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Original Article

Implementation of IOT and Intelligent Control in Rectifiers and Control of Pneumatic Valves for the Optimization of the Process of Chrome Plating and Pickling of Hydraulic Components

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Abstract - *This article analyzes how to integrate IoT technology in industrial rectifiers to optimize the chrome plating and pickling process in a more productive, efficient, and accurate way to improve production time by human manipulation and replace daytime work with remote and automated monitoring; obtain precision in terms of calibration of parameters and functions in chrome plating and pickling of hydraulic components through the pneumatic agitation system, using DC rectifiers and pneumatic valves, as these regulate the direct current necessary to perform the electrochemical process. The implementation allows monitoring via web server using an independent HTTP server for each component, allowing the visualization of real-time parameters such as voltage, current, rectifier failures, and temperature, while an intelligent control with ESP32 performs automatic adjustments and improvement in the quality of the process, such as proper timing, depending on hours required by the component, this approach also favors energy efficiency and predictive maintenance in rectifiers, thus contributing to the optimization of costs and resources in this industry.*

Keywords - *Industrial IoT (IIoT), Electrochemical process optimization, Pneumatic valve control, DC rectifier monitoring, Smart automation.*

1. Introduction

In recent years, the integration of the Internet of Things (IoT) and intelligent control has allowed significant advances in the optimization of industrial processes in a variety of industries where remote and automated monitoring has allowed to improve the sustainability of these; the focus is on the electrochemical sector, mainly in the area of chrome plating and pickling of hydraulic components.

This project focuses on the implementation of IOT technologies to improve the efficiency by productivity times and accuracy of the electrochemical processes of hard chrome plating for the manufacture of hydraulic pistons for mining purposes, using DC rectifiers as the main equipment to regulate the direct current needed to perform the chrome plating of components, in addition to this the low-pressure air agitation system further benefits the quality of the product. The key objectives of the project are energy optimization, failure monitoring, and real-time control of critical parameters such as voltage, current, and temperature of the rectifiers, monitoring and control parameters fundamental to the process.

The project is developed through the implementation of an IoT technology that allows remote monitoring of DC rectifiers, using an HTTP web server for real-time data collection and analysis, facilitating monitoring from any device globally. Additionally, non-invasively connected sensors constantly measure voltage, current, and temperature, while an intelligent control system programmed in an ESP32 would perform automatic adjustments to optimize the process and production, prioritizing current stability in these rectifiers and the necessary agitation opening according to the required hydraulic component, timing according to operating hours, error alerts, etc. This solution would not only ensure more accurate and efficient control of chrome plating and pickling due to more automated monitoring. With the implementation of IoT and intelligent control, a significant improvement in energy efficiency would also be achieved, reducing unnecessary electricity consumption and optimization of costs and chemical resources in the industry. This approach not only increases the quality of chrome plating and pickling because these electrochemical processes need stability and a prompt reaction to situations of variation of voltages or current but also allows an automatic control to verify or make modifications in a remote way through an alert via dashboard when critical actions are required, which facilitates decision-making and change of parameters such as voltage in the cells, therefore, such optimization improved operating results in the industry. This study addresses the implementation of a remote and intelligent control system based on IoT technologies to optimize production time, quality, and accuracy, aiming to control rectifiers and pneumatic valves, obtaining greater control in the management of costs and resources of this electrochemical process. This approach seeks to optimize material quality, productivity times, and manufacturing accuracy by promoting the development of control technologies, ensuring a more reliable and sustainable process in the process of chrome plating and pickling of hydraulic components.

2. Related Works

The current development of this study shows implementation similarities in several fields at the industrial level, such as electrochemistry, hydraulics, networks, and protocols, as well as electronics, as the case of [1] in the implementation of LPWAN networks for IoT in telecommunications, focusing on the LoRa protocol for building monitoring systems. LoRa, due to its long-range, is suitable for these networks, but the lack of a mesh network limits its potential, especially in terms of cost and collision management. MAC protocols are proposed to mitigate collisions in LoRa mesh networks, evaluating their performance in conditions of high media contention with 30 NE and overlapping coverage, as well as in [2] describes the use of IoT (Internet of Things) technologies applied to electrical transformer monitoring, replacing traditional analog and manual measurement methods by advanced digital systems. In this context, an IoT-based monitoring system using LoRa (Long Range) communication for transformer data transmission is proposed. This system uses the Ebyte E32 DTU LoRa module, which allows data transmission both indoors and outdoors with variable range, depending on distance and conditions. In the tests conducted, transmission was tested at a height of 1 meter from the ground, with distances between units varying between 150 meters and 2.5 kilometers. The study aims to improve the efficiency of transformer energy management, although it highlights the need for further development of these methods to optimize the accuracy and effectiveness of monitoring.

In [3], the development of an automated system to monitor the health and safety of wastewater workers exposed to hazardous gases and adverse environmental conditions. Current methods, based on manual inspections, are slow and prone to human error. To improve this situation, an IoT system using a wearable sensor with three types of sensors, MQ2, MQ135, and a pulse sensor, is proposed to continuously monitor gas levels and physiological parameters in real-time. The system employs two ESP32 microcontrollers, one as a central node and the other as a working node, with data communication through the LoRa protocol. Data detected by the work node is sent to the central node, which in turn notifies the worker via buzzers and e-mails in case of hazardous conditions. In addition, the worker's health information is sent to a nearby medical center for rapid intervention in case of exposure to harmful gases. The proposed system has the potential to significantly improve safety in high-risk industrial environments, such as sewer systems, by providing real-time monitoring and rapid incident responses.

Further [4] addresses the implementation of LoRa, based on CSS modulation by chirp, as a long-range, low-power wireless connectivity solution for IoT. Mesh LoRa networks extend coverage but face challenges in reliability, latency, and longevity due to energy efficiency and delay handling in data forwarding protocols. These protocols, based on link quality and forwarding capacity, can lead to delays and premature energy depletion. To improve, the End-to-End Delay and Delivery Ratio and Delay Rate (E2EDRD) metric are proposed, which optimizes forwarding protocols by considering duty cycles, link quality, and remaining energies. This approach improves the trade-off between delay, packet delivery rate, and network lifetime, as shown by simulations, thus optimizing the performance of mesh LoRa networks for IoT.

In the case of [5], This study employs LoRa to monitor DC motors, adjusting the motor speed according to the ambient temperature. LoRa transmitters and receivers were used, evaluating their performance in barrier and barrier-free scenarios, with successful communication in both cases. Encoder sensors and INA 219 were compared, demonstrating that the measurement tools worked correctly. LoRa, with its low power consumption and long-range, enables efficient remote monitoring in IoT systems. As for the electrochemical process, alkaline pressure leaching to extract chromium (Cr) from electroplating sludge (CES) is shown in [6]. With optimum conditions of 125 °C, NaOH 1.5 mol/L, 2 MPa oxygen, and 2 h of reaction, a Cr leaching rate of 89.9% was achieved. The solubility of chromium and the diffusion coefficient of the oxidant improved with increasing temperature, reducing the concentration of NaOH required. The kinetics of the process showed chemical control with an activation energy of 112.1 kJ/mol, highlighting the importance of temperature on the leaching efficiency in [7]; a chromium film was synthesized by reverse pulse (RP) electroplating in a bath of hexavalent chromium (Cr6+) and sulfuric acid (H2SO4), varying the anodic time. The PR electroplating showed a reduction in crack density, hardness, and chromium thickness with increasing anodic time. The chromium film obtained by PR showed better corrosion resistance than that by direct current (DC) due to lower crack density. The optimum anodic time to improve the film properties was 0.001 s, optimizing the quality of the electroplating. As well as in [8], the study develops a two-step process to recover valuable elements from chromium electroplating slurry (CES), highlighting galvanometry in the measurement of chromium (Cr) recovery. A low sulfur/carbon Fe-Si-Cr alloy (31.61%Fe, 31.78%Cr, 36.59%Si, 0.01%C, 0.01%S) was produced, achieving a Cr recovery of 98.62%. The CES was pre-desulfurized between 1000-1200 °C, where the reaction between CaSO4 and Fe2O3 generated CaFe4O7 as the main desulfurization mechanism. Subsequently, the desulfurized CES was reduced with silicon at 1600 °C to prepare the Fe-Si-Cr alloy. The SiO2 formed during reduction aided the vitrification of the slag. The presence of silicon in the alloy and CaO in the slag were key factors in reducing the sulfur content in the alloy. In addition, CaO decreased the slag viscosity, improving metal-slag separation and reducing metal losses. In terms of valve control, a similar system is acquired as in [9]; this study focuses on the development of normally closed pneumatic valves for precise fluid management in point-of-care testing (POCT) microfluidic devices. Pneumatic valves are essential for controlling and directing fluids in precise sequences facilitating biochemical reactions. However, existing valves often have low reliability and inaccurate control of opening pressure due to uncontrolled elastomer stretch. The study proposes a method to improve valve reliability by precise control of elastomer pre-stretch, allowing reliable closing and proper control of opening pressure. A robust valve was designed and fabricated, and its effectiveness in pneumatic applications was experimentally validated.

Also, in [10], a pilot-operated pneumatic high-pressure on/off (HPPV) valve was designed to rapidly control air inlet in high-pressure, high-flow, continuous-ejection compressed air ejection devices. A multiphysics simulation model was developed using AMESim, covering mechanical aspects, gas flow, pipeline heat exchange, and pilot valve operation. The model was validated by experiments, showing a tolerance of less than 7.3% between simulation and experiments. The effects of gas thermodynamics, pipeline heat exchange, and pilot valve operation were investigated, highlighting that pipeline heat exchange significantly affected the model accuracy. The dynamic characteristics of the valve remained stable under different conditions, demonstrating that the HPPV pneumatic valve is reliable for high-pressure applications.

3. Methodology

This article presents the design and implementation of IOT technologies in DC rectifiers and agitation system control for the electrochemical sector, focusing on the area of chrome plating and pickling of hydraulic components in order to optimize the process and avoid failures due to exposure time, monitoring, and human downtime in the process. The purpose of the project arises due to a high rate of errors, lack of a protection standard in rectifiers, exposure time in cells, deficiency in the agitation process, and monitoring with lack of parameters in the equipment; the main improvement features are:

- Correct current and voltage monitoring in DC rectifiers.
- Fault protection indicator for temperature, short-circuit in power semiconductors in DC rectifiers.
- Automation in the pickling process, remote control of pneumatic valves, and correct timing for activation of the agitation system.
- Reduction and optimization of energy consumption through appropriate timing according to application or working hours.
- LoRa WAN network integration in valves for agitation system.
- Real-time monitoring on the dashboard for visualization and modification of correct parameters.

Table 1. Components used

Type	Model	Quantity
Slave and Master Module	PCB with LoRa RYLR998 and ESP32	17
Pneumatic Valves	DWYER Pneumatic Valve 220VAC	08
Current sensor	Shunt 10000A/60Mv M7123T	08
Temperature Sensor	10K3950	16
Modem	TP-link with internet	01
Dashboard	11” Tablet	01

An evaluation of the devices to be controlled was performed to proceed with the manufacture of small cards for remote monitoring based on LoRa with the RYLR998 module and ESP32 in order to be installed in each valve and DC rectifier being a total of 16 devices from which data will be obtained, The peripheral used in this case is a Tablet, which will be used by the supervisor in charge of the electrochemical process and implementation of a main control card with RYLR998 using ESP32 configured as master using the HTTP protocol to send data to the web server. Due to a high rate of damage generation to hydraulic components such as porosity or poor chrome plating, the correct use of stable current and voltage is a primary objective to be met and is calculated according to the following equation:

$$I = density * area\ dm^2$$

In addition to standard parameters such as density, depending on the component having as the main one, the steel from 5 to 15A/dm^2. After these evaluations, parameters and appropriate locations of each component were considered, undergoing software and hardware tests and contamination before falling dust or acid particles in order to have maximum performance for each component used. The structure of the methodology used is shown in a flowchart (See Figure 1).

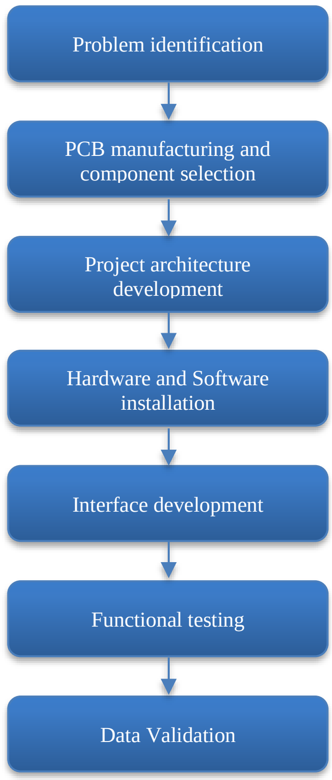
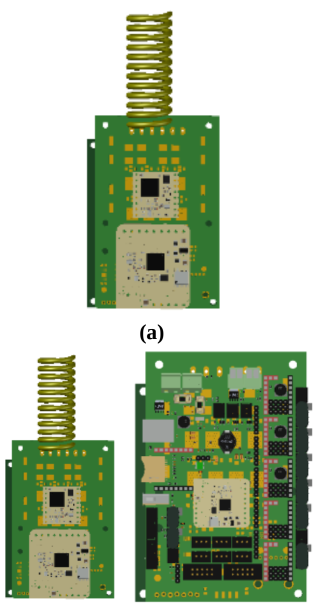


Fig. 1 Methodology flow chart

3.1. Component Selection

Careful selection of components is required, based on their selection according to the requirement and the need to be fulfilled considering their quality, size, cost, and reliability. These components were considered for local purchase, which will allow easy replacement for later repairs and/or implementation improvements.



(a)

(b)

Fig. 2 Auxiliary and master modules

The project includes components for data transmission, communication between equipment, and remote monitoring peripherals (see Figure 2). Among which there is an auxiliary module governed by the ESP32 microcontroller and the RYLR998 configured as master (b), providing high-speed processing and wireless connectivity, which are essential for the application, auxiliary modules with the same composition that allow data transmission up to 5km from another antenna configured according to the data sheet of the LoRa component and the ESP32 configured as a slave (a), the module used for the control of the pneumatic valves DWYER compared and performed as in [9] and data transmission by the DC rectifiers, once collected this data will be sent to a web server, where the graphical interface programmed in Visual Studio using the HTTP protocol will show all the variables obtained as voltage, amperage, short circuit, timing time, time in use and valve actuation.

For voltage and amperage measurement in the equipment, the 60mV/10000A M7123T invasive sensors are used in the rectifier equipment, which projects a voltage value of 0-10V according to its maximum amplification required, similar to [2]. Likewise, for voltage reading, the equipment offers a maximum voltage of 12V configured in its control card.

Likewise, the analog over temperature reading was implemented using the 10K3950 temperature sensor that offers analog readings from -20°C to 125°C; by performing an additional electronic configuration, the voltage, amperage, and temperature sensing values of the rectifier can be obtained, ensuring suitability for its duty cycle in the slave module, which will send the respective parameters to the master module for monitoring (see Figure 3) and pneumatic valves were located in each strategic zone according to the chrome plating area plan (see Figure 4) and have their respective codification or tag:

DC RECTIFIERS

- CRM-RECT-4000-001: 12V - 5000A
  - ➢ 26 meters to master
  - ➢ 32ms latency
- CRM-RECT-4000-002: 12V - 5000A
  - ➢ 23 meters to master
  - ➢ Latency 30ms
- CRM-RECT-4000-003: 12V - 5000A
  - ➢ 21 meters to master
  - ➢ Latency 28.4ms
- CRM-RECT-6000-004: 12V - 6000A
  - ➢ 18 meters to master
  - ➢ Latency 19.8ms
- CRM-RECT-6000-005: 12V - 6000A
  - ➢ 15 meters to master

  - 16ms latency
- CRM-RECT-6000-006: 12V - 6000A
  - 12 meters to master
  - Latency 15ms
- CRM-RECT-8000-007: 15V - 8000A
  - 8 meters to master
  - Latency 6ms
- CRM-RECT-10000-008: 15V - 10000A
  - 5 meters to master
  - Latency 3.2ms

PNEUMATIC VALVES

- CRM-RECT-VAL-01: 24V - RECT01
  - 28 meters to master
  - 32ms latency
- CRM-RECT-VAL-02: 24V - RECT02
  - 28 meters to master
  - Latency 32ms
- CRM-RECT-VAL-03: 24V - RECT03
  - 28 meters to master
  - Latency 32ms
- CRM-RECT-VAL-04: 24V - RECT04
  - 28 meters to master
  - Latency 35ms
- CRM-RECT-VAL-05: 24V - RECT05
  - 28 meters to master
  - Latency 35ms
- CRM-RECT-VAL-06: 24V - RECT06
  - 28 meters to master
  - Latency 35ms
- CRM-RECT-VAL-07: 24V - RECT07
  - 28 meters to master
  - Latency 35ms
- CRM-RECT-VAL-08: 24V - RECT08
  - 28 meters to master
  - Latency 35ms

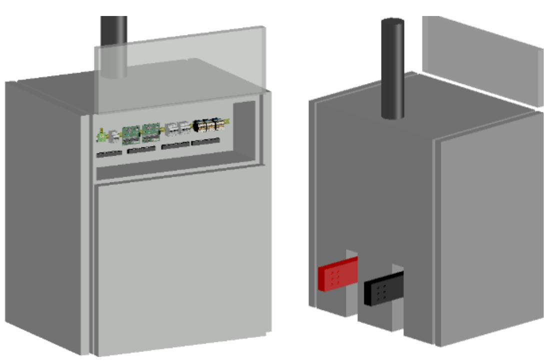


Fig. 3 DC Rectifiers

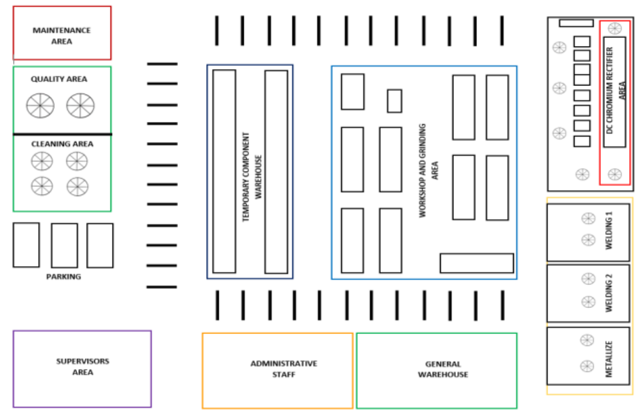


Fig. 4 Location plan by areas

3.2. System Architecture

To develop this section, the monitoring, and control of the chrome plating and pickling cells were performed manually to obtain data to obtain the data referred to in [7], as well as the rectifiers based on the connectivity of the slave module to rectifiers and pneumatic valves, divided into sub-processes of signal conditioning from the sensing to the transmission through the antenna to the master module.

The voltage, amperage, and temperature sensing sub-process are directly in the rectifier equipment, and the valve opening/closing monitoring is directly through the slave module, both equipped with the LoRa module.

The second sub-process is the communication stage, where the auxiliary module equipped with the RYLR998 module sends data at 915Mhz reading/writing variables in conjunction with the ESP32 slave with a range of 5km; the transmission of this data is governed via LoRaWan to the cloud using the master module to subsequently use a Gateway to upload this data to the cloud, transmission based on LoRaWAN (see Figure 5).

Finally, the sending of data is visualized in a graphical interface created in Visual Studio, using the HTTP protocol for monitoring sensors and valve control in each pickling cell with a different address to obtain multiple monitoring at once and saturate the network generating data loss at the friendly interface is provided for a correct visualization and optimal control from the supervision office.

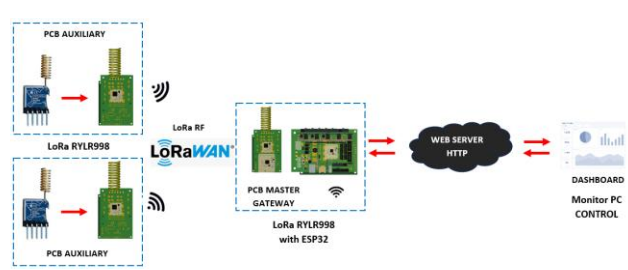
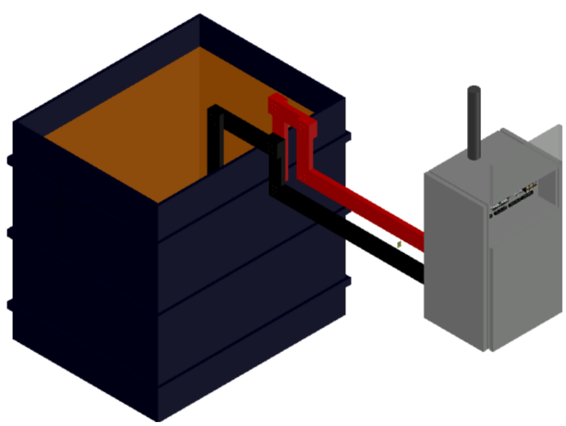


Fig. 5 Data sending subprocesses

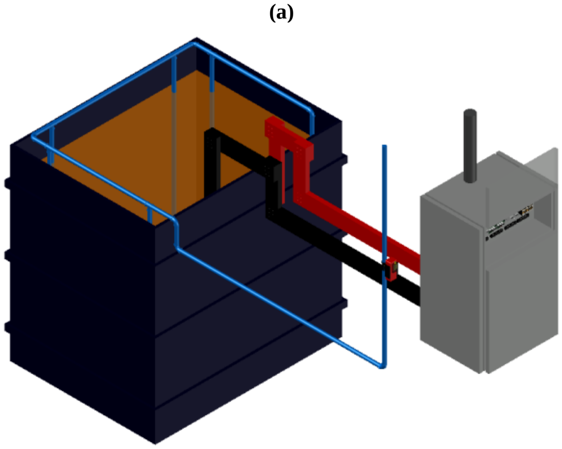
4. Developed System

4.1. Hardware Development

In each pickling cell, a valve will be used, which will allow the passage of air, making the agitation system reduce the processing time; because the system lacked a proper pneumatic installation, the pipe connection to the cell was carried out. A before-and-after comparison is presented to evaluate the new process conditions (see Figure 6); these improvements increase the effectiveness of the electrochemical process by eliminating hydrogen bubbles that may adhere to the parts, homogenizing the temperature, and reducing local impurities from previous chemical baths; the control of pneumatic valves will be governed by the slave module with LoRa receiving the activation or deactivation signal via RF from the master module or from an auxiliary electrical board; the pneumatic valve was selected with 220VAC power supply using the module power supply and a 4-20mA control signal for opening or closing; through the web server interface, the valve activation or deactivation status can be controlled or monitored. Likewise, for the activation or ignition of the rectifier, since it has intelligent control, it will be activated if the protection alarms allow the activation, in any case, the master module will send to the cloud a change of status by failure alert and thus evaluate the substandard situation with an operator.



(a)



(b)

Fig. 6 Cells before and after pneumatic implementation

The communication frequency used is 915MHz, which is a standard frequency. A network strategy known as a star network, like that in [1], was selected., where communication nodes, in this case, each control valve, connected directly to a central gateway, in this case, the master card (see Figure 7), this configuration is more efficient and minimizes the power consumption of each node use.

A different address was given for each valve in a total of 7 and 8 for the rectifier control; a different network for the rectifier control in the case of supervision has different access for each area, such as the rectifier room and chrome plating area.

In addition, each node was configured to work at the same frequency, and there are no problems in terms of LoRaWAN network parameters; such data transmission is guaranteed for environments less than 5KM, covering the plant area less than 2KM, thus ensuring that data loss is not a factor for control or communication failures, ensuring optimal coverage for the application.

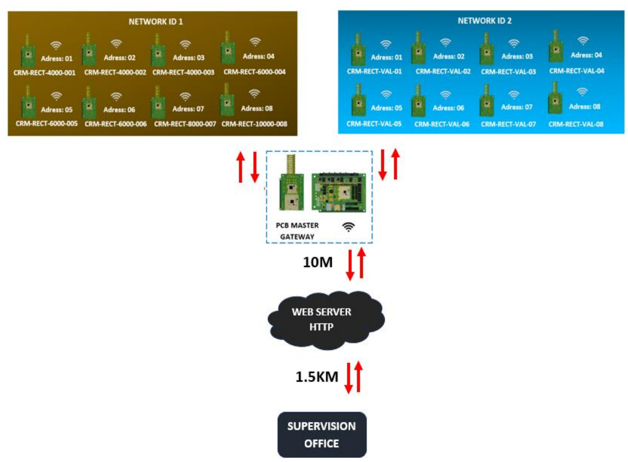


Fig. 7 Address and control network per node

The master card will serve as a gateway for data transmission, which was strategically installed with a stable WIFI network point to avoid data loss in the monitoring interface (see Figure 8); the power distribution for the pneumatic valves is 220V with external power supply from the main board.

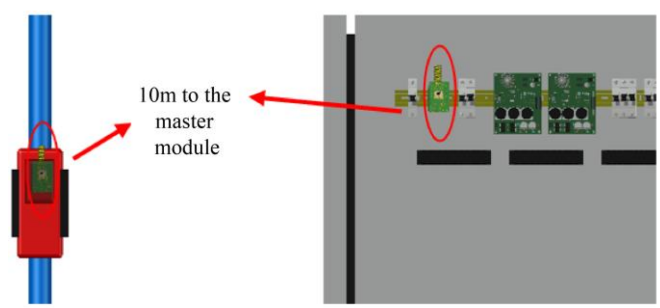


Fig. 8 Location of the slave module to the master module

4.2. Software Development

The control interface and parameter monitoring were done in Visual Studio, which was divided into windows where the control is independent for each rectifier corresponding to its address in its corresponding network id, for better control of the same and alerts for faults.

The configuration with the slave module was performed in the Arduino IDE software using the sending of data at 115200 baud by configuration in the module antenna and configuration of AT commands according to the RYLR998 datasheet, likewise for each remaining slave module; the respective scaling was implemented based on electronic cards for easy transmission of data sent via LoraWAN via HTTP to the interface, the configuration of the master card or Gateway was a fundamental part of the development, the ESP32 module was configured to receive data from each RYLR998 as nodes and configure a different address for the control of rectifiers and pumps, the data sent via HTTP to the network interface have a minimum latency loss since the supervisors control office is located at 1. 5KM away from the point to be controlled, graphic data is shown for the control of rectifiers, control by push buttons and analogical data of sensors integrated in the network interface, as well as the activation status of the corresponding valves of the agitation system and their control. The correct data transmission is corroborated through a platform called Blynk, which will show basic sensor data through the network (See Figure 9).

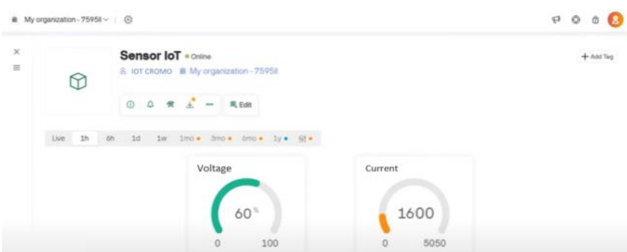


Fig. 9 Networked sensing contrast through blynk

5. Test and Results

In order to evaluate the optimization of the developed intelligent control, exhaustive tests were carried out in terms of proposed locations of loss due to transients in the network due to the fact that the welding area is close to the chrome area since some inverter equipment presents electrical noise, the following status was obtained in the face of this problem, the current data loss is estimated after the implementation, making the respective calculations for the maximum performance between each card implemented in the rectifier and valve equipment, in a free space since the master module will be close to this equipment according to the formula:

$$PL(dB) = 20.log_{10}(d) + 20 * log_{10}(f) + 32.45$$

Using values of the first rectifier as:

- CRM-RECT-4000-001: 12V - 5000A
  - 26 meters to master
  - Latency 32ms

Replacing d and f:

Using the constant value of 32.45 when distance is in km and frequency in Mhz.

$$PL(dB) = 20 * log_{10}(0.026) + 20 * log_{10}(2400) + 32.45$$
$$PL(dB) = 20 * (-1.585) + 20 * (3.3802) + 32.45$$
$$PL(dB) = -31.7 + 67.6 + 32.45$$
$$PL(dB) = 68.35$$

The signal obtained for the received power of dBm is verified with the formula, taking the typical transmission data for the ESP32 of 20dBm with gain on its PCB:

$$P_{received}(dBm) = P_{transmitted}(dBm) - PL(dB)$$
$$P_{received}(dBm) = 20dBm - 68.35dB = -48.35dBm$$

Considered a value of -48.35dBm as a good signal but not enough when new installations are made, which will seek that this signal is excellent, taking the same values of the first rectifier moving the master to 8 meters:

$$PL(dB) = 20 * log_{10}(0.008) + 20 * log_{10}(2400) + 32.45$$
$$PL(dB) = 20 * (-2.0969) + 20 * (3.3802) + 32.45$$
$$PL(dB) = -41.93 + 67.6 + 32.45$$
$$PL(dB) = 58.12$$

$$P_{received}(dBm) = P_{transmitted}(dBm) - PL(dB)$$
$$P_{received}(dBm) = 20dBm - 58.12dB = -38.12dBm$$

Thus achieving an excellent link compared to the other decibels obtained likewise the respective calculations were made for data transmission between the distance of the master module and the supervisors' room.

Table 2. Status in dBm from supervisors' room

Distance to Master Module (1.5Km)	Signal Level (dBm)	Status
0.5	-60	Success
1	-72	Success
1.5	-85	Success
2	-100	Failure

To obtain data and corroborate the reliability of the system a pilot plan was implemented for 30 days. During this time, comparisons were made in 2 cells to obtain the corresponding data on how efficient is the optimization of the system, obtaining a rate of 95% in a better control by remote monitoring than one manual voltage and current obtained by the DC rectifiers; the comparison was made with 2 teams of the same characteristics with the same pickling components, used 22 working days the graph shows its effectiveness in the respective control (See Figure 10).

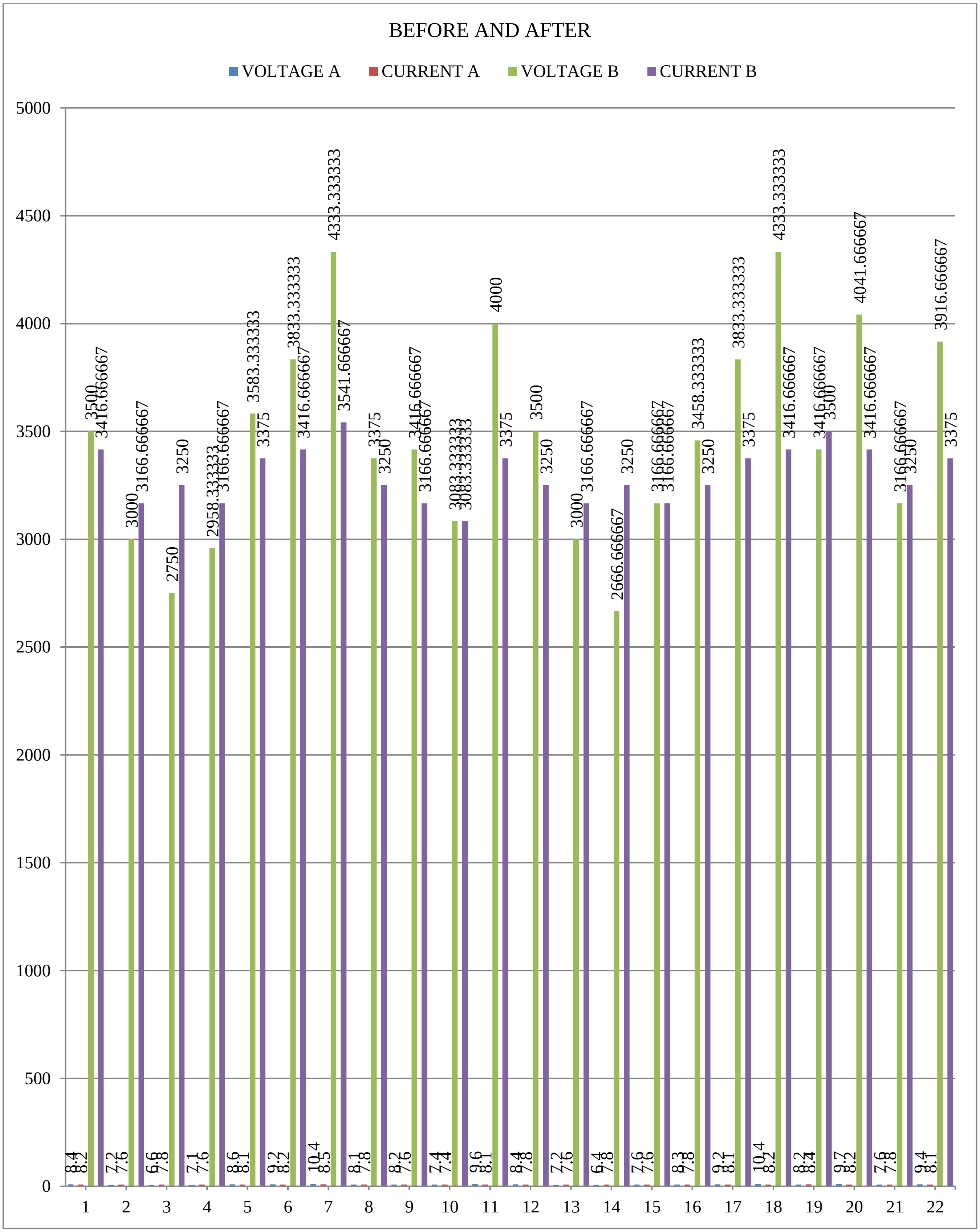


Fig. 10 Comparison with implementation (voltage and amperage control)

For the calculation of acquired efficiency, data is obtained from previous and current applications such as power, energy consumed, and useful energy used using the first value referred to comparison after implementation:

Case 1: 3500Amperes at 8.4V:

$$Power = Voltage * Current$$
$$Power = 8.4v * 3500A = 29.4kW$$

$$Energy\ consumed = Power * t(1hour)$$
$$Energy\ consumed = 29.4kW * 3600$$
$$Energy\ consumed = 105.84MJ$$

Finding the efficient process current at 3500A using deposited mass, obtaining data according to the chrome plating operator:

$$Current = 3500A$$
$$Time = 3600seg$$
$$M = \frac{51.996g}{mol(cromo)}$$
$$n = 3\ electrons$$
$$F = \frac{96485C}{mol}$$
$$m_{theory} = \frac{M * I * t}{n * F}$$
$$m_{theory} = \frac{51.996 * 3500 * 3600}{3 * 96485} = 2263.2g$$

Obtaining a real value of 568.8g after one hour in the laboratory, the efficiency would be 25%:

$$\eta = \frac{568.8}{2263.2} * 100\% = 25\%$$

Calculating the useful energy deposited with the formula:

$$Useful\ energy = \eta * Energy\ consumed$$
$$Useful\ energy = 0.25 * 105.84MJ = 26.46MJ$$

Performing the same calculations for case 2 3416Amperes at 8.2V:

$$Power = 8.2v * 3416A = 28.01kW$$
$$Energy\ consumed = 100.84MJ$$
$$\eta = 15\%$$
$$Energy\ useful = 15.13MJ$$

Comparing the useful energy, a 74.87% relative improvement is obtained after the use of this new monitoring.

$$\frac{Energy\ useful_1}{Energy\ useful_2} = \frac{26.46MJ}{15.13MJ} = 1.75$$

In the same way, the optimization of the ignition time in rectifiers for the pickling process in cells with the timing control and pneumatic valves that activate the agitation system is maximized, taking advantage of 30% of the time invested, managing a better control of the materials used and corresponding energy savings (see Figure 11).

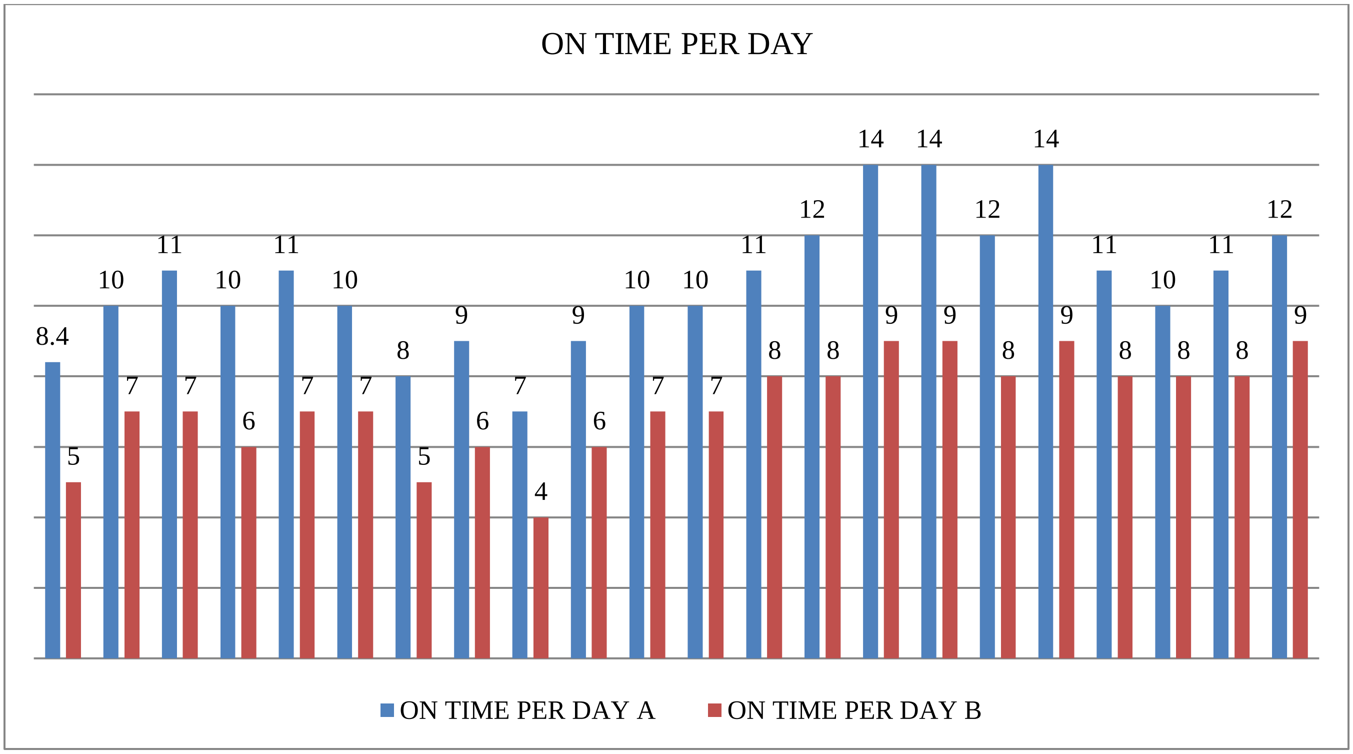


Fig. 11 Reduction of operation time

6. Conclusion

In conclusion, the integration of the Internet of Things (IoT) in the industrial processes of chrome plating and pickling of hydraulic components through the use of intelligent control and remote monitoring systems represents a key innovation to improve production efficiency and accuracy. The article details the implementation of the Internet of Things (IoT) in the control of direct current (DC) rectifiers and pneumatic valves, which are essential for the precise regulation of electrochemical processes. The use of DC rectifiers, which control the direct current required for chrome plating and pickling, is optimized through real-time monitoring of critical parameters, including voltage, current, temperature, and potential rectifier failures.

The use of a separate HTTP server for each component allows remote viewing of these parameters via a web server, facilitating constant monitoring and reducing the need for manual intervention. This approach not only ensures accurate process calibration but also enables automatic adjustments through an ESP32-based intelligent control system, which adjusts the parameters according to the required working hours for each component, thus improving the quality of chrome plating and pickling.

Additionally, the implementation of IoT in the pneumatic valves used in the agitation system ensures dynamic and precise control of fluid flow, thereby optimizing the electrochemical process conditions. The integration of these technologies not only improves production accuracy but also supports predictive maintenance of the rectifiers, contributing to increased energy efficiency and a reduction in unplanned failures.

Consequently, this IoT implementation not only optimizes the chrome plating and pickling processes but also generates significant savings in operating costs and resources, positioning the industry on a path towards greater sustainability, productivity, and competitiveness in an advanced production environment, and can be implemented in other systems where real-time and accurate linkage is required, such as the food industry, as in the case of product packaging.

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