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Application of the IoT concept and open-source platforms for condition monitoring of low voltage electrical panels

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***Abstract**: In an increasingly dynamic, complex and competitive market, an adequate maintenance strategy is essential for companies to get their processes and equipment operating safely and reliably, in aiming to meet quality requirements and reduce overall costs. In this assumption, the implementation of condition monitoring solutions plays an important role in Maintenance Management. This work aims to present a development of a low-cost equipment prototype based on IoT (Internet of Things) concepts and technologies with the application of an ESP32 microcontroller and open-source platforms intending to monitor electrical and environmental data from an electrical panel, as well as using the concept of Big Data for the construction of a model for providing data for health prognosis and failure prediction of electrical equipment. Bench tests and sensor calibration were conducted to validate the consistency of sensor readings and for guarantee the measurement in the database. For installation in an industrial environment, thresholds were set for each variable in a monitoring software which allows for sending alerts, identifying measurement deviations and composing maintenance/performance indicators based on electric current, voltage, humidity, temperature, pressure, active power, reactive power and power factor, besides opening/closing some equipment and physical MCC doors.*

Keywords: maintenance management; internet of things (IoT); ESP32 microcontroller; electric panel; open source IoT platform

1 Introduction

The globalized economy has caused an increased demand for better performing products and systems at competitive costs. Simultaneously, the need arose to reduce the likelihood of product failures, whether failures that simply increase product-related costs or failures that could pose security risks.

In this context, the role of maintenance has been receiving more and more attention in manufacturing as companies understand that well performed industrial maintenance can be a strategic factor in achieving corporate objectives, including cost reduction, increased productivity and plant availability, improving safety and quality of products/processes, meeting delivery deadlines and reducing risks (Ghani, Kumari and Ahmad, 2022; Aburakhia and Alshayeb, 2024; Cao and Alyousuf, 2025).

Seeking ways to predict the equipment lifespan, and under which conditions they need to operate so that this time is better used, is essential thus ensuring the availability and reliability of the industrial plant. Thus, having subsidies to carry out prognoses that allow acting at the right time, when the equipment is in the incipient stage of its failure mode, can represent the opportunity to reduce direct and indirect maintenance costs (M. C. Santos, 2019; Elmaadawy, El Hassan and Sallam, 2024). And also, one of the great challenges of maintenance teams.

With the emergence of Industry 4.0, maintenance is considered vital for the survival of production companies in a demanding environment and competitive market (Roda, Macchi and Fumagalli, 2018;

Jasiulewicz-Kaczmarek and Gola, 2019), in which specific actions can consolidate a competitive advantage (Tran Anh, Dabrowski and Skrzypek, 2018). Among them, we can highlight the development and implementation of efficient maintenance strategies based on trends for the predictive approach, exemplified by the Prognosis and Health Management (PHM) and Condition Based Maintenance (CBM) techniques, driven by using technologies such as Internet of Things (IoT), cloud computing, advanced data analysis and augmented reality (Kiangala and Wang, 2018; Toloo and Mirbolouki, 2019; Ruiz-Sarmiento et al., 2020; Zhong et al., 2020; Ghani, Kumari and Ahmad, 2022).

Still in this parallel, it can be said that the emergence of the Internet of Things (IoT) and the Industry 4.0 paradigm paved the way to improve the monitoring capabilities (Einabadi, Baboli and Ebrahimi, 2019) of companies with the extensive use of physical and virtual sensors to identify significant insights about the performance of the business and/or predict undesirable situations and therefore allow engineers to decide and act proactively (Praxedes and Alvares, 2019). This path is even more accessible with the insertion of low-cost electronic sensors in the market (Belchior, Ribeiro and Carvalho, 2016; Ferreira, 2019).

Within this context, a fault detection system in electrical panels should be seriously considered as part of the manufacturing strategy, both for cost and safety reasons, since the availability and reliability of the substations and electrical equipment in which they are inserted are essential for running any business (D. M. P. Santos, 2019; Silva, 2019; Ahmed et al., 2024). In this way, through the use of a network of sensors, one can led to significant gains in productivity and product quality through a diagnostic system (Ferreira, 2007).

The merit of this research can be attributed both in the industrial scope and in the scope of the scientific community, for the possibility of applying the concepts of industry 4.0 for solving real problems and capturing value in the maintenance function, by reducing the time of unavailability of the equipment, associated direct and indirect costs and optimized allocation of resources. Also noteworthy is the high potential for scalability for other types of equipment, which, based on the implementation of management and prognosis of the health of the machinery, can increase its performance, safety and reliability. In addition, it also justifies the effort to be made in terms of hardware and software for the development of the solution, the fact that it can cover the most diverse manufacturing segments, such as, for example, the service sector and hospital areas (Cunha, 2007; Lopes, 2010).

This work aims to develop a low-cost equipment prototype based on IoT concepts and technologies for monitoring and data collecting operating conditions of an electrical panel in an industrial plant. Additionally, it is intended to create a model that, based on these data, can generate alarms in anomalous operating situations, enable the creation of performance and maintenance indicators, and provide subsidies for the prediction of a potential failure.

2 Literature review

Academic works will be presented exploring the importance of industrial maintenance as a strategic tool for competitiveness for using this to optimize maintenance processes, such as: the approach and use of industry 4.0 technologies in the context of maintenance; predictive techniques combined with Artificial Intelligence, Neural Networks, equipment vibration analysis; use of embedded systems to develop predictive systems and leverage Condition-Based Maintenance; contribution of automation and monitoring systems in the maintenance dimension; applications of monitoring systems in specific electrical equipment such as transformers, circuit breakers, battery banks, photovoltaic systems, and a technique widely used in electrical maintenance, which is thermography (Ghani, Kumari and Ahmad, 2022; Aburakhia and Alshayeb, 2024; Elmaadawy, El Hassan and Sallam, 2024; Cao and Alyousuf, 2025).

In (M. C. Santos, 2019), the author develops a very complete approach in its research, by presenting and discussing the applicability of a maintenance plan focused on reliability in a company located in the city of João Pinheiro – MG, Brazil, in the immunized eucalyptus sector, in an automated production process, prioritizing the maximization of the availability of production equipment. At the end, in a consistent manner, improvements in the maintenance performance of the industry in question were presented, endorsed by the quantitative analysis of the performance of the main maintenance indicators. However, the work of this author (M. C. Santos, 2019) did not consider the use of Industry 4.0 tools in the maintenance program and its benefits, not even as a suggestion for future work.

By providing insights into the future role of maintenance in the context of Industry 4.0, (Roda, Macchi and Fumagalli, 2018) brings relevant information on how much maintenance can benefit from the digitalization of manufacturing, what are the challenges, threats and weaknesses involved in this process.

A barrier highlighted by the work is the cost involved in these technologies and the intrinsic difficulty in establishing the payback of an investment for the digital transformation of maintenance.

The term Maintenance 4.0 is used by (Jasiulewicz-Kaczmarek and Gola, 2019) to define the next generation approach to production equipment maintenance. Maintenance 4.0 is about predicting future failures in assets and ultimately prescribing the most effective preventive measure by applying advanced analytical techniques in Big Data on the technical condition, usage, environment, maintenance history and similar equipment elsewhere and, in fact, anything that can correlate with the performance of an asset (Jasiulewicz-Kaczmarek and Gola, 2019).

Bringing the focus more to predictive maintenance, in the context of the digitalization of the industry, (Tran Anh, Dabrowski and Skrzypek, 2018) points out this strategy as an important tool for optimizing maintenance processes and achieving financial performance for corporations to survive in the demanding and competitive modern market (Zhong et al., 2020). In this perspective, maintenance is no longer seen as a direct cause of costs for the business and begins to add value to the production chain by facilitating highly efficient and reliable production or service. By outlining the most diverse maintenance strategies, including their characteristics, advantages and disadvantages, as well as (Tran Anh, Dabrowski and Skrzypek, 2018; Jasiulewicz-Kaczmarek and Gola, 2019) considers that a limitation still present in the application of predictive maintenance is the high investment involved, not only in terms of hardware, but also in investment in data science and/or physical expertise, in order to develop models, algorithms and decision-making strategies. decision based on collected data (Toloo and Mirbolouki, 2019).

When investigating work that explores a more specific application of industry 4.0 technologies in the maintenance environment, the case study of (Ruiz-Sarmiento et al., 2020), in a hot rolling process for the production of stainless-steel sheets, is a good example that the interaction between predictive maintenance and the digitalization of manufacturing is already a reality. Through a prognostic model based on Artificial Intelligence (AI), intelligent scheduling of maintenance operations becomes possible to maintain high plant efficiency.

Another work that demonstrates an interesting practical application was conducted by (Kiangala and Wang, 2018), in which data generated by vibration sensors feed a fault detection model in electric motors on a conveyor belt at a bottling plant. For such, (Kiangala and Wang, 2018) they use a well-known platform in the industrial automation environment, a combination of a SCADA system (Supervision and Data Acquisition System) and PLC (Programmable Logic Controller).

Introducing the theme of cost optimization more explicitly and relevant maintenance indicators such as the RUL (Remaining Useful Life) of equipment in an automotive industry, (Einabadi, Baboli and Ebrahimi, 2019) show that it is possible to carry out work that brings a balanced interaction between theory and practice, involving the universe of factory floor maintenance and the development of an Artificial Neural Network of sensors to create a mathematical model for planning and scheduling optimized interventions.

When looking for work that associates the use of the Arduino platform as an element to reduce costs in the implementation of Condition-Based Maintenance, the work developed by (Praxedes and Alvares, 2019) is a great example of this combination, when developing a Condition-Based Supervision, Control and Maintenance System for Photovoltaic Solar Generation Plants within the IoT Concept, using 2 Arduino microcontrollers, a Raspberry Pi 3 embedded computer and free software (Jean, Brasil and da Silva, 2023; Lima et al., 2024).

Another example of the use of Arduino in this context of predictive maintenance can be seen in (Ferreira, 2019) in the implementation of a continuous monitoring system and acquisition of parameter data to predict the state of conservation in three-phase electric motors. In this sense, it is imperative to use IoT, Machine Learning, Big Data and Analytics tools and the use of an embedded computer (Raspberry Pi) as a data hub or a cloud computing environment (Aburakhia and Alshayeb, 2024; Ahmed et al., 2024).

The author (D. M. P. Santos, 2019) deals with the use of an architecture that meets the requirements of industry 4.0 in a television factory in industrial welding equipment, with the application of the Systematic Mapping (MS) research technique to identify the methods used to implement predictive maintenance in the industry, with the aim of creating an application to collect real-time data from a machine and create predictions about possible future failures.

The author in (Silva, 2019) satisfactorily presents the gains in financial terms of having a predictive approach to maintenance, by exploring the use of event list data, pickups, dropouts, oscillography of existing protections in IEDs (Intelligent Electronic Devices) correlated with knowledge existing in the literature for power equipment, in order to predict their operational condition in real time, making it possible to adopt new strategies for the maintenance of existing equipment at Eletronorte, a Brazilian energy distribution company. It is worth highlighting that the cost of implementing this prediction system in terms of hardware and software is practically zero in companies in the electrical sector, as they already have IEDs in their substations for the purpose of protecting equipment.

A proposal for an integrated automation model for the maintenance and operation processes of the electrical energy system was presented by (Ferreira, 2007), identifying the main engineering functions that must be developed and implemented in the various automation systems of companies in the electrical sector, prioritizing a systemic integrative vision between the real-time operation and maintenance processes linked to transmission lines of electricity companies.

A maintenance model supported by specialized computational tools was proposed by (Cunha, 2007) aiming to meet the needs and shortcomings of the maintenance areas of energy utilities and companies in the industrial electrical sector. Presupposes an integrated and transcendent way allowing to minimize the risks of blackouts, both electrical and managerial, and, consequently, contribute to the sustainable development of the electrical sector.

The thesis (Lopes, 2010) proposes the application of a risk management methodology in the operation, maintenance and monitoring of power transformers and details actions to improve their operation and maintenance. This methodology aims to identify which of the monitored equipment would be most prone to failure. The author of (Lopes, 2010) attributes an innovative character to his research because the adoption of studies on risk management and identification techniques, with their application to the maintenance, monitoring and operation of transformers is not addressed in the technical literature.

Considering Condition-Based Maintenance (CBM), (Yano et al., 2017) applied this concept to monitoring and diagnosing the mechanical condition of gas-insulated electromagnetic vacuum circuit breakers from 7.2kV to 84kV, through the analysis of the current profile of the actuator operating coil. This system was able to predict the mechanical condition of the circuit breaker, without the need to install a displacement sensor, which cannot be easily monitored just by placing the displacement sensor, as the contact is enclosed in the vacuum valve.

The authors (de la Peña Llerandi, de Mingo and Ibáñez, 2019) present another condition-based maintenance technique, applied to Uninterruptible Power Supplies (UPS) of the Madrid Metro train, based on a low-cost prototype for continuous measurement of the internal resistance of platform-based seat lead-acid batteries Arduino prototyping system. The authors demonstrate the potential and versatility of low-cost embedded systems as an alternative for solving problems encountered in the industrial environment and point out as a gap to be covered the availability of information collected by the system in a maintenance center, via WiFi, radio or 4G, instead of storing data on a micro-SD card.

About preventive maintenance, (Ng and Teoh, 2019) point out the importance of using preventive maintenance based on thermal images to guarantee the safe operation of the electrical system, as they are capable of detecting, in advance, a possible failure by monitoring the abnormal rise in temperature in electrical equipment. The authors developed a low-cost thermal camera using embedded hardware, such as a Raspberry Pi 3, a MLX90640 32x24 pixel thermal sensor, a Pi NoIR camera and a 7" touchscreen display for continuous monitoring of electrical equipment, through measurement of temperature without contact and triggering of alerts in case the measurement exceeds a pre-determined value. Just like in (de la Peña Llerandi, de Mingo and Ibáñez, 2019), once again, the potential and versatility of low-cost embedded systems for solving problems encountered in the industrial environment was demonstrated.

In accordance with (Mariprasath and Kirubakaran, 2018), by using the appropriate maintenance technique, it is possible to significantly increase the useful life of a transformer, up to 60 years, compared to an average life expectancy of around 20 to 35 years. As contributions of this work, it can mention the detailed analysis of transformer condition monitoring methods, weighing their advantages and limitations. Another point to highlight was the presentation of case studies in which transformer thermography was used to predict possible failures in transformers for determining recommended actions, such as: load profile analysis, oil analysis/replacement and bushing cleaning.

Still in the context of maintenance based on (CBM) in transformers, (Al Mhdawi and Al-Raweshidy, 2020) start from a problem that is related to the availability of electricity supply in Iraq. This is affected by failures in distribution transformers, mainly due to overload because of the sudden increase in demand. To improve the reliability of distribution lines, the authors propose an IoT system based on a combination of an Arduino microcontroller, LORA (Long-Range) WAN (Wide Area Network) long-range transmitters/receivers and a custom Software-Defined Network (SDN) wireless, redundant, fault-tolerant and self-recoverable for remote monitoring and failure prediction using artificial neural network algorithms, with a prediction accuracy of 96.1%.

In another work that reinforces the application of IoT platforms as a tool for implementing CBM, (Gong et al., 2022) reports the application of a completely open-source platform for monitoring a photovoltaic power generation system located in Spain, with 3MW of power, consisting of 24 inverters and 156 string boxes. This time, the IoT gateway hardware selected was the MOXA UC-2112-LX microcomputer, the IoT Edge Framework Eclipse Kura as software, and the Eclipse Kapua cloud platform. The imperative to reduce costs with infrastructure, hardware, technical support and licenses, as well as a more comprehensive integration with third-party software motivated the search for an alternative to the current system based on the conventional PLC + SCADA solution.

The authors (Lopez-Vargas, Fuentes and Vivar, 2019) describe the implementation of a datalogger prototype developed in Arduino, capable of monitoring up to 14 electrical and environmental parameters in small isolated rural photovoltaic power generation systems, with the accuracy required by the IEC61724 standard (Photovoltaic system performance), and 3G connectivity for monitoring remote, with the aim of improving the maintenance process of several Stand-Alone PhotoVoltaic systems (SAPV), or geographically isolated off-grid generation units (Ammar et al., 2023).

The paper (Medina-Santiago et al., 2020) developed a technique and method for real-time measurements based on sensor fusion (DHT22) and embedded systems (Arduino Uno + Ethernet shield); with connectivity to the communication network in the generation of a dedicated database for information processing; with open software and hardware resources for monitoring in a humid tropical climate region, in Mexico. With the data collected by the system, they observed that in certain periods of time the humidity values exceeded the established ranges, which supported the recommendation to purchase a dehumidifier or a suitable refrigeration system for the system.

Moving towards practical applications of the use of IoT-based systems, the work of (Jacob and Mani, 2018) drew attention for addressing the need to create a generic model to validate and verify the performance and efficiency of IoT devices in all aspects, in a more comprehensive way, integrating software, hardware and communication protocols. After experimental application of the model in a case study for intrusion detection system (IDS) using IoT (based on Raspberry Pi with Windows 10 IoT core, PIR (Passive Infrared) motion sensor, and a camera), (Jacob and Mani, 2018) found that this model can be used as a reference model for IoT developers to evaluate the performance and capabilities of an IoT system in an efficient and cost-effective manner, with reduced testing time, support for concurrent testing, and improved reliability.

The capacity, flexibility and robustness of using embedded and prototyping platforms in the implementation of IoT systems for continuous monitoring of variables of interest was evident, in order to leverage the Condition-Based Maintenance (CBM) process, as well as improve Predictive techniques.

The vision of the strategic function of maintenance is peaceful, and the vast majority presented implementations of CBM, but there is an opportunity to enhance the gains obtained through industry 4.0 tools, and/or low cost, in addition to exploring elements such as maintenance management. Another gap to be explored is the demonstration of improvement in maintenance indicators after the implementation of process improvements.

In this way, the main gaps to be explored by the research in question can be listed as the need to complement existing scientific production with regard to the practical applications of industry 4.0 in the maintenance environment, to produce a solution that does not require high investments and that explore not just the detection of equipment failures, but all the developments involved in maintenance management as a whole (improvement of system reliability, improvement in maintenance performance indicators, elimination of recurring failure modes, construction of a historical of failures for subsequent analysis, among others).

3 Methodology and developments

The work object of the paper explores the results obtained in phases 2, 3 and 4 described in Figure 1, which represents the whole structuring of work.

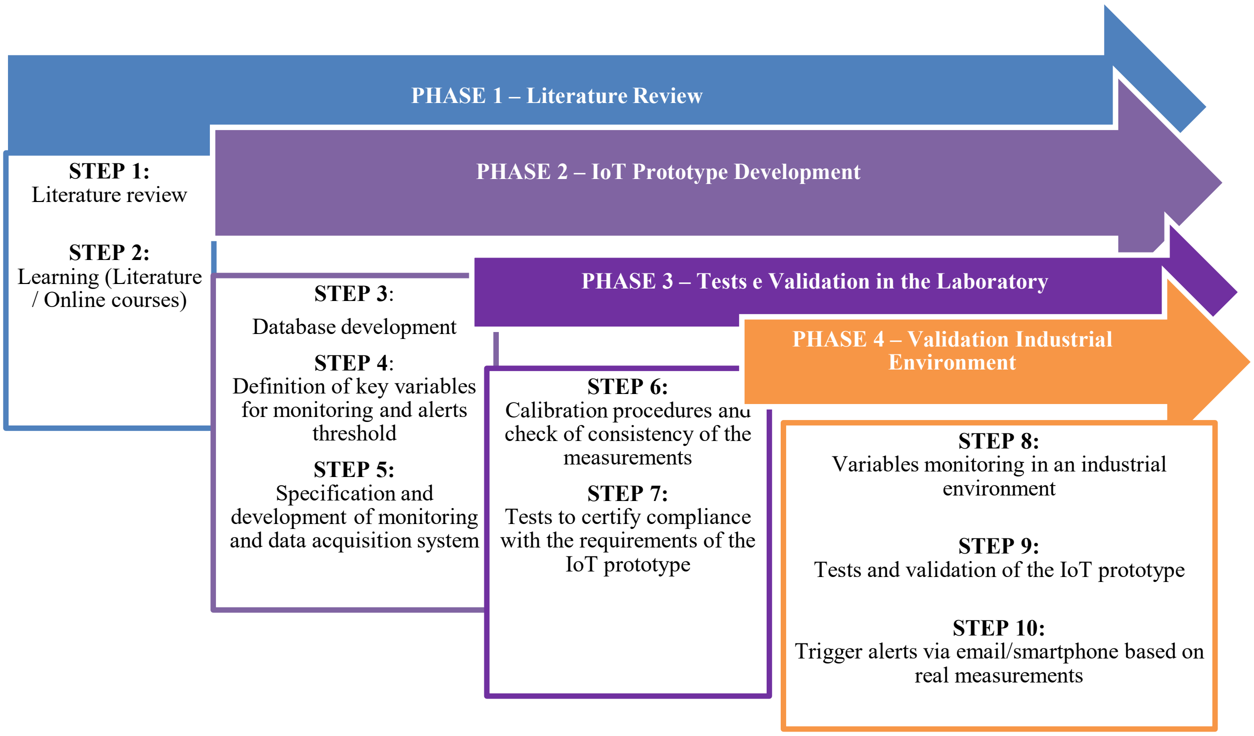


Figure 1. Research Phases and steps.

During phase 2, a survey was carried out to determine all the necessary hardware and software to meet the functional requirements of the solution, elaboration of the specification and development of the database that allows storing information to help the process of identifying the root cause of the failures of the equipment. In addition to the specification and development of the prototype of the monitoring and data collection system for the electrical panel to be studied. The list of components that were used can be viewed in Table 1:

Table 1. System hardware list.

Item	Quantity	Function
4G modem	1	Cloud database connection
ESP32 microcontroller	1	Monitoring system controller
5VDC power supply	1	Controller and sensors Power supply
24VDC power supply	1	Digital inputs Power supply
DS18B20 Temperature Sensor	3	Temperature monitoring at strategic points
Electrical magnitude sensor PZEM-04T	1	Monitoring of electrical data Engine 1
Humidity, Temperature and Pressure Sensor BME280	1	Monitoring of environmental conditions and performance of the exhaust system
Current sensor SCT013 100A	1	Engine 2 current monitoring
8 channel optocoupled isolator module	1	Digital input signals isolation
Micro limit switch 1NO+1NF	8	Panel door opening detection
Auxiliary contact 1NC	1	Contactor status monitoring
Auxiliary contact 1NC	1	Trip breaker monitoring

Table 2 lists the components of the prototype, unit costs and global solution.

Table 2. Estimated Cost.

Item	Quantity	Unit Cost (USD)	Total Cost (USD)
4G modem	1	$ 108.16	$ 108.16
ESP32 microcontroller	1	$ 3.15	$ 3.15
5VDC power supply	1	$ 3.72	$ 3.72
24VDC power supply	1	$ 3.85	$ 3.85
DS18B20 Temperature Sensor	3	$ 0.55	$ 1.65

Item	Quantity	Unit Cost (USD)	Total Cost (USD)
Electrical magnitude sensor PZEM-04T	1	$ 5.09	$ 5.09
Humidity, Temperature and Pressure Sensor BME280	1	$ 1.97	$ 1.97
Current sensor SCT013 100A	1	$ 3.71	$ 3.71
8 channel optocoupled isolator module	1	$ 0.85	$ 0.85
Micro limit switch 1NO+1NC (included in the panel)	8	-	-
Auxiliary contact 1NC (included in the panel)	1	-	-
Auxiliary contact 1NC (included in the panel)	1	-	-
Total Cost:	-	-	$ 132.15

In Figure 2, which is composed of 2 photos, in which the one on the left side (Figure 2a) depicts a general view of the control panel where the circuit was assembled and the one on the right side (Figure 2b) shows an enlarged view of frame mounting plate with system components.

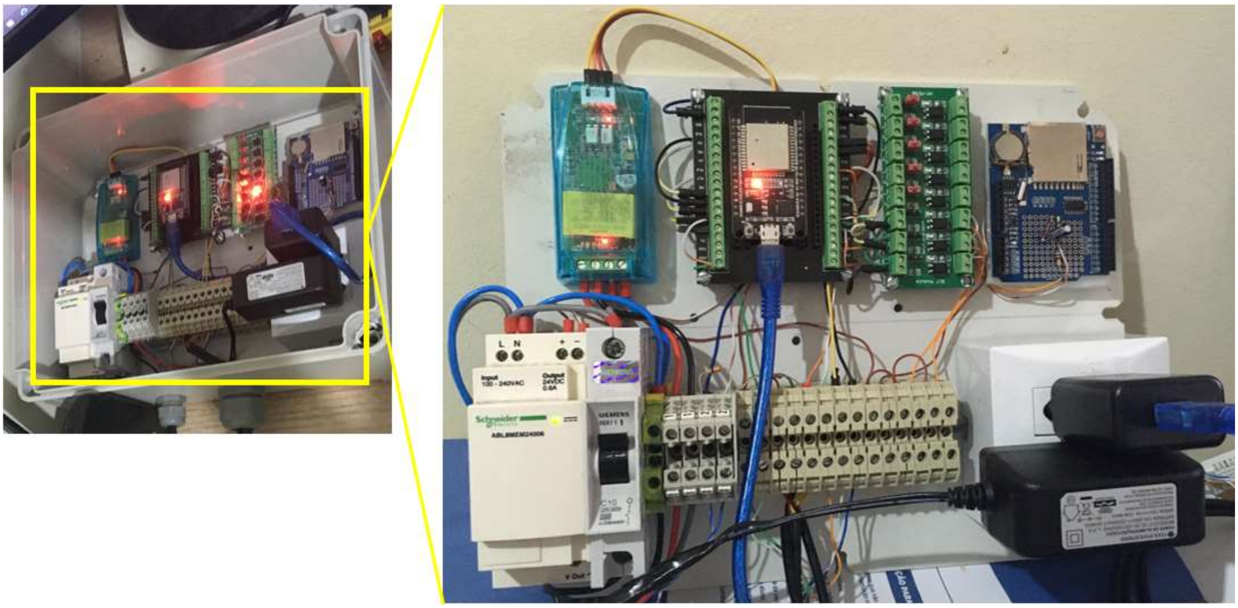


Figure 2. Assembly of the prototype in a 215mm x 265mm control panel.

The software chosen for the development of the research is categorized as “open source”, that is, it does not require the acquisition of licenses for use. This premise was adopted to ensure the implementation of the solution at a low overall cost. Table 3 lists the software with their respective functions:

Table 3. System software list.

Software	Version	Function
Tasmota	11.1.0	ESP32 Programming
InfluxDB	2.3.0	Database
Mosquitto	2.0.14	Broker MQTT (Message Queuing Telemetry Transport)
Grafana	8.2.3	View Dashboards and trigger alerts
Node-Red	2.1.3	Entering data into the database

Figure 3 schematically illustrates the flow of information, from the transduction of the monitored variables into electrical signals by the sensors; conversion into an engineering unit and data publication via MQTT (Message Queuing Telemetry Transport) protocol by ESP32; writing in the InfluxDB database through Node-Red and visualization of data in the form of Dashboards composed of indicators in Grafana.

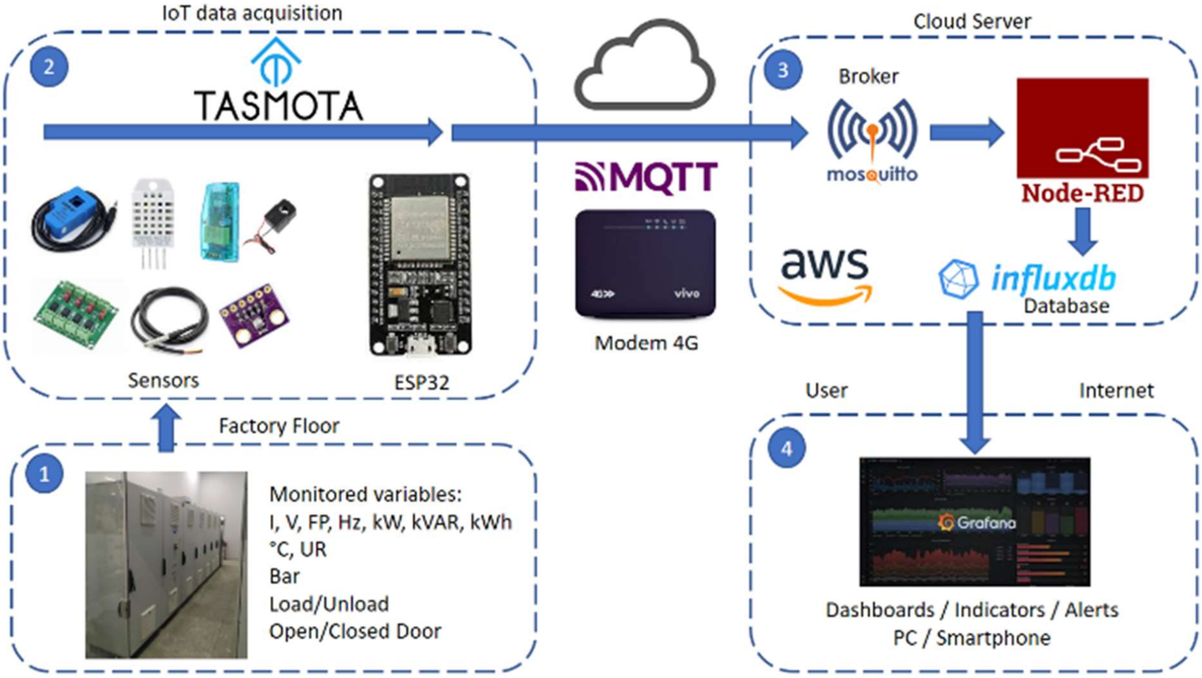


Figure 3. System communication topology.

It is also planned in this phase the definition of which variables should be monitored, as well as the respective theoretical alert limits, to be adjusted later in the practical application.

In phase 3, called "Tests and validation in the laboratory", tests were carried out to certify compliance with the requirements of the prototype, in order to identify deviations and treat them in a timely manner. It is worth mentioning that in this phase, procedures were also carried out to calibrate the sensors throughout the measurement range and verify the consistency of the measurements in relation to standard reference instruments.

The following calibration procedures were conducted:

1). Comparison of the measurements of the DS18B20 temperature sensors against a portable digital thermometer – model TH-095 from the manufacturer Instrutherm, in an ice water bath, which was heated until the mixture boiled;
2). Measurement of electric current in a series circuit composed of a shower resistance, confronting the non-intrusive current sensors CT1 and CT2 against an ammeter clamp model ET-3200 from the manufacturer Minipa;
3). Comparison of temperature and relative humidity measurements of the BME280 sensor against a Thermo-Hygrometer with data logger model HT-4000 from ICEL, in an enclosure in which variations in the variables of interest were simulated with the aid of a portable ultrasonic humidifier 25W and a 2000W hair dryer.

In phase 4 called "Tests and validation in an industrial environment", the prototype was installed in an industrial environment, in order to prove its robustness and ability to perform its functions to which the electrical panel is inserted. That is, it is immune to the presence of vibrations, noise and electromagnetic fields, high temperatures, among other characteristics typical of the industrial environment.

This is a cereal milling industry, located in the state of Goiás, where the three-phase MCC (Motor Control Center) was selected as a pilot, rated voltage 380VAC, rated current 1,000A, to which the critical loads of the milling process are connected, as can be seen in Figure 4.

Figure 4. Target monitoring MCC.

The drives selected as critical for monitoring are responsible for the first wheat milling through a bank of cylinders, which is crucial equipment for the process. If this equipment stops, all subsequent equipment stops due to interlocking and, consequently, the entire wheat milling process.

In this way, the state of the drive (operating, operating idling or stopped) determined by the value of the electric current can be used to compose the indicators of Physical Availability and OEE (Overall Equipment Effectiveness) of the bank of cylinders, and by extrapolation the milling process.

In this phase, the alert thresholds of the variables of interest were adjusted based on the observed behavior of the real measurements and the triggering of alarms via cell phone or e-mail of a potential failure was implemented, which would allow planning a more effective intervention. The main product of this phase is understood to be the proposition of an intervention plan based on monitoring the condition of the equipment and analysis of standards, which aims to minimize maintenance costs, recurrence of failures and operational risk.

4 Result’s analysis

4.1 Sensors calibration

For the calibration of the DS18B20 contact temperature sensors, a portable digital thermometer – 2 channels – model TH-095 from the manufacturer Instrutherm, equipped with 2 J/K thermocouples (T1 and T2 respectively) was used as a reference instrument. The resolution, scale and precision of the thermocouples can be seen in Table 4.

Table 4. Termocouples K and J.

Sensor Type	Resolution	Range	Accuracy
Type K	0.1°C	-50.0 a 1300.0°C	± (0.4% + 0.08°C)
		-50.1 a -199.9°C	± (0.4% + 1°C)
Type J	0.1°C	-100.0 a 1100.0°C	± (0.4% + 0.08°C)
		-50.1 a -199.9°C	± (0.4% + 1°C)

Measurements from DS18B20 sensors were compared with the average between measurements from thermocouples T1 and T2, as per Table 5.

Table 5. Temperature readings in °C recorded during calibration of DS18B20 sensors.

Data	DS18B20-1	DS18B20-2	DS18B20-3	T1	T2	AVG (T1;T2)
2022-11-01 09:26	25.5	25.1	25.2	24.7	25	24.85
2022-11-01 09:35	0.2	-0.2	-0.2	1	0.3	0.65
2022-11-01 10:03	14.1	13.6	14.1	14	14.4	14.2
2022-11-01 10:08	20.6	20.1	20.1	20.9	20.8	20.85
2022-11-01 10:17	32.2	31.9	32	32.3	32.2	32.25
2022-11-01 10:24	40.5	40.2	40.4	40.3	40.5	40.4
2022-11-01 10:34	50.8	50.5	50.7	50.7	50.9	50.8
2022-11-01 10:44	60.5	60.2	60.4	60.2	60.8	60.5
2022-11-01 10:57	71	70.9	71	71.3	71.7	71.5
2022-11-01 11:01	80.5	80.1	80.4	80	80.8	80.4
2022-11-01 11:05	90.7	90.2	90.5	90.7	90.7	90.7
2022-11-01 11:16	96.9	96.9	97.1	96.6	96.4	96.5

Based on the readings, it was possible to determine the calibration equation for each sensor, when applying a linear regression, as can be seen in Figure 5.

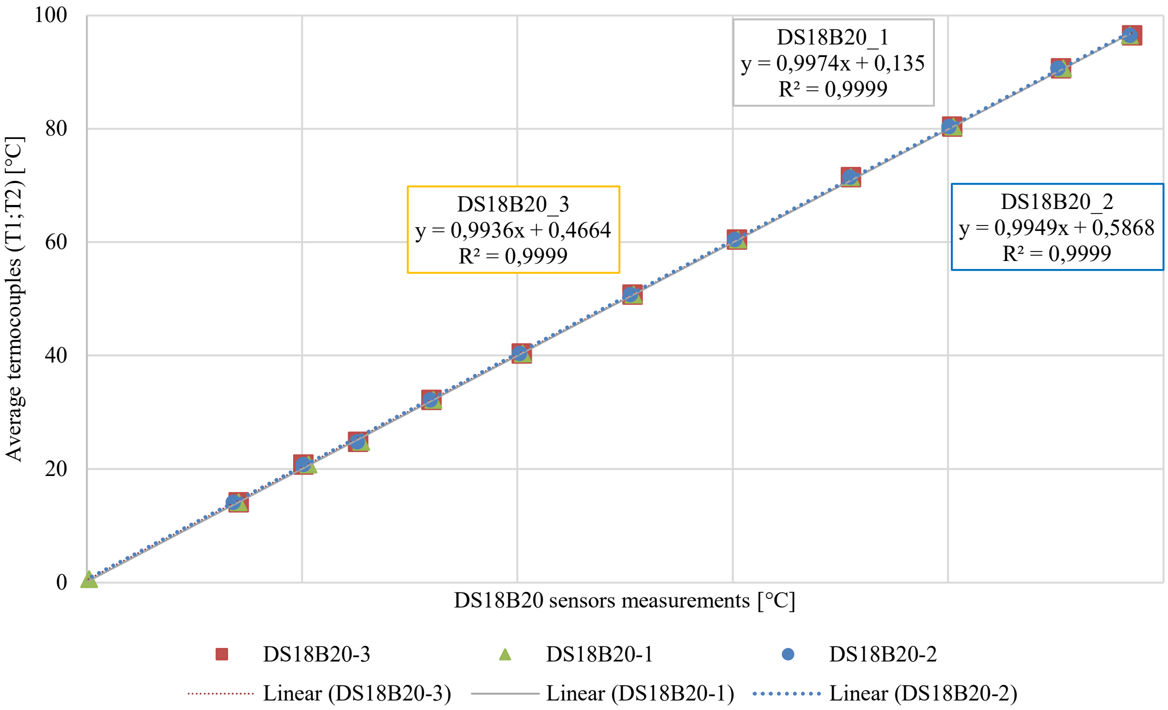


Figure 5. Calibration equations for DS18B20_1, DS18B20_2 and DS18B20_3 temperature sensors.

For the calibration of current sensors PZEM-04T and SCT-013, a digital pliers ammeter model Minipa ET-3200 was used as reference, with jaw opening of 50mm and accuracy of ±2.5% for the range of 20A, considering the room temperature in the range of 23ºC ± 5ºC and relative humidity < 80% (*Minipa do Brasil*, 2024). The precision and resolution for the measurement ranges used in the procedure can be seen in Table 6.

Table 6. Datasheet ET3200 - Alternating Current Measurement (AC). Source: (*Minipa do Brasil*, 2024).

Range	Accuracy	Resolution
20A	± (2.5% + 8 Digits)	10mA
200A	± (2.5% + 5 Digits)	100mA

The calibration procedure of the current sensors was carried out by assembling a series circuit using a flexible copper cable with a nominal section of 2.5mm² and a shower electrical resistance of 4600W at 220V, model 055B Lorenzetti, in its total length, resulting in an ohmic resistance of 18.2Ω.

As it is a purely resistive load, according to Ohm's Law, the expected current in the circuit can be calculated by dividing the assumed voltage at 220V by the resistance of 18.2Ω, obtaining 12.09A. In order to be able to simulate current values in the entire measurement range of the sensors (0 to 100A), turns were made in the main conductor through the windows of the current transformers (CT) and, at each increment, the measured current was recorded. The measured values can be seen in Table 7.

Table 7. Current readings in Amps recorded during calibration procedure.

Number of turns	PZEM-04T (A)	SCT-013 (A)	Ammeter (A)	Expected current 220V
0	12.623	9.721	13.14	12.09
1	17.447	18.198	26.3	24.18
2	37.846	28.048	38.8	36.26
3	51.169	39.122	51.7	48.35
4	64.765	47.019	69.1	60.44
5	77.054	56.075	80.1	72.53
6	89.865	68.457	98	84.62
7	103.363	79.187	112.8	96.70

From the readings, the calibration equations of the sensors were determined through a linear regression, as can be seen in Figure 6.

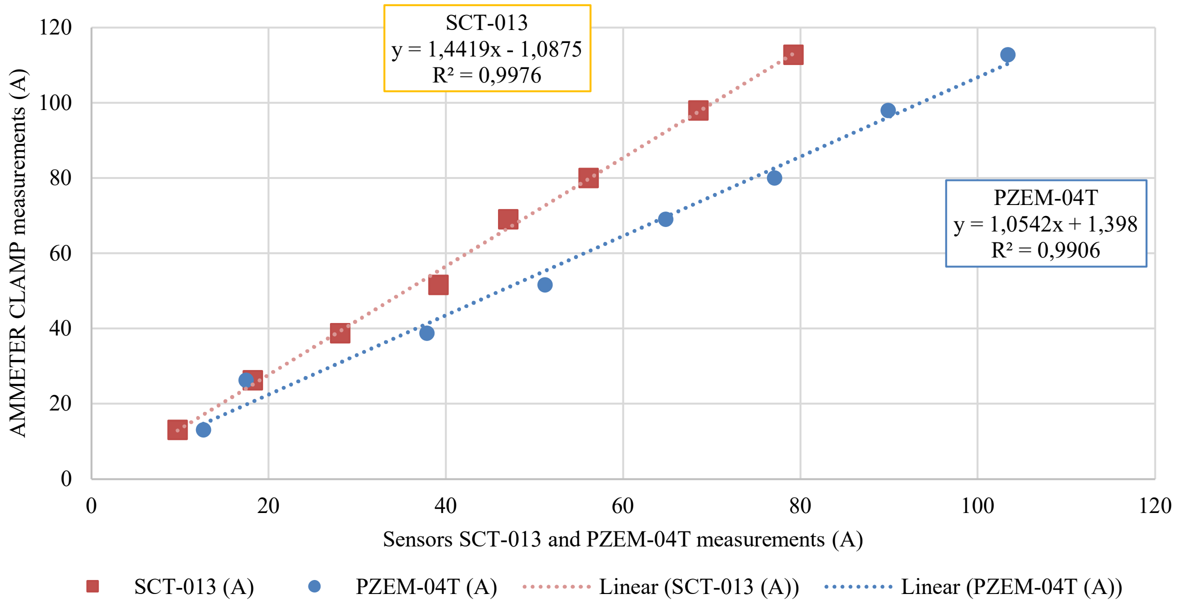


Figure 6. PZEM-04T and SCT-013 Sensor calibration equations

4.2 Installation of sensors in the field

In Figure 5, the installation location of the control panel and 4G modem for internet connection can be seen. In addition to the BME280 sensor, which has its application for monitoring the temperature inside the Motor Control Center (MCC) to observe whether it will exceed the optimum operating limit of the electronic components.

The relative humidity of the air, also monitored by the sensor, is relevant for the calculation and monitoring of the dew point, so that it is possible to detect situations of condensation inside the panel and mitigate them before they generate significant impacts.

Atmospheric pressure measurement will be used to assess the efficiency of the MCC exhaust/pressurization system. Still in Figure 7, it is possible to observe one of the micro switches installed on the panel door to identify if the doors are open, to preserve its interior against the presence of impurities present in the air.

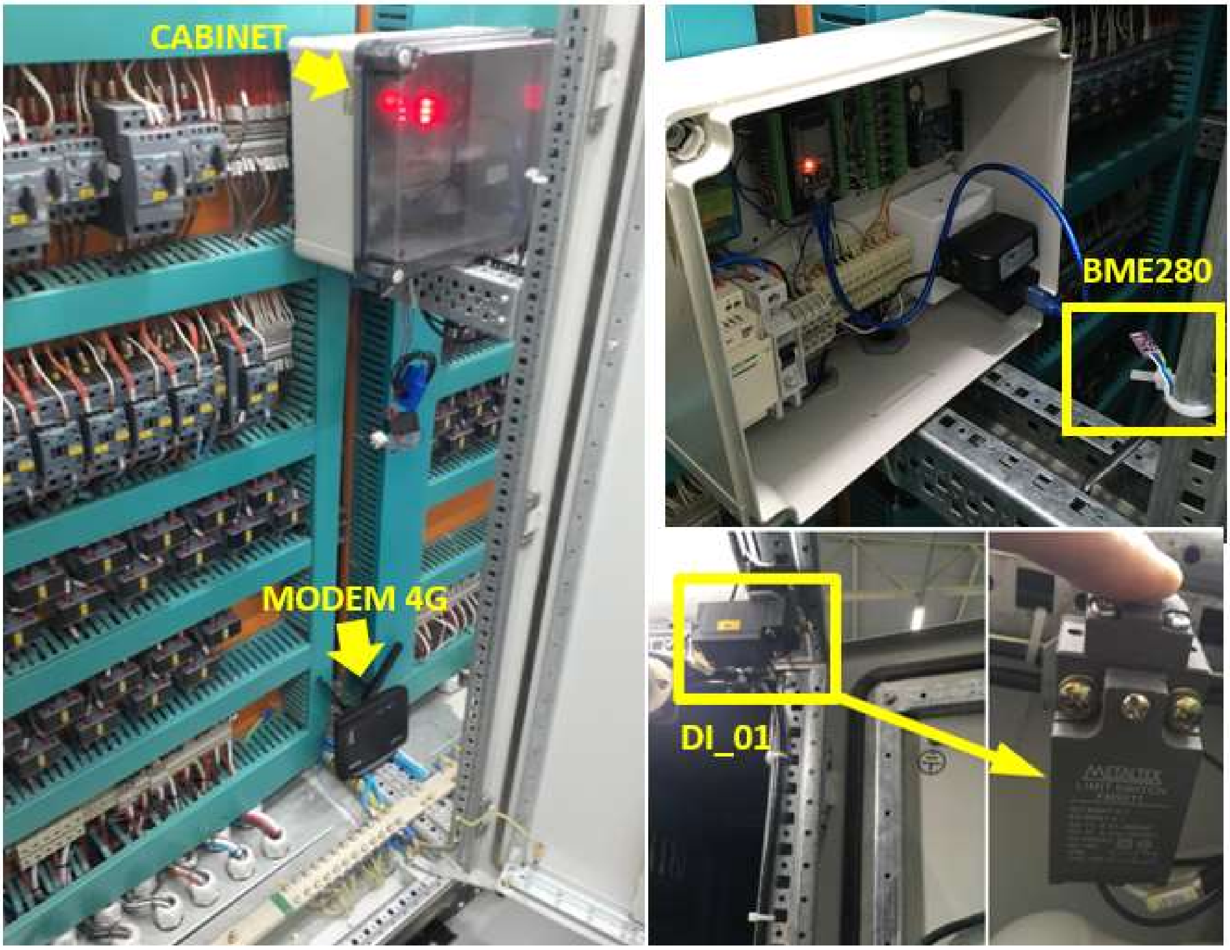


Figure 7. Overview of the prototype installation in the field. (a) left view of control panel and 4G modem; (b) upper right corner BME280 temperature, humidity and atmospheric pressure sensor; (c) lower right corner Micro Switch for open door detection (digital input DI_01).

Humidity monitoring is particularly important as it is related to failure modes associated with the corrosion process, triggered by high humidity (wet corrosion) or very low humidity (dry corrosion), condensation inside the panel and triggering of static electrical discharges (Alvan Prastoyo Utomo et al., 2019; Medina-Santiago et al., 2020).

The paper (Škultéty, Pivarčiová and Karrach, 2018) points out that moisture in electrical equipment penetrates the cracks and pores of insulation, especially older insulation, and provides low-resistance paths for leakage currents and potential sources of dielectric failure. Therefore, the presence of moisture will tend to lower the insulation resistance, reduce the ability to dissipate heat, and promote thermal aging and eventual failure.

Figure 8 shows the installation locations of the DS18B20 sensors responsible for measuring the operating temperature of the contactor and circuit breaker for activating the Motor of the Cylinder Bank BCT1_M1, and the ambient temperature of the column where the PLC (Programmable Logic Controller), which controls the operation of the Mill is installed.

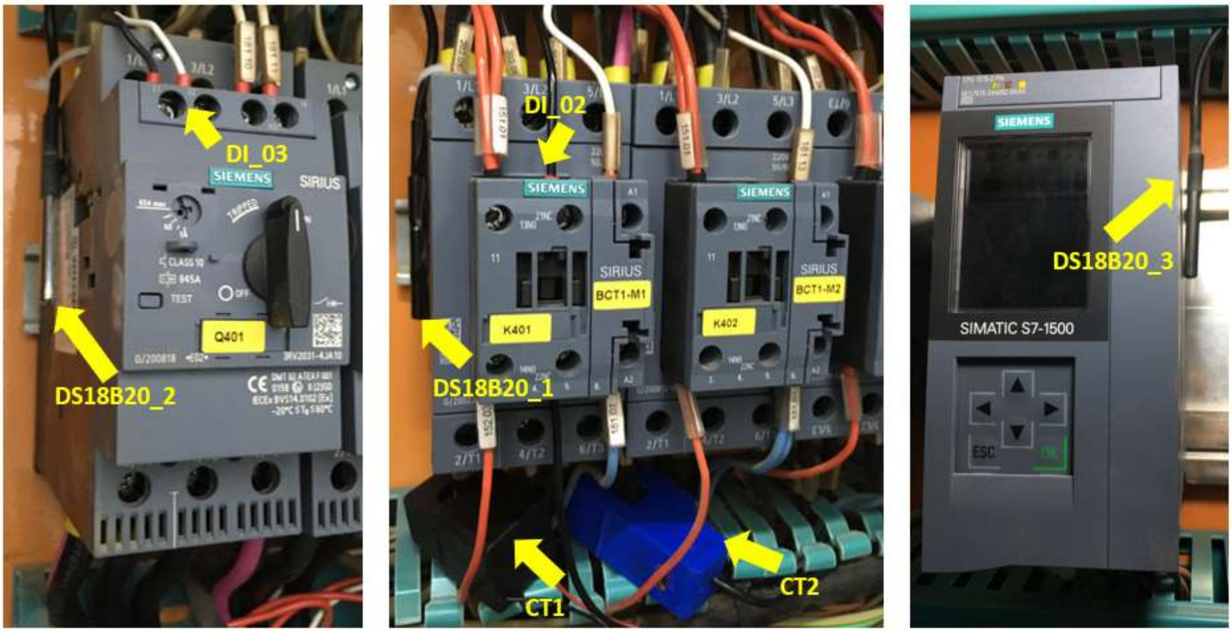


Figure 8. Installation locations for DS18B20 contact temperature sensors, CT1 and CT2 current sensors, and digital inputs for monitoring breaker and contactor status.

The installation of these sensors is relevant because temperature is considered one of the most important thermodynamic properties to determine the state of matter (Škultéty, Pivarčiová and Karrach, 2018) and its elevation is related to an exponential acceleration of the failure rate of electronic components (Yu et al., 2020), or may indicate the presence of poor contacts in connections (Usamentiaga et al., 2018), overload and/or deterioration of electrical cable insulation (Ahmad and Kamaruddin, 2012).

In (Willis and Rashid, 2009), the temperatures are added (even slightly above design levels) for prolonged periods can significantly shorten the electrical life of organic insulating materials. Insulation deterioration can eventually trigger malfunction, electrical failure due to physical disintegration of insulating materials, or complete loss of function.

4.3 Variable monitoring software

A screen in dashboard format was developed for the continuous monitoring of the following variables:
- Internal temperature of the MCC (°C);
- Internal temperature of the PLC cabinet (°C);
- Barometric pressure inside the MCC (hPa);
- Opening/closing of MCC doors;
- Relative humidity inside the MCC (%RH);
- Dew point inside the MCC (°C);
- Opening/closing of M1 motor contactor;
- Motor M1 circuit breaker tripped;
- M1 contactor operating temperature (°C);
- Electric current of phase R of motor M1 (A);
- Electric voltage of phase R of motor M1 (V);
- Active power of phase R of motor M1 (kW);
- M1 motor phase R reactive power (kVAr);
- M1 motor phase R power factor
- Electric current from phase R of motor M2 (A);
- Electric voltage of phase R of motor M2 (V).

Still in the software, the thresholds for each variable were configured, such as zones in which the green color indicates acceptable limits, yellow for tolerated values that require attention and the red color for values that exceed the operating limits recommended by the equipment manufacturers. As can be seen in Figures 9, 10 and 11.

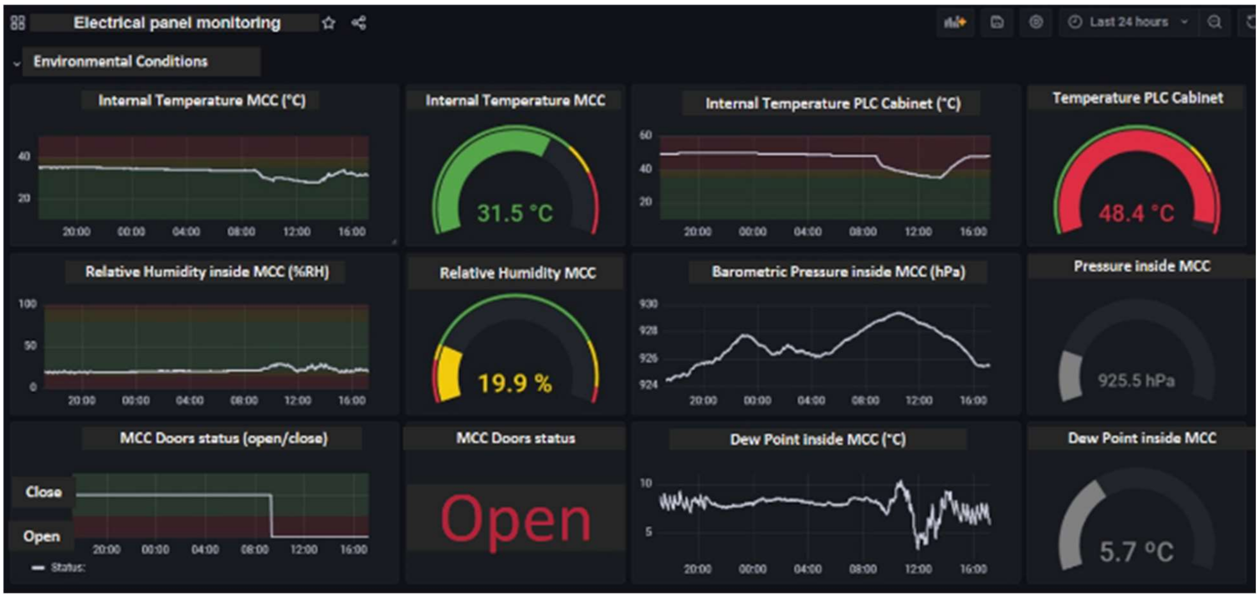


Figure 9. Dashboard monitoring - Environmental Conditions tab.

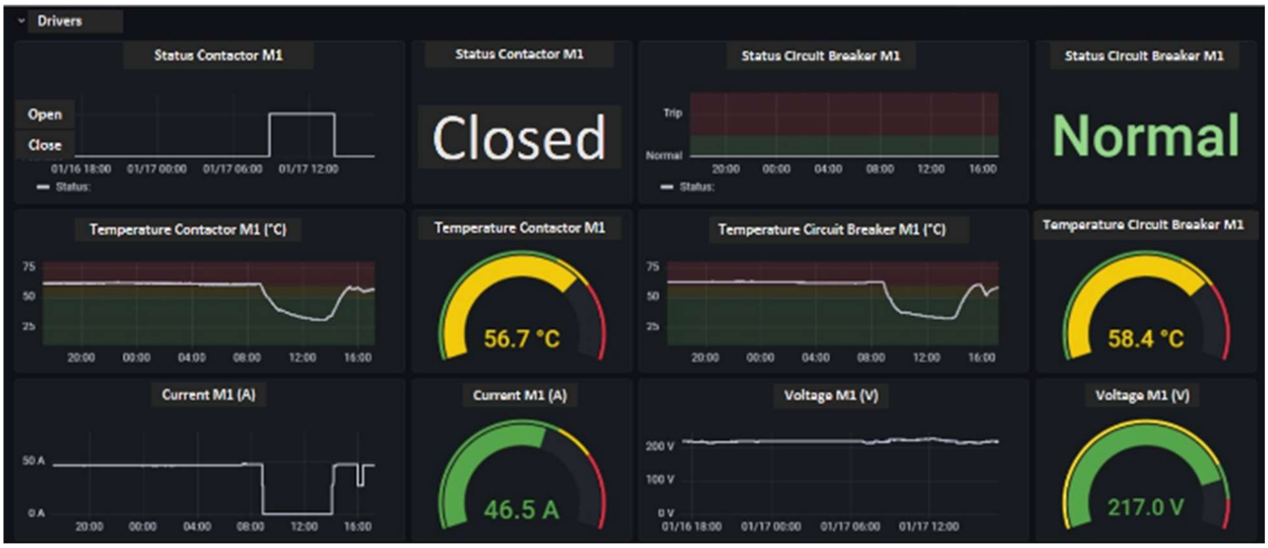


Figure 10. Dashboard Panel monitoring – Driver's tab.

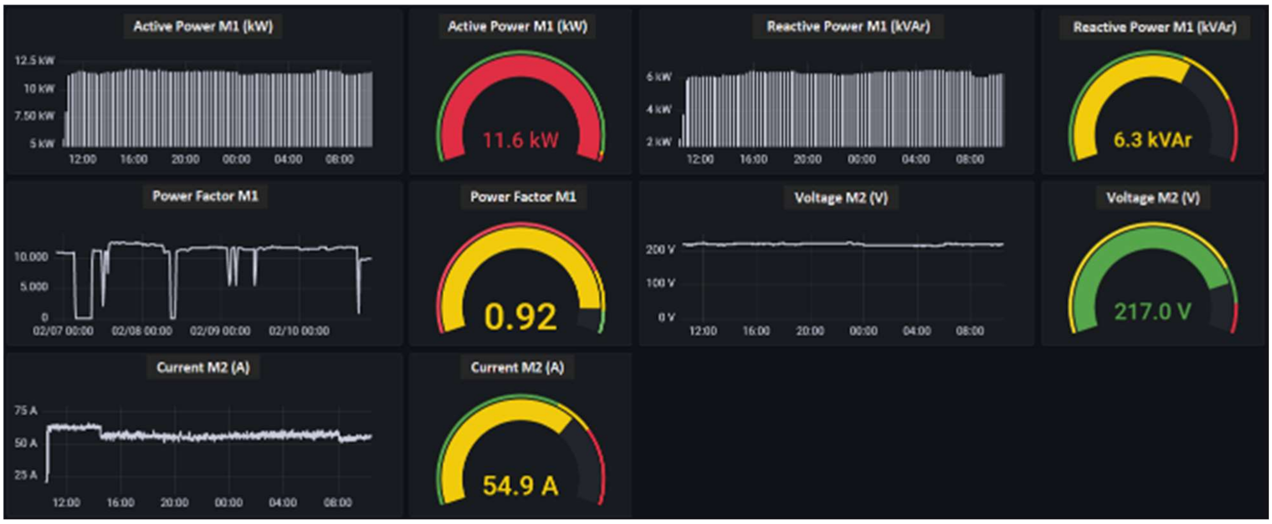


Figure 11. Dashboard Panel monitoring – Driver's tab.

Alerts were configured for the MCC door remaining open for more than 15 minutes, Circuit Breaker on Trip, Motor operating empty, Motor operating overloaded and Motor stopped. According to Figure 12.

ALERTS

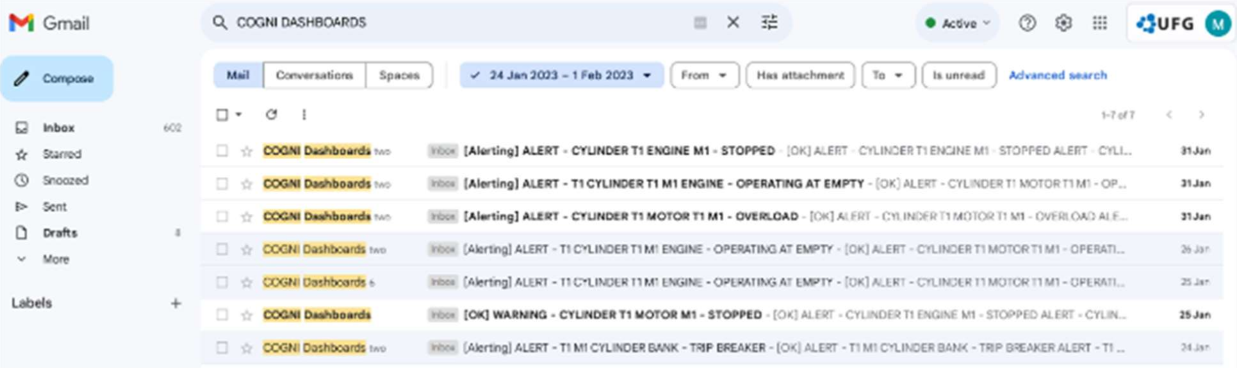
ALERT – CYLINDER T1 ENGINE T1 M1 – RUNNING WITHOUT LOAD
OK | jan 26, 2023 13:24:04

ALERT – CYLINDER T1 ENGINE T1 M1 – RUNNING WITHOUT LOAD
ALERTING | jan 26, 2023 13:23:06 | current {point_name=ENERGY_PZEM}=34.93939444444444

ALERT – CYLINDER T1 ENGINE T1 M1 – RUNNING WITHOUT LOAD
PENDING | jan 26, 2023 13:17:18 | current {point_name=ENERGY_PZEM}=34.24981944444445

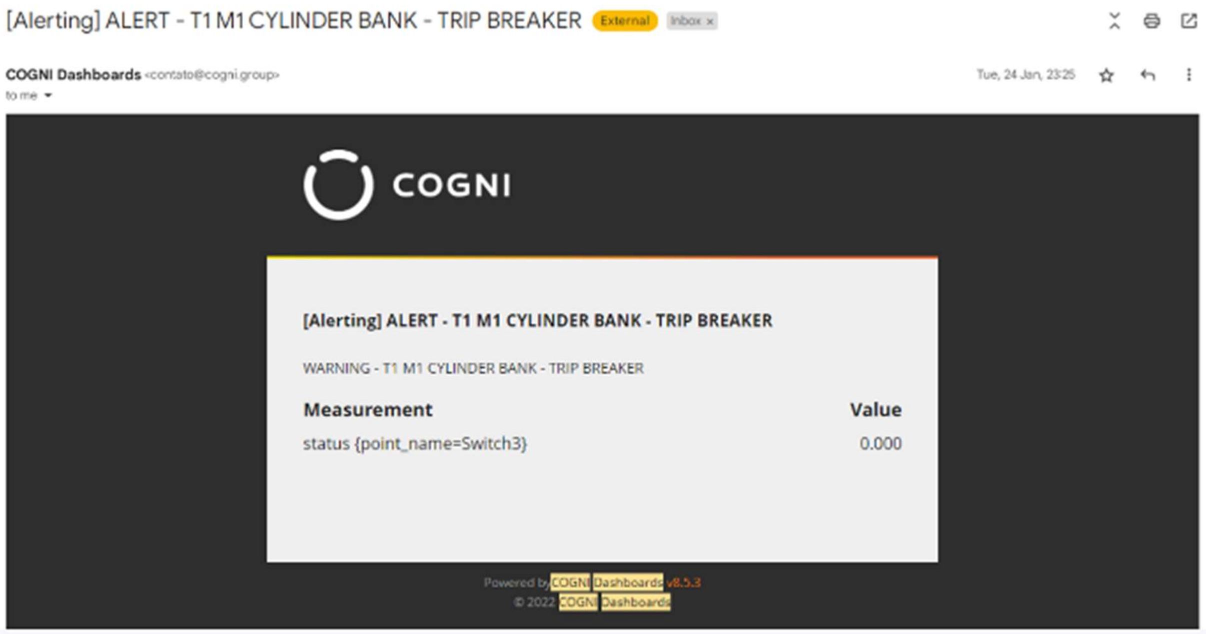
Figure 12. Alerts Module via email/Telegram.

These alerts are triggered automatically to a pre-configured Grafana broadcast list. Examples of alerts generated by e-mail are illustrated in Figure 13 and 14.



COGNI Dashboards two — Inbox [Alerting] ALERT - CYLINDER T1 ENGINE M1 - STOPPED - [OK] ALERT - CYLINDER T1 ENGINE M1 - STOPPED ALERT - CYLI... — 31 Jan
COGNI Dashboards two — Inbox [Alerting] ALERT - T1 CYLINDER T1 M1 ENGINE - OPERATING AT EMPTY - [OK] ALERT - CYLINDER T1 MOTOR T1 M1 - OP... — 31 Jan
COGNI Dashboards two — Inbox [Alerting] ALERT - CYLINDER T1 MOTOR T1 M1 - OVERLOAD - [OK] ALERT - CYLINDER T1 MOTOR T1 M1 - OVERLOAD ALE... — 31 Jan
COGNI Dashboards two — Inbox [Alerting] ALERT - T1 CYLINDER T1 M1 ENGINE - OPERATING AT EMPTY - [OK] ALERT - CYLINDER T1 MOTOR T1 M1 - OPERATI... — 26 Jan
COGNI Dashboards 6 — Inbox [Alerting] ALERT - T1 CYLINDER T1 M1 ENGINE - OPERATING AT EMPTY - [OK] ALERT - CYLINDER T1 MOTOR T1 M1 - OPERATI... — 25 Jan
COGNI Dashboards — Inbox [OK] WARNING - CYLINDER T1 MOTOR M1 - STOPPED - [OK] ALERT - CYLINDER T1 ENGINE M1 - STOPPED ALERT - CYLIN... — 25 Jan
COGNI Dashboards two — Inbox [Alerting] ALERT - T1 M1 CYLINDER BANK - TRIP BREAKER - [OK] ALERT - T1 M1 CYLINDER BANK - TRIP BREAKER ALERT - T1 ... — 24 Jan

Figure 13. Example of Alerts sent by the system by email.



[Alerting] ALERT - T1 M1 CYLINDER BANK - TRIP BREAKER External Inbox ×

COGNI Dashboards <contato@cogni.group>
to me
Tue, 24 Jan, 23:25

COGNI

[Alerting] ALERT - T1 M1 CYLINDER BANK - TRIP BREAKER

WARNING - T1 M1 CYLINDER BANK - TRIP BREAKER

Measurement	Value
status {point_name=Switch3}	0.000

Powered by COGNI Dashboards v8.5.3
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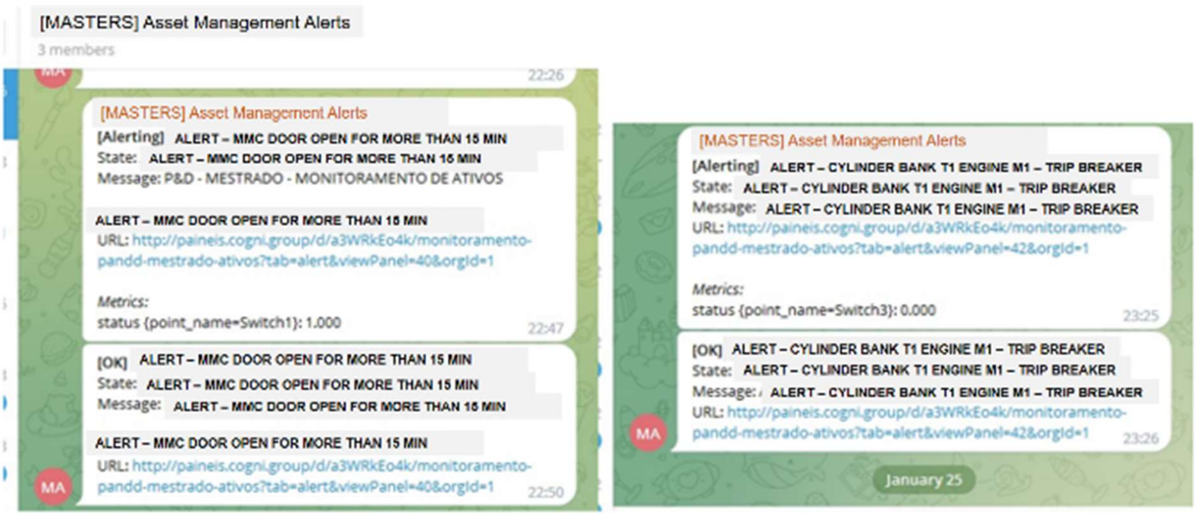
Figure 14. Example of the body of an alert email.

And Figure 15 illustrates examples of alerts sent via Telegram.



[MASTERS] Asset Management Alerts
3 members

22:26

[MASTERS] Asset Management Alerts
[Alerting] ALERT – MMC DOOR OPEN FOR MORE THAN 15 MIN
State: ALERT – MMC DOOR OPEN FOR MORE THAN 15 MIN
Message: P&D - MESTRADO - MONITORAMENTO DE ATIVOS

ALERT – MMC DOOR OPEN FOR MORE THAN 15 MIN
URL: http://paineis.cogni.group/d/a3WRkEo4k/monitoramento-pandd-mestrado-ativos?tab=alert&viewPanel=40&orgId=1

Metrics:
status {point_name=Switch1}: 1.000
22:47

[OK] ALERT – MMC DOOR OPEN FOR MORE THAN 15 MIN
State: ALERT – MMC DOOR OPEN FOR MORE THAN 15 MIN
Message: ALERT – MMC DOOR OPEN FOR MORE THAN 15 MIN

ALERT – MMC DOOR OPEN FOR MORE THAN 15 MIN
URL: http://paineis.cogni.group/d/a3WRkEo4k/monitoramento-pandd-mestrado-ativos?tab=alert&viewPanel=40&orgId=1
22:50

[MASTERS] Asset Management Alerts
[Alerting] ALERT – CYLINDER BANK T1 ENGINE M1 – TRIP BREAKER
State: ALERT – CYLINDER BANK T1 ENGINE M1 – TRIP BREAKER
Message: ALERT – CYLINDER BANK T1 ENGINE M1 – TRIP BREAKER
URL: http://paineis.cogni.group/d/a3WRkEo4k/monitoramento-pandd-mestrado-ativos?tab=alert&viewPanel=42&orgId=1

Metrics:
status {point_name=Switch3}: 0.000
23:25

[OK] ALERT – CYLINDER BANK T1 ENGINE M1 – TRIP BREAKER
State: ALERT – CYLINDER BANK T1 ENGINE M1 – TRIP BREAKER
Message: ALERT – CYLINDER BANK T1 ENGINE M1 – TRIP BREAKER
URL: http://paineis.cogni.group/d/a3WRkEo4k/monitoramento-pandd-mestrado-ativos?tab=alert&viewPanel=42&orgId=1
23:26

Figure 15. Alerts sent via Telegram.

4.4 Maintenance indicators based on monitoring variables

From the analysis of the behavior of the electrical current of the M1 engine, it was possible to determine the following operating ranges for the cylinder bank, as observed in Figure 16:

- Current less than 25A stopped equipment;
- Current between 25 to 35A equipment running without load (situations that may occur as a result of wheat feed cut, adjustment of cylinders, stop of some downstream equipment for example). This type of situation must be reported by the system for controlling the productivity of the mill;
- Current between 35 to 50A equipment in normal operation;
- Current greater than 50A equipment operating in overload. In this case, the system must generate an alert for the maintenance team.

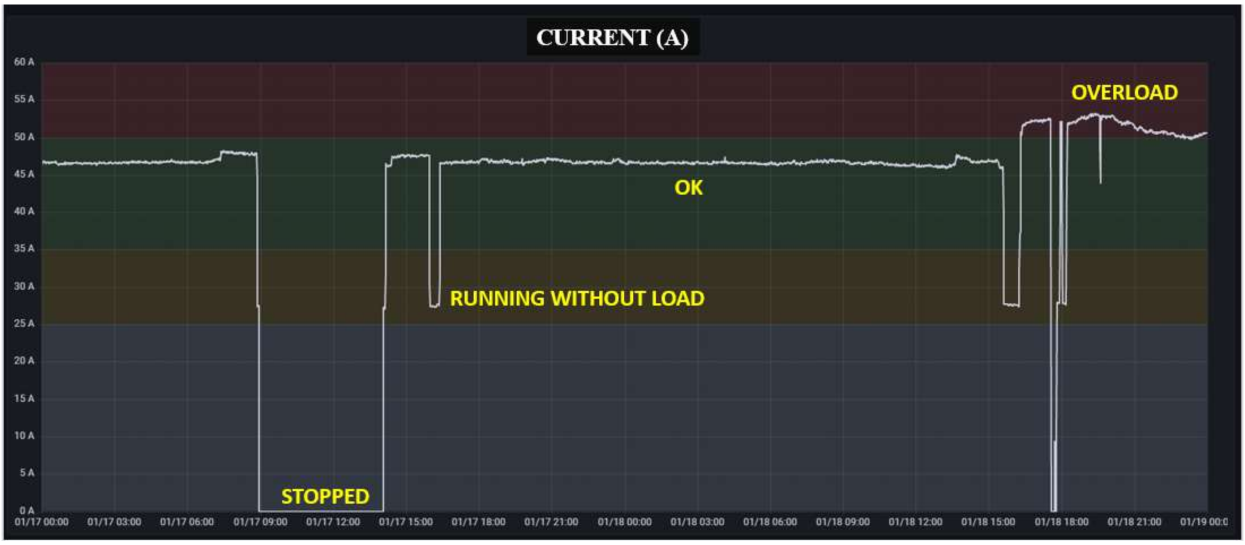


Figure 16. Behavior of the current in A of motor M1 between 2023-01-17 to 2023-01-19.

Taking as reference the interval between 00:00h on 2023-01-17 to 00:00h on 01/19/23, there is a total of 2875 minutes, among which the equipment was available for operation for 2554 minutes, which corresponds to a Physical Availability of 89%. However, part of the available time was not used for effective production, as the equipment was operating with no load for 90 minutes, which represents 86% of the total time. If the operating time in overload (414 minutes) is excluded, it can be stated that the operation within the pre-established parameters was 71% during the observed period. In Figure 17, this summarized information can be seen.

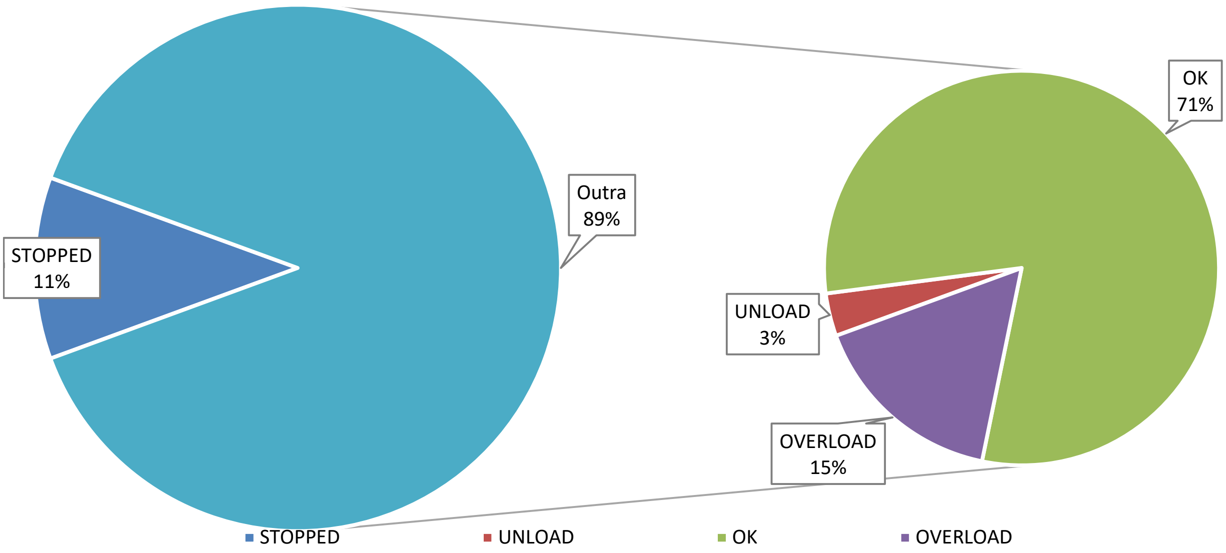


Figure 17. Condition of Operation of the Cylinder Bank between 2023-01-17 to 2023-01-19.

This type of analysis is fundamental for decision-making both regarding the health of the equipment that is in operation and the efficiency of the maintenance and operation processes. Once this data is being monitored in continuous time and business rules are defined, it becomes possible to automatically implement the calculation of performance and maintenance indicators, as well as triggering alerts when a critical level is reached.

5 Conclusions

In this work, the development of a low-cost prototype was proposed, with the application of an open-source electronic prototyping platform and the concept of IoT (Internet of Things), to cover the functionality of collecting data from an electrical panel in real time.

The versatility of the proposed solution can be evidenced by expanding the scope of use of the information collected by the system, in order to be able to generate maintenance and efficiency indicators for the Mill's production process. At the design stage, it was believed that the use of this information would be restricted to monitoring the condition of the low voltage electrical panel under study.

Another relevant aspect is the expansion capacity for monitoring more measurement points, or adapting the system to measure other physical quantities, different from the pre-conceived ones, with the addition of new sensors. This will not require a notable software development effort, but it is recommended that calibration procedures and reference instruments suitable for each type of sensor are considered.

This work represents an excerpt from a research and development project that is in progress, and foresees as next steps the implementation of functionalities such as: improvement of the asset management module with the automation of the calculations of maintenance indicators; online thermography; support for assisted and unassisted maintenance and; predictive module, for predictions based on pattern analysis.

It is expected that in addition to the positive impact caused on the Mill's operation and maintenance team, this work can contribute to the development of similar monitoring systems in the most diverse segments, or even serve as a starting point for the improvement of the developed prototype.

As next steps to be developed there is the implementation of functionalities such as: automated maintenance indicators, online thermography and predictive module.

Referências bibliográficas

Aburakhia, A. and Alshayeb, M. (2024) “A Machine Learning Approach for Classifying the Default Bug Severity Level,” *Arabian Journal for Science and Engineering*, 49(9), pp. 13131–13148. Available at: https://doi.org/10.1007/s13369-024-09081-8.

Ahmad, R. and Kamaruddin, S. (2012) “An overview of time-based and condition-based maintenance in industrial application,” *Computers and Industrial Engineering*, 63(1), pp. 135–149. Available at: https://doi.org/10.1016/j.cie.2012.02.002.

Ahmed, S. et al. (2024) “IoT based intelligent pest management system for precision agriculture,” *Scientific Reports*, 14(1). Available at: https://doi.org/10.1038/s41598-024-83012-3.

Alvan Prastoyo Utomo, M. et al. (2019) “Server Room Temperature & Humidity Monitoring Based on Internet of Thing (IoT),” *Journal of Physics: Conference Series*. Institute of Physics Publishing. Available at: https://doi.org/10.1088/1742-6596/1306/1/012030.

Ammar, H.H. et al. (2023) “An Efficient Design and Control Techniques of Photo-Voltaic Pumping System (PVPS),” *Arabian Journal for Science and Engineering*, 48(11), pp. 14865–14882. Available at: https://doi.org/10.1007/s13369-023-07861-2.

Belchior, F.N., Ribeiro, P.F. and Carvalho, F.M. (2016) “Comparative analysis of instruments measuring time varying harmonics,” *International Journal of Emerging Electric Power Systems*, 17(4), pp. 463–469. Available at: https://doi.org/10.1515/ijeeps-2015-0175.

Cao, Y. and Alyousuf, F.Q.A. (2025) “A new framework to assess the impact of new IT-based technologies on the success of quality management system,” *Journal of Big Data*, 12(1). Available at: https://doi.org/10.1186/s40537-025-01061-5.

Cunha, D.G. (2007) *Modelo de manutenção integrada para equipamentos de sistemas elétricos e ferramentas computacionais de suporte*. Dissertação de Mestrado. Universidade Federal de Minas Gerais. Available at: https://repositorio.ufmg.br/bitstreams/90a7aea1-1aca-43c8-b99b-33cdbf998147/download (Accessed: November 3, 2025).

Einabadi, B., Baboli, A. and Ebrahimi, M. (2019) “Dynamic Predictive Maintenance in industry 4.0 based on real time information: Case study in automotive industries,” *IFAC-PapersOnLine*. Elsevier B.V., pp. 1069–1074. Available at: https://doi.org/10.1016/j.ifacol.2019.11.337.

Elmaadawy, K.G., El Hassan, M.M.A. and Sallam, A.M. (2024) “Rock Typing and Reservoir Quality Analysis of the Abu Madi Reservoir: Distribution Prediction Using Artificial Neural Networks in the West El Manzala Area, Onshore Nile Delta, Egypt,” *Arabian Journal for Science and Engineering*, 49(1), pp. 913–944. Available at: https://doi.org/10.1007/s13369-023-08403-6.

Ferreira, C.A. (2019) *Sistema de monitoramento em motores de indução trifásico utilizando a plataforma arduino*. Trabalho de Conclusão de Curso. Universidade Tecnológica Federal do Paraná. Available at: https://repositorio.utfpr.edu.br/jspui/bitstream/1/11836/2/GP_COMIM_2019_2_03.pdf (Accessed: November 3, 2025).

Ferreira, D.G. (2007) *Visão integrada da automação da operação e manutenção de sistemas elétricos de potência*. Dissertação de Mestrado. Universidade Federal de Minas Gerais. Available at: https://repositorio.ufmg.br/bitstreams/078bef25-35c8-4250-a29f-7616da5a70a0/download (Accessed: November 3, 2025).

Ghani, S., Kumari, S. and Ahmad, S. (2022) “Prediction of the Seismic Effect on Liquefaction Behavior of Fine-Grained Soils Using Artificial Intelligence-Based Hybridized Modeling,” *Arabian Journal for Science and Engineering*, 47(4), pp. 5411–5441. Available at: https://doi.org/10.1007/s13369-022-06697-6.

Gong, L. et al. (2022) “An IoT-based intelligent irrigation system with data fusion and a self-powered wide-area network,” *Journal of Industrial Information Integration*, 29. Available at: https://doi.org/10.1016/j.jii.2022.100367.

Jacob, M. and Mani, P. (2018) *A REFERENCE MODEL FOR TESTING INTERNET OF THINGS BASED APPLICATIONS*, *Journal of Engineering Science and Technology*.

Jasiulewicz-Kaczmarek, M. and Gola, A. (2019) “Maintenance 4.0 Technologies for Sustainable Manufacturing - An Overview,” *IFAC-PapersOnLine*. Elsevier B.V., pp. 91–96. Available at: https://doi.org/10.1016/j.ifacol.2019.10.005.

Jean, W., Brasil, A.C.P. and da Silva, E.C.M. (2023) “Smart grid systems infrastructures and distributed solar power generation in urban slums–A case study and energy policy in Rio de Janeiro,” *AIMS Energy*, 11(3), pp. 486–502. Available at: https://doi.org/10.3934/energy.2023025.

Kiangala, K.S. and Wang, Z. (2018) “Initiating predictive maintenance for a conveyor motor in a bottling plant using industry 4.0 concepts,” *International Journal of Advanced Manufacturing Technology*, 97(9–12), pp. 3251–3271. Available at: https://doi.org/10.1007/s00170-018-2093-8.

de la Peña Llerandi, J., de Mingo, C.S. and Ibáñez, J.C. (2019) “Continuous battery health diagnosis by on-line internal resistance measuring,” *Energies*, 12(14). Available at: https://doi.org/10.3390/en12142836.

Lima, G.M. et al. (2024) “Hybrid electrical energy generation from hydropower, solar photovoltaic and hydrogen,” *International Journal of Hydrogen Energy*, 53(2), pp. 602–612. Available at: https://doi.org/10.1016/j.ijhydene.2023.12.092.

Lopes, J.I. (2010) *Metodologia de gerência de riscos na operação e manutenção de transformadores de potência*. Dissertação de Mestrado. Universidade Federal de Minas Gerais. Available at: https://repositorio.ufmg.br/server/api/core/bitstreams/b9c3d726-2781-42ec-9190-aa14dcd9f2b1/content (Accessed: November 3, 2025).

Lopez-Vargas, A., Fuentes, M. and Vivar, M. (2019) “IoT Application for Real-Time Monitoring of Solar Home Systems Based on Arduino^{TM} with 3G Connectivity,” *IEEE Sensors Journal*, 19(2), pp. 679–691. Available at: https://doi.org/10.1109/JSEN.2018.2876635.

Mariprasath, T. and Kirubakaran, V. (2018) “A real time study on condition monitoring of distribution transformer using thermal imager,” *Infrared Physics and Technology*. Elsevier B.V., pp. 78–86. Available at: https://doi.org/10.1016/j.infrared.2018.02.009.

Medina-Santiago, A. et al. (2020) “Adaptive Model IoT for Monitoring in Data Centers,” *IEEE Access*, 8, pp. 5622–5634. Available at: https://doi.org/10.1109/ACCESS.2019.2963061.

Al Mhdawi, A.K. and Al-Raweshidy, H.S. (2020) “A Smart Optimization of Fault Diagnosis in Electrical Grid Using Distributed Software-Defined IoT System,” *IEEE Systems Journal*, 14(2), pp. 2780–2790. Available at: https://doi.org/10.1109/JSYST.2019.2921867.

Minipa do Brasil (2024). Available at: https://www.minipa.com.br/ (Accessed: May 5, 2024).

Ng, M.Q. and Teoh, S.S. (2019) “Development of a low-cost thermal camera for electrical condition monitoring,” *Universal Journal of Electrical and Electronic Engineering*, 6(5), pp. 94–99. Available at: https://doi.org/10.13189/ujeee.2019.061511.

Praxedes, A.B. de V. and Alvares, A.J. (2019) “Desenvolvimento de sistema de supervisão, controle e manutenção baseada em condição para usinas de geração solar fotovoltaicas dentro do conceito IoT,” *XIII Simpase - Simpósio de Automação de Sistemas Elétricos* [Preprint]. Available at: https://www.researchgate.net/publication/341909462.

Roda, I., Macchi, M. and Fumagalli, L. (2018) “The future of maintenance within industry 4.0: An empirical research in manufacturing,” *IFIP Advances in Information and Communication Technology*. Springer New York LLC, pp. 39–46. Available at: https://doi.org/10.1007/978-3-319-99707-0_6.

Ruiz-Sarmiento, J.R. et al. (2020) “A predictive model for the maintenance of industrial machinery in the context of industry 4.0,” *Engineering Applications of Artificial Intelligence*, 87. Available at: https://doi.org/10.1016/j.engappai.2019.103289.

Santos, D.M.P. (2019) *MEMP - Método de manutenção preditiva aplicado em máquinas de solda industriais*. Monografia. Universidade Federal do Amazonas . Available at: https://riu.ufam.edu.br/bitstream/prefix/5706/3/TCC_DiogoSantos.pdf (Accessed: November 3, 2025).

Santos, M.C. (2019) *Desenvolvimento de um plano de manutenção preventiva e preditiva para a melhoria da confiabilidade de um processo industrial automatizado*. Dissertação de Mestrado. Universidade de Brasília. Available at: http://repositorio2.unb.br/bitstream/10482/36110/1/2019_MarianeCristinadosSantos.pdf (Accessed: November 3, 2025).

Silva, V.G.A. (2019) *Manutenção preditiva em sistemas elétricos de potência utilizando registros de dispositivos eletrônicos inteligentes (IEDs)*. Dissertação de Mestrado. Universidade Federal do Pará. Available at: https://repositorio.ufpa.br/bitstreams/c12412a8-c39f-4939-894e-c8ec66e284ba/download (Accessed: November 3, 2025).

Škultéty, E., Pivarčiová, E. and Karrach, L. (2018) “The Comparing of the Selected Temperature Sensors Compatible with the Arduino Platform,” *Management Systems in Production Engineering*, 26(3), pp. 168–171. Available at: https://doi.org/10.1515/mspe-2018-0027.

Toloo, M. and Mirbolouki, M. (2019) “A new project selection method using data envelopment analysis,” *Computers and Industrial Engineering*, 138. Available at: https://doi.org/10.1016/j.cie.2019.106119.

Tran Anh, D., Dabrowski, K. and Skrzypek, K. (2018) “The Predictive Maintenance Concept in the Maintenance Department of the ‘industry 4.0’ Production Enterprise,” *Foundations of Management*, 10(1), pp. 283–292. Available at: https://doi.org/10.2478/fman-2018-0022.

Usamentiaga, R. et al. (2018) “Temperature monitoring for electrical substations using infrared thermography: Architecture for industrial internet of things,” *IEEE Transactions on Industrial Informatics*, 14(12), pp. 5667–5677. Available at: https://doi.org/10.1109/TII.2018.2868452.

Willis, H.L. and Rashid, M.H. (2009) *Electrical Power Equipment Maintenance and Testing*. Taylor & Francis. London: CRC Press.

Yano, T. et al. (2017) “Development of Mechanical CBM System for Electromagnetically Actuated Vacuum Circuit Breaker,” *Electronics and Communications in Japan*, 100(2), pp. 50–57. Available at: https://doi.org/10.1002/ecj.11934.

Yu, X. et al. (2020) “Optimizing Sensor Deployment and Maintenance Costs for Large-Scale Environmental Monitoring,” *IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems*, 39(11), pp. 3918–3930. Available at: https://doi.org/10.1109/TCAD.2020.3012232.

Zhong, M. et al. (2020) “Multi-AGV scheduling for conflict-free path planning in automated container terminals,” *Computers and Industrial Engineering*, 142. Available at: https://doi.org/10.1016/j.cie.2020.106371.