which proposes a structured and interdisciplinary approach that integrates mechanical, electronic, and software design [22].

This methodology is based on a “V” model, in which the development process begins with the definition of requirements, followed by conceptual and detailed design, and concludes with system integration and validation [23].

In this model, the left side of the “V” corresponds to the decomposition of the system into design levels, while the right side represents the process of integrating and validating the complete system [23].

Figure 2 shows the “V” model used as the basis for the project’s development. This model establishes a direct relationship between the design stages (left side) and the validation phases (right side), ensuring that the defined requirements correspond to the system’s final behavior.

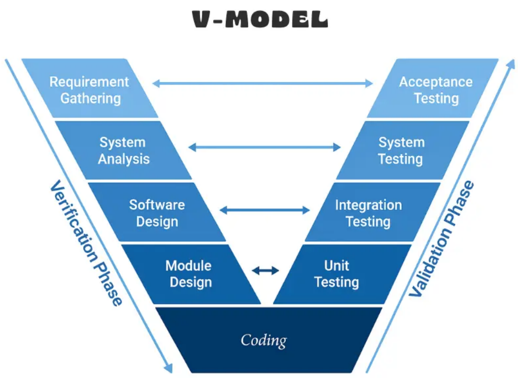


Fig. 2. The V-Model Applied to the Development of Mechatronic Systems

Application of VDI 2206 to the Project

The development of the RMU follows the main phases defined by the VDI 2206 methodology, which provides a structured framework for the development of complex mechatronic systems [22]:

- Requirements phase
- Conceptual design
- Detailed design
- Integration and validation

Each of these phases is adapted to this project with the goal of developing a functional system capable of remotely monitoring cathodic protection parameters.

System Development Based on V-Model

On the left side of the model, the system requirements and design are defined, while on the right side, each of the developed components is implemented, integrated, and validated.

In this project, this structure ensures that every design decision is subsequently verified through experimental testing.

Requirements Phase

In this phase, the needs that the proposed system must meet are defined, classified into functional requirements, non-functional requirements, and system constraints.

Functional Requirements

- The system must measure the pipe-to-ground potential within the typical range for cathodic protection.
- The system must acquire electrical data periodically.
- The system must transmit the acquired data to a remote platform.
- The system must allow data to be viewed via a web interface.
- The system must store measurement histories.

Non-Functional Requirements

- The system must ensure adequate measurement accuracy with a resolution of 1 mV.
- The system must operate with low power consumption for field applications.
- The system must be compact and easy to implement.
- The system must be robust against electrical noise.
- The system must have a high input impedance greater than 10 MΩ.

System Constraints

- Power consumption limitations due to battery use.
- Communication limitations in remote areas.
- Use of commercially available electronic components.
- Validation performed in a controlled environment.

Conceptual Design

In the VDI 2206 methodology, conceptual design allows for defining the system architecture and evaluating different alternatives before proceeding to detailed implementation, which is essential for managing the complexity of mechatronic systems [24].

Figure 3 presents the logical architecture of the system, describing the complete data flow from the acquisition of the potential in the cathodic protection system to its display on the user interface.

The system includes blocks for signal acquisition, conditioning, analog-to-digital conversion, processing in the microcontroller, wireless transmission, and storage on the server for subsequent visualization.

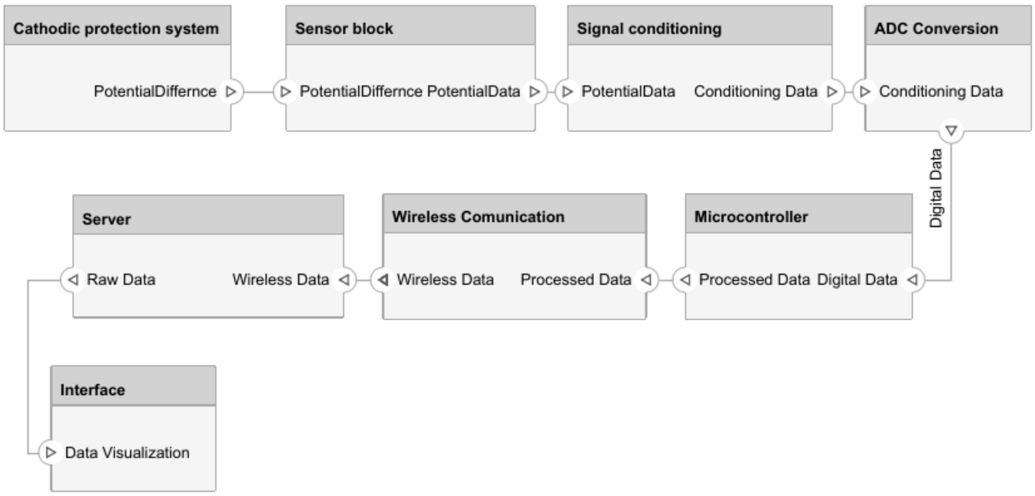


Fig. 3. Logical Architecture of the RMU System

System Architecture

The system is divided into the following modules:

- Signal acquisition module
- Processing module (microcontroller)
- Communication module (GSM)
- Web-based visualization platform
- Power supply system

Figure 4 shows the system's functional architecture, describing the flow of information from the capture of the electrical signal in the pipeline, through its conditioning and digitization, to the processing and transmission of data to the monitoring platform.

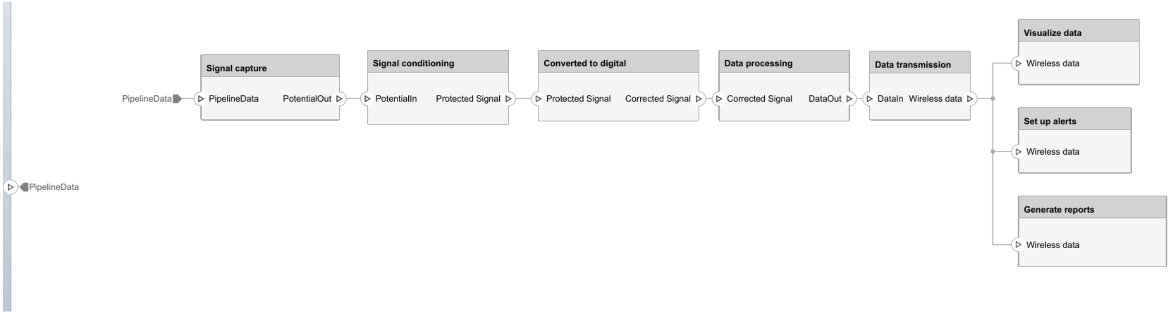


Fig. 4. Functional Architecture of the RMU System

Evaluated Alternatives

During the design process for the signal acquisition system, multiple architectures with varying levels of complexity and accuracy were evaluated. The main alternatives considered were:

- Implementation based on an instrumentation amplifier (INA333)
- Use of a voltage divider with reading via an external ADC (ADS1115)
- A design based exclusively on operational amplifiers to form an analog voltmeter

Operational Amplifier-Based Design. In an initial stage of the project, a fully analog design was considered, using operational amplifiers together with networks of resistors, diodes, and filters, with the goal of building a voltmeter capable of conditioning the signal before it is read.

Figure 5 shows a reference circuit taken from the technical literature, which was used as a conceptual guide for the development of this alternative [1], while Figure 6 summarizes the proposed architecture at the block level.

This approach involved designing multiple signal conditioning stages, including rectification, amplification, and stabilization. However, it was determined that this solution had the following disadvantages:

- Greater design complexity due to the need to implement multiple signal conditioning stages in discrete form
- Greater dependence on component tolerances and external conditions, affecting measurement stability and accuracy
- More demanding calibration requirements due to the accumulation of errors at each stage of the circuit
- An increase in the number of discrete components, which increases the system's size, cost, and potential for failure

Due to these limitations, this alternative was ruled out in the early stages of the project in favor of simpler and more robust solutions.

Design Using an Instrumentation Amplifier (INA333). Subsequently, a proposal was developed based on the use of an INA333 instrumentation amplifier for signal conditioning, combined with a voltage divider circuit. This design reached a more advanced stage, including experimental tests and a partial physical prototype; the schematic of this implementation is shown in Figure 7. The use of the amplifier was considered due to its favorable characteristics for measuring low-amplitude differential signals. Its main advantages include:

- High input impedance, suitable for avoiding disturbance of the measured signal
- Ability to measure potential differences with high common-mode rejection
- Gain configurable via a single external resistor

Resolution of the Acquisition System. The final acquisition stage uses the ADS1115 analog-to-digital converter in direct differential measurement mode, without the INA333 instrumentation amplifier and without the offset stage. The ADC measures the potential difference directly between its differential inputs, while the input protection and filtering network reduces noise and protects the measurement interface. The ADS1115 has a resolution of $N = 16$ bits, which implies [25]:

$$2^{16} = 65536 \text{ levels} \tag{2.1}$$

The cathodic protection signal of interest is located approximately within the range:

$$V_{in} \in [-1.2V, -0.8V] \tag{2.2}$$

Therefore, the useful variation that must be resolved is:

$$\Delta V = 0.4V \tag{2.3}$$

Since the offset stage was discarded in the final design, the signal is not shifted by a reference voltage before the ADC. Instead, the ADS1115 is configured to read the differential input directly. Considering the conservative configuration used in the prototype, with a programmable gain range of $\pm 4.096V$, the full-scale range is:

$$\text{FSR} = 4.096V - (-4.096V) = 8.192V \tag{2.4}$$

The theoretical resolution per bit is:

$$\text{LSB} = \frac{8.192V}{65536} = 125\,\mu V = 0.125\,mV \tag{2.5}$$

Compared to the required resolution of 1 mV:

$$\frac{1mV}{0.125\,mV} = 8 \tag{2.6}$$

Therefore, even in this conservative ADC range, the ADS1115 provides a theoretical resolution approximately eight times finer than the project requirement. This confirms that the direct ADC-based architecture is sufficient for detecting small variations in cathodic protection potential.

Input Protection and Final Measurement Interface. The INA333-based architecture was evaluated but discarded from the final implementation. Although the amplifier offered high input impedance and common-mode rejection, it also introduced additional complexity, power requirements, calibration sensitivity, and the need for an offset reference stage. For the final prototype, the acquisition stage was simplified by measuring the differential voltage directly with the ADS1115.

To protect the ADC input and improve signal stability, the final circuit includes a basic protection and filtering stage using 1N4148 diodes and decoupling capacitors. This approach reduces the number of analog conditioning stages and avoids the offset calibration required by the amplifier-based solution, while preserving the required measurement resolution.

Consequently, the final acquisition architecture was selected because it:

- Reduces the number of analog conditioning components
- Eliminates the need for the INA333 and the voltage offset stage
- Maintains sufficient ADC resolution for the 1 mV requirement
- Simplifies calibration and improves prototype robustness

Final Selection. After evaluating the above alternatives, a simplified solution based on direct differential measurement using the ADS1115 external ADC was chosen. This decision reduced system complexity by removing the INA333 and offset stage without compromising the performance required for the prototype.

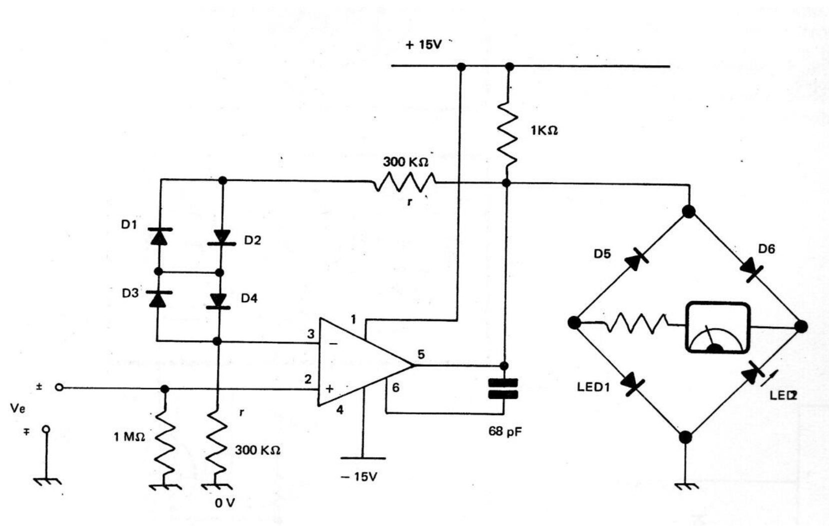


Fig. 5. Reference circuit for a high-impedance analog voltmeter, used as a conceptual guide for design (adapted from [1])

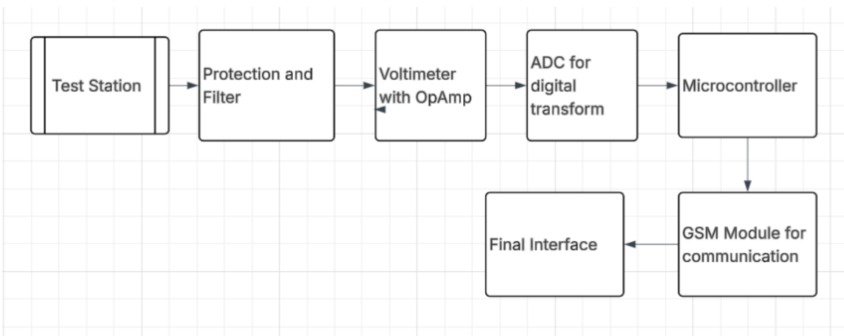


Fig. 6. High-Level Architecture of an Operational Amplifier-Based Design

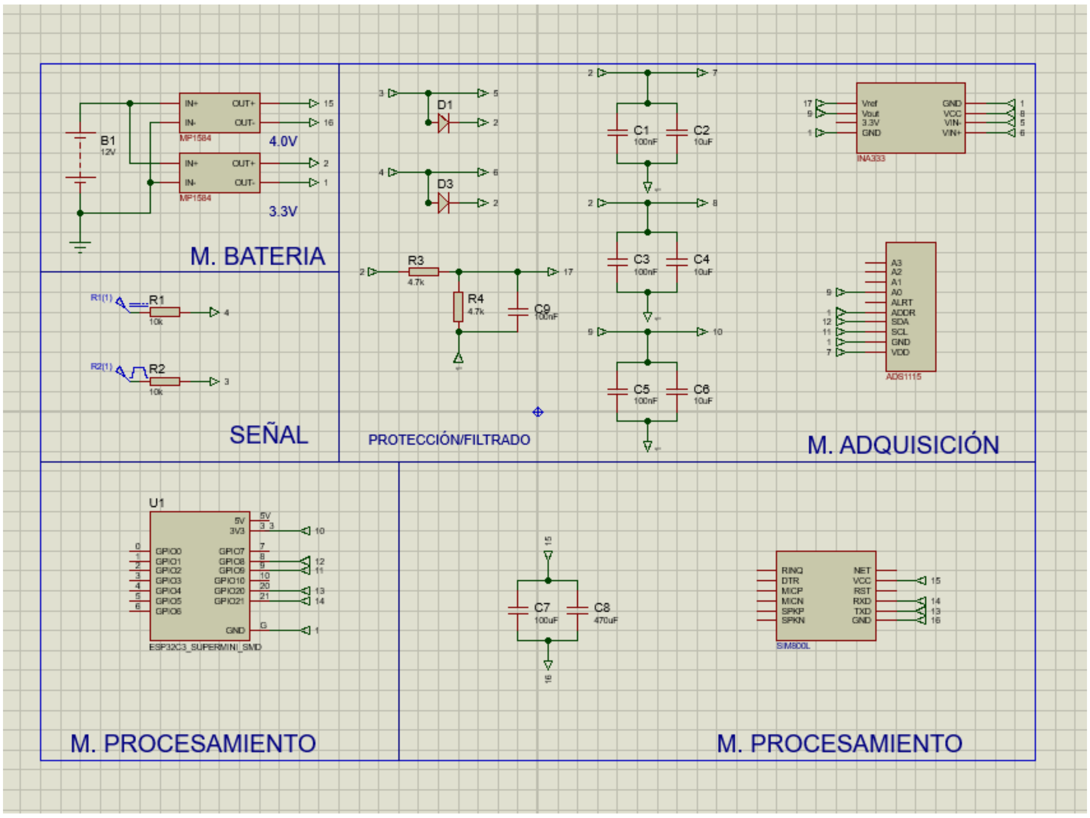


Fig. 7. Initial connection diagram based on the INA333 (design discarded)

Selection Criteria

The final architecture was selected based on the following considerations:

- Measurement accuracy
- Design simplicity
- Power consumption
- Number of components
- System cost

Specific Design

The specific design phase focuses on the detailed implementation of the system, including the selection of components, tools, and technologies, following the interdisciplinary approach characteristic of the VDI 2206 methodology [22].

Figure 8 shows the physical architecture of the developed system, illustrating the interconnection between the different hardware modules, including signal acquisition, processing via the microcontroller, the power supply system, and the GSM communication module.

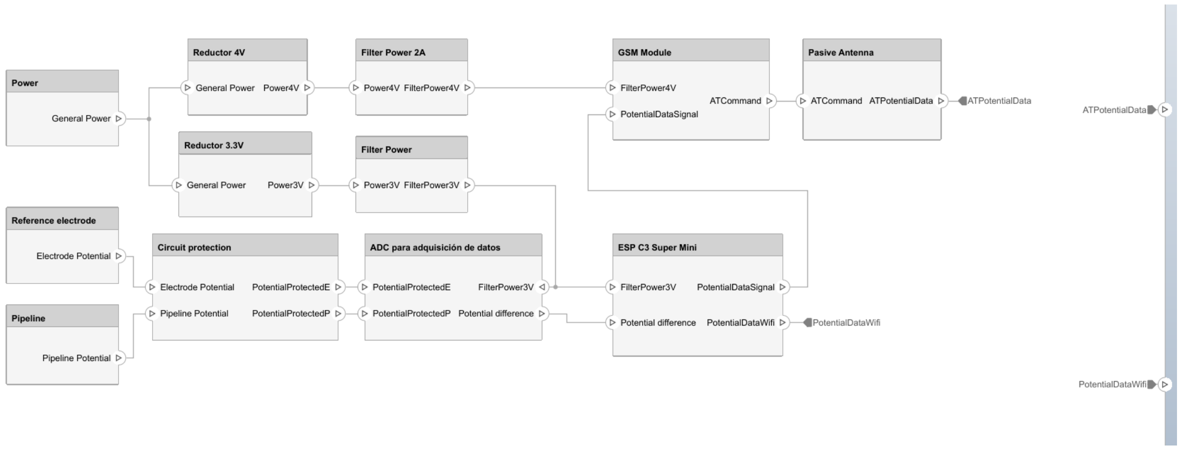


Fig. 8. Physical Architecture of the RMU System

Figure 9 shows the final system connection diagram, which was developed after evaluating various design alternatives.

This version implements an optimized architecture that includes clearly defined modules for power supply, signal acquisition, protection and filtering, processing, and wireless communication.

The system uses an external ADC (ADS1115) for data acquisition, an ESP32-C3 microcontroller for processing, and wireless communication through Wi-Fi and/or the SIM800L module for data transmission, ensuring a compact, efficient, and functional design.

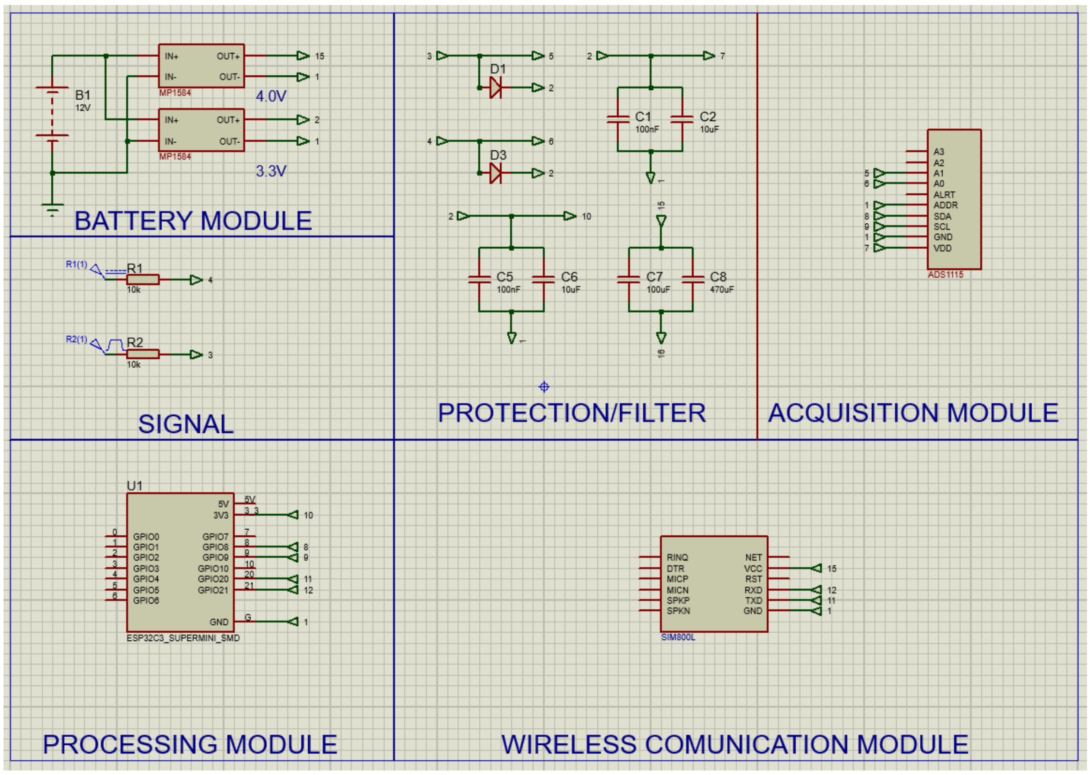


Fig. 9. Final Connection Diagram for the RMU System

Software Architecture

To describe the system's logical operation, flowcharts were developed for the main components: the embedded system (ESP32-C3), the backend server, and the user interface.

ESP32 Firmware Flow. The operational flow of the embedded system is shown in Figure 10. The process begins with system initialization and the configuration of the communication and data acquisition modules.

Next, the availability of the ADS1115 ADC is verified. If it is not detected, the system halts execution to prevent invalid readings.

Once the system has been validated, an initial calibration process is performed based on the acquisition and filtering of multiple voltage samples, with the goal of stabilizing the signal before processing.

During normal operation, the system performs the following steps cyclically:

- Reading the voltage from the ADS1115
- Filtering the acquired signal
- Calculating the potential difference
- Evaluating the state change (ON/OFF) by comparing it to defined thresholds

Depending on the result, the system updates the state and logs the data. Finally, it checks whether the transmission time has elapsed; if so, the data is transmitted to the server via GSM or Wi-Fi.

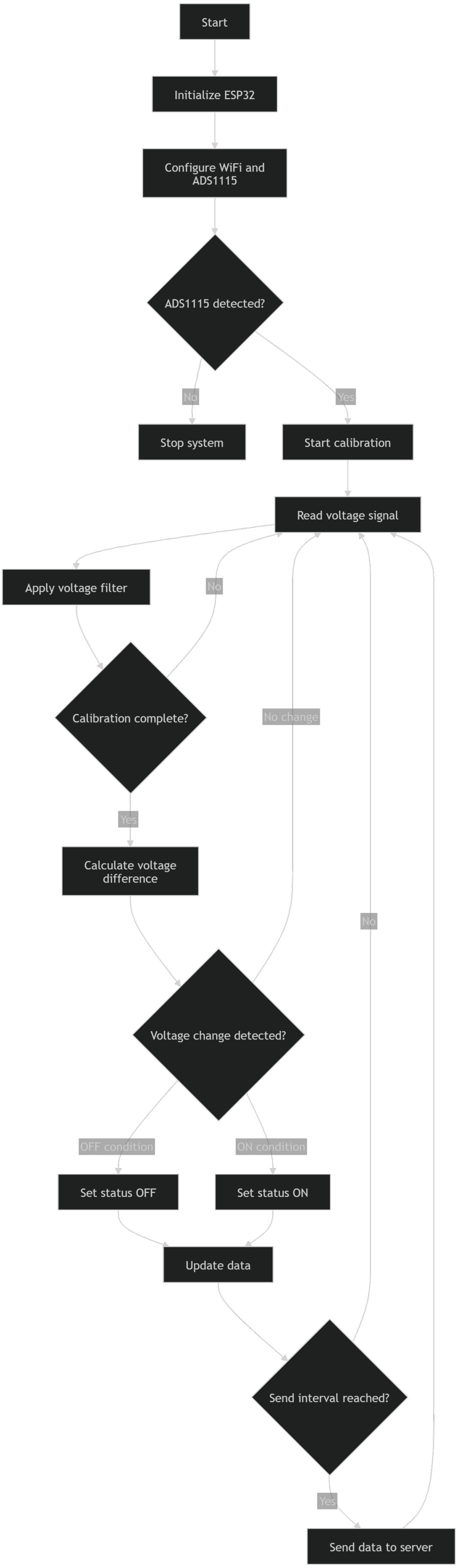


Fig. 10. ESP32 Firmware Flowchart

User Interface Flow. The user interface flow is shown in Figure 11. The process begins with the dashboard loading, followed by the initialization of the graphical elements and visualization structures.

The system periodically sends requests to the server to retrieve the most recent data. If no information is available, the system enters a waiting state until the next update.

When data is available, the latest record is retrieved, and the status indicators (ON/OFF) are updated, as are the system conditions, which are classified as “protected status” or “alert status” based on the defined limits.

Finally, the display tables and graphs are updated, and the process is repeated at defined time intervals.

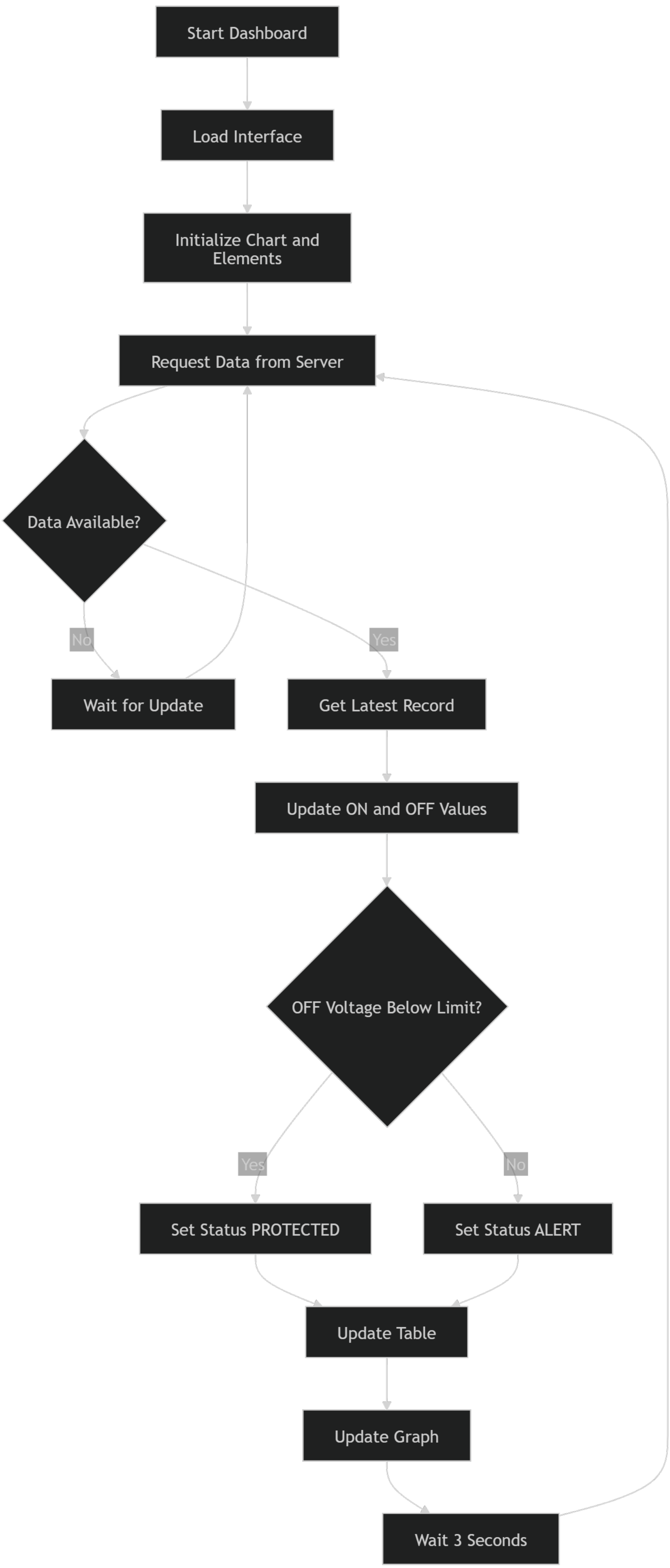


Fig. 11. User Interface Flowchart

Server Processing Flow. The backend server flow is shown in Figure 12. The system begins by loading the Express framework, configuring the communication port, and enabling JSON data handling.

The server remains on standby for HTTP requests, which can be classified into two main types:

- **POST /api/data**: used by the ESP32 to send data to the server. In this case, the server receives the information, generates a record, adds the corresponding timestamp, and stores the data.
- **GET /api/data**: used by the user interface to request the stored data. The server responds by sending the available information.

Once each request has been processed, the server returns a response confirming that the operation was executed successfully.

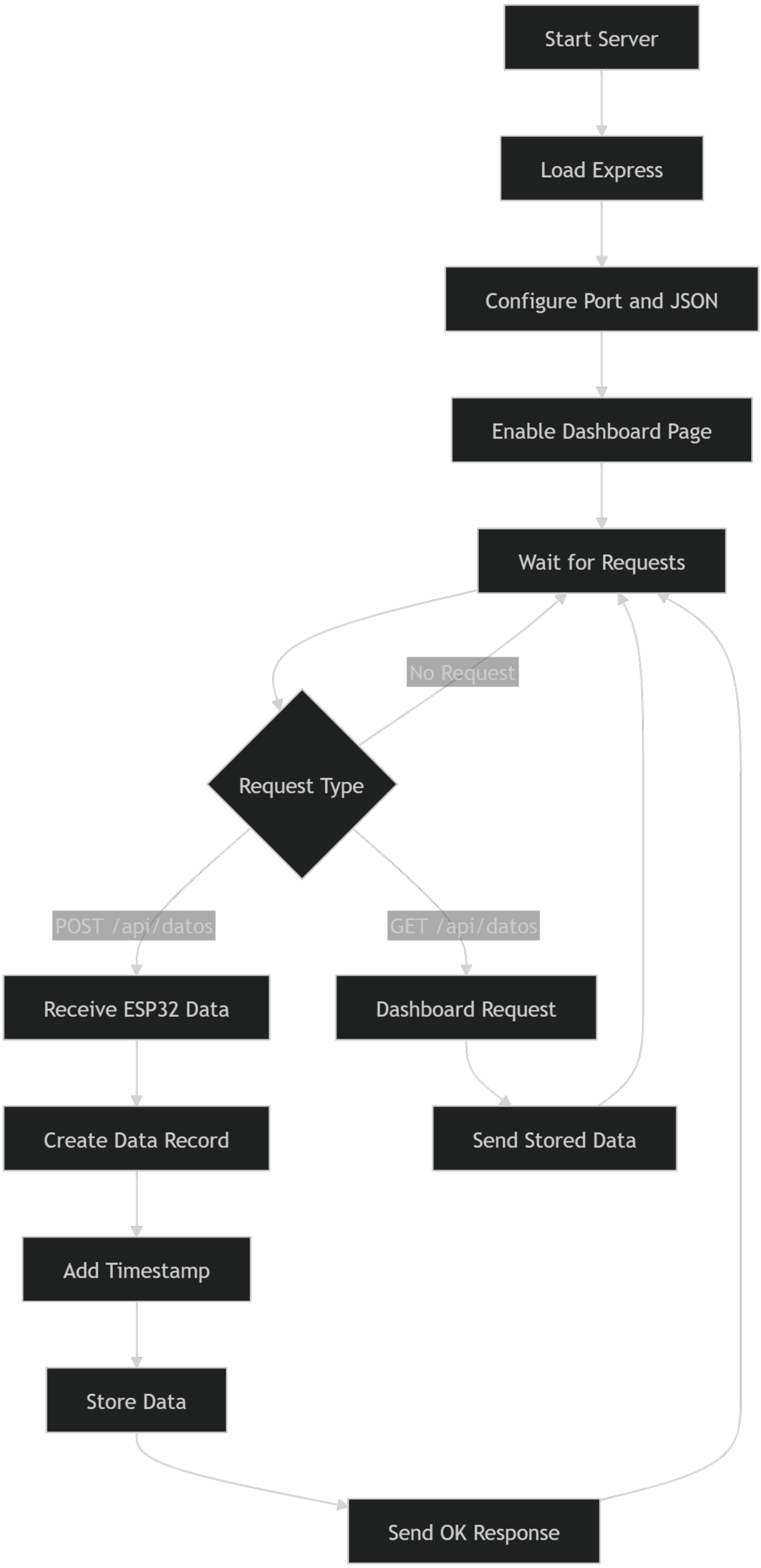


Fig. 12. Server Processing Flowchart

Signal Acquisition System

The signal acquisition system is based on the ADS1115 analog-to-digital converter, which allows for the measurement of low-level signals with high resolution (16 bits).

To protect the system's input and reduce noise, a basic protection and filtering stage was implemented, consisting of 1N4148 diodes and a network of capacitors (100 nF, 10 μF, and 470 μF). This configuration mitigates transients and stabilizes the signal before digital conversion.

Processing Unit

An ESP32-C3 microcontroller is used as the processing unit, responsible for:

- Acquiring data from the ADC
- Processing and preparing the information
- Managing system communication

Communication Module

The system incorporates a SIM800L module for data transmission via GSM communication, enabling operation in remote environments without access to local networks.

Additionally, the system implements a redundant communication mechanism via Wi-Fi, available on the ESP32-C3, with the goal of increasing the reliability of data transmission.

It should be noted that the SIM800L module operates on 2G networks, which limits the choice of service provider.

Power Supply System

The power supply system relies on DC-DC converters (MP1584 and LM2596) to generate the voltage levels required by the various modules (3.3 V and 4.0 V).

During the testing phase, the system was powered by an external power supply. For the final implementation, a LiPo battery is being considered as an autonomous power source.

Decoupling capacitors were incorporated into the various modules to improve system stability and reduce voltage fluctuations.

Power Consumption Analysis

The system's power consumption is not constant, as the SIM800L module exhibits high current spikes during data transmission. According to the manufacturer's datasheet, these spikes can reach values of up to 2 A in short bursts during GSM communication [26]. For this reason, the system design accounts for worst-case power consumption conditions.

TABLE 2
Estimated power consumption of the system components

Component	Current	Condition
ESP32-C3	250 mA	WiFi Operation [27]
SIM800L	2000 mA	Peak transmission [26]
ADS1115	0.15 mA	Continue conversion [25]
Resistances (10k)	0.1 mA	1 V Signal (Ohm's Law)
MP1584 (x2)	0.2 mA	Quiescent current [28]
Total	**2250.45 mA**	Estimated maximum consumption

The system's total power consumption under critical conditions is approximately:

$$I_{total} \approx 2.25A \tag{2.7}$$

Assuming an operating voltage of 4 V (determined by the SIM800L module), the power required is:

$$P = V \cdot I \tag{2.8}$$

$$P = 4V \cdot 2.25A = 9W \tag{2.9}$$

Therefore, the system requires approximately 9 W under maximum operating conditions. This analysis is essential for sizing the power supply and selecting capacitors capable of withstanding current spikes during GSM transmission.

System Integration and Implementation

Once the system design was defined, we proceeded to build the physical prototype of the remote monitoring unit (RMU).

The validation process was carried out in three stages:

- Individual testing of each module
- Integration on a breadboard
- Final implementation on a PCB

The PCB was designed to integrate the components into a compact and functional layout, taking into account primarily the physical arrangement of the modules and their dimensions. **??** shows an early prototype of the board design.

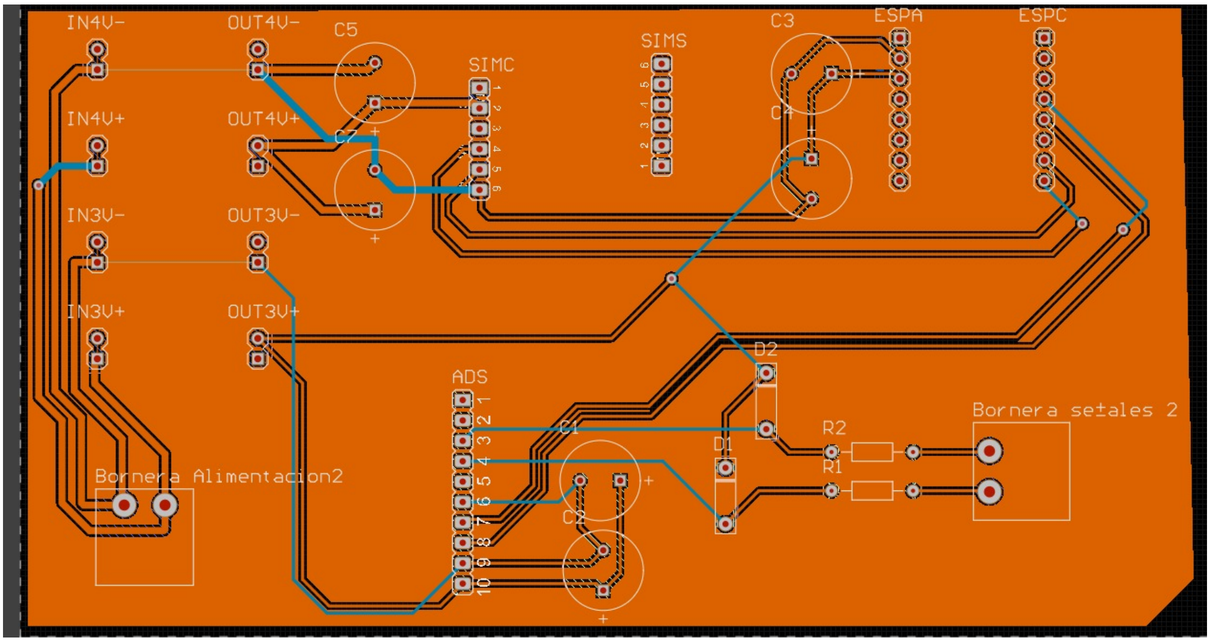


Fig. 13. Prototype of printed circuit board (PCB)

In the implemented system, the signal is acquired via the ADS1115, processed by the ESP32-C3, and then transmitted via the SIM800L module or via a Wi-Fi connection, depending on network availability. However, the originally designed PCB utilized technologies that were difficult to obtain in the country. Given that the requirements included the use of commercially available components or locally accessible services, a second design was created shown in **??** that complies with local electronics design specifications.

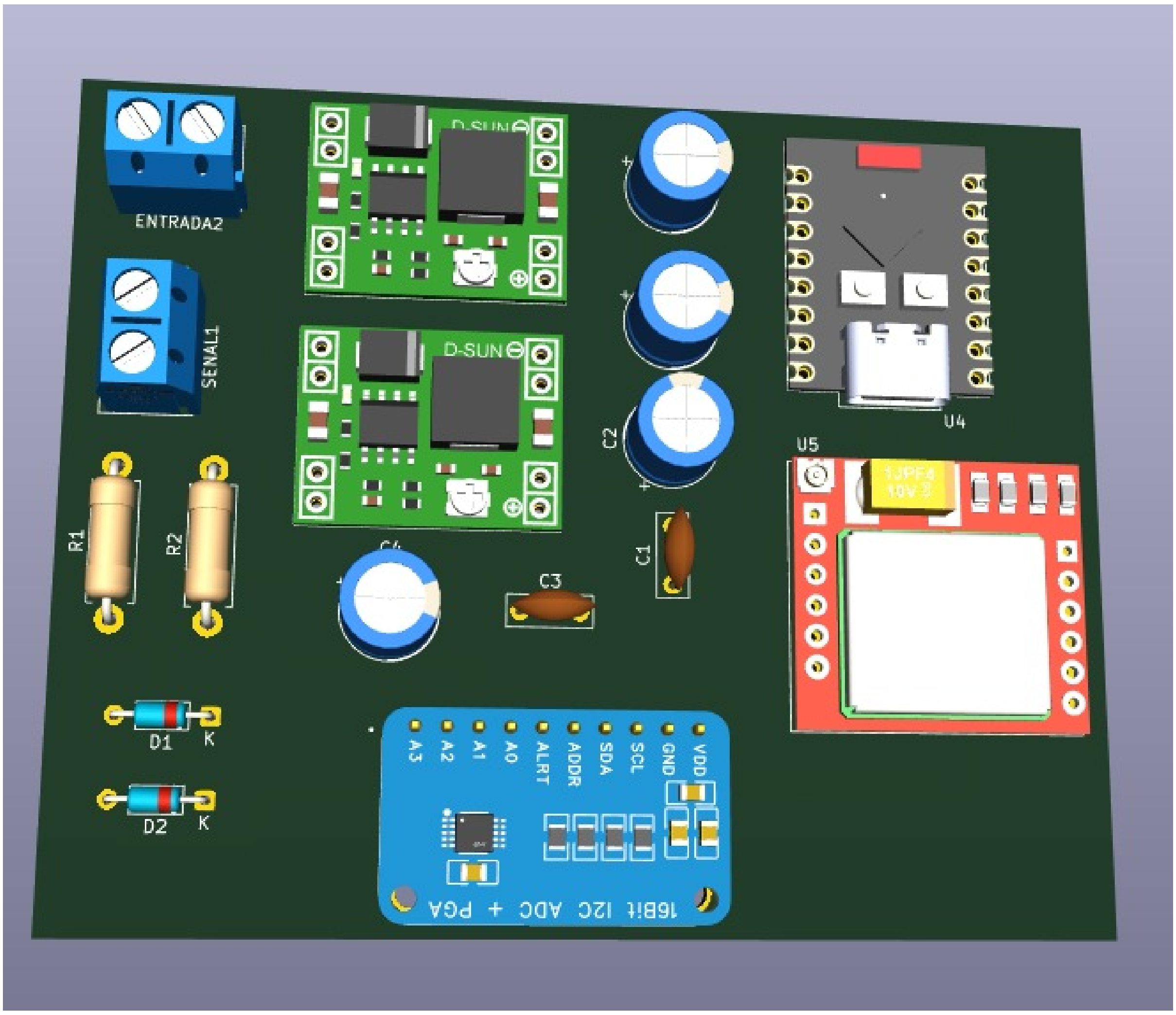


Fig. 14. Final printed circuit board (PCB) developed for the prototype

Experimental Setup

To validate the proposed system, a test station was set up to simulate a cathodic protection system under controlled conditions.

The station consists of:

- An electrolytic medium (container with a conductive solution)
- A metal element (steel) that simulates the structure to be protected
- Sacrificial anodes (magnesium or aluminum)
- A reference electrode for measuring potential

This configuration allows for the reproduction of a galvanic cathodic protection system. Although the developed system is applicable to both galvanic and impressed-current configurations, the experimental tests were conducted in a galvanic environment due to its simplicity of implementation in the laboratory. Figure 15 shows the block diagram of the test station used to validate the prototype.

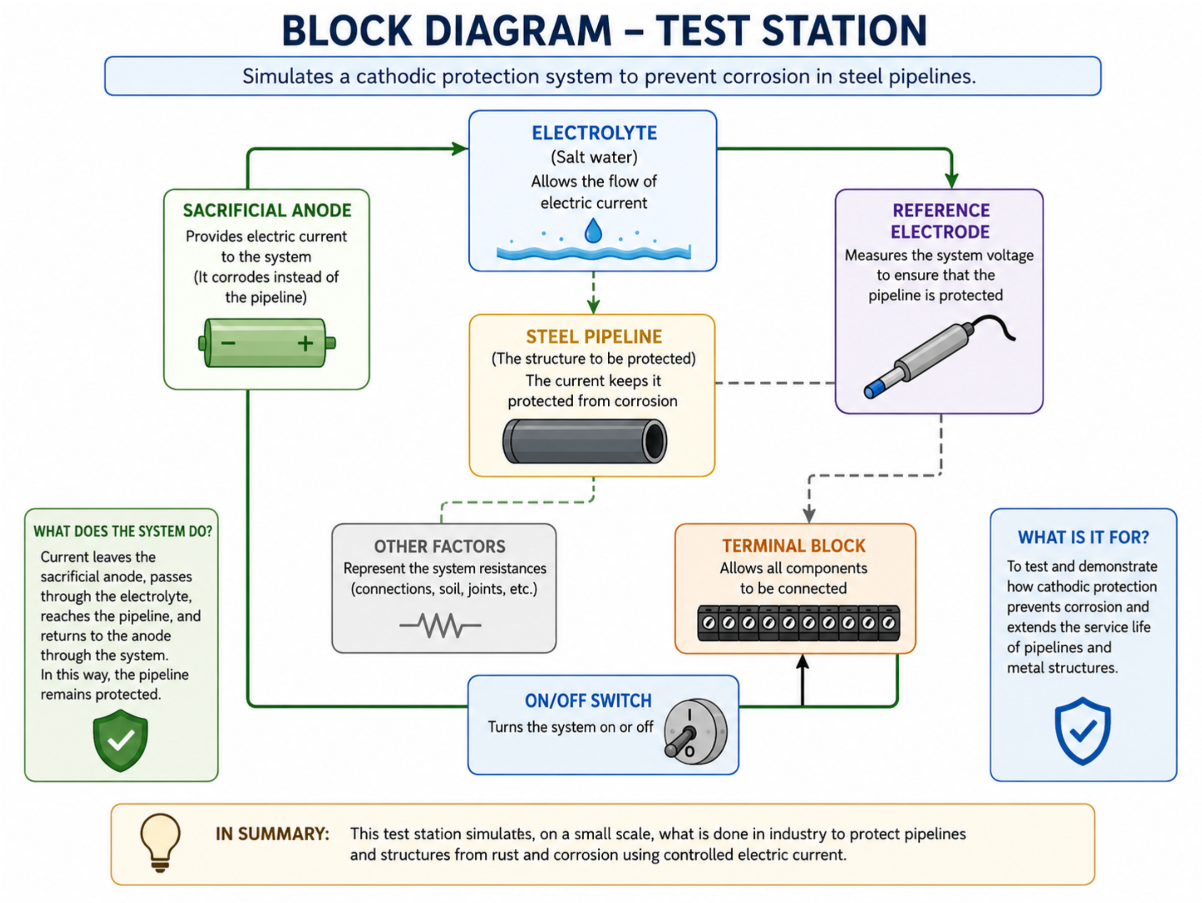


Fig. 15. Block diagram of the test station used for system validation

In addition, Figure 16 shows a simplified equivalent electrical model of the system, used as a conceptual reference for understanding the behavior of the measurement system.

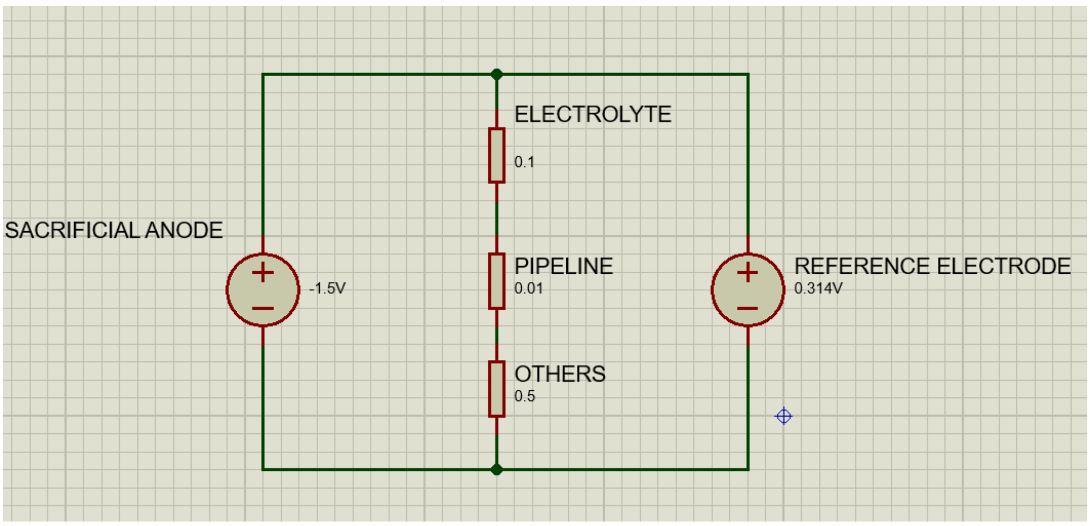


Fig. 16. Simplified Equivalent Electrical Model of the Cathodic Protection System

In this model, the electrolyte is represented by a resistance, as are the losses associated with interfaces, coatings, and connections. The pipe is modeled as a very low resistance due to the high conductivity of steel.

The copper/copper sulfate ($Cu/CuSO_4$, CSE) reference electrode allows the potential of the pipe relative to its surroundings to be measured. This electrode has an approximately constant potential of +0.316 V relative to the standard hydrogen electrode.

During the measurement, the potential obtained includes contributions from voltage drops in the electrolyte and other components (IR drops). For this reason, the ON/OFF technique is used in real-world systems, where the current is momentarily interrupted, eliminating these drops (I=0) and allowing only the polarization potential of the structure to be measured.

According to international standards such as NACE SP0169 and ISO 15589-1, a common protection criterion stipulates that the OFF potential of the pipe must be more negative than -850 mV relative to a CSE electrode to ensure adequate protection against corrosion [5, 6].

In galvanic systems, magnesium anodes are commonly used in buried structures due to their high electrochemical potential (approximately -1.7 V), while aluminum anodes are primarily used in marine environments.

Finally, it is important to note that the model presented here is simplified and conceptual, since in real-world applications, multiple additional factors come into play—such as soil resistivity, environmental conditions, and coating characteristics—which are not considered in detail in this scheme.

Experimental Procedure

The experimental tests were conducted by comparing the measurements obtained by the RMU with those from a reference instrument (digital multimeter).

During the process, iterative adjustments were made to the detection thresholds and digital filtering, with the goal of minimizing the deviation from the reference values.

The following parameters were evaluated:

- Measurement accuracy
- Relative error with respect to the reference value
- Signal stability

The relative error was calculated using:

$$Error(\%) = \frac{V_{medido} - V_{referencia}}{V_{referencia}} \times 100 \tag{2.10}$$

Signal stability was evaluated by analyzing the variation between consecutive measurements under constant conditions, allowing for the identification of system fluctuations.

Data Acquisition Validation

Experimental tests were conducted to validate the performance of the data acquisition system.

The validation process was carried out in two stages, during which 10 measurements were recorded for each data set.

In the first stage, inconsistencies were observed in the identification of the system's ON/OFF state, attributable to the initial detection logic.

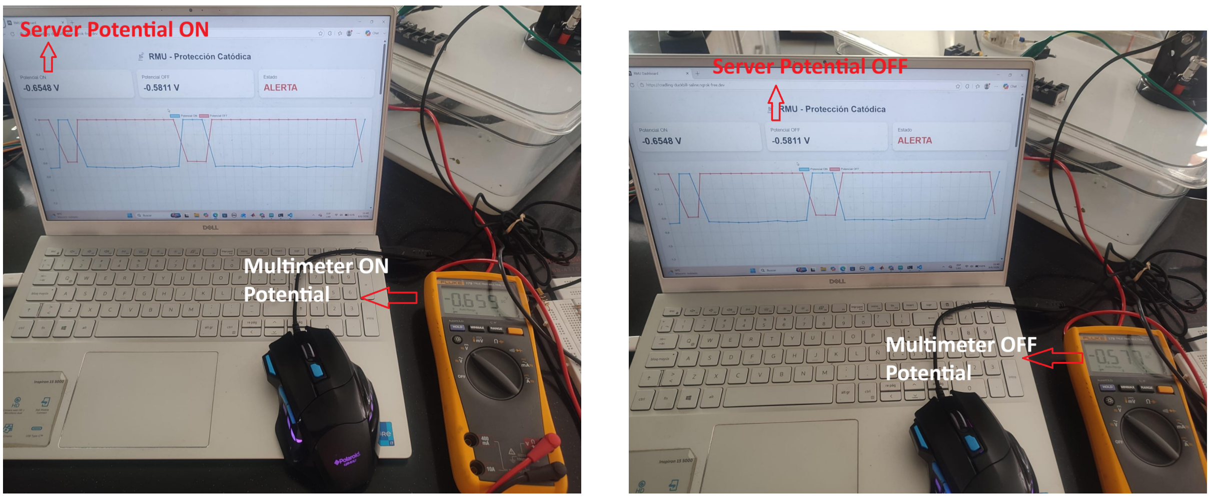
Subsequently, improvements were implemented in the classification algorithm, correcting these inconsistencies.

Figure 17 shows the experimental setup during the system validation tests, where the measurements obtained by the RMU are compared with a reference digital multimeter.

Figure 17(a) shows a measurement corresponding to the ON state, with an approximate value of -659 mV as measured by the multimeter, which matches the value reported by the system.

On the other hand, Figure 17(b) shows a measurement in the OFF state, with an approximate value of -577 mV.

These results demonstrate the system's ability to correctly distinguish between the ON and OFF states, as well as the agreement between the obtained measurements and the reference instrument.



(a) Measurement in the ON state (≈ -659 mV) **(b)** Measurement in the OFF state (≈ -577 mV)

Fig. 17. Experimental Validation of the RMU System Compared to a Digital Multimeter Under Different Operating Conditions

Table 3 presents the results for the first stage, while Table 4 shows the results obtained after optimizing the system.

The results demonstrate an improvement in measurement accuracy and, above all, in the correct identification of the system's state.

TABLE 3
Test 1: Initial Data Acquisition and State Detection

Real Value (V)	Measured Value (V)	Real Status	Measured Status	Error (%)
-0.743	-0.743	ON	ON	0
-0.690	-0.690	OFF	ON	0
-0.688	-0.691	OFF	ON	0.44
-0.754	-0.755	ON	ON	0.13
-0.688	-0.691	OFF	ON	0.43
-0.751	-0.751	ON	ON	0
-0.689	-0.691	OFF	ON	0.29
-0.753	-0.754	ON	ON	0.13
-0.688	-0.690	OFF	ON	0.29

TABLE 4
Test 2: Data Acquisition with Corrected Detection

Real Value (V)	Measured Value (V)	Real Status	Measured Status	Error (%)
-0.759	-0.760	ON	ON	0.13
-0.694	-0.695	OFF	OFF	0.14
-0.758	-0.759	ON	ON	0.13
-0.694	-0.695	OFF	OFF	0.14
-0.753	-0.753	ON	ON	0
-0.693	-0.694	OFF	OFF	0.14
-0.759	-0.759	ON	ON	0
-0.694	-0.695	OFF	OFF	0.14
-0.760	-0.761	ON	ON	0.13
-0.700	-0.698	OFF	OFF	0.29

Data Communication and Visualization System

To display the data, a web server was implemented using Node.js and the Express.js framework.

The system consists of two main files:

- `server.js`: responsible for handling HTTP requests, receiving data sent from the device, and storing it for later display.
- `index.html`: a visual interface that enables real-time visualization of the data received from the server via periodic requests.

Communication between the RMU and the server was carried out using HTTP protocols, allowing data to be sent from the device to the web platform.

Additionally, the Ngrok tool was used to generate temporary public domains that expose the local server to the Internet, allowing data to be received from the ESP32 via both Wi-Fi and cellular networks (SIM800L).

Data transmission tests were conducted using:

- Local communication via Wi-Fi
- Remote communication via a GSM module (SIM800L)

In both cases, the data was successfully received and displayed on the web platform in real time.

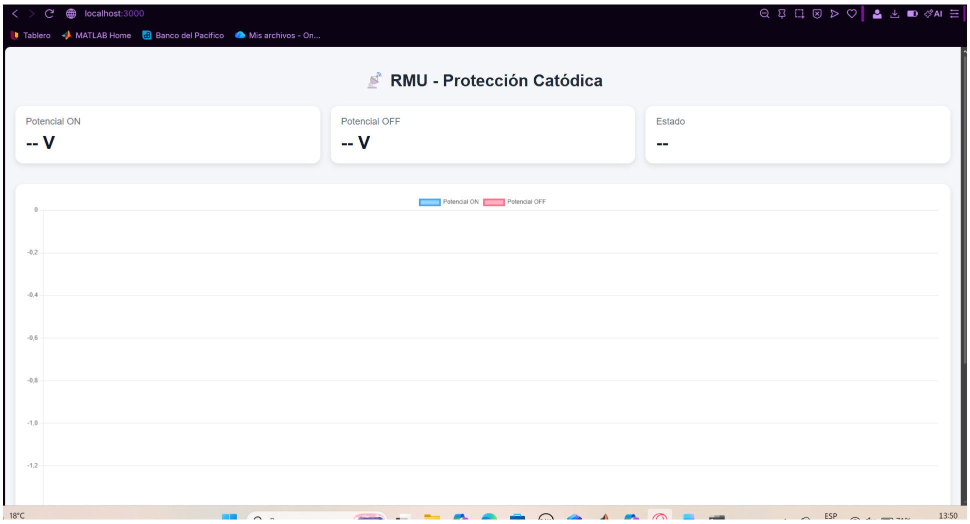


Fig. 18. Web platform for real-time data visualization

Fig. 19. Remote Viewing on a Cell Phone via a GSM Connection

I)

Once the system design and experimental procedure have been established, the following chapter presents the results obtained, along with their analysis and discussion.

Chapter III

Results and discussions

Results

Measurement Results

The results obtained during the experimental tests demonstrate the RMU system's performance in acquiring the duct-to-ground potential.

Figure 20 presents a comparison between the values measured by the RMU and the reference multimeter across the acquired samples.

A high degree of agreement is observed between the two signals, as evidenced by the superimposition of the curves. This indicates that the system is capable of accurately reproducing variations in electrical potential.

In addition, a periodic pattern can be observed in the measurements, corresponding to the alternation between the ON and OFF states of the cathodic protection system. This response confirms the system's ability to correctly capture changes in the signal.

Furthermore, Figure 21 summarizes the absolute error by ON/OFF state. The ON state presented a mean absolute error of 0.6 ± 0.5 mV, while the OFF state presented a mean absolute error of 1.6 ± 1.0 mV. The maximum observed absolute error was 3.0 mV, which remains suitable for the validation objective of the prototype.

It can be seen that the OFF state has a higher dispersion than the ON state, mainly due to the transient behavior of the test station and the threshold-based state detection. Even so, the overall agreement with the reference multimeter confirms the suitability of the data acquisition system.

These results validate the system's proper operation and its ability to perform reliable measurements within the defined operating range.

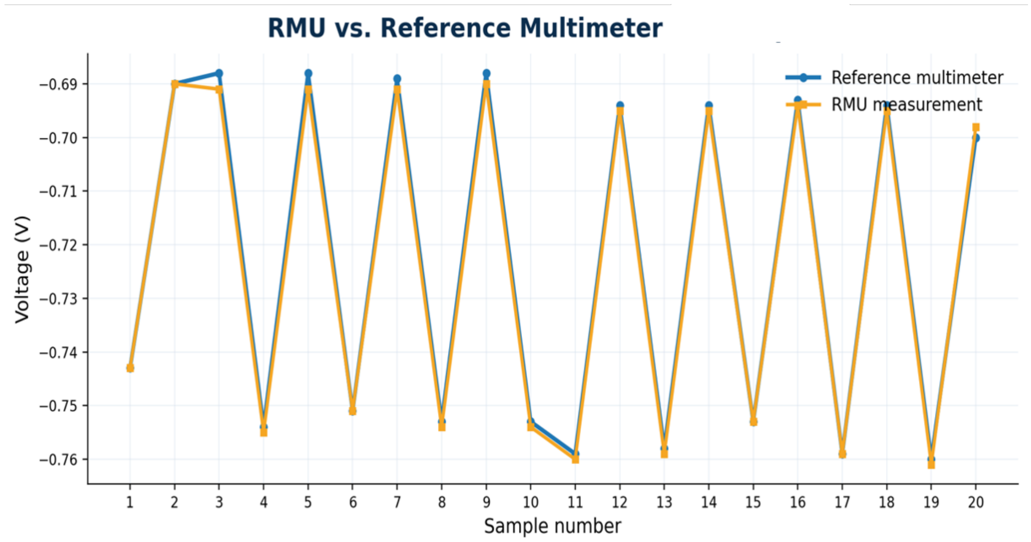


Fig. 20. Comparison between RMU measurements and the reference multimeter during the experimental tests

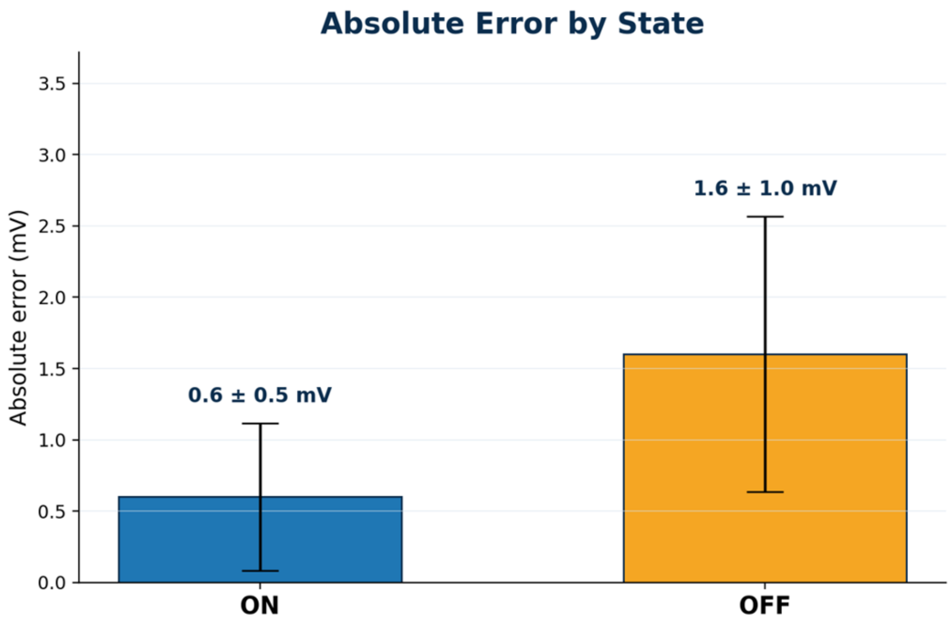


Fig. 21. Absolute error by ON/OFF state, expressed as mean absolute error $\pm$ standard deviation

Error Analysis

To evaluate the system’s accuracy, the absolute error with respect to the reference multimeter was analyzed. The results show millivolt-level agreement, with 0.6 ± 0.5 mV in the ON state and 1.6 ± 1.0 mV in the OFF state.

The results obtained show that the system exhibits low measurement error. The final improvement was achieved through threshold tuning and digital filtering, rather than through an analog offset stage, because the final acquisition design measures the differential voltage directly with the ADS1115.

In the cases analyzed, as shown in Figure 17, the difference between the values measured by the system and the multimeter is minimal, which validates the accuracy of the data acquisition system.

System Performance Evaluation

The system's performance was evaluated based on three main aspects: measurement accuracy, state detection, and signal stability.

Measurement Accuracy. The system was able to measure the potential with a high degree of agreement with the reference instrument, demonstrating the ADC ADS1115's ability to detect small variations in voltage.

State Detection (ON/OFF). A significant improvement in the detection of the ON/OFF state was observed between the first and second testing phases.

Initially, the system exhibited classification errors due to the threshold comparison logic. After optimizing the algorithm, the system was able to correctly identify the state based on the measured potential.

Signal Stability. Signal stability was evaluated by observing the variation between consecutive measurements under constant conditions.

The results show that the system produces a stable signal with minimal fluctuations, confirming the effectiveness of the implemented filtering and the proper data acquisition.

Cost Analysis

Table 5, Table 6, and Table 7 present the estimated cost analysis of the developed system, including the RMU electronic components, the test station elements, and labor.

TABLE 5
Estimated cost of the RMU components

Item	Quantity	Estimated Cost (USD)
Resistors (10 kΩ)	2	0.20
Diodes (1N4148)	2	0.20
Screw terminals	2	1.50
Capacitors (100 nF, 10 μF, 470 μF, 100 μF)	6	2.50
ADS1115 ADC	1	6.00
SIM800L Module	1	8.00
GSM Antenna	1	2.00
ESP32-C3 Mini	1	6.00
Voltage regulator / AMS1117	1	1.50
MP1584 DC-DC converters	2	3.00
LiPo Battery (2.2 Ah)	1	10.00
PCB fabrication	1	10.00
RMU Subtotal		**50.90**

TABLE 6
Estimated cost of the test station components

Item	Quantity	Estimated Cost (USD)
$Cu/CuSO_4$ reference electrode	1	25.00
Magnesium anode	1	15.00
Aluminum anode	1	12.00
Steel pipe sample	1	8.00
Terminal block (12 positions)	1	5.00
Test station enclosure	1	20.00
Switch	1	2.00
Acrylic base	1	10.00
Container	1	5.00
Wiring and connectors	1	5.00
Encapsulation materials	1	5.00
Test Station Subtotal		**112.00**

TABLE 7
Estimated labor and total project cost

Item	**Quantity**	**Estimated Cost (USD)**
Engineering development (80 hours approx.)	1	400.00
RMU Subtotal		**50.90**
Test Station Subtotal		**112.00**
Labor Cost		**400.00**
Total Estimated Cost		**562.90**

The total estimated cost of the system is approximately $568 USD, where the main contribution corresponds to labor costs associated with system development.

It is important to note that the cost of electronic components is relatively low compared to the engineering effort required for system design, integration, and validation.

This analysis demonstrates that the proposed solution is economically feasible, especially considering its potential application in remote monitoring scenarios, where it can reduce maintenance costs and manual inspection efforts.

Discussion

The results obtained show that the developed system meets the stated objectives, demonstrating good accuracy in potential measurement and correct identification of the protection status. The small difference between the measurements from the RMU system and the reference multimeter validates the reliability of the data acquisition system. Furthermore, the improvement observed between the two testing phases highlights the importance of parameter tuning and algorithm optimization in measurement systems.

From a practical standpoint, the developed system represents a viable solution for the remote monitoring of cathodic protection systems, reducing the need for manual inspections and enabling real-time data visualization. However, it is important to note that the tests were conducted in a controlled laboratory environment; therefore, future evaluations under real-world field conditions would allow for a comprehensive validation of the system's performance.

Additionally, factors such as external interference, environmental variations, and soil conditions could influence the system's behavior in real-world applications. Despite these limitations, the results indicate that the proposed solution is suitable for implementation in remote monitoring systems, meeting the requirements for accuracy, energy consumption, and reliability.

Chapter IV

Conclusions and Recommendations

Conclusions

During the course of this project, a remote monitoring unit (RMU) for cathodic protection systems was designed and implemented, fulfilling the primary objective of acquiring, processing, and displaying relevant electrical parameters, as well as evaluating its performance in terms of accuracy and energy consumption.

A data acquisition system based on direct differential measurement with the ADS1115 analog-to-digital converter was successfully designed and implemented, capable of measuring potentials within the range of interest for cathodic protection applications. The offset and INA333 stages were discarded from the final design, while the ADC still provided sufficient theoretical resolution for the 1 mV requirement.

To assess the system's accuracy, a comparison was performed with a reference instrument (digital multimeter), yielding a high degree of agreement between the measurements. The error analysis showed millivolt-level absolute errors, with 0.6 ± 0.5 mV in the ON state and 1.6 ± 1.0 mV in the OFF state, which validates the reliability of the data acquisition system for this type of application.

A web platform was developed that enables the transmission, storage, and visualization of data in real time. This component facilitates remote monitoring of the system, eliminating the need for frequent manual inspections and improving operational efficiency.

Analysis of energy consumption revealed that the system experiences high current spikes, primarily due to the SIM800L module during data transmission. However, the system remains within an acceptable range for field applications, provided the battery is properly designed.

Recommendations

Based on the results obtained, the following recommendations are proposed for future work and system improvements:

- Implement alternative communication technologies, such as satellite communication systems, in order to expand the system's coverage in remote areas where GSM connectivity is limited or nonexistent. This improvement would enable a more robust application of the system in real-world operating scenarios.

- Optimize the system’s energy consumption by implementing low-power modes in the microcontroller and more efficient data transmission strategies, such as periodic or on-demand transmission.
- Conduct tests under real-world field conditions, where factors such as electromagnetic interference, environmental variations, and soil characteristics may influence the system’s behavior.
- Integrate local data storage (backup) systems to ensure data integrity in the event of communication failures.
- Incorporate more advanced data processing and analysis algorithms to detect anomalies and anticipate potential failures in the cathodic protection system.

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