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Intelligent Monitoring and Diagnosis System of Power Transformers applied Microservice Architecture

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HIGHLIGHTS

- The embedded system is composed by physical infrastructure and in logical instruction sets.
- The Web Application was developed using the pattern of back-ends for front-ends.
- Each microservice has its own responsibility for processing, and transmitting the information.
- The Factory Acceptance Test (TAF) of the monitoring panel and its commissioning were carried out.

Abstract: This work presents a customized and configurable solution for the online monitoring and diagnosis of power transformers that is already installed in the field and provides the main diagnostics of the asset, such as, aging acceleration factor, hotspot, apparent power, gas generation rate in the oil, temperature for the formation of free water in the oil, for blistering and hot spot formation, water content in the paper. The focus of this article is to describe the embedded system, which covers the hardware part, the information from the sensors installed for asset monitoring and communication with the server, as well as the development of the Web application of the monitoring system, based on the microservices architecture. The solution consists of the analog signal acquisition modules, RS-485 communication module, and digital inputs and outputs module, controlled by the NI central processing unit, CompactRIO through the NI LabVIEW development environment. The embedded system program is based on the MQTT protocol and the "Actor Framework" architecture, where "actors" responsible for the operations within the implemented logic are defined. The access or sending of information is done through messages between the actors, one of whom is responsible for managing the exchange of data between the others. The main focus of this structure is to receive the information from the sensors and link it to a "topic", where the algorithm allows directing this information to the registered senders. This work is part of the ANEEL R&D project to Campolarguense Energy Company – COCEL.

Keywords: Power transformers; Online monitoring; Embedded system; Labview; Actor Framework; MQTT; Microservice.

INTRODUCTION

One of the pieces of equipment that is present throughout the Electric Power System - SEP is the transformer, from the generation, transmission and distribution of energy. As a result, it is essential that it operates safely, reliably and continuously, as it is a strategic asset within the SEP and its failure leads to great economic losses. For this, it is essential that its constant monitoring is carried out and, allied to this, a fault diagnosis strategy that accurately identifies the operational condition of the asset and subsidizes the decision-making of predictive maintenance and/or equipment replacement.

Among the ways to evaluate the operating conditions of high-voltage equipment, the online monitoring of oil-immersed transformers allows immediate actions as problems are detected and, thus, preventing the asset from reaching a more serious condition [1].

In general, the gestation of the transformer's useful life is mainly related to oil deterioration factors, thermal factors, dielectric factors, mechanical factors and environmental factors [2]. In this sense, some variables of interest for monitoring stand out, such as in relation to bushings: capacitance deviation and dissipation factor (tangent delta); active part: oil temperature, winding temperature, winding current and oil gas detection; tank and oil: water oil content in oil, relative saturation of water in oil, relative saturation of ambient and reference temperature; cooling system: current of fans or pumps and vibration of pumps; Switch: Tap Position, Changer Temperature, Load Current, Line Voltage [3].

Given this amount of data from the instrumentation of the monitored transformer, it is necessary to structure it and make correlations to generate a diagnosis of the operational state of the equipment and the detection of failures. One of the widely used diagnostic methods is the analysis of gas dissolved in oil (DGA – Dissolved Gas Analysis), in which, the transformer operating under abnormal conditions can generate gases that are dissolved in the insulating oil, with three main groups of gases – hydrogen and hydrocarbons (methane, ethylene, ethane, acetylene, etc.), carbon oxides and non-defective gases (oxygen, nitrogen, among others), and different combinations and proportions indicate different anomalies [4]. In general, DGA depends on factors such as the gas profile of the most recent sample, the ratio of the concentration of different gases in the sample, and the rate of change of these concentrations between samples taken in a given period. Thus, the interpretation methods, for the most part, try to establish statistical correlations between the observed gases and the particular modes of operation or failures of the transformer [5].

And to carry out this entire process, from the measurement of the quantities of interest by the sensors installed in the transformer, to their processing together to elaborate a reliable and accurate diagnosis, there is a need for a robust embedded system. In this sense, both hardware aspects, such as signal acquisition modules, communication module and a processing unit, as well as software aspects, related to the methodology and algorithm implemented to manage and control the variables, indication of alarms and anomalies of the equipment and elaboration of performance indicators that support the decision making by the Engineer.

In this sense, the objective of this article is to describe the solution developed for the online monitoring of power transformers, a system that integrates a monitoring and diagnosis solution structured in 4 pillars: hardware for signal acquisition; transformer instrumentation (sensors for measuring physical quantities); centralized server for processing and issuing the diagnosis composed of an artificial intelligence layer - AI; and web interface for real-time monitoring of asset status. This work is part of ANEEL's R&D project entitled project Intelligent System for Monitoring and Diagnosis of Power Transformers – ISMDPT executed by the Energy Management Laboratory of the Itaipu Technological Park – PTI to Campolarguense Energy Company – COCEL.

SOLUTION DESCRIPTION

The solution of the proposed system is to develop and implement a transformer management system consisting of a supervision and monitoring system for two transformers, totaling two local panels (merger unit) integrated via network to a communication panel and this also connected via network to a server of the monitoring system (web server), located in the control room of COCEL, and, an artificial intelligence tool using data analytics techniques.

The objective of this project is to develop and implement a management platform for transformers, which includes a highly effective monitoring system, designed specifically for two transformers. This infrastructure encompasses two local panels that connect to a communication panel through a robust fiber optic network. The latter establishes a network connection with a server dedicated to the monitoring system (web server), strategically positioned in the control room of the Substation. To further enrich the solution, a state-of-the-art tool based on artificial intelligence is incorporated, which uses refined data analysis techniques to increase the effectiveness and operational efficiency of transformers.

The monitoring system was installed in two 40MVA three-phase transformers, insulated with mineral oil and responsible for lowering the voltage from 138kv to 13.8kV.

By means of the instrumentation installed in the transformers, several significant quantities are captured. From this data, fundamental assessments on the operational situation of the asset are elaborated. Measured variables and diagnoses issued by the Monitoring System include ambient temperature, moisture concentration in oil, oil temperature, relative aging, winding temperatures A, B, and C, capacitance deviation, apparent power, water vapor pressure, internal temperature, hotspot temperature AT, high current B, BT hotspot temperature, oil moisture concentration, temperature for free water formation in oil, concentration of dissolved gases in oil, relative loading, gas and humidity sensor fault signal alarm, water content in paper, bushing voltage fault signal alarm, and tension of bushings A, B, and C.

In addition, the system offers features such as monitoring the captured quantities through a web interface, storing historical data, generating reports, customizing alerts, recognizing alarms and configuring monitoring channels. The monitoring interface, along with examples of variables measured in the transformer, is illustrated as an example in Figure 1.

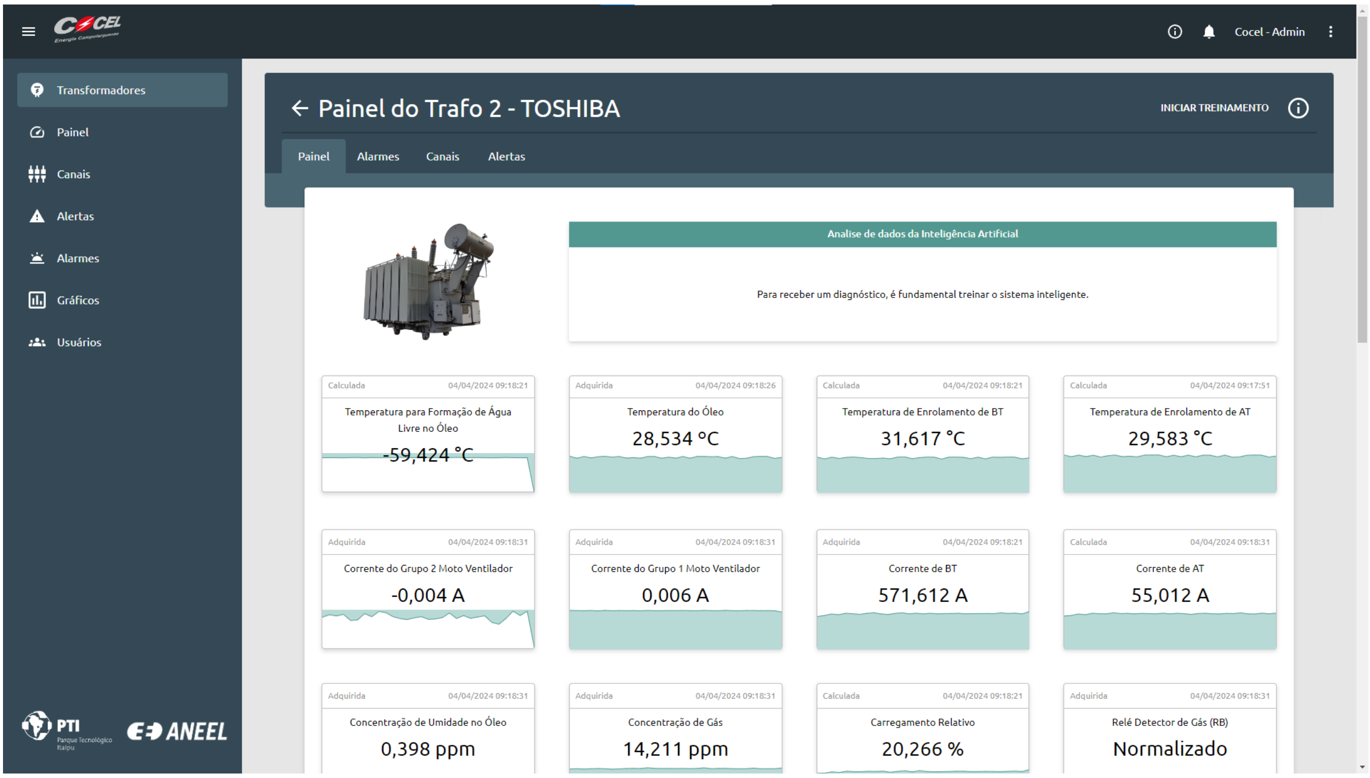

Figure 1. Monitoring panel screen in the WEB application.

OVERALL ARCHITECTURE OF THE MONITORING SYSTEM

The configuration of the monitoring system was elaborated, starting with the sensors positioned to capture the essential variables of the transformer's state. This information is essential to evaluate the performance and health of the equipment. After collection, the signals are directed to a local panel, which serves as the first processing point.

The next step involves transmitting this processed information to a central server. This data transfer is vital to the expansive functionality of the system, allowing for more in-depth analysis and secure storage of the data collected. In addition, the system's architecture is designed to facilitate not only continuous monitoring of transformer operating conditions, but also to enable configuration adjustments and customizations to be made remotely. This ensures flexibility and advanced operational control for system administrators.

The ability to make adjustments and monitor the system remotely adds a layer of efficiency and practicality, ensuring that operations can be optimized based on accurate, real-time analytics.

To visually illustrate this integrated architecture, Figure 2 was created. It provides a detailed schematic representation, highlighting how each component of the system interacts to ensure effective monitoring and optimal transformer management.

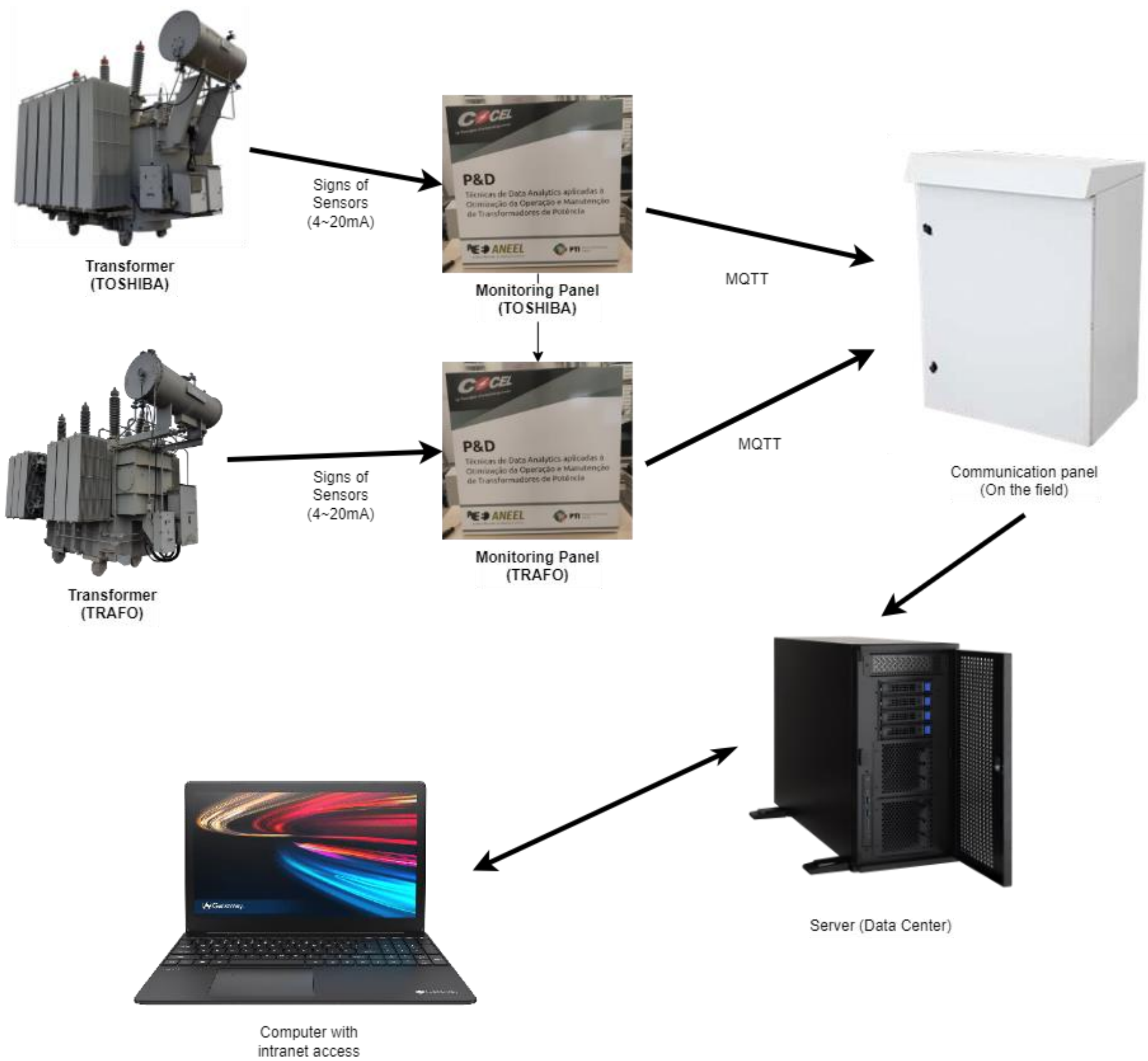

Figure 2. General architecture of the monitoring system.

SENSORS

In this section, the sensors used to monitor the quantities of interest are commented, such as temperature of the windings and insulating oil, ambient temperature and internal temperature of the monitoring panel. In addition, gas concentration and moisture in the oil, current, and voltage in the transformer bushings

Temperature Sensors

The temperature of the transformer oil is measure by PT100, native sensor from the transformer, and its windings is calculated by the system. The ambient temperature and internal temperature of the monitoring panel are also measured using Pt100 transducers.

The temperature values of the high-voltage winding, low-voltage winding, insulating oil, and ambient temperature are used in the artificial intelligence layer algorithms of the monitoring system and in the transformer loading and aging calculations.

High Voltage Bushings Current Sensor

To monitor the current, a current transformer (CT) was connected to the secondary of the pre-existing CT of the transformer's S phase. In this way, it provides an output of 4-20 mA proportional to the RMS value of the primary current. This data is also used in the intelligent diagnostic algorithms and in the calculations of asset loading and aging.

Sensor of dissolved gases in oil and moisture content

The gases dissolved in the oil can provide information about the internal processes that involve the active part of the equipment and its insulation. This influence causes changes in the insulation pattern and a decrease in the useful life of the equipment. Another important condition to be analyzed is the moisture content of the transformer's dielectric, because to ensure a long service life, the moisture content of the oil and cellulose must be kept at low levels.

In this sense, the equipment that performs this monitoring is the MTE's gas and moisture analyzer (Meter Test Equipment AG), which measures moisture and identifies 6 main gases in the oil: hydrogen (H2), carbon monoxide (CO), methane (CH4), acetylene (C2H2), ethylene (C2H4) and ethane (C2H6). The communication between the gas analyzer and the monitoring panel is through 2 analog outputs of 4-20 mA for gases dissolved in oil and humidity and 4 digital outputs for alarms.

The values of water content and gas concentration, specifically hydrogen, are used in intelligent diagnosis and other indicators of transformer health.

Voltage sensor in bushings

Another important aspect to evaluate the operating condition of power transformers is the monitoring of high voltage condensative bushings, which, although they are accessories with a relatively low unit cost in relation to the total equipment in which they are associated, the failure in their insulation causes significant damage to the transformer. In this sense, an electronic bushing monitor was used, from Treetech, which monitored the voltage, capacitance and dissipation factor of the insulation. The information provided by the electronic sensor is forwarded to the monitoring panel via RS-485 communication using the MODBUS protocol.

MONITORING DASHBOARD

The monitoring panel is located close to the transformer, which houses the embedded software for the acquisition of signals from the sensors. Figure 3 shows the front of the panel.

Figure 3. Front of the monitoring panel.

Internally, the panel is organized into four main sections: power and protection, electronic equipment of the embedded system, digital acquisition, and analog acquisition. It is equipped to handle both alternating current (AC) and direct current (DC) loads, including a central processing unit, modules dedicated to signal acquisition, a module for serial communication, and a converter that allows the transition of fiber optic media to Ethernet, thus facilitating the connection of the panel to the server. Figure 4 details the interior of the panel, displaying all the integrated components.

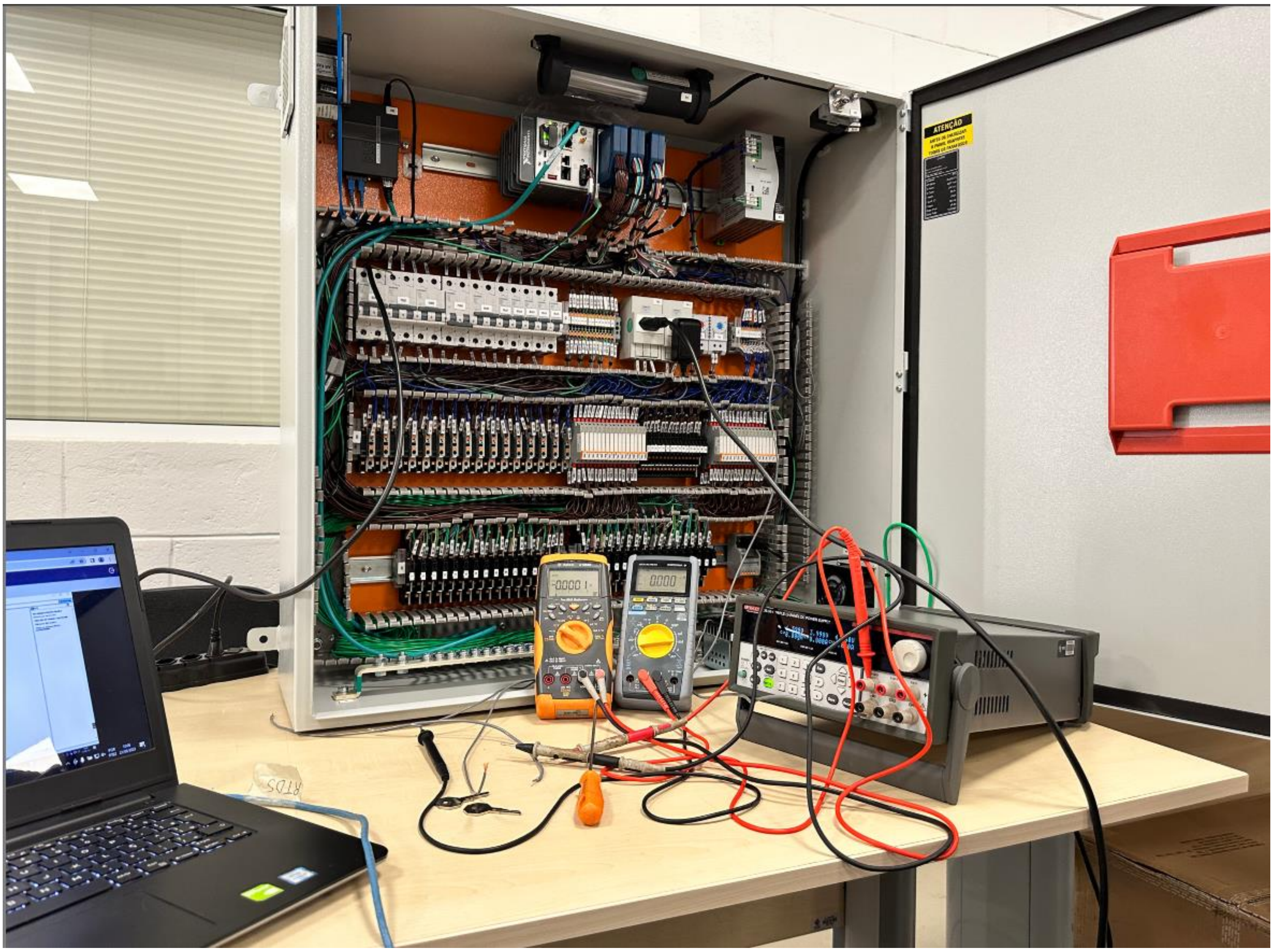

Figure 4. Inside of the monitoring panel.

ON-BOARD SYSTEM

The core of the embedded system is meticulously architected around two fundamental pillars: the physical infrastructure (hardware) and the logical instruction set (software). This duo is essential for the efficient execution of the tasks assigned by the project, from collecting data from sensors to complex communications management and data exchange with the server. This integration ensures that all activities are carried out smoothly and in accordance with the established requirements.

As for the physical aspects, the structure of the embedded system is composed of a central processing unit, which acts as the brain of the system, interpreting data and commanding actions. Accompanying this unit are modules specialized in the collection of analog signals, which capture the nuances of environmental or process information. There are also modules responsible for the management of digital inputs and outputs, essential for the control of external devices and for the reception of simple digital signals. In addition, a serial communication module is incorporated to facilitate the reception of data from certain sensors operating under the MODBUS protocol, the industry standard for communication between devices.

For the needs of this project, it was decided to use hardware from National Instruments - NI, a choice motivated by the recognized robustness and modular adaptability of these devices. These characteristics ensure not only operational reliability, but also the ability to customize and expand the system as needed. Complementary to this arrangement, a media converter is employed to promote effective communication with the server positioned in the control room, using the fiber optic medium, known for its high speed and immunity to electromagnetic interference. Figure 5 visually details the essential components of the embedded system in the panel, offering a clear understanding of the complexity and ingenuity involved in building this system.

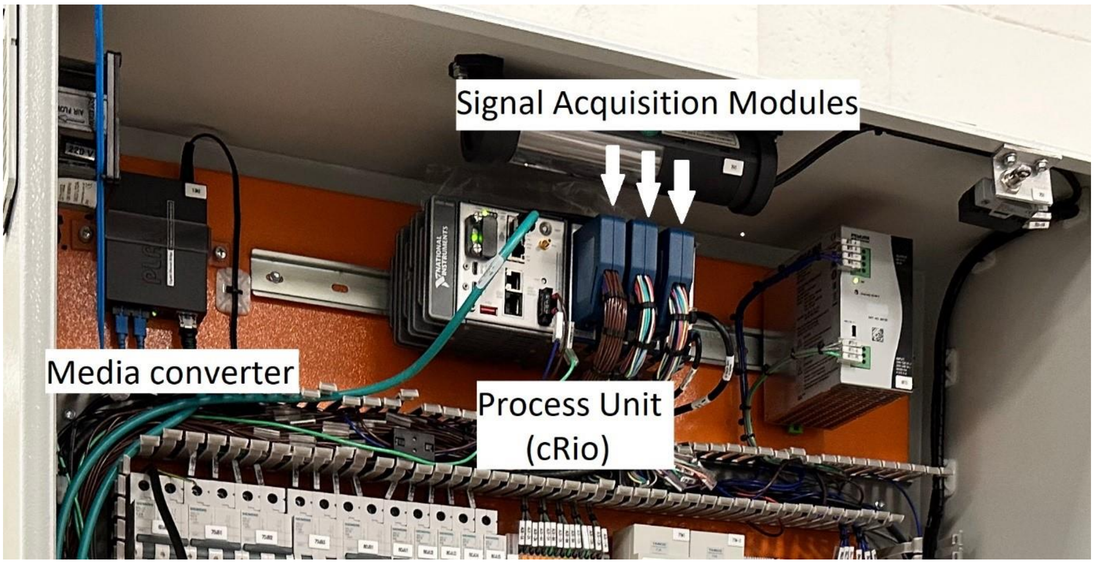

Figure 5. Embedded system equipment.

Processing Unit

All processing of the data collected by the embedded system in the local panel is performed by an NI embedded controller unit, CompactRIO (cRIO). This is a high-performance controller aimed at industrial monitoring and control applications. Because it has modular inputs and outputs, in addition to enabling the insertion of integrated motion, vision, industrial communication and HMI (Human Machine Interface) capabilities, it is a robust processing unit with industry standard certification.

All control logic, variable handling, alarm triggering, and server communication is based on the NI LabVIEW architecture, a graphical programming environment for the development of automated systems.

The implemented code was based on the architecture called "Actor Framework", consisting of a software library that supports the writing of applications in which various operations are executed independently while communicating with each other.

In this structure, the parts of the code are divided into "actors", where each of them represents a state of an independent operation. The access of information or sending it is carried out through messages between the actors, in this way, they operate individually without creating a dependency on each other. This favors in the event of a failure in one actor, because in this case the system as a whole is not harmed and can continue operating.

Signal Acquisition

Acquisition of analog signals (4-20 mA current signals) and digital inputs and outputs is done by the NI 9208 and 9375 modules, respectively. In addition, the NI 9871 module is used to receive data from sensors with serial communication. Within the algorithm developed in LabVIEW, there are 4 main actors that operate in a continuous cycle in this signal acquisition process.

a) *9208 Input Actor*: This actor is responsible for receiving the information from the analog signal acquisition modules. Your role is to read the information on the ports connected to your module, group that data into a JSON-like format (*JavaScript Object Notation*) and send it to the actor responsible for organizing these messages.
b) *9375 Input Actor*: Performs the acquisition of the digital information from the 9375 module. Similarly to the previous actor, this one receives the information from the digital ports and formats it into a JSON to then send it to the actor responsible for managing the messages.
c) *9375 Output Actor*: the digital outputs are also performed by the 9375 module, but in the case of this actor, its operation is based on receiving and verifying the information of the actor who manages the messages to then make a decision to turn on or off the outputs of the module.
d) *BM-MM Actor*: This actor is the one who receives the information from the bushing monitor. The embedded system sends the request for the necessary information to the electronic sensor that responds through the RS-485 network through the MODBUS protocol. The received information is compressed into JSON format to be forwarded to the management actor.

Server Communication

Communication with the server is given through a media converter, installed in the local panel, which connects to a DIO module, which by means of fiber optics, connects to another media converter next to the server in the control room.

To send or receive information with the server, the MQTT protocol (Message Queuing Telemetry Transport). This protocol performs communication between machines by means of publishing and subscribing, i.e. a device that is a Publisher, publishes information, and another device that is a Subscriber, receives them. Numerous pieces of information can be published, as well as numerous devices can receive and/or publish information, as illustrated in Figure 6. What's more, sending or receiving can simply be data or even commands.

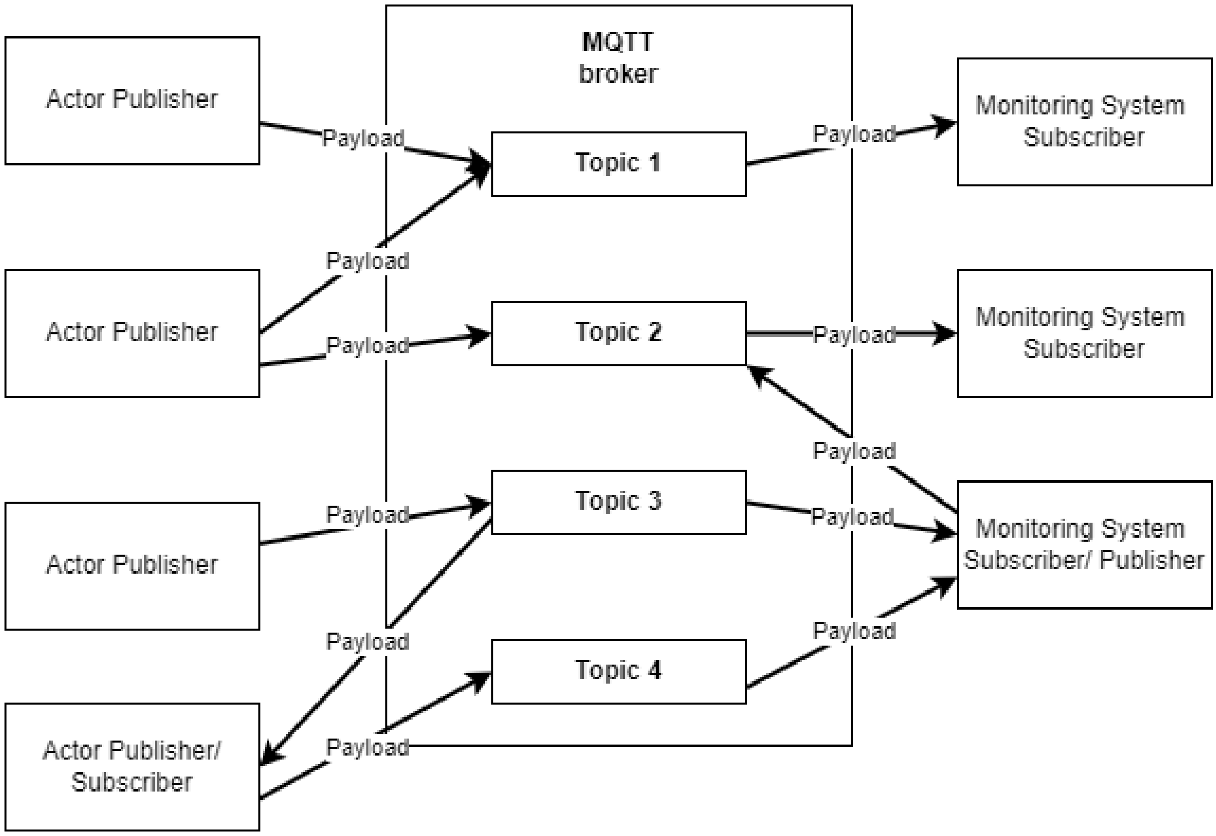

Figure 6. Representation of the operation of the MQTT protocol.

For the communication process with the server, there are 3 main actors plus the watchdog actor that detects and recovers possible problems detected in the signal acquisition or communication process.

a) *Server*: This is the most important actor in the entire embedded system, it is responsible for executing and managing the messages of all the other actors. Through a *Message Broker* system, the actors are launched by the server with a Name, or Topic, so that they send the messages to the Broker and thus, the actors are subscribed to the topic necessary to receive their proper commands. This organization is very advantageous, as it does not generate dependence on the processes within the algorithm, making the system operate in a modular way.

b) *MQTT Publiser Actor*: this actor is responsible for communicating with the server using the MQTT protocol. All the other actors send the messages to an internal broker, which is an actor that manages the messages, the actors send it the topic and the message, then the *MQTT Publiser Actor* sends these messages to the server.

c) *MQTT Subscriber Actor*: this actor operates in the receipt of information from the server also through the MQTT protocol in a message in JSON format. The embedded system then processes this information and distributes it to the actors responsible for receiving the messages from the server.

d) *Watchdog Actor*: this actor aims to make the process of acquiring and sending data more secure. Its operation is associated with a timer with automatic reset, that is, the timer needs to be reset periodically, otherwise the *watchdog* forces the restart of the system as a whole. This becomes quite effective so that the system does not stop working if it has any problems.

Figure 7 illustrates the interrelationship of all the actors involved in the process of monitoring and communicating the developed solution.

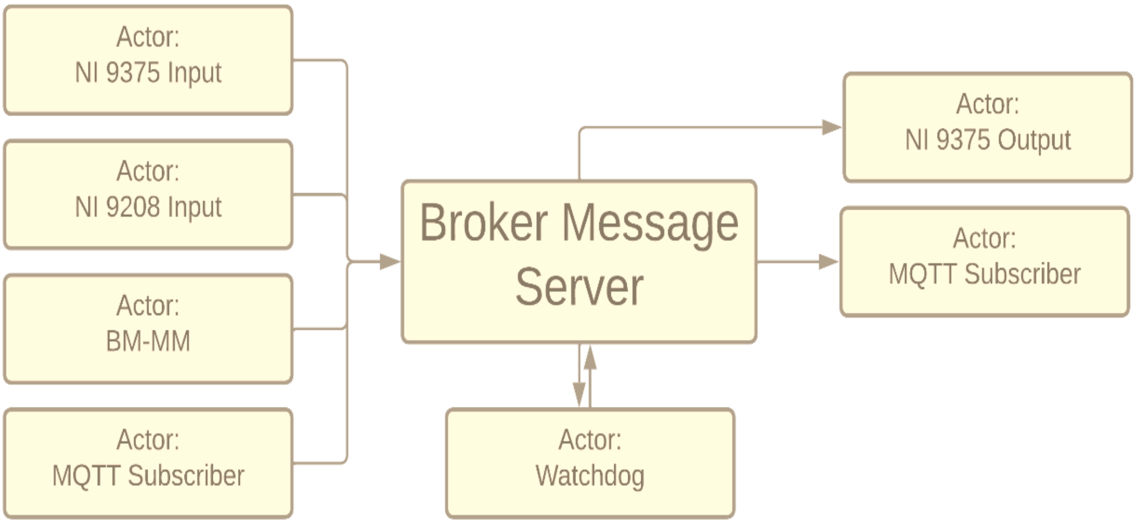

Figure 7. SIMDT actors.

WEB APPLICATION

The Web Application was developed using the pattern of *back-ends* for *front-ends*, this pattern consists of separating the application into two parts, one being responsible for processing and persisting the data, declared as *the back-end*, and the other for consuming the information in an organized and clear way to the user through graphical interfaces, the *front-end.*

Back-End

For the development of the *back-end,* the microservices architecture was used, this architecture is based on multiple services and components to develop a modular structure. This model is a great solution to speed up development, as it allows scalability and independence of the modules. Microservices allow a large application to be separated into smaller, independent parts, with each segment having its own responsibility [7]. This application is exemplified in the diagram in Figure 8.

As shown in the diagram in Figure 8, the raw data from the dashboard is sent to a topic in *the MQTT Broker Message*. For communication between the services, a messaging system called Apache Kafka was used.

Communication via Apache Kafka

The Apache Kafka ecosystem consists of a set of main components, such as *connectors*, *brokers* (usually used together to form a *cluster* of Kafka agents, and Zookeeper), responsible for organizing the Kafka cluster. The Kafka broker is a middleware layer that enables integration between producers and consumers. This is made up of topics and each topic, in turn, is made up of partitions to ensure the integrity of the data received.

Zookeeper is a centralized service for maintenance and configuration of information, i.e., responsible for managing the Kafka cluster, redistributing the *broker leader* in the event of a failure [8]. Kafka *Connect* is a framework included in the Apache Kafka ecosystem that allows the integration of this tool with other systems.

The so-called *source connector* was used to acquire the data from MQTT to Apache Kafka, and the *sink connector* to make the reverse connection, from Apache Kafka to MQTT. In other words, Apache Kafka publishes and subscribes to *MQTT Broker Message* topics.

Communication between the microservices shown in Figure 8 occurs through topics in the *Apache Kafka* Broker.

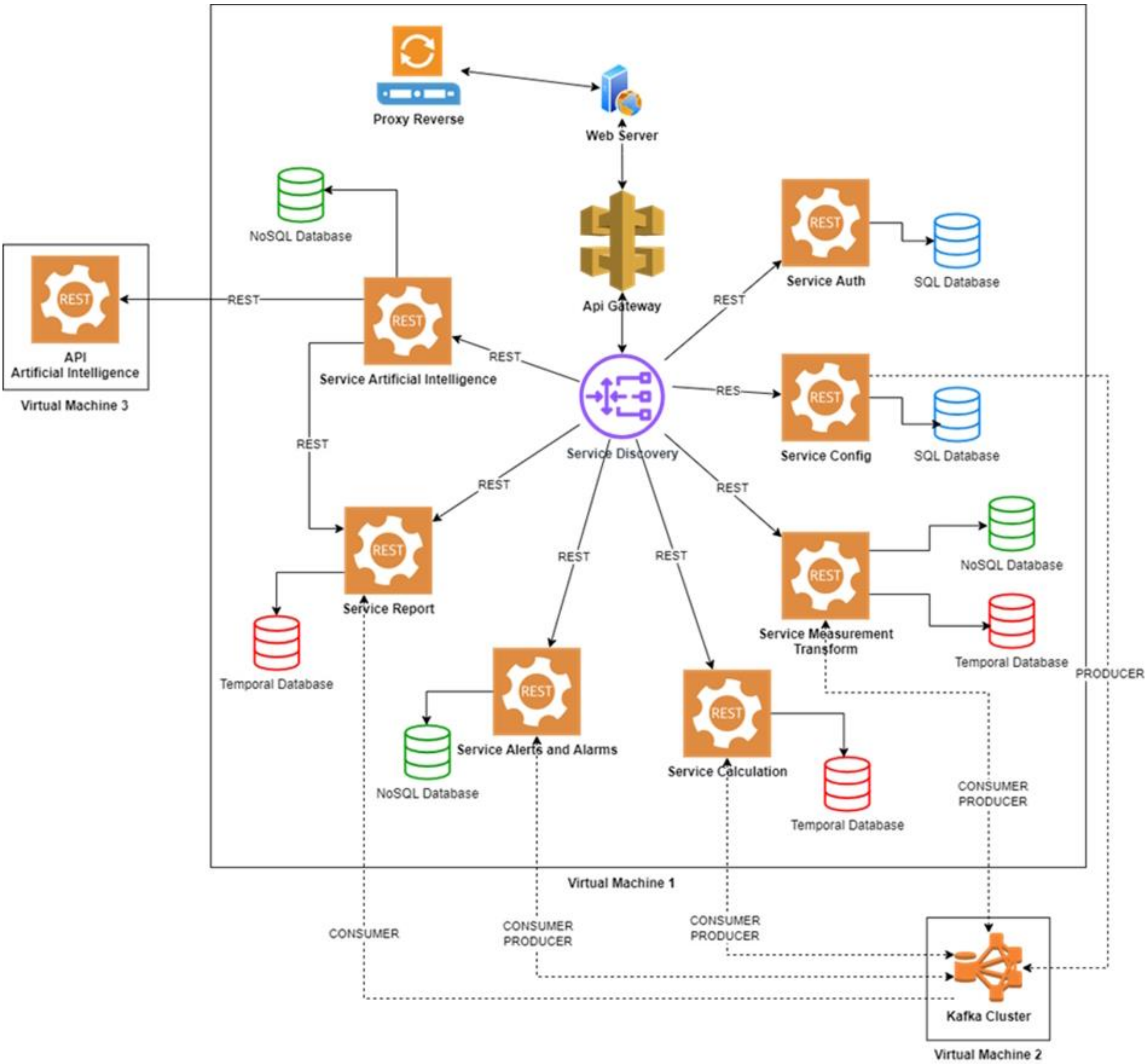

Figure 8. Diagram of the architecture of the microservices applied in the SIMDT solution.

Microsservices

Each microservice has its own responsibility, whether it's processing, persisting, and transmitting the information. In the development of SIMDT, 7 microservices were developed, separating each one with its respective performance.

Microsservice Discovery

Service Discovery is one of the key components when it comes to microservices-based architecture. This service is a design pattern by which client or API (*Application Programming Interfaces*) discovers the network information (IP address and ports) of the server. Being responsible for logging and orchestrating all the *individual services* of the architecture and storing the IP addresses/ports [9]. Every time a service loses connection or is scaled up, a *trigger* will trigger a signal to *Service Discovery*, to perform an update and rebalancing of all microservices instances.

Microsservice Gateway

The *Service Gateway* is the single API access point, which acts as a proxy for the multiple microservices. The *Service Gateway* is the mediator to handle the requests for the multiple services, acting in conjunction with *Service Discovery*.

Microsservice Auth

Service *Auth* is responsible for managing and authenticating system users, both to create a user and to assign access to it.

Microsservice Config

Service Config is responsible for configuring the embedded system channels. All the quantities to be configured are previously registered in the system, being executed the first time the system is put on the air. In this service, the respective channels, whether analog, digital or serial (MODBUS), are registered in the system. When a channel is configured, it is saved in a SQL database and then, *Service Config* publishes the configuration of the channel created in a topic in Apache Kafka, which stores it for a pre-established period or until it is processed/consumed by another microservice.

Microsservice Measurement Transform

Service *Measurement Transform* is responsible for subscribing to the *Service Config* topics and the topic that publishes the raw data from the Monitoring Dashboard, through the *source connector* via MQTT for Apache Kafka. Thus, the relationship between the data coming from the transformer sensors and the channel configuration received from *the Service Config* is made, constructing a new data with its name and value. This information is then stored in a temporal database, and *Service Measurement Transform* publishes the message containing its value to a new topic in Apache Kafka.

Microsservice Calculation

The *Service Calculation* is responsible for processing the data, such as performing complex calculations and diagnostics from the values collected from the transformer. This service subscribes to the originating topic of *Service Measurement Transform* in Apache Kafka to retrieve the data. Thus, the persistence of this information in a temporal database is carried out, in order to then perform the pre-established calculations in the source code. With the calculations finished, a quantity is created that is stored in the temporal database, and then published in a new topic in Apache Kafka, called calculated quantity.

Microsservice Service Alarms-Alerts

Service Alarms-Alerts is responsible for setting thresholds, capturing, storing, and visibility of alerts and alarms. This service subscribes to the topics from *Service Measurement Transform* and *Service Calculation*. Thus, with the data received, comparisons of the values are made, verifying if they are within the expected, and if the value is different from the configured limit, it will be registered in a NoSQL database, providing the option for the user to recognize and describing what caused the alert.

The embedded system will be responsible for issuing the alarms, and it is not necessary to configure limits, as the value is true or false. If the system emits an alarm, it will be persisted in the database with the same options as an alert so that it can be recognized.

Every quantity will be checked by this microservice, once an alert or alarm occurs, the state of the quantity will be changed, and later published in a new topic in Apache Kafka. The embedded system is inscribed in the topic of this service, so that when an event occurs in the topic, visual identification is made through the LED on the monitoring panel installed in the field. Whenever an alarm or alert occurs, a notification will also be sent to the web system.

Microsservice Report

The *Service Report* is responsible for subscribing to all the topics already mentioned and storing all the data received, making the endpoints available to the Web system to make the monitoring requests, generating the graphs and the like. It also provides an endpoint for *Service Artificial Intelligence* to consume and generate the diagnosis.

Microsservice Artificial Intelligence

The *Service Artificial Intelligence* is responsible for consuming the data of the monitored quantities and processing them in order to issue an intelligent diagnosis of the transformer's operating status.

Front-end

For the development of the *front-end*, i.e., the user interface, React was used, which is based on the concept of components. A component is a block of code (JavaScript class or function) that has its own logic and states. A component in conjunction with other components creates complex and powerful interfaces.

React was designed to build SPA applications and offers routing features optimized to run in today's browsers. In addition, React's architecture enables a performance increase in the manipulation of the DOM (*Document Object Model*) through a technique called virtual-DOM, which optimizes the process of updating *Hypertext Markup Language* (HTML) elements in the real DOM through an intelligent algorithm that controls the process of updating and rendering the elements.

Together with React, for the development of the SIMDT solution, JSX, a syntax specification for writing JavaScript similar to XML, was used. JSX has a syntax very similar to HTML tags, which are common in the realm of web application development.

CONCLUSION

In general, the system acquires information from the sensors, these signals are forwarded to the centralized monitoring panel, located near the transformer, to then be processed. The Factory Acceptance Test (TAF) of the monitoring panel and its commissioning were carried out, with the system being active and providing the data and real-time operational diagnosis of the monitored transformer within the conditions established by the manufacturer.

The LabVIEW programming environment provides simplified integration of different components into a system designed specifically for measurement and control applications, with quick access to the hardware and the data generated by it.

The Architecture of Sending and Receiving Information "Actor Framework" enables the different actors to operate individually, without interdependencies. Just like the microservices architecture, implemented for the more agile and efficient development of the Web monitoring interface.

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