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Studying and Realizing the Based-Intelligent IoT System for Pipeline Cathodic Protection

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Abstract

Cathodic protection (CP) emerges as the optimal approach for mitigating metal corrosion in pipeline networks. To ensure the continued efficiency of the CP system, monitoring the potential distribution throughout the network is crucial. In distribution networks, the pipeline potential is influenced by time-varying environmental factors, making it challenging to estimate the potential at locations away from the measurement point. This paper presents a proposed CP system for pipelines, utilizing an intelligent IoT system. The sensor nodes of the system designed based on the STM32 microcontroller perform the measurement of voltages from the reference electrodes, process the signal as well as perform wireless communication about the control stations via LoRa (Long Range Radio) communication. Besides, the control stations are designed to implement voltage compensation control through autotransformer and to communicate with the server through the GPRS communication. The objective is to deploy an affordable system capable of effectively monitoring and regulating the potential of the pipeline at a designated measurement location in industrial plants.

Keywords: Electrochemical corrosion, impressed current CP, IoT, LoRa.

1. Introduction

Corrosion is an electrochemical process that leads to the destructive deterioration of metal. It occurs through two reactions: oxidation, known as the anodic reaction, which involves the loss of electrons from the metal, and reduction, commonly referred to as the cathodic reaction, which involves the consumption of those electrons through oxygen or water reduction. The oxidation reaction results in metal loss, while the reduction reaction is essential for electron consumption to maintain charge neutrality [1]. Corrosion rate of metals is influenced by various factors associated with the metal's properties and the surrounding environment. Additionally, environmental parameters such as temperature, oxygen content, moisture, and electrolyte conductance have an impact on the corrosion rate [2].

There exist various effective methods for combating corrosion, including surface protection, sacrificial anode, and impressed current cathodic protection (CP) methods [3, 4]. Among these, the application of impressed current CP using forced external current holds significant advantages, particularly when employed in underground pipeline systems. This approach offers exceptional protection capabilities for large metal surfaces. Furthermore, the integration of automatic measurement systems enhances the effectiveness of anti-corrosion measures. Currently, there is a positive trend towards the utilization of IoT-based automation systems with wireless sensors in industrial settings [5, 6]. The application of the fuzzy control algorithm has significantly increased the response time of the system, which may affect the bias voltage compensation quality in underground pipeline protection. These systems provide a unique solution by leveraging wireless communication, enabling easy data collection with improved spatial and temporal resolution. The demand for intelligent IoT applications in measurement and monitoring systems is on the rise [7, 8], wherein the data is collected, processed, and control decisions are made by a central server, ensuring efficient operation and timely alerts for users. The high cost is one of the disadvantages of these systems in practical application.

This study presents a comprehensive investigation into the research, design, and implementation of an automated measurement, monitoring, and control system for underground pipeline electrochemical corrosion prevention, utilizing advanced smart IoT technology. The development of intelligent Impressed Current CP meters has addressed various specific requirements. Incorporated algorithms within the system enable precise measurements, efficient signal processing, and effective compensation for voltage deviations along the underground pipelines. Furthermore, the Web Server software facilitates simultaneous connection to

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multiple devices, ensuring accurate, continuous, and user-friendly storage and display of measurement results.

2. Measuring Principle

The management of the Cathodic Protection (CP) system is regulated by international standards and national legislation. They define the methods to guarantee and verify the CP, the characteristics of the measurement points, and the main features of the measurement devices. The main parameter used to evaluate the effectiveness of the CP in a buried structure is the potential between the metal and the electrolyte boundary; in practice, this is done using a reference electrode placed on the soil, above the pipeline. Different kinds of reference electrodes are available (e.g., saturated calomel electrode, saturated silver/silver chloride electrode, and copper/saturated copper sulfate electrode), providing a fixed and stable potential. The use of a particular kind of electrode depends on the application.

A cathode protection system using the Impressed Current CP method is presented in Fig. 1. The cathode of the rectifier transformer is connected to the pipeline that needs to be protected to compensate for the loss of electrons due to electrochemical corrosion, the anode is buried in the ground.

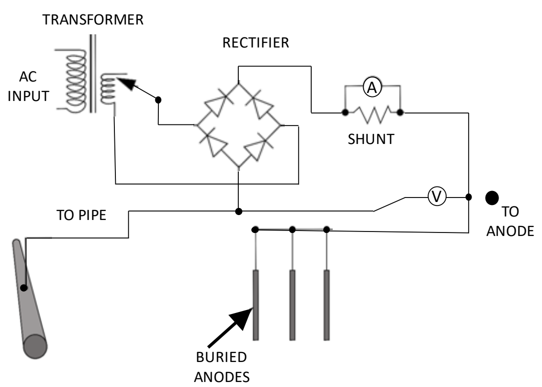


Fig. 1. Cathode protection system using Impressed Current CP method.

A Testbox includes:

- 1 Cu/CuSO4 (RE) reference electrode.
- 1 sample of bare steel buried underground connecting electricity to the pipeline through a switch (C1).
- 1 bare steel sample buried underground at the location to be assessed and unprotected (C2).

Fig. 2 shows the structure of a Testbox.

According to the standard [9], the conditions for an effective electrochemical corrosion protection system are:

$$-1100 \text{ mV} < V_{off} < -850 \text{ mV}$$

$$V_{shift} > 100 \text{ mV}$$

where:

- V_{off} is the bias voltage, which is the measured voltage between C1 and RE after about 300ms when the output current of the rectifier transformer is disconnected.
- $V_{shift} = V_{off} - V_{na}$

V_{na} is the natural potential, which is the measured voltage between C2 and RE.

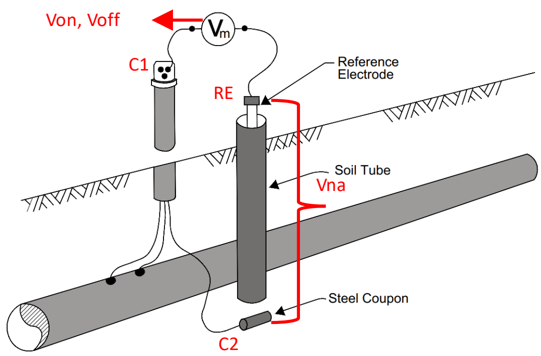


Fig. 2. The structure of a Testbox.

Thus, in order to operate the electrochemical corrosion protection system for underground pipeline systems, it is necessary to periodically measure and calculate the V_{off} and V_{shift} values at the Testboxes, thereby offering a voltage control plan for rectifier transformers.

3. System Design

The maximum distance between a wireless sensor and a wireless controller is about 1km. Therefore, we choose the LoRa wireless communication technology to communicate between the controller and the sensors. For the wireless controller to communicate with the Server, we choose the GPRS data transmission service.

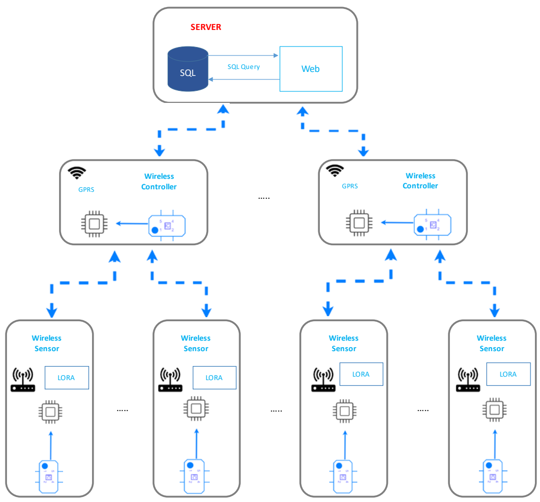


Fig. 3. System Block Diagram.

The system is built on a tree network architecture, each wireless controller will receive measurement data from 3 to 4 wireless sensors closest to it via the LoRa technology, then the wireless controller transmits the data to the Server via GPRS. The overview of the system is shown in Fig. 3.

3.1. Sensor Node Block Diagram

The block diagram of the sensor node (Testbox) is shown in Fig. 4. The sensor node is built based on the STM32F103 microcontroller. The microcontroller has functions including reading, processing measurement results, and exchanging data with LoRa communication blocks. Voltage measurement block is responsible for converting voltage signals V_{na}, V_{on}, and V_{off} into appropriate voltage and putting them into the ADC of the microcontroller. The LoRa communication block is responsible for transmitting measurement results from the sensor node to the controller node. The power block has the function of supplying power to other blocks to operate according to the required voltage and current quality.

The microcontroller (MCU) is used to enhance the ability to process information as well as activate functions for the device, it is necessary to have a strong MCU to perform this task. However, the price of the MCU should be taken into account. In this study, STM32F103C8T6 of ST Microelectronics has been chosen. These are enhanced performance chips of ARM Cortex-M3 core, 32-bit RISC operating at 72 MHz frequency, which can handle all communicative tasks as well as fast transmitting to sensor elements.

Voltage Measuring Element uses a 3P KF128 terminal to connect the measuring points to the circuit. Pin 3 of the bridge will connect to the RE reference electrode at Testbox, pin 2 is connected to C2 steel sample to measure V_{na} voltage, and pin 1 is connected to C1 steel rod to measure V_{on} and V_{off} voltages.

Besides, we use Opamp LM358 as inverting amplifier circuit. $V_{on/off}$ and V_{na} voltage outputs are connected to ADC pins of STM32F103C8T6 microcontroller.

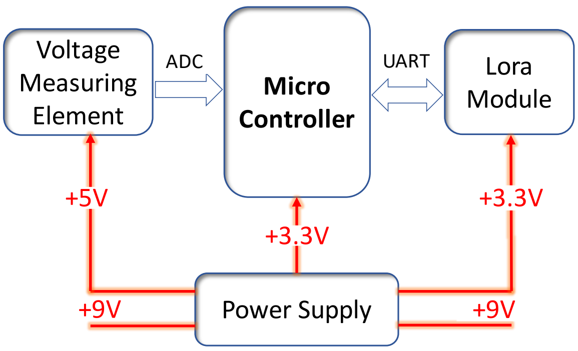


Fig. 4. Block Diagram of Sensor Node.

The Communication Part of the system utilizes the SX1278 wireless transceiver module developed by SEMTECH, which can function as both a transmitter and a receiver. This module incorporates LoRa spread spectrum technology, resulting in significant improvements in both the transmitting distance and penetration capability when compared to conventional FSK technology. With a maximum communication distance of 3.0 km, it is capable of facilitating effective communication over considerable distances. By leveraging the SX1278 module's advanced features, this communication solution provides enhanced performance and reliability for the intended applications.

3.2. Controller Node Block Diagram

The control station is built based on the STM32F103 microcontroller. The MCU controls the power interruption of the transformer, then sends a signal to the sensor node. The measured data from the sensor nodes is sent to the control station via a wireless communication protocol. The MCU receives data from the communication module via the UART protocol, displays it on the LCD, processes the data sent back to control the rotation angle of the transformer, and sends the received data to the Web Server according to the specified transmission frame.

In addition to data acquisition and processing, the control station is also integrated with voltage and current measurement circuits of the transformer, thereby creating a feedback control loop that accurately controls the autotransformer through the servo motor.

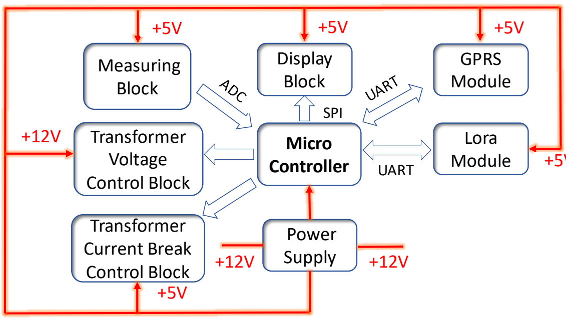


Fig. 5. Block Diagram of Controller Node.

The networking component using the SIM800L module provides a complete-quad-band GSM/GPRS solution in the SMT type, which can be embedded in user applications. The SIM800L module supports the Quad-band 850/900/1800/1900MHz. Besides, it can transmit voice, SMS, and data information with low power consumption.

3.3. Algorithm Flowchart Design

3.3.1. Algorithm flowchart of the system

Initially, the system installer will initialize the network for the wireless controller and wireless sensor.

After the network is initialized, at (H_0-1) hour 45 minutes daily (with H_0 hour as the time to get measurement data), the system will synchronize the time, measure V_{on}, V_{off}, and V_{na}, and send them to the Server. V_p, I_p will be continuously measured and checked by the controller (Fig. 6). If a problem is detected, the controller will send an alert message to the Server; if there is no problem, the V_p, and I_p values will be sent to the Server at the 8th minute of every hour. The wireless controller controls the output voltage value of the transformer if it receives the control signal from the Web Server.

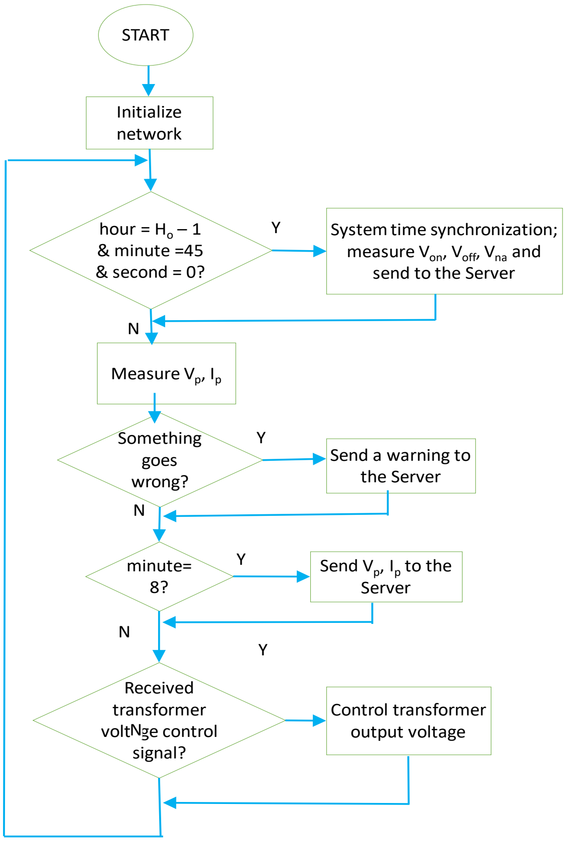


Fig. 6. Algorithm flowchart of the system.

3.3.2. Algorithm flowchart of sensor node

After powering, the wireless sensor initializes the peripherals: GPIO, USART, ADC, TIMER, and RTC. The sensor checks if it is an address initialized by checking the Backup registers. If not initialized, the sensor sets the LoRa module parameters to the default address. If the sensor is already addressed-initialized, it sets the LoRa module parameter with the corresponding address (Fig. 7).

The sensor checks if there is a message from the controller: If an initialization message is received, the sensor stores the allocated address value and the value of its superior controller in the backup registers so that these values are not deleted in the event of a power failure. The sensor sets the parameters of the LoRa module with the address corresponding to the address just received. The sensor then sends a message to the controller to confirm that it has been initialized. The sensor then sends the controller a real-time value request message. If the sensor receives a message from the controller requesting to send measured values of V_{on}, V_{off}, and V_{na}, the sensor will resend the controller a message containing its measured values.

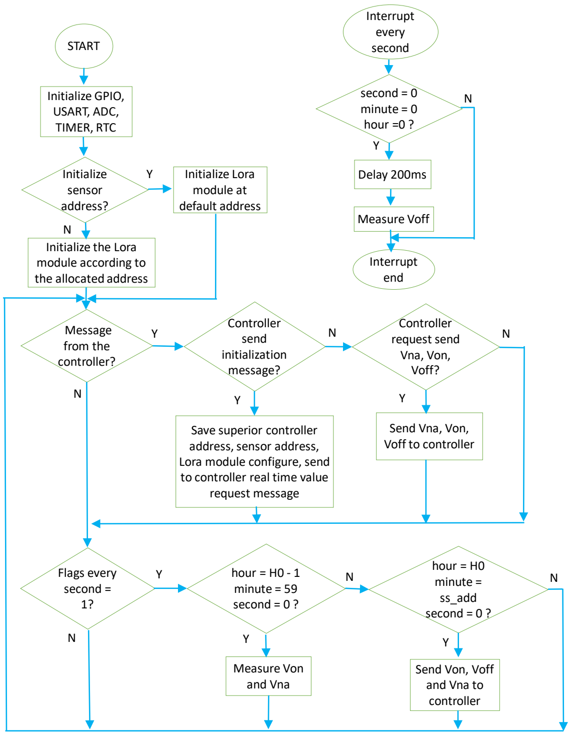


Fig. 7. Algorithm Flowchart of Sensor Node.

The sensor checks every second, when it encounters a programmed time event, it will do the corresponding job: At (H_0 - 1) hours and 59 minutes each day, the sensor measures V_{on} and V_{na} values. At H_0 hours *ss_add* minutes (where *ss_add* is the address of the sensor), the sensor sends the measured V_{on}, V_{off}, and V_{na} values to its superior wireless controller. When encountering a time-out event at H_0 h, the wireless sensor will wait for 200ms and then measure the V_{off} voltage value.

3.3.3. Algorithm flowchart of controller node

After powered, the wireless controller initializes the peripherals: GPIO, USART, ADC, TIMER, SPI, RTC. Then the controller connects to Broker MQTT, registers Topic “STATIONS”. The controller checks if it is address-initialized by checking the Backup registers. If not initialized, the controller sends an initialization request message to the Server. If the controller is already address-initialized, it sets the LoRa module parameter to the corresponding address. Next, the controller displays important parameters such as the controller address, and the number of subordinate sensors that have been registered on the screen. The controller checks the connection flag to the Server. If the connection is lost, it will reconnect. The controller checks if there is a message from the Server.

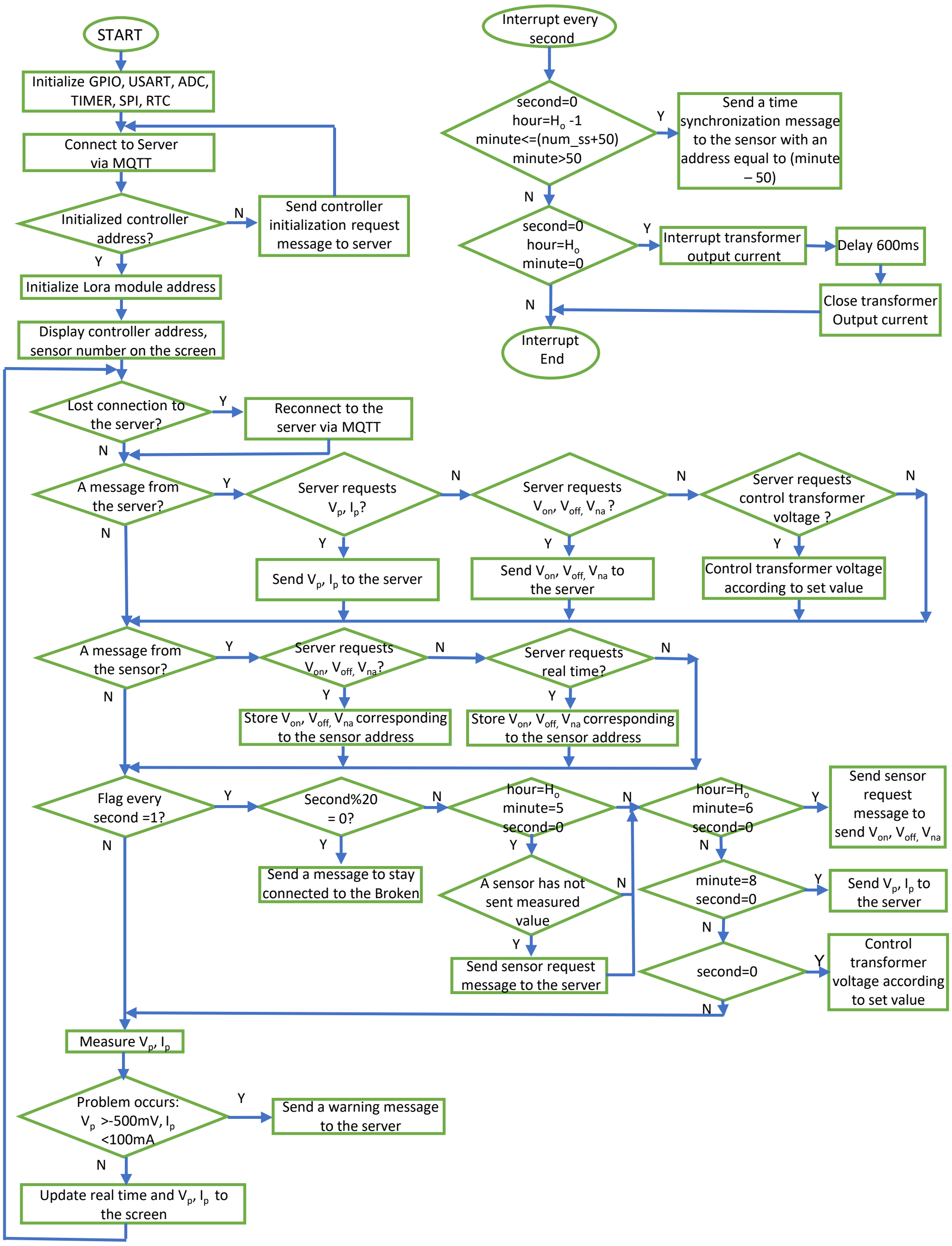


Fig. 8. Algorithm flowchart of Controller Node.

Next, the control station communicates with the Server and sensor nodes according to preconfigured messages. (Fig. 8).

4. Software Implementation

4.1. Web Server Requirements

The Web Application needs to have the capability to monitor, display and store and manage the measured metrics. It also needs to reliably detect and notify users whenever there is a problem in the system so it can be fixed as fast as possible.

The Application must have user authentication capability and there should be a role system so the supervisor can control which user may access which functionality.

4.2. Server System Blocks

Block diagram for the smart IoT-based measuring and monitoring system for the underground pipeline electrochemical corrosion protection system is shown in Fig. 9.

We developed multiple sensor nodes, divided into multiple clusters, each cluster is monitored by a station node using LoRa as the means of communication. These stations are also bidirectionally connected to the cloud server using an MQTT Broker deployed on the server. The Broker's purpose is to dispatch messages between the stations and the server.

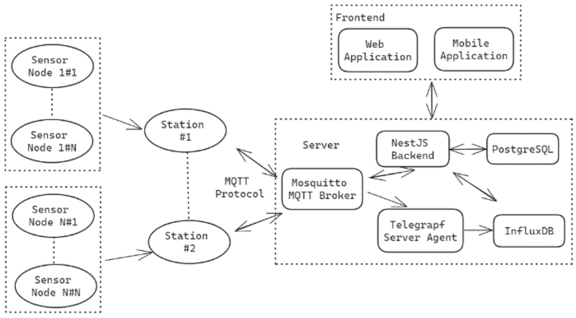


Fig. 9. Block diagram for the smart IoT based measuring and monitoring system.

Server structure

Data received from the station are then dispatched to both the NestJS Backend and the Telegraf Server Agent.

Telegraf Server Agent is an open-source server-based agent for collecting and sending all metrics and events from databases, systems, and IoT sensors. Using this, the data sent from the stations are pushed directly to the database without any effort and minimized the chance of breaking in the data flow.

NestJS Backend on the other hand is simply a Node.JS server, written in JavaScript. The purpose of this backend is to handle Frontend (Web Applications, Mobile Applications) requests, broadcast and send messages to the stations, update and notify in real-time the current status of the system, and handle fetching sensor node data, etc.

In this project we used two separated databases, each serves a different purpose:

PostgreSQL is a powerful, open-source object-relational database system with a good reputation for reliability, feature robustness, and performance. PostgreSQL is used to store regular relational data like Users Data, Roles, Notifications, Devices metadata and any other data that are not related to the sensor metrics.

To store sensor metrics sent from the stations, we opted to use a Time Series oriented database InfluxDB [10]. InfluxDB is similar to a SQL database, but different in many ways. InfluxDB is purpose-built for time series data. Relational databases can handle time series data but are not optimized for common time series workloads. InfluxDB is designed to store large volumes of time series data and quickly perform real-time analysis on that data.

On the event of data transfer, Telegraf will listen and transport the metrics data sent by the stations directly into InfluxDB, and the NestJS Backend will send the data to the frontend for visual monitoring.

4.3. Server's Main Features Diagram

4.3.1. Synchronization

Synchronization is done periodically every *X* minutes (*X* can be set manually) or manually by users. Synchronizing the server will get important information about the connected devices (stations, sensors) like health status, battery level, and temperature. The stations will be able to synchronize their internal clock and keep the timestamp precise when sending sensors metrics. (Fig. 10).

4.3.2. Sensor data gathering

In this project, for the sensor measurement to be precise, the pipeline's power system needs to be shut off completely before any operation happens. There are two methods of doing this:

<u>*2-Way Confirmation:*</u> By the time the measurement is needed, the server broadcast a pre-measuring event, this will signal every station node to start turning off the pipeline's power system. After every station node has sent its confirmation message, the server will continue to broadcast an event to start measuring. After that, the measurements are sent back to the server. Doing this will confirm that there is no active power source causing noise in the measurement data, but this, in theory, will be slower than the alternative method, which may or may not interfere with the accuracy of the metrics. (Fig. 11).

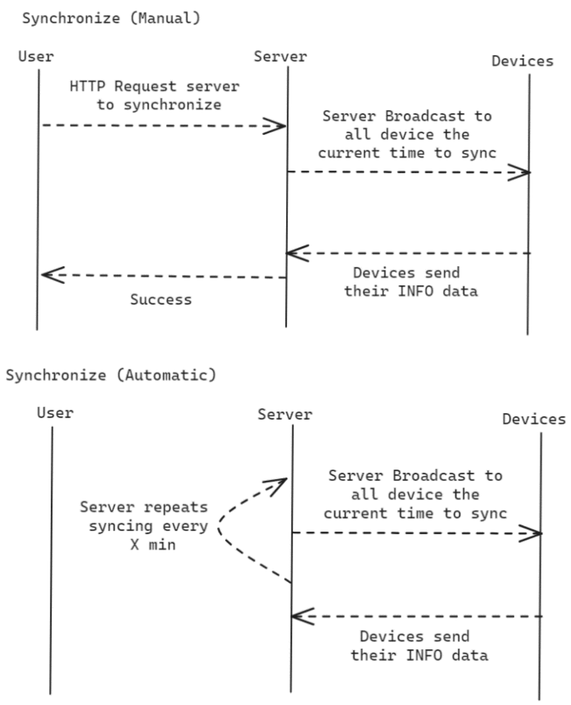


Fig. 10. Diagram of synchronization.

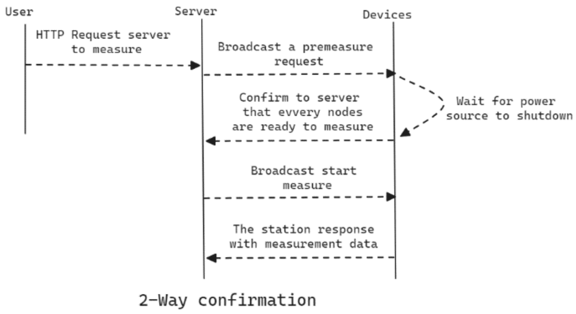


Fig. 11. Diagram of 2-Way Confirmation method.

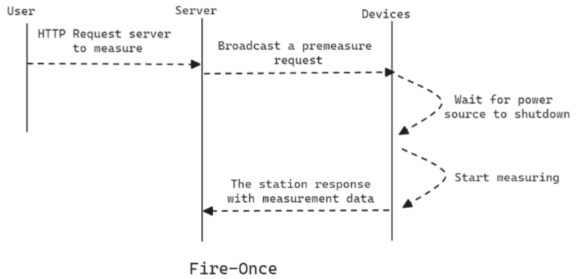


Fig. 12. Diagram of Fire-Once method.

Fire-once method: Using this method, the server will not care about whether the power source is fully disconnected or not. The server will only broadcast one "start measure" event and wait for the data to flow back. This will be faster than "2-Way Confirmation" but will not be as precise and reliable as "2-Way Confirmation" can be a de-synchronization between the devices. (Fig. 12).

5. Experimental Results

5.1. Sensor Node

We have conducted laboratory tests, calibrated accuracy, and conducted voltage and current measurements at the Hanoi University of Science and Technology. Initial results show that the long-term operation of the device was stable. Data from these devices was transmitted completely to the Web Server. The experimental hardware of the device measures the voltage and current is shown in Fig. 13.

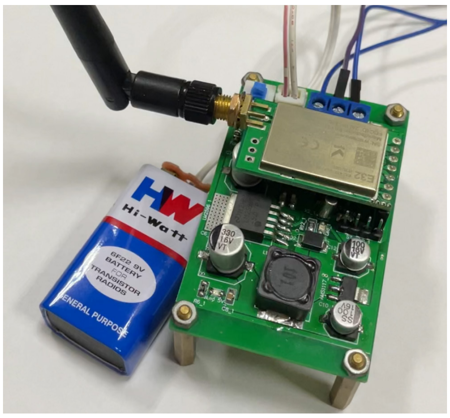


Fig. 13. Sensor node Hardware.

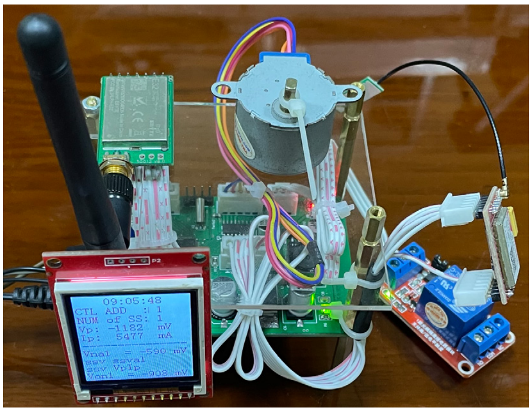


Fig. 14. Controller Node Hardware.

Fig. 15. Wireless controller display.

5.2. Controller Node

Fig. 15 is a screen showing the network configuration parameters, measurement results and operating status of the wireless controller.

5.3. Software Interface in Web Server

The Web Server has functioned well including collecting, displaying, storing data, sending control signals to wireless controllers, exporting data reports as specific excel files, and giving an alarm when there is a problem.

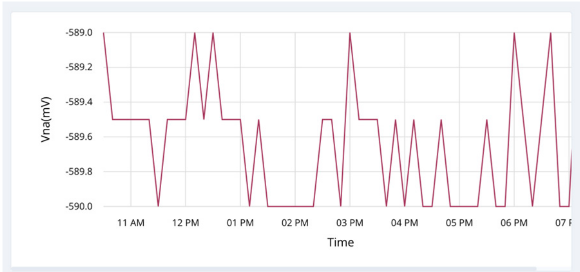
The wireless sensor is capable of measuring various parameters, including the natural voltage (V_{na}) within the range of -0.65÷0 V, the bias voltage (V_{off}) within the range of -1.1÷0 V, and the protection voltage (V_{on}) within the range of -2.2÷0 V.

Fig. 17. Web Server displays measurement results in the form of graphs.On the other hand, the wireless controller is designed to measure different parameters, such as the output current (I_p) of the rectifier transformer, which ranges from 0÷10A, and the output voltage (V_p) of the rectifier transformer, which ranges from -2.2÷0 V. These measurements enable accurate monitoring and control of the respective components in the system.

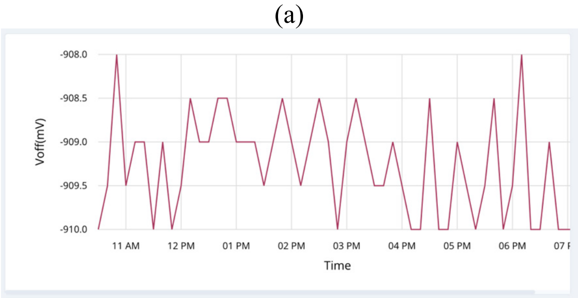
Time	Measurement	Value	Node ID	Node Type
Time	Measurement	Value	Node ID	Node Type
2023-03-05T12:25:58.564320381Z	v_shift		2	station
2023-03-05T12:20:00Z	v_shift		2	station
2023-03-05T12:10:00Z	v_shift	320	2	station
2023-03-05T12:00:00Z	v_shift	321	2	station
2023-03-05T11:50:00Z	v_shift	320	2	station
2023-03-05T11:40:00Z	v_shift	320	2	station
2023-03-05T11:30:00Z	v_shift	321.5	2	station
2023-03-05T11:20:00Z	v_shift	320.5	2	station
2023-03-05T11:10:00Z	v_shift	320	2	station
2023-03-05T11:00:00Z	v_shift	321	2	station
2023-03-05T10:50:00Z	v_shift	320.5	2	station
2023-03-05T10:40:00Z	v_shift	321	2	station
2023-03-05T10:30:00Z	v_shift	319.5	2	station

Fig. 16. Station's status.

(a)



(c)



(b)

Fig. 17. Web Server displays measurement results in the form of graphs.
(a) Protection Voltage measurement results
(b) Bias Voltage measurement results
(c) Natural Voltage measurement results

I	V_shift	V_on1	V_off1	V_na1	V_on2	V_off2	V_na2	V_on3	V_off3	V_na3	Vp	timestamp
Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter	Filter
2000	100	-850	-600	-450	-850	-600	-450	-860	-650	-500	-860	2022-07-18 03:44:38.509367
2500	100	-850	-600	-500	-860	-610	-510	-870	-620	-520	-860	2022-07-24 09:30:57.146426
2200	110	-900	-600	-490	-880	-590	-480	-895	-595	-485	-900	2022-07-24 09:32:15.637665
2200	120	-870	-660	-540	-870	-660	-540	-870	-660	-540	-870	2022-07-24 09:33:13.291003
1000	100	-850	-650	-550	-850	-650	-550	-850	-650	-550	-850	2022-08-01 04:09:06.469611
1000	100	-850	-650	-550	-850	-650	-550	-850	-650	-550	-850	2022-08-01 04:12:18.172054
1000	100	-850	-650	-550	-850	-650	-550	-850	-650	-550	-850	2022-08-01 04:33:08.434110

Fig. 18. Measurement results are stored as excel files.

6. Conclusion

In this paper, the architecture of a based-intelligent IoT system for impressed current CP in pipeline CP is proposed. It is based on a low-cost meter able to monitor the pipeline potential, placed in the section of the network with the worst potential profile, namely near the limit of the protection condition. The data will then be transmitted to Web Server, afterward, they will be processed according to algorithms before being displayed and stored. Smart algorithms and errors compensation algorithms (due to changes in temperature, and humidity) have operated properly designed. Initial tests have shown that the system designed for intelligent measurement on the IoT platform has run stably. The sensor nodes created in this system are inexpensive, allowing them to expand the network with a larger number of points. The expansion of multiple points will allow large amounts of data to be processed, helping us develop a new system widely used in electrochemical corrosion protection systems for underground works.

The subsequent phase of this research entails the practical implementation of this system with our focus directly towards its application in underground pipeline operations within the oil and gas field.

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