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Original Article

Design and Implementation of an ESP32-Based Electronic Module for Monitoring and Protecting Industrial Electrical Panels Using the Modbus TCP/IP Protocol

Cesar Lenin Chavez Arque[1], Jhonatan Elvis Muñuyco Jinez [2], Raúl Ricardo Sulla Torres[3]

[1,2,3]*Universidad Nacional de San Agustín de Arequipa, Arequipa, Perú.*

[1]*Corresponding Author : cchaveza@unsa.edu.pe*

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Abstract *- This paper presents the design and implementation of an ESP32-based electronic module for the monitoring and preventive protection of industrial electrical panels using Modbus TCP/IP. The system integrates non-invasive sensors to measure up to 400 A, NTC thermistors for temperature in distribution bars, and sensors for detecting fine smoke and gases. In addition, it uses an analyzer to record 3rd and 5th harmonics, allowing for advanced power quality diagnostics. The ESP32 processes the information in real time. In the presence of smoke or flammable gases, it activates an actuator that triggers the "TRIP" button on the main switch to prevent fires and disable the mains voltage used. According to INDECI, OSINERGMIN, and the Peruvian Fire Department, 70% of industrial fires in the country are electrical in origin. Implementing the system can reduce the risk of fire by 52.2%, increase the timely detection of incidents by 85%, and improve automatic response by 89%. It also promotes predictive maintenance of the electrical panel by identifying excessive current, overheating, and harmonic distortions, offering a low-cost, high-efficiency, and quick-to-implement solution.*

Keywords *- ESP32 Microcontroller, Industrial Electrical Panels, Modbus TCP/IP Communication, Predictive Maintenance, Fire Prevention System.*

1. Introduction

In the industrial sector, especially in production plants with high operational demands, the implementation of preventive maintenance strategies for electrical panels is a critical factor in ensuring operational continuity and equipment safety. However, in many facilities, especially those with continuous processes or high production pressure, maintenance schedules for these panels are nonexistent, outdated, or only carried out reactively after failures occur, even more so if it is a main panel that does not have a backup that can function while it is being serviced. This practice not only reduces the useful life of assets but also increases the risk of unscheduled downtime, economic losses, workplace accidents, and environmental damage.

In this context, the present project aims to design and implement an intelligent electronic system for the monitoring, supervision, and control of industrial electrical panels, focused on the early detection of abnormal conditions and the prevention of critical failures. The core of the system will be based on an electronic card with an ESP32 microcontroller, responsible for acquiring, processing, and transmitting electrical and environmental variables from the panel in real time using the Modbus TCP/IP protocol and controlling the TRIP button via an actuator to disable the main switch. The system will integrate HAK 40 non-invasive current sensors to monitor consumption up to 400 A, NTC 10k thermistors with M6 terminals to measure overheating in copper bars, GP2Y1014AU0F optical smoke sensors, and MQ-135 and MQ-2 gas sensors to detect signs of combustion due to false contacts or overloads.

A Lovato DMG610 network analyser will also be incorporated to record voltages, currents, and 3rd and 5th order harmonics from different areas, allowing the identification of disturbances caused by non-linear industrial loads and the determination of corrective actions such as the installation of filters or subsequent inspections of the detected equipment. The proposal seeks not only to continuously monitor the electrical status of the panel but also to execute automatic preventive actions, such as tripping the main switch in the event of simultaneous detection of smoke and abnormal current increase, thus preventing the spread of fires or major failures. In this way, the system is presented as a

comprehensive protection, monitoring, and predictive diagnostic solution, capable of increasing safety, reducing downtime, and contributing to more efficient industrial maintenance management.

2. Related Works

In recent years, the monitoring and protection of electrical panels has become increasingly important due to the rise in faults caused by overvoltage, overcurrent, and harmonics, which are the main causes of fires and operational losses in the industry. The lack of real-time monitoring and predictive maintenance systems exacerbates this problem. Recent research proposes the use of IoT technologies and protocols such as Modbus TCP/IP to integrate current, temperature, and power quality sensors, improving early diagnosis and promoting the transition to smart monitoring schemes with preventive alerts. In this context, [1] shows the development of an IoT system for voltage monitoring aimed at preventing risks from overvoltage and undervoltage in residential and industrial environments. The solution, based on the ZMPT101B sensor, an ESP32 microcontroller, and the Blynk platform, enables real-time data acquisition and transmission with immediate alerts for decision-making. The tests demonstrated accuracy, reliability, and rapid response, validating its effectiveness in protecting electrical infrastructure. As a projection, the plan is to integrate predictive algorithms, expand scalability, and link the system to Smart Grids, highlighting the contribution of IoT to energy security, efficiency, and sustainability. Also in [2], an ESP32-based system was designed for the detection and monitoring of disturbances in electrical systems, motivated by the distortions generated by power conversion circuits that affect the grid and users.

The developed system allows real-time signal acquisition and analysis, providing key information about the nature of these disturbances. In addition, integration with Arduino technology makes it an accessible and useful tool for both practical applications and for training electrical engineering students. Similarly, disturbances such as the starting of induction motors, similar to the detection design shown in [3], where high-resistance contacts generated by faulty connections represent a risk to efficiency and safety. Traditional detection techniques are often costly and impractical, so a remote and automated method based on the analysis of induction motor start-up transients is proposed. The main objective is to accurately identify the presence, severity, and location of such defects without additional instrumentation, validated by testing on 380 V and 6.6 kV motors in the laboratory and in the field, thus providing an effective tool for predictive maintenance and the reliability of industrial electrical systems. Similarly, in [4], where electrical fault detection is essential to ensure grid resilience, current methods are limited. In this study, machine learning and data analysis techniques were applied to electrical parameters of line current and voltage, evaluating different classification algorithms. The results showed that the KNN model performed best, achieving the highest overall and class-specific accuracy in the identification and classification of electrical faults. In [5], where the detection and diagnosis of faults in electric drive systems is essential for their safety, traditional methods based on Canonical Correlation Analysis (CCA) have limitations in that they assume Linearity and Gaussian distribution, which do not fit the nonlinear nature of these systems. To overcome these restrictions, an improved method called RRNCCA is proposed, which combines CCA with a reversible residual network. This approach reformulates the CCA objective function, designs a specific FDD scheme for electric drives, and allows diagnosis to be performed directly from the differences in the detection results. Experimental validation demonstrates the effectiveness of the proposal, offering a more robust and accurate tool for fault monitoring in complex electrical environments.

For the operation of a device, [6] evaluates the use of Artificial Neural Networks (ANNs) to detect and predict faults in electrical automation equipment, outperforming traditional methods such as KNN. With an average accuracy of 88.15% and up to 97.4% in the best cases, ANNs demonstrate high effectiveness in identifying faults in complex systems. Their application allows for the implementation of data-based preventive maintenance strategies, increasing the reliability, safety, efficiency, and economic benefits of industrial processes. In [7], a system for detecting and monitoring disturbances in electrical networks is presented, generated by the increasing use of electronic circuits that distort energy. These distorted signals affect other consumers and require detailed analysis.

To this end, a tool was developed in MATLAB/SIMULINK that allows these disturbances to be characterized in both real and simulated signals, using the NI USB 6009 card for data acquisition. The main objective is to offer a practical solution for studying these alterations and, at the same time, to serve as a training resource for students in the area of electrical power quality. According to [8], a study focused on improving the reliability of Electrical Distribution Systems (EDS), whose main problem is the total loss of power for users, even when there are alternative means of maintaining the supply. The proposal consists of implementing a protection system capable of redirecting the flow of power to the loads once a feeder with a short-circuit fault is isolated. Development and validation will be carried out with a Real-Time Digital Simulator (RTDS) under the Hardware-In-the-Loop (HIL) methodology. As a preliminary advance, the article presents the modeling and the first simulations in DIgSILENT PowerFactory, including load flow studies to validate the data of the network components. Initial results show that, after isolating the faulty feeder, another feeder from a different substation can continue to supply power to the loads by manually opening circuit

breakers. These findings support the hypothesis that the proposed protection system will increase the reliability of the EDS, significantly reducing the number of customers affected by outages. In [9], the complexity of establishing Relay Protection and Automation (RPA) configurations in Electrical Power Systems (EPS) is addressed. Traditionally, this has been done through the analysis of symmetrical components, which can lead to errors in the identification of operating modes and in the modeling of devices.

To overcome these limitations, a phase coordinate modeling method is proposed that simultaneously integrates the operating modes of high-voltage networks and secondary circuits connected to Instrument Transformers (IT) and Symmetrical Component Filters (SCF). This approach allows for more accurate calculation of power flow in controlled segments and improves the configuration of DPS systems, with potential applications in cyber-physical power systems. Validation was performed by analyzing 140 operating modes under variable loads, which allowed for the adjustment of transmission line models through parametric identification.

The simulation results show high accuracy in the calculation of currents and voltages, with an average error of only 0.6% in the modules and 0.26° in the phase angles, confirming the effectiveness of the proposed method. For a peak and transient protection system in [10], the objective is to design a surge and undervoltage protection system in administrative buildings. To this end, voltage measurements were taken over several days and compared with the building's load program, which made it possible to determine the appropriate cable size and circuit breaker, in accordance with the Philippine Electrical Code. The design also provides for the transfer of power to a generator set in case of need.

The results showed that the voltages measured on the main boards ranged from 218 to 231 V, indicating that there are no critical variations and that the electrical loads are operating under normal conditions, thus ensuring their protection and continuity of service. Similar incidents occurred in [11], where the study evaluated the performance of Oil Circuit Breakers (OCBs) in the EKEDC network, analysing trip records between 2014 and 2018, physical inspections, and oil dielectric strength tests.

The results showed that the highest frequency of trips was in 2014 and the lowest in 2018, identifying charred contacts and oils with DSV values below the standard of 40 kV. It is concluded that the deterioration of the oil and contacts reduces the reliability of the system and that oil filtration or replacement is necessary to improve the performance of the OCBs. Similar to power protections, [12] analyzes how geomagnetic storms induce almost continuous currents in power transformers due to the non-linearity of the magnetic circuit, generating thermal overload and risk of collapse in transmission systems. A method for compensating for these currents is proposed, first validated in a single-phase model and then in a three-phase model. Simulations and laboratory tests confirmed the effectiveness of the compensation process in preventing transformer failures. Regarding data transmission by protocol, as in [13], used for the monitoring of critical variables in industrial processes, specifically the pressure and percentage of work of motors with Variable Frequency Drives (VFD).

The growing digitization in the industrial sector demands technologies capable of ensuring proactive maintenance, real-time monitoring, and early fault detection in order to optimize the performance of autonomous systems. The IIoT integration process begins with the acquisition of parameters using communication protocols such as Modbus TCP/IP, which are widely used in PLCs for plant monitoring and control. The data is then sent to the cloud for management, storage, and visualization, and validated through remote interaction between the DAIREL system and the HMI interface of the constant pressure plant.

3. Methodology

This article proposes the design and implementation of a smart electronic card based on the ESP32 microcontroller, intended for the monitoring and preventive protection of industrial electrical panels, with direct application in productive sectors where electrical failures represent a critical risk to operational continuity. The system integrates digital and analog electronics for the acquisition and processing of variables, incorporating industrial communication via Modbus TCP/IP protocol for centralized, real-time monitoring.

In addition to comparing other panels with the proposed one, highlighting the electronic card's own protection and alert functions, integrated sensors, and fast-acting actuators in the event of any type of failure, the main features of the design are mentioned below:

- Integration of the Modbus TCP/IP protocol.
- Harmonic detection and analysis.
- Implementation of non-invasive current sensors, temperature sensors, gas sensors, fine smoke sensors, and humidity sensors.
- Customized control card for processing, detection, and activation of physical protection components.
- Local alarm and notification system.
- Modular design and simplified maintenance.
- High reliability and operational continuity.

The control module was designed using EAGLE 9.6 software, which integrates components such as DHT 22, Buzzer, microSD, TFT 2.4", as well as providing the necessary voltage to activate actuators such as pilot lights and the protection module's electromagnet.

Table 1. Materials used

Type	Model	Quantity
Microcontroller	ESP32-WROM-32	01
Electronic module	Tarjeta de control PCB V1.0	01
Current sensor	HAK 40	06
Temperature sensor	10KB3435	06
Gas/smoke sensor	MQ-135	02
Vibration sensor	SW-420	06
Dust sensor	GP2Y1010AU0F	01
Humidity sensor	DHT-22(PCB)	01
Time sensor	RTC DS3231	01
HMI	TFT 2.4”	01
LED indicators	Pilot 24VDC	04
Piezoelectric	Buzzer (PCB)	01
SD memory	MicroSD (PCB)	01
Protection module	Electromagnet 12V	01
Fans	PMD2409	03
Analyzer	Lovato DMG610	01
Expansion module	Ethernet EXP1013	01

The control module uses the ESP32-WROM-32 microcontroller with the Modbus TCP/IP protocol via its Wi-Fi connection programmed in the ARDUINO IDE software, sending variables such as current, harmonics, temperature, humidity, and vibration. Simulations and sensor operation, such as current, were performed in the MULTISIM software and the WOKWI platform to verify and calibrate the action of the electromagnet in the main protection actuator module. It also activates alerts and notifications about possible serious problems on the board. The proposed module case was designed using AUTOCAD 3D software, and a 3D simulation of the board and sensor locations was also made so as not to interfere with the existing power distribution.

A diagram shows the stages of the proposed design through to its implementation (see Figure 1), starting with the definition of requirements and objectives to be determined according to the specific needs of the system, such as monitoring of current, voltage, humidity, smoke, dust, temperature, harmonics, and automatic protections, as well as establishing operating parameters and environmental conditions of the installation environment and choosing the appropriate communication protocol.

When selecting the microcontroller, sensors, and electronic modules, the range of accuracy and robustness, processing capacity, and speed are considered, in addition to including additional models for communication such as Wi-Fi, storage, and actuator control. For the electrical design of the system, a diagram is drawn up integrating the sensors, voltage sources, electronic module, and protection module for their subsequent location. For the electronic part of the system, the correct configuration and distribution are carried out for the voltage connection and data acquisition from the sensors, their calibration, activation of the actuator in the protection module, general sensing, and activation of alerts. The mechanical design for the functionality of the protection module was based on magnetic switches molded according to the case of each device. In this case, an adaptable design was created for the most commonly used thermomagnetic switches from SCHENEIDER, ABB, or CHINT, and the layout of the space in the cabinet or distribution board was structured accordingly. The monitoring firmware and software were developed using libraries that are easy to program, as well as free software that allows for subsequent modifications and programming in the HMI, which can be used for further modifications without the need to modify the installed firmware.

The devices were assembled on the main panel according to the designs and simulations carried out in the aforementioned software, in addition to verifying the locations arranged according to the climatic conditions, purpose, or use of the panel for the configuration of the necessary protections.

For the testing and calibration phase, the correct functioning of the sensors is verified under real working conditions, including calibrations such as current, humidity, temperature, monitoring of maximum current used, audible and visual alerts for excessive vibrations, dust, humidity, temperature, or problems such as smoke, short circuits, activating the protection before a fire starts. Finally, continuous monitoring and improvements are carried out by analyzing the data collected to optimize humidity and temperature control, implement firmware updates for future improvements through the HMI, and adjust the system according to new needs or seasonal environmental conditions.

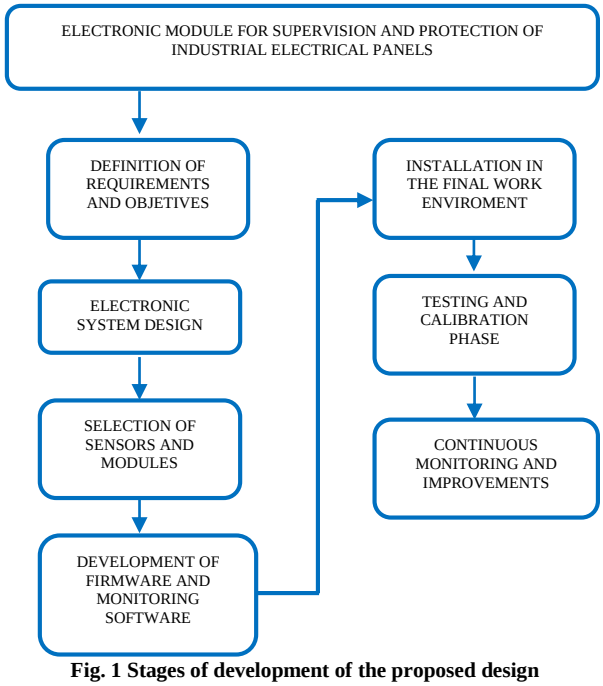

Fig. 1 Stages of development of the proposed design

4. Development System

The control module is developed based on the ESP32-WROM-32 microcontroller, which performs the acquisition, real-time processing, and transmission of critical variables via Modbus TCP/IP. Its purpose is to prevent overcurrent, overheating in busbars, overvoltage, the presence of smoke/gases, humidity in the cabinet or panel, dust, and harmonic distortion. In critical conditions, it performs physical actions such as tripping the main molded switch. The modular design is robust for industrial environments and scalable for multiple boards. Figure 2 shows the operating architecture according to the detection of variables in the programmed firmware, as well as external protection steps such as the molded switch itself or the corresponding thermomagnetic switch.

The module's operating mode starts with the acquisition of data such as voltage. The monitoring evaluates the overvoltage to validate the correct voltage, which in this case is 380VAC and 440VAC, considering 5% as the maximum accepted voltage margin, issuing an overvoltage alert from ±3% error. In addition to being set to a certain current specified by the manufacturer, the main switch and the protection module evaluate other conditions, such as busbar temperature, cabinet humidity, busbar vibrations, dust, and smoke from short circuits. Data acquisition, such as current, comes from HAK 40 (400/5V) transducers to measure the current in each R-S-T phase, in this case from a 300KVA electrical substation, temperature sensors such as NTC 10KB3435 thermistors located on the electrical distribution busbars, and a Lovato DMG610 network analyzer detecting harmonics, mainly the 3rd and 5th. These devices send analog and digital signals to the control module, which contains the electronic card with ESP32. The ESP32 acts as a central unit receiving analog current and temperature signals, which it converts to digital using its ADC, sending data via Modbus TCP/IP from the Lovato DMG610 network analyzer to the card using dedicated integrated circuits for this function, whose dedicated firmware implements the analysis algorithms for detecting harmonic distortions and generating alarms when the values exceed preconfigured thresholds. Communication and supervision are carried out through the control module. The integrated ESP32 connects to the Modbus TCP/IP industrial network, sending real-time data to a monitoring server and the HMI, which allows the configuration of parameters such as current limits, temperature, voltages, and dirt on the board due to dust particles. Protective actions are activated when a dangerous condition is detected, activating a physical actuator such as an electromagnet which allows the main thermomagnetic switch or molded switch of the panel to be opened, records the event and the causes for which it was activated, and finally sends an immediate alert to the HMI with audible and visual alerts. Each stage is detailed, starting with data acquisition. The voltage sensing terminals are located under the main thermomagnetic switch on the panel and the control module power supply upstream of it, so that it can activate or send an alert after detecting the error. The supply voltage to be monitored is 380VAC and 440VAC. Voltage variability causes faults in power supplies or other equipment, which is why a maximum error margin of ±5% is considered for these voltages.The control module performs this voltage reading through a voltage divider configuration to an operational amplifier that will send an analog value between 0 - 3.3VDC for reading in the ESP32 ADC (See Figure 3).

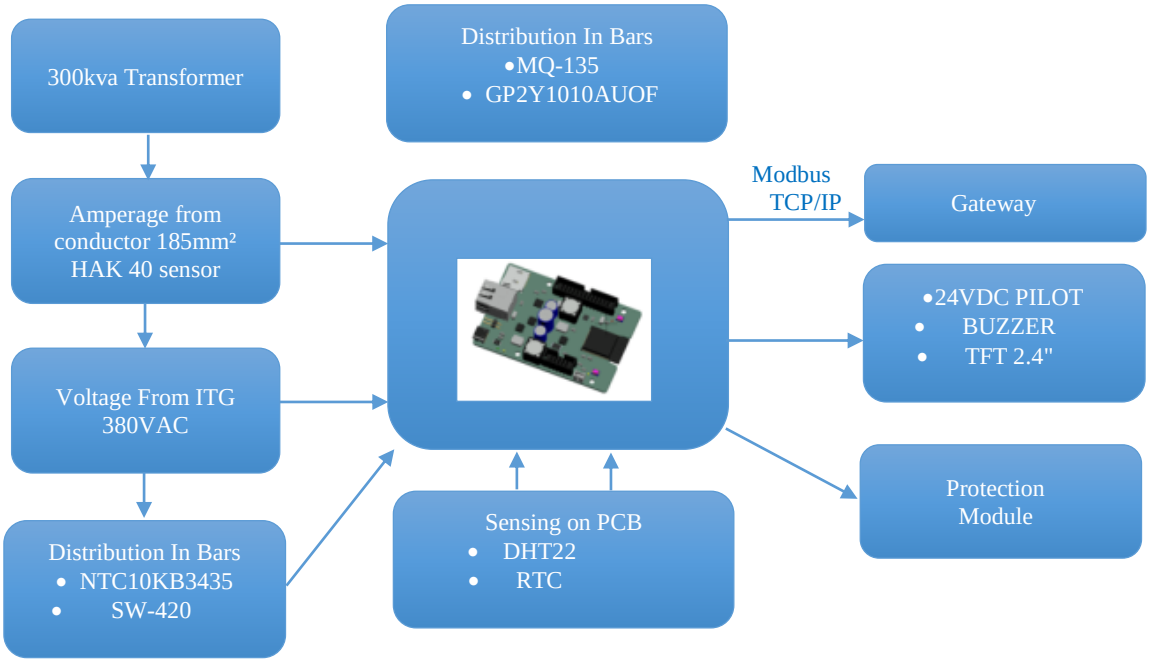

Fig. 2 Operating architecture

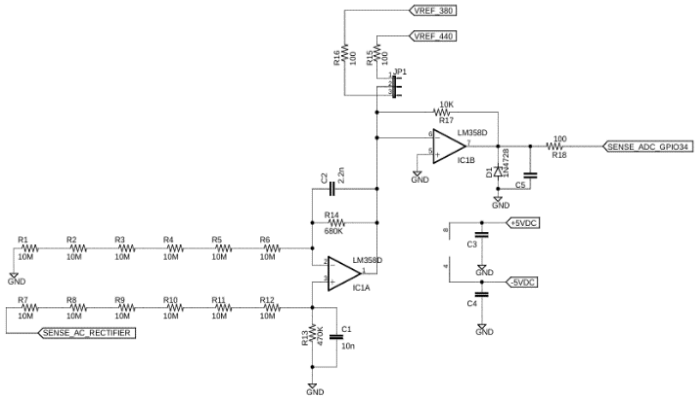

Fig. 3 Analog reading from 380VAC and 440VAC network

HAK 40 current transducers with a reading range of 400 amps scaled to 5V are also used, as well as an operational amplifier to reduce the voltage and send a correct reading between 0 and 3.3VDC (see Figure 4). The NTC thermistors are placed directly on the copper bars. Depending on their configuration, they can send analog values between 0 and 10VDC. The reduction to 0–3.3VDC will also be performed with another operational amplifier with low-pass filters (see Figure 5). This achieves isolation from electrical noise caused by false thermal readings. The SHARP GP2Y1010AU0F dust sensor will be strategically located so that it can assess the state of dust contamination in other thermomagnetic distribution valves. Similarly, a low-pass filter will be used for its reading to avoid noise or false readings in the microcontroller's ADC. The SW-420 vibration sensor will be configured so that it can be attached to the copper bar via a terminal and low-pass filters for proper reading in the microcontroller.

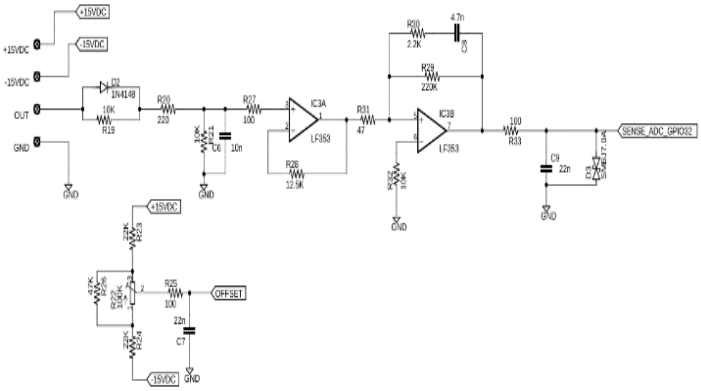

Fig. 4 Current sensing from HAK40

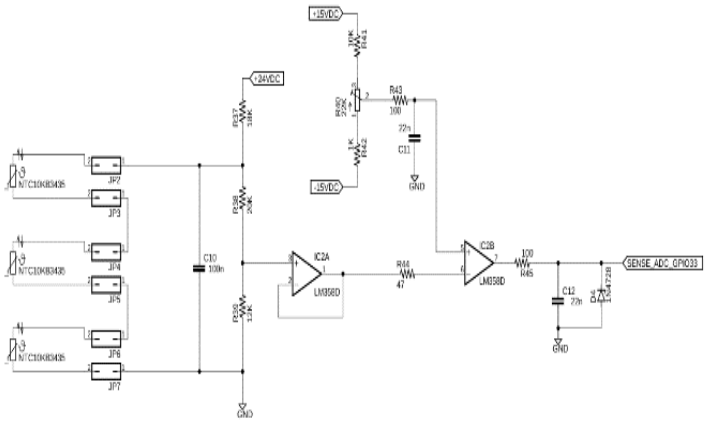

Fig. 5 Variable analog temperature sensing

As for the MQ-135 smoke sensor, it has a digital output, so it will be connected directly to the module via a dedicated connector. This sensor has its own dedicated PCB for output types, in this case, digital. Adjusting the PCB only requires using the built-in trimpot. The DHT22 humidity sensor requires a direct connection to the microcontroller and is the only sensor that has an operating voltage of 3.3VDC for correct reading. The voltage values and proportional readings are shown according to the data acquisition by the microcontroller in the control module.

Table 2. Sensor reading ranges used

Sensor	Voltage	Reading range
HAK40	±15VDC	400A/5VDC
10KB3435	+10VDC	60°C/10VDC
MQ-135	+5VDC	110ppm/5VDC
SW-420	+5VDC	60Hz/5VDC
GP2Y1010AU0F	+5VDC	600ug/m^3/5VDC
DHT-22(PCB)	+3.3VDC	100%HR/+3.3VDC
RTC DS3231	+5VDC	Hours, Minutes, Seconds

The advantage of using multiple supply voltages, in addition to filtering the signal down to +3.3VDC digital or analog, allows for easy diagnosis of faults and protections at each stage until reaching the ESP32 microcontroller, preventing damage from conflicts or voltage variations. The control module offers voltages of +24VDC, ±15VDC, +10VDC, ±5VDC, and +3.3VDC; these voltages are regulated through the main power source that regulates the voltage of 380VAC or 440VAC, through a switched source with the integrated UC3843B. It should be noted that the modules do not have excessive current consumption, other than the 15V electromagnet with a consumption of 0.68 amps.

The operational amplifiers in the control module for selection and application use the integrated LM358N, LF353, and LM339 in follower, integrator, and summing configurations for use in different stages, as well as to compensate for readings after the low-pass filter. The data simulation was performed on the WOKWI online platform, as it handles most of the sensors for subsequent implementation.

In addition, connectivity via the ETHERNET port to the Lovato DMG610 module is achieved through an external EXP1013 module, as this can convert data from Modbus RTU to Modbus TCP/IP (see Figure 6) for reading harmonics using digital alarms sent to the control module for subsequent data recording. Since actions need to be taken quickly in the event of a possible failure, the ESP32 microcontroller capable of operating at 240 MHz is chosen, as it also has Wi-Fi connectivity for wireless Modbus TCP/IP communication (see Figure 7).

Fig. 6 Modbus TCP/IP connection from Lovato DGM610

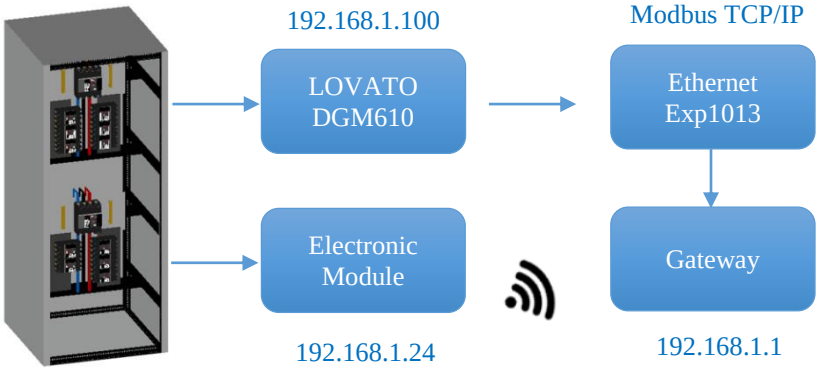

Fig. 7 Modbus TCP/IP network to gateway

The ESP32-WROM-32 will be the core of the card, integrated into the control module. In addition to acquiring data from transducers and sensors, it controls actuators such as fans, electromagnets, buzzers, and pilot lights. The function of these depends on the logic programmed into their firmware, where the fans will act in response to an excessive increase in dust and humidity in the cabinet. The electromagnet's main function is to disable the main voltage to the entire distribution system in the event of detected problems. The Buzzer indicates local alerts such as voltage surges in increments of 1% up to a total of 5%, activating an audible signal through relays integrated into an overvoltage alarm, as well as for vibration fault detection alerts in bars and alerts for lack of scheduled maintenance. There will be a total of 4 indicator

lights: to validate the correct working voltage, normal or excessive operating current, detected harmonics, and critical error after activation of the main protection (see Figure 8).

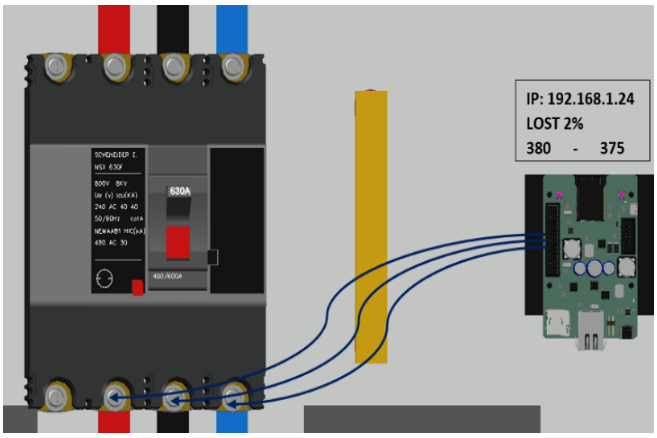

Fig. 8 Voltage sensing in an electronic module

The mechanical design of the protection module was carried out using AutoCAD 3D software, evaluating the dimensions of three molded switches from well-known and widely used brands. The purpose of this device will be to completely disable the passage of voltage in the electrical panel distribution. Its functionality will allow it to be adapted to a main switch from 630 amps to 250 amps as general thermomagnetic switches (see Figure 9). In addition to simulating the locations of the sensors depending on the climate and adverse situations due to pollution that could enter the panel, the layout of the sensors on the bars and the location of the control module were also considered.

According to the single-line diagram, the correct setpoint value and inductive load balance of the system are calculated to take into account the maximum amperage or voltage peaks generated by the equipment in the industrial plant where the implementation will be adapted. Equipment such as variable speed drives, 8-meter industrial winches, rectifiers, hydraulic equipment, and DC rectifiers for electrochemical use is considered. This measurement data was taken manually with a multimeter to consider the modifiable data in the control module's firmware through its HMI, as well as values set for initial work before advanced configuration.

Table 3. Initial configuration ranges

Sensor	Initial Value	Configurable Range
HAK40	250A	0 - 400A
10KB3435	30°C	0 - 60°C
MQ-135	45ppm	0 - 110ppm
SW-420	15Hz	0 - 60Hz
GP2Y1010AU0F	250 ug/m^3	0 - 600ug/m^3
DHT-22(PCB)	35%HR	0 - 100%HR
RTC DS3231	600h	Settable in dates or times

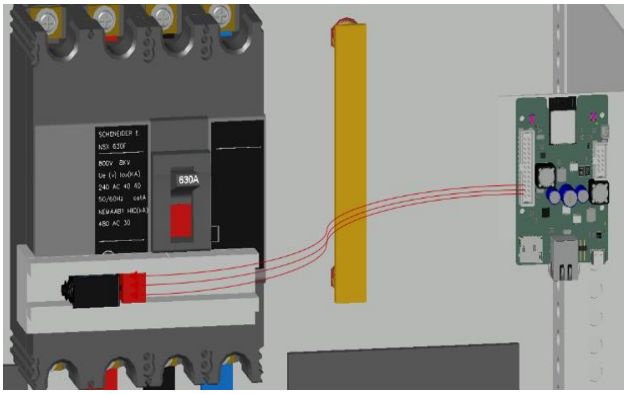

Fig. 9 Protection module in ITG

In addition, the control module will save critical values with date and time whenever there are relevant problems, such as harmonic prevalence time or high currents, latest updates, and seasonal alarms such as temperature, humidity, and dust in the electrical panel.

As for the HMI, it will display the current general monitoring values such as current, voltage, power, THD, harmonics, temperature, active ventilation, and humidity.

As soon as an alarm is triggered, it will change its monitoring data to a sub-window where it will display the alert with a message such as “Voltage Alert” showing the voltage, “Excessive Humidity Alert”, and local review of the status of the panel.

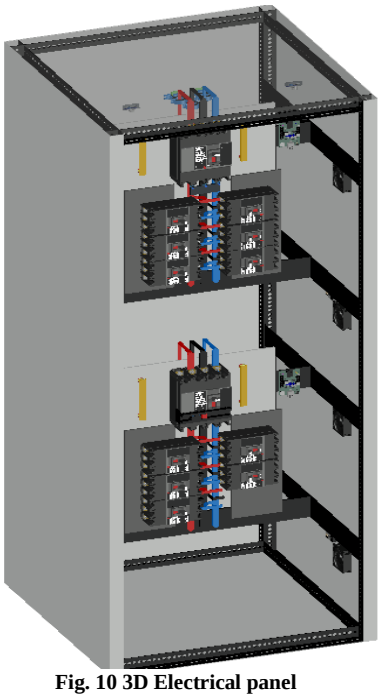

Fig. 10 3D Electrical panel

To optimize the distribution of sensors, a preliminary assessment is carried out by placing the sensors on the 3D

electrical panel where the implementation will take place. In addition, readings will be taken for an initial configuration using a thermal imaging camera from the transformers of the electrical substation and the distribution panel to be worked on, thus performing an initial calibration for proper operation. The electrical panel will have dimensions of 2000x800x800, in which the thermomagnetic switches are distributed according to its single-line diagram (see Figure 10). For this application, two independent modules will be used for each voltage, since the substation transformer offers 380VAC and 440VAC with different and isolated windings.

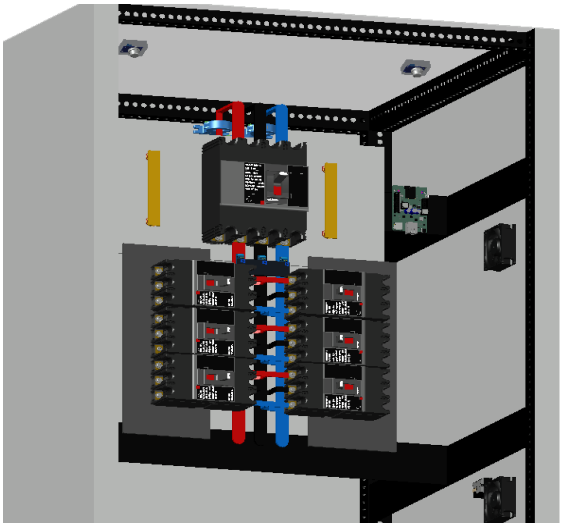

Fig. 11 Sensor locations

The control modules will be located at the front of the panel, along with the error indicators, to access a modification of setpoint values other than those already configured and to visualize the alarms better. It should be noted that to connect and implement this module with other sensing devices, it is necessary to turn off the voltage in the medium-voltage transformer, which reduces the voltage from 10kV to 380-440VAC. Below is a suitable location for each sensor based on simulations of the variables in the sensor (see Figure 11).

Fig. 12 Lovato DGM610 module in panel

Likewise, after placing the modules on the electrical panel, a comparison is made with an adjacent 200KVA panel located in the substation to verify its functionality and functionality after the implementation of the electronic module with the Lovato DMG610 module (see Figure 12). After implementation, operational tests, and monitoring comparisons of variables such as voltage, amperage, power, temperature, and humidity were performed on the panel with the electronic module and the adjacent panel with only a PIV (Power, Amperage, and Voltage) monitoring device.

Table 4. Comparison of functionalities between panels

Feature	Electronic Module	Conventional Board
Basic measurement (V, A, kW)	✓	✓
Measurement of harmonics and THD	✓ (3° y 5° harmonic	X
Bar temperature monitoring	✓ (NTC 10k)	X
Localized overcurrent detection	✓ (HAK 40)	X
Automatic active protection	✓ (Actuation on solenoid)	X (only for overcurrent)
Historical event log	✓ (Storage on ESP32)	X
Remote Communication	✓ (Modbus TCP/IP)	X (Local display only)
Preventive alarm	✓	X

The unique feature of this electronic control module is that it can act before a fire or its spread, as happened in this panel (see Figure 13), because it did not have scheduled maintenance, and the lack of over-temperature detection in a copper bar caused the molded switch to suffer hot spot damage. Likewise, the lack of gas and smoke detection after the fire did not detect the situation in time, causing further damage due to a short circuit between switches due to their melting, causing the transformer to overheat and trip the fuse located in the medium voltage lines in the main distribution transformer from 22.9KV to 10KV (see Figure 14).

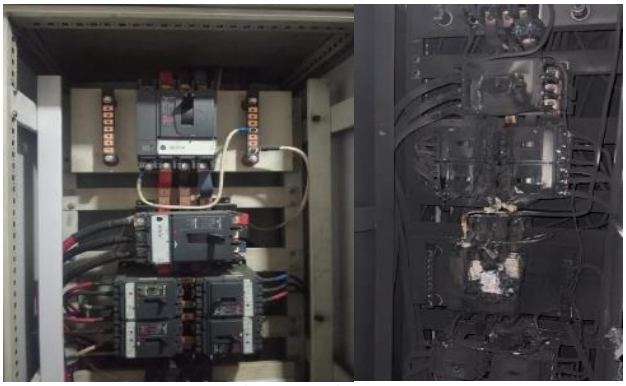

Fig. 13 Before and after the incident

Fig. 14 External problems after the incident

Due to this problem caused by this company, it was decided to implement this control module for monitoring from a local server via Modbus TCP/IP, to activate alarms and act in response to this dangerous situation that could have resulted in a larger-scale fire. The control module was tested for 30 days until the next inspection by maintenance personnel, finding errors reported by the module regarding excessive vibration, high voltages, and harmonics in equipment, an advantage over the other panel, which does not have these functionalities. This implementation took place at an industrial plant in the electrochemical sector located in Cerro Colorado, Arequipa, where humidity is high due to the emission of chemical acids, continuous productivity, and the lack of scheduled inspections.

5. Results and Discussion

To evaluate the functionality of the electronic module after implementation, such as fire reduction, timely detection of incidents due to weather conditions or lack of maintenance, and improvement in automatic and accurate response to critical failures, a comparison was made with the adjacent panel without maintenance. This comparison allows for the identification of problems such as bar overheating, overvoltage, and harmonic distortions in real situations, offering a low-cost, efficient, and easy-to-implement solution for any panel that requires this type of monitoring. The comparison of values in terms of manual and automatic acquisition between the two implemented panels and alarms regarding possible failures is shown.

Table 5. Automatically acquired data

Parameter	Advanced Board	Traditional Board
Voltage	400.5V / 401.2V / 398.7V	400V(average)
Current	310A / 298A / 325A	311A (average)
Total active power	198.5kW	198kW
Reactive power	68 kVAR	--
Power factor	0.94	--
THD voltage	3.5% / 3.2% / 4.0%	--
Current THD	12.5% /10.8% /13.1%	--
3rd voltage harmonic	1.8%	--
5th voltage harmonic	2.4%	--
Current 5th harmonic	6.7%	--
Vibration	59.8 Hz (1.5 m m/s) - normal	--
L1 bar temperature	48°C	--
L2 bar temperature	45°C	--
L3 bar temperature	54°C – alert	--

Table 6. Functionality of the electronic module

Variable	Unit	Manual Method	Method with Electronic Module
Voltage (V)	Volts (v)	Digital multimeter connected phase-phase or phase-neutral	Continuous reading from network analyzer (e.g., Lovato DMG610) via Modbus TCP/IP
Current (I)	Amps (A)	The clamp meter is placed on each phase	Automatic and continuous calculation by the network analyzer
Power (P)	kW	Multimeter with power function or manual calculation P=V*I*FPP =V*I*FP	Automatic and continuous calculation by the network analyzer
THD	%	Not measured on basic equipment; requires a portable analyzer	Real-time reading from the network analyzer
Harmonics (3^{rd}, 5^{th},etc)	% per order	Requires specialized equipment (portable analyzer) and temporary connection	Permanent record in the analyzer with history
Vibration	Hz/ mm / s	Portable accelerometer or point vibration meter	Integrated sensor sending data in real time
Temperature in bars	°C	Thermal imaging camera or spot infrared thermometer	Continuous reading from the NTC thermistor installed on the bar

Measuring instruments such as a multimeter, clamp meter, and thermal imaging camera were used for data acquisition and value verification.

The drawback was that an operator had to report problems locally, taking time away from monitoring.

To validate the 52.2% reduction in fire risk, values from incident reports in OSINERGMIN, SEAL, and INDECI were used to create a quantitative model of the impact of the control and protection module, modeling the probability of a minor incident developing into a fire.

$$P_{fire} = 1 - (D.R.A)$$

Where:

D: Timely incident detection
R: Initiate response in a timely manner after detection
A: Action taken to prevent the incident from developing into a fire

As well as a base case with a board without implementation, where the detection rate is 20% since there is no early detection on the board, the response time after detection is 30% due to the location of operator protections or the location of a fire extinguisher, and 50% after the action taken to prevent the spread of a fire.

$$P_0 = 1 - (0.2x0.3x0.5)$$

$$P_0 = 1 - 0.03 = 0.97$$

The probability that the fire will not be controlled is 97%, a very high value considering the reality of the values tabulated by the relevant agencies.

Now we present the other model after implementation in terms of reducing this probability.

$$P_1 = 1 - (0.7x0.85x0.9)$$

$$P_1 = 1 - (0.5355) = 0.4645$$

Reduction:

$$R = 1 - \left(\frac{0.4645}{0.97}\right) = 52.2\%$$

The probability was reduced to 46.4% with the implementation of the module, and the reduction in the incidence of fires was reduced to 52.2% compared to a current value of 70% obtained by the study carried out by the relevant agencies, demonstrating the efficiency of the electronic monitoring module. In terms of realistic estimates with the sensors after monthly implementation, calibrations were carried out for subsequent monitoring over 15 days, estimating probable monthly values in terms of the effectiveness of the sensors in detecting possible faults.

Dust sensor: 50%
Smoke/gas sensor: 45%
Humidity sensor: 35%
Current sensor: 60%
Temperature sensor: 30%

$$P = (1 - 0.5)x(1 - 0.45)x(1 - 0.35)x(1 - 0.6x0.3) = 0.1465$$

Combined detection yields:

$$D_{combined} = 1 - 0.1465 \approx 0.8534 = (85.34)\%$$

Depending on the acquisition and speed of data, they are divided into decision-making, communication, activation of protective devices, and confirmation of activation.

$$S_d = Correct\ decision\ via\ firmware$$

$$S_c = Communication\ via\ Modbus\ TCP/IP$$

$$S_a = Electromagnet\ activation\ in\ TRIP$$

$$S_f = Protection\ confirmation$$

$$S_d = 0.99\ risk\ assessment\ and\ detection$$

$$S_c = 0.98\ local\ communication\ via\ Modbus\ TCP/IP$$

$$S_a = 0.95\ Protection\ activation\ response$$

$$S_f = 0.97\ Confirmation\ feedback\ after\ activation$$

$$R = 0.99\ x\ 0.98\ x\ 0.95\ x\ 0.97\ \approx 89\%$$

The following table shows values ranging from simple faults (adjustment of hardware) to critical faults (fire), showing the discrepancies in terms of inaccurate readings by other modules, such as the PIV, as well as interference from harmonics and voltage drops on a typical working day.

Due to limited space for the placement of more control instruments on an electrical panel, certain application factors of the electronic module were omitted, as it would present deficiencies if it were an exposed distribution panel, such as those used in workshops or extensions with attachable industrial plugs. Due to these post-implementation deficiencies and to cover even more monitoring area, an improvement would be made by waterproofing the control cards with epoxy materials to protect them from dust, moisture, or particle projection.

Fig. 15 Comparison of PIV parameter readings and harmonic distortion

6. Conclusion

The implementation of the electronic monitoring, supervision, and protection system for industrial electrical panels has proven to be a highly effective tool for preventing incidents and improving operational continuity. The results indicate an 85% increase in the timely detection of faults, ranging from minor problems such as loose fasteners and localised overheating to critical incidents such as incipient fires. Likewise, a 90% improvement in automatic response was achieved, allowing corrective actions, such as power cut-off, activation of cooling systems, or alarms, to be executed in seconds, drastically reducing the risk of major damage. Failure analysis suggests that, thanks to the system, preventive interventions for simple failures (e.g., mechanical adjustment or cleaning) can be performed before they escalate to serious events, reducing unscheduled downtime by 52.2%. For critical failures, rapid response helps minimise material losses and protect the integrity of personnel and equipment. This implementation not only optimises industrial electrical safety but also generates significant savings in maintenance and equipment replacement costs, establishing itself as a scalable solution that can be adapted to different industrial environments that comply with industry principles and data-driven predictive maintenance.

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