IoT Application for Monitoring and Storage of Temperature History in Electric Motors

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Abstract: The three-phase induction motor is the most used type of motor. It is estimated that more than 90% of the mechanical energy used in industry is supplied by three-phase induction motors. Therefore, an early and unexpected failure of an electric motor is quite costly to the industry. This paper aims to present the development of an IoT (Internet of Things) application for monitoring and storing the operating temperature history of three-phase electric motors through a wireless sensor network. Real-time temperature values, peak temperature values, tables and graphics of internal engine temperatures are displayed from web pages. Two 1200 HP motors were monitored. The temperatures were obtained through PT100 transducers installed in the motor windings and the ambient temperature read by a digital sensor. The data read by the sensors is kept in a database in the clouds, in order to generate relevant information to support the maintenance management of these assets. Part of the application processing is performed in the clouds, such as the parameterization of the microcontroller program and sending notifications via email, for cases of reading failure, communication failure and high temperature alert. The results demonstrate the applicability and functionality of the application in an industrial environment, allowing the identification of various engine behaviors over time.

1 INTRODUCTION

It is estimated that one third of maintenance costs are wasted as a result of unnecessary or incorrectly performed maintenance (MOBLEY, 2002, p.1). These unnecessary maintenance often occur within the scope of preventive maintenance, as their management is based on time intervals defined by statistical trends, which often do not reflect the actual operational condition of the equipment. Predictive maintenance arises to solve this problem, as interventions are based on the condition of the equipment, rather than the operating time. The operational condition of the equipment is obtained through regular monitoring of quantities such as temperature, vibration, among others.

Detective maintenance is an evolution of predictive maintenance, has more automation features and uses intelligent electronic devices. It's based on systematic measurements of items that may have hidden failures, where the loss of function cannot be perceived by the operator and maintainer (SEIXAS, 2011).

A large part of the anomalies observed in electric motors are linked to the increase in operating temperature, whether it's the cause, or the consequence, of this temperature rise. Therefore, monitoring the temperature of an engine in real time, and maintaining a database with the temperature history, in a structured way to generate relevant information, provides ways to manage the maintenance of these equipment more efficiently and reliably. The measurement history can support studies

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of failures and possible errors in the design, installation or operation of equipment.

The objective of this work is to develop an IoT application for monitoring and storing the temperature history of electric motors, using wireless sensors connected to the internet and services available in the cloud, in order to generate information to support the management of the maintenance of these assets. To carry out this monitoring, a system with a microcontroller will be used, which takes readings from PT100 sensors installed in electric motors and sends these readings to a database in the clouds. A WEB interface is used for interaction with the user, allowing the user to access this data, configure system parameters, receive notifications and use the temperature history to generate relevant information for maintenance management.

2 OVERVIEW

2.1 Maintenance on Electric Motors

In short, maintenance actions can be divided into three main types: corrective, preventive and predictive. Corrective maintenance, the most costly type, is carried out after a failure occurs, where the equipment stops (NBR 5462, 1994). Preventive maintenance is a type of time-based maintenance. It must be carried out on predetermined dates, with the aim of reducing the probability of failures ALMEIDA, 2013). Despite having lower costs, it also generates costs that could be avoided (MOBLEY, 2002, p.4).

Predictive maintenance seeks to obtain the actual operating conditions of the machine. For this, it uses specific equipment for monitoring phenomena such as temperature, vibration, noise, etc. (ALMEIDA, 2013). The results of these inspections determine the ideal time for intervention in the equipment. With the evolution of embedded systems and industrial networks, a new term appears in the area of maintenance, detective maintenance. It differs from predictive maintenance, by continuous monitoring and the use of intelligent electronic devices (PAULINO, 2014), with increased reliability according to the level of the implemented system, in addition to the possibility of storing the history of equipment variables.

2.2 Effect of Temperature Rise on Electric Motors

Copper losses are the major heat source of the machine and are directly proportional to the load to which the equipment is subjected. They occur due to the joule effect on the resistive element of the machine winding. Core losses or iron losses are due to eddy currents and due to the hysteresis effect (ALMEIDA, 2013). Harmonic currents and phase voltage imbalances also cause temperature rise.

Delayed starts, due to loads with very high resistant torque and successive starts also increase the temperature of the equipment, as the starting current reaches peaks of up to eight times the rated current. In applications driven by frequency inverters, it should be noted that when the motor speed is reduced, the air flow produced by the fan coupled to the motor shaft is reduced in the same proportion, which may result in an increase in the temperature of the equipment.

High temperature is the main villain of the insulating material. The life of the insulation will be reduced by half for each 10 °C increase in temperature (GILL, 2009, p.9). In case of sudden temperature rises in a short period of time, a failure may occur due to material melting, causing an immediate failure. On the other hand, temperatures above the limit of the insulating class, but well below the melting point, can for a long term cause internal chemical effects, which make the material look more dry, brittle, with micro-cracks, which causes premature aging and degradation of insulation. With the aging of the insulation, there are partial discharges, which cause the progressive deterioration of the insulating materials, leading to a total electrical failure (TOLIYAT et al., 2013, p.11-12).

By monitoring and maintaining the temperature history of the windings, it is possible to determine if the winding is at risk of thermal deterioration and degradation of the insulating material. In addition, the finding of an increase in temperature under the same operating conditions (load, ambient temperature and voltage) may be indicative of failure or degradation of the cooling and heat dissipation system (TOLIYAT, et al. 2013, p.13) .

2.3 Wireless and IoT Sensor Network

Advances in technology, such as large-scale integration, micro-electromechanical systems and wireless communications, contribute to the feasibility of implementing distributed sensor systems. When many sensors cooperatively monitor large physical environments, they form a wireless sensor network. A wireless sensor has, in addition to the transducer component, processing, communication and storage resources (DARGIE & POELLABAUER, 2010, p.7). The wireless sensor network has the advantage of not requiring cabling infrastructure, in addition to being easily expandable and reconfigurable.

The wireless sensor network will be able to use the internet infrastructure to interconnect its nodes and use storage and processing services in the cloud. In this context, the concept of IoT is entered. The term has several definitions, however there is in common, among the understanding of several authors, the idea of being an environment of physical objects interconnected through the internet, through small sensors and actuators, introducing functional solutions in everyday processes (MAGRANI, 2018, p.20).

Large manufacturers such as WEG and ABB provide applications for remote temperature monitoring through wireless sensors. However, the cost is still high for many cases. These applications have a commercial nature, and their system and source code are inaccessible and unalterable by users. This is a major disadvantage, as it does not allow integration to systems already implemented, adaptation to user needs and the natural evolution of these needs.

2.4 Related Works

Fabricio (2018) developed an application for monitoring equipment on a production line, through monitoring the consumption of electrical currents, in order to detect operational deviations that could lead to failures. The system uses an intermediate concentrator node between the sensors and the database, which is hosted on a personal computer. It uses an IoT application to visualize the data in textual and graphical form and send notification in the event of operational deviations, with the history being stored in the database to assist in the maintenance of these equipment.

Pedotti's (2019) work presents a low-cost device, which aims to diagnose failures through continuous monitoring of vibration in rotating machines. The ESP32 development board and WiFi communication were used. Data transfer is done through the MQTT protocol to a cloud computing platform, for the storage and display of results.

Muta' Ali (2021) developed an IoT application for monitoring water quality in large areas. The system consists of two microcontrollers, one performs variable readings on the water and sends it to the other through a long-range network. The second microcontroller works as a gateway for connecting to the internet, as it uploads the data to a cloud server. This application uses the Google spreadsheet application as its database. The user interface is accessed through a WEB page. In the same line of development, Kavitha and Vallikannu (2019) developed a pollution control system, by monitoring the level of gas or fuel by intelligent sensors in an industry. This monitoring is carried out by a network of wireless sensors, which detect gas leaks and their location. Sensor data is also sent to the Google spreadsheet.

3 MATERIALS AND METHODS

The project presented the following steps: bibliographic study on the causes and effects of high temperature in electric motors and on the use of monitoring this temperature to help manage the maintenance of these equipment; bibliographic study on the use of wireless sensor networks and the use of IoT in monitoring electrical equipment; survey of application requirements; assembly of the electronic circuit and development of the microcontroller and WEB part software; tests and fixes; device installation and data monitoring, to extract information about the operating condition of the equipment.

Figure 1 shows the architecture and functional layers of the developed system. A microcontroller performs temperature sensor readings in the engine and the external environment, and after pre-processing it sends this data over a wifi network to a database hosted in a spreadsheet. This submission is done through the forms feature, by an HTTP request. The spreadsheet performs data processing in the cloud and extracts relevant information, which feeds WEB pages, which can be accessed by users.

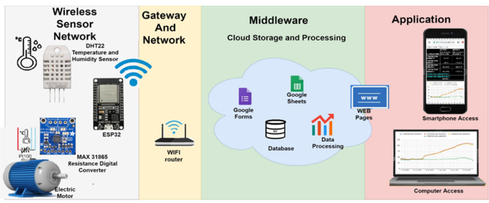


Figure 1: System architecture and his functional layers.

The device was installed on two engines. The monitored motors have a mechanical power of 1,200 CV, fed at medium voltage, for 2,300 V, and have Class F insulation, which supports temperatures, without compromising their useful life, of up to 140 °C. These motors are used to drive centrifugal pumps.

In the physical device, the following were used: ESP32 and ESP8266 development boards, the MAX 31865 resistance digital converter, the DHT22 temperature and humidity sensors, and LEDs for signaling. To program the development board the IDE (Integrated Development Environment) of Arduino was used. For the development of the WEB application, the Google Spreadsheet service and Google Apps Scripts were used. For monitoring the temperature of electric motors, in the way it was conceived, the PT100 is the most suitable sensor. Mainly due to its accuracy and greater immunity to electrical noise.

ESP32 is a low-cost, power-consuming development board with built-in Wi-Fi and Bluetooth capabilities. Its use is very suitable for IoT project solutions, due to the integration of components in a single module (MAIER, SHARP, VAGAPOV, 2017). As a digital resistance converter, the MAX 31865 was used, optimized for thermoresistance (PT100 and PT1000), with a resolution of 0.03125 °C, precision of 0.5 °C and an interface compatible with SPI (serial peripheral interface) (MAXIM INTEGRATED, 2015).

For hosting the data in the clouds, Google Sheets was used, with storage and processing in the cloud. For the development of the user notifications application, Google Apps Scripts was used, a cloud scripting language based on the JavaScript language, which provides means for automating tasks, creating functions, applications and integrating google spreadsheets with other services from WEB and the development of graphical interfaces to be used in WEB applications (MAGUIRE, 2016, p.2-3).

4 RESULTS

For the electronic circuit, two temperature readers were developed, one using the ESP32, which has more features and the other using the ESP8266 which, despite its lower performance, met the application requirements and has a lower cost, being more accessible for some applications. The electronic circuit that uses the ESP32, was assembled as shown in Figure 2, the other was assembled in a similar way, changing only the input and output pins. The system uses 3 resistance digital converters to read the PT100 temperature. The communication between the microcontroller and the resistance digital converters uses the SPI - Serial Peripheral Interface protocol, which uses 3 shared pins for control, and one more pin per device for device selection. SPI is a high-speed full-duplex synchronous serial bus, with Master/Slave control (Master/Slave) (DARGIE & POELLABAUER, 2010, p.58).

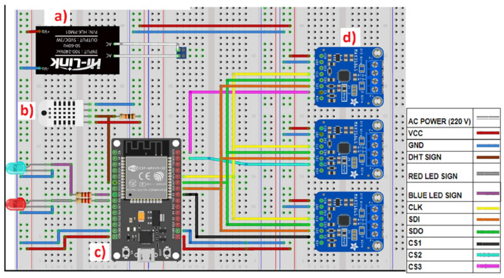


Figure 2: Assembly of the electronic circuit. Where is shown: (a) power supply; (b) outdoor temperature and humidity sensor; (c) ESP32 controller; (d) MAX 31865 digital converter.

As the heating of an electric motor can be related to the rise in the ambient temperature, and the ambient temperature is also influenced by the engine temperature, a digital ambient temperature and humidity sensor, the DHT22, was used. Two LEDs (Light Emitting Diodes) were used for signaling. The blue LED flashes when communication is successful, the red LED flashes when there is a failure.

There are several ways to edit the spreadsheet, by an external system. The simplest is using Google Forms, which is a form that can be linked to a spreadsheet. In this way, it is possible to feed the spreadsheet by sending responses through this form, without the need for authentication. Another advantage of using Forms is that it fills in the date and time automatically when sending it, eliminating the use of RTC (Real Time Clock) in hardware.

Clients and servers communicate through the HTTP (Hypertext Transfer Protocol), which defines how clients request files from servers and how they transfer them to clients. An HTTP request message has a header and an entity body. Among the methods used by HTTP requests, the most common are GET and POST. In the POST method the entity body will contain the data typed in the fields of a form, for example. In the GET method, these data are contained in the requested URL itself and the entity's body is sent empty.

To compress the data volume without losing information, a conditional was inserted in the program, so that the device sends temperatures only when the temperature varies by an amount greater than a predefined value. This reference value is a program parameter that, along with other parameters, can be defined by the user in the spreadsheet itself, in an exclusive tab for configuring the parameters used by the microcontroller program, and by the WEB application.

Unlike data submission, which uses the form feature, spreadsheet reading requires API key activation and use of authenticators. In the simplest form, leaving the spreadsheet as public for reading, it is only necessary to activate the API key, a simple process that can be performed on Google's API management platform.

The other parameters were used to define the number of readings of the temperature converter to calculate the temperature average, the number of program cycles for updating the parameters and finally the maximum number of readings without sending data, where the device will send the data, even not satisfying the temperature variation condition, in order to enable the detection of failures. For the web application, there are the temperature limit parameters for notification, the maximum time without receiving data for failure notification and the registration of emails to receive these notifications.

In this way, the user can adapt the parameter values according to the equipment to be monitored and its working condition, in addition to taking into account the number of sensors used. Using a minimum variance of 0.5°C for submission, and a maximum number of reads without submission equal to 50, the number of submissions reduced to an average of one submission every five minutes. Thus, the same spreadsheet will support temperature storage for a period exceeding 8 years.

The user also has the possibility to allow this parameterization to be automatic, which determines the best value for the parameters according to the condition in which the equipment is found. Some equipment is off for a long time, a situation in which its temperature will be well below its working temperature, so monitoring is not relevant. The graph in Figure 3 shows an example of a device that was turned off for more than 12 hours. It would not be efficient, in terms of space occupation in the spreadsheet, to maintain the same sending rate during this period.

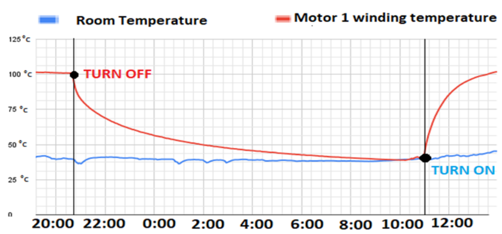
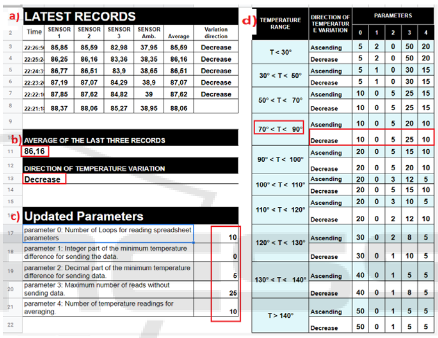


Figure 3: Motor 1's temperature graph. Points that demarcate the period in which the engine remained off is highlighted.

This way a script runs on the server, every time temperature data is received. It searches within a table with predefined values, table (d) in Figure 4, for a group of parameters more suitable for the condition the equipment is in, according to table (a) in Figure 4. Automatic choice of the parameter group, takes into account the temperature range in which the equipment is located and the direction of variation, as explained by the red rectangle markings in table (b) of Figure 4. The selected parameter group is inserted in the table (c) of Figure 4 for reading the microcontroller. During the tests, at times of greatest temperature variation, which occurred after the equipment was turned on, the sending rate was approximately 1 shipment every 30 seconds. On the other hand, at times of thermal equilibrium, which occurred most of the time, this send rate dropped to 1 send every 12 minutes on average.



a) LATEST RECORDS

Time	SENSOR 1	SENSOR 2	SENSOR 3	SENSOR Amb.	Average	Variation direction
22:26:5	85,85	85,59	82,98	37,95	85,59	Decrease
22:25:2	86,25	86,16	83,36	38,35	86,16	Decrease
22:24:3	86,77	86,51	83,9	38,65	86,51	Decrease
22:23:2	87,19	87,07	84,29	38,9	87,07	Decrease
22:22:1	87,85	87,62	84,82	39	87,62	Decrease
22:21:1	88,37	88,06	85,27	38,95	88,06	

b) AVERAGE OF THE LAST THREE RECORDS

86,16

DIRECTION OF TEMPERATURE VARIATION

Decrease

c) Updated Parameters

parameter 0: Number of Loops for reading spreadsheet parameters	10
parameter 1: Integer part of the minimum temperature difference for sending the data.	0
parameter 2: Decimal part of the minimum temperature difference for sending data.	5
parameter 3: Maximum number of reads without sending data.	25
parameter 4: Number of temperature readings for averaging.	10

d)

TEMPERATURE RANGE	DIRECTION OF TEMPERATURE VARIATION	PARAMETERS				
		0	1	2	3	4
T < 30°	Ascending	5	2	0	50	20
	Decrease	5	2	0	50	20
30° < T < 50°	Ascending	5	1	0	30	15
	Decrease	5	1	0	30	15
50° < T < 70°	Ascending	10	0	5	25	15
	Decrease	10	0	5	25	15
70° < T < 90°	Ascending	10	0	5	20	10
	Decrease	10	0	5	25	10
90° < T < 100°	Ascending	20	0	5	15	10
	Decrease	20	0	5	20	10
100° < T < 110°	Ascending	20	0	3	12	5
	Decrease	20	0	5	15	10
110° < T < 120°	Ascending	20	0	3	10	5
	Decrease	20	0	2	12	10
120° < T < 130°	Ascending	30	0	2	8	5
	Decrease	30	0	1	10	5
130° < T < 140°	Ascending	40	0	1	5	5
	Decrease	40	0	1	8	5
T > 140°	Ascending	50	0	1	5	5
	Decrease	50	0	1	5	5

Figure 4: Spreadsheet used for automatic parameterization: (a) table of last readings; (b) table of average and direction of temperature variation; (c) table of selected parameters and (d) parameter groups table.

The same script that updates the parameters, analyzes the data received, and in cases where the temperature exceeds predefined values by the user or when there is a failure in the sensors, it sends notifications via e-mail to registered users. Another script with a time-based execution trigger, different from the first one that has an event-based trigger, is executed on the server every pre-defined time period. This script monitors the past time interval of the last record and compares it with a predefined value. If it exceeds this limit, it notifies, via e-mail, the user of a possible communication failure.

Finally, the interface for the visualization of data by users was developed. All information generated by the data is available on WEB pages. The WEB pages are multiplatform, that is, they can be accessed by different devices, such as computers and smartphones. The great advantage is that the user does not need special applications to view the information, only an internet browser, which is available on any device with internet access.

In the developed system, a kind of supervisory was created in a spreadsheet tab, which displays the latest readings and the graph of the last 24 hours, as can be seen in Figure 5. Screens a and b in Figure 5 present the application's home page , where it shows the temperatures of the last reading of each of the monitored equipment and the temperature graph of the last 24 hours.

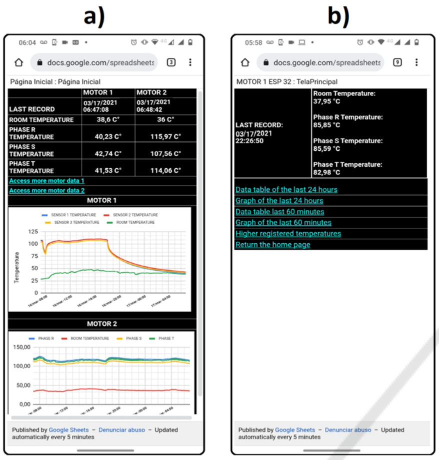


Figure 5: Application screen viewed by a browser on an Android device: (a) Application Home page, shows latest sensor readings and graphs for the last 24 hours and (b) exclusive page to access Motor 1's data.

On screen (b), there is the Engine 1 detail page, which has hyperlinks to access more detailed information about the operation of this engine, such as tables and graphs of the last 24 hours, or the last 60 minutes and tables with peak temperature values reached in each sensor of the equipment. Figure 6 shows a temperature graph within the engine 1 detail pages.

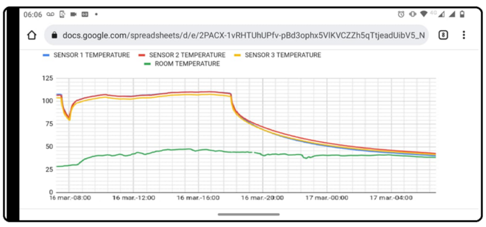


Figure 6: Graphs for the last 24 hours.

During monitoring the equipment, Motor 1 had an average winding temperature of 104°C and motor 2 of 111.6°C. Regarding the peak values, the highest temperature recorded in engine 1 was 112.27°C and in engine 2, 125.9°C. As the monitored equipment has insulation class F, which withstand up to 140° degrees, it is concluded that they are working with adequate temperatures, and with a certain clearance to the class limit. This indicates that the loads are well dimensioned and that the heat dissipation process is taking place efficiently.

The ambient temperature sensor has been installed, in a suitable plastic frame, on the sensor connection box. The assembly was in exactly the same location as the two engines. The ambient temperature sensor was very close to the equipment frame, in order to reflect the external temperature of the motor when measuring the ambient temperature. When comparing the average temperatures of the three PT100s with the ambient temperature of the two engines simultaneously, it was observed, as shown in Figure 7, that Engine 1, which worked at a temperature below Engine 2, generated more heat to the environment, as the ambient temperature around it was higher than that of Engine 2.

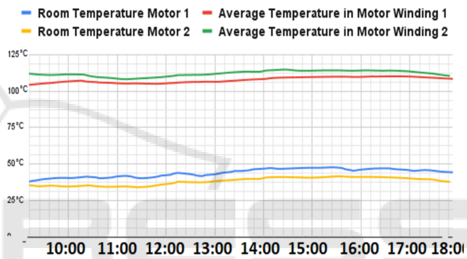


Figure 7: Comparison between ambient temperature and internal temperature of both engines simultaneously.

This indicates that the heat transfer from Motor 1 is more efficient than from Motor 2. The heat generated inside the motor must be dissipated to the environment through the surface of the equipment. Cooling is aided by the fan mounted on the motor shaft. To reduce the internal temperature of an engine, there must be a good heat transfer from the engine's interior to the external surface (GONÇÁLEZ, 2007). Therefore, Motor 1, by transferring more heat to the environment, further reduces the internal temperature.

When analyzing the effect of the operating state of one engine on the temperature of the other, it was found, as shown in the graph in Figure 8, that when turning Motor 1 off, indicated by the left arrow in Figure 8, Motor 2 raises its internal temperature. On the other hand, when Motor 1 is turned on again, indicated by the arrow on the right in Figure 8, Motor 2 reduces its internal temperature again. This temperature variation in the motor is due to the load variation. According to (ELETROBRÁS, 2005, p. 137), a pump associated with another in parallel will always provide a lower flow rate than when it works in isolation. Therefore, the parallelism of the pumps reduces the flow in the pump, which implies a reduction in the power demanded from the motor.

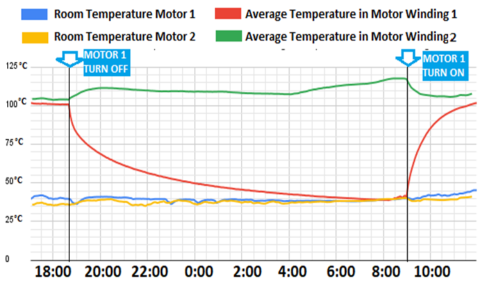


Figure 8: Temperature variation in one engine due to the state of the other engine.

5 CONCLUSIONS

Electric motors are fundamental to most industrial processes. Keeping this equipment in operating condition is essential to ensure the effectiveness and efficiency of these processes. Continuous monitoring combined with good maintenance management of these equipment can guarantee both reliability and cost reduction, by determining the most appropriate time to carry out interventions on these machines.

Advances in wireless sensor networks make this continuous monitoring possible. These solutions have a lot of computing resources, and can autonomously perform complex operations, such as sending data to a database hosted on an internet server, used as a means to connect these sensors. The internet can also be used for remote monitoring, data storage and data processing by a multitude of existing web applications. With advances in IoT technology and with the expected arrival of the 5G internet, the internet tends to become an increasingly powerful tool.

Bringing together the simplicity of the methodology used, the accuracy of the data generated and the quality of the information displayed to the user were only possible due to the use of applications already consolidated on the internet, which provide, through the use of APIs, a simple way to integrate. them to simple projects, in order to maximize the results, at very low cost, or often, as in the case of this project, free of charge. The results achieved met all the requirements raised at the beginning of the project.

The data generated showed that the two monitored devices were operating at an adequate temperature, and with a gap to the limit of their insulation class, which shows that the loads are well dimensioned and that heat dissipation is efficient. However, it was possible to observe, through the graphic analysis, that the heat dissipation of Motor 1 was more efficient, due to its lower internal temperature and higher external temperature.

The results achieved open the way for future projects, where this monitoring can extend to other variables, in addition to temperature, such as current and vibration, allowing for the correlation between the quantities and increasing the diagnostic power. It will also allow for long-term monitoring, enabling analysis of how temperature behaves as parts, such as bearings, begin to degrade. The generated data can also be used by data science projects to create predictive models to be used in predictive and detective maintenance.

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