A remote MQTT-based data monitoring system for energy efficiency in industrial environments☆

Um sistema remoto de monitoramento de dados com base em MQTT para eficiência energética em ambientes industriais

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Abstract

The concept of the new industry seeks not only to improve production processes, but also to bring solutions to environmental problems, in addition to reducing resource consumption, while maintaining high yields. This constant search for process optimization has been the main agent in the development of new technologies aimed at improving the performance of industrial production lines. Thus, this article proposes to raise some important concepts of Industry 4.0, and present the development of a remote IoT-based system that, through MQTT and Modbus protocols, will be responsible for monitoring the entire electrical network of an industrial plant, sending its data to the cloud, where it can be monitored and analyzed by the industry management sector or even by an artificial intelligence system, in a simple and effective way, in real time and from anywhere, in order to assist in decision-making focused on energy efficiency.

Keywords

Energy Efficiency • Industrial Internet of Things • Modbus • MQTT • Raspberry Pi

Resumo

O conceito da nova indústria busca não só melhorar os processos de produção, mas também trazer soluções para os problemas ambientais, além de reduzir o consumo de recursos, mantendo os rendimentos elevados. Essa busca constante pela otimização de processos tem sido o principal agente no desenvolvimento de novas tecnologias que visam a melhoria do desempenho das linhas de produção industrial. Assim, este artigo se propõe a levantar alguns conceitos importantes da Indústria 4.0, e apresentar o desenvolvimento de um sistema remoto baseado em IoT que, através dos protocolos MQTT e Modbus, será responsável por monitorar toda a rede elétrica de uma planta industrial, enviando seus dados para a nuvem, onde podem ser monitorados e analisados pelo setor de gestão da indústria ou mesmo por um sistema de inteligência artificial, de forma simples e eficaz, em tempo real e de qualquer lugar, a fim de auxiliar na tomada de decisões com foco na eficiência energética.

Palavras-chave

Eficiência Energética • Internet das Coisas Industrial • Modbus • MQTT • Raspberry Pi

1 Introduction

Emerging rise in power costs and sustainability of the available energy has prompted industries to seek alternative solutions that could address energy consumption as the second highest contributor to business expenditure compared

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to salaries and rentals [1]. Globally, industry accounts for about 30% of final energy consumption and about 23% of the world's workforce. Improvement in energy efficiency is needed in all sectors but targeting industrial energy consumption offers major advantages for policy makers because it is more concentrated in terms of entity numbers and often a small number of big energy-intensive enterprises consume the majority of energy in the sector [2].

The analysis of this energy consumption is done, in most cases, through measurements of electrical variables, voltage and instantaneous current, which become essential for obtaining Key Performance Indicators (KPIs) responsible for helping to measure the performance or effectiveness of any activity performed in a company. In industries, where the use of electric motors predominates, these performance indicators help to predict and identify failures, plan preventive maintenance, identify a drop-in performance or excessive wear and tear on electrical equipment [3].

However, the traditional way to perform these measurements requires technicians to travel to each consumption point to perform each measurement. This method implies a high cost, difficult access to information and the possibility of human error when performing each measurement. But on the other hand, due to successive advances, developments and technological innovations, the global industrial landscape has drastically transformed over the last years by increasingly adopting solutions based on standard protocol networks, in their different levels of automation, integrating the factory floor level with the corporate level. This integration then, brings out the concept of Industry 4.0 (I4.0), also known as the Fourth Industrial Revolution (IR4), with the connection of different levels through the concept of Internet of Things (IoT) [4].

Therefore, this work aims to generate a remote monitoring system for electrical variables in industrial plants, using IIoT technologies integrated into an existing industrial system. The system will be responsible for acquiring the data spread over a Modbus network composed of IEDs and other electrical measurement devices, storing them in the cloud through the IoT-based, MQTT protocol. In this way, it will be possible to use data analysis tools or the business intelligence to assist in decision making that collaborates with environmental sustainability and the final result of productivity and profitability in industrial production.

The next section of this paper sets out a brief summary of the fundamentals of Industry 4.0 and some of its digital key technologies. Section 3 discusses the reasons why addressing energy efficiency in industry should be a priority, particularly in developing countries where industry often accounts for a large proportion of energy use. Additionally, section 4 deals with the convergence between already consolidated industrial communications and the management sector through the introduction of IoT (or IIoT), with the purpose of aggregating the most relevant data from the industry in order to have easy access, redundancy, and other advantages. The 5th section comments on the devices that will be used, while in section 6, the methodology for developing the proposed system is presented. Moreover, in section 7, the results from the tests are shown and discussed, and finally, section 8 concludes the paper.

2 Related Work

Ever since the beginning of industrialization, technological leaps have led to paradigm shifts which today are ex-post named “industrial revolutions”: in the field of mechanization (the so-called 1st industrial revolution), of the intensive use of electrical energy (the so-called 2nd industrial revolution), and of the widespread digitalization (the so-called 3rd industrial revolution) [5].

Therefore, the fourth industrial revolution, called Industry 4.0, aims to transforming traditional industries into intelligent ones by incorporating innovative technologies. It is a universal movement that consolidates the deep transformation of companies through technologies such as Internet of Things (IoT), Cyber-Physical Systems (CPSs), Artificial Intelligence (AI), Big Data, Additive Manufacturing and others, and it is characterized by using these digital technologies to optimize processes, improve the quality of products and services, reduce energy consumption and contribute to a more assertive management [6].

The convergence between industrial plants and the Information Technology (IT) area has been one of the main changes in this so-called Industry 4.0. This results in a convergence of multiple disparate technologies, something that brings management and security challenges never seen before. This new reality can be called Industrial IT, an environment where three types of technology converge: Information Technology, Operational Technology (OT), and Industrial Internet of Things (IIoT) [7].

In the context of this new industry, the "hyper-connectivity" of the various systems involved in the production process, on which Industry 4.0 is based, multiplies the data generated in real time from different sources and varied formats that must be stored and analyzed with technologies and advanced algorithms [8]. The adoption of IIoT increases the total volume of the generated data transforming the industrial data into industrial Big Data, considering that the machines and sensors produce more data than a person and such data is always connected. It also allows to determine patterns and correlate data for the improvement of industrial processes, make decisions in real time for operational efficiency and design new services associated with existing products and machine learning [9]. For such reasons, Cloud Computing and Big Data are two major technologies applied by the approach.

2.1 Energy Efficiency in Industry 4.0

Similarly to renewable energies, energy efficiency has truly advanced over the past years. Emerging economies have shown higher energy intensity improvements than industrialized countries, with China leading the way by decreasing its energy intensity by 5.6% from 2014 to 2015 [2].

For companies to remain competitive, ensuring their market share, it is necessary to adapt to this new system that aims to optimize their production chains. To identify these possible improvements, a detailed and constant monitoring of the main indicators of the electricity, gas and water systems is necessary. It is common to find large production lines, whether manufacturing or process, with large quantities produced, but that do not achieve the expected profitability per product unit and many of these problems are related to the optimization of the production line [10]. Therefore, energy efficiency is one of the main benefits and one of the pillars of industry 4.0 [6].

In a strictly technical definition, energy efficiency is measured as the ratio between the useful output of the end-use service and the associated energy input [2]. In other words, it is the relationship between how much energy is needed to power a technology (for example, a light bulb, boiler, or motor) and the end-use service (for example, lighting, space heating, or motor power) that the technology provides. Conceptually speaking, energy efficiency is doing the same or more, consuming fewer natural resources and in a smarter way, always focusing on operational safety and comfort and product quality [10].

Therefore, it can be said that there is no way to talk about Industry 4.0 without talking about energy efficiency, because in reality these two concepts complement each other, as being efficient in our contemporary world has been, for some time, synonymous with survival [10]. This new industry concept, however, goes further. It seeks not only to improve production processes, but also to bring solutions to environmental problems, improve the quality of the work environment and, above all, reduce the consumption of resources, maintaining high yields [6].

Amidst all this, in order to enhance and transform the current manufacturing systems into intelligent ones, capable of optimizing production chains, the need to implement new technological resources becomes evident.

To identify and monitor the most energy intensive components of a process is the first stage for taking further actions to improve the energy efficiency. Complex industrial processes often have a large number of devices and components, each consuming different amount of energies and working in different states [11]. Parallel to this, to enhance industrial acceptance, it is crucial to design the monitoring system to be minimal invasive, such that sensing, data acquisition and transmission cause little interruptions to the process [12].

2.2 Integration of IT and OT technologies in Industry 4.0

The OT (Operational Technology) refers to industrial networks that are commonly used in industrial control strategies. These industrial networks have been consolidated for decades and are composed of different technologies, depending on the type of application and industrial process. Profibus DP, Devicenet and Profinet networks protocols stand out in manufacturing control networks, and FF, HSE and Profibus PA networks in continuous process control. In the context of power system networks, the Modbus, DNP3 and IEC61850 networks stand out [13].

However, despite solving a wide range of applications, these fieldbus networks, such as Modbus that will be presented in this paper, are quite limited, since they do not have support for several specific applications, such as: applications where devices keep changing network or have an unknown address; applications where a layer of data security or access control is required; and mainly, applications that involve sending data to cloud services [14].

In order to solve problems as listed above, it is necessary to implement new technologies, responsible for integrating these field networks (OT), to the IT sector. For this, there are so-called IoT gateways (or IIoT gateways), cutting edge devices willing to “intermediate” these two ends, communicating the data extracted from the OT, to servers in local data centers or in the cloud (IT).

In its simplest form, a gateway can be just a hardware or software to collect and aggregate data from input and output devices. However, in this new scenario of IIoT, the most common use of IoT gateways is as an edge device. It can connect directly to field equipment (sensors, actuators, etc.) or through programmable logic controllers (PLCs), intelligent electronic devices (IED), supervisory control and data acquisition (SCADA), etc. that aggregate field data. It must therefore, support a wide variety of interfaces, including wired, wireless and even serial connections (e.g. RS-232 or RS-485). Among the main IoT gateway technologies existing in Industry 4.0 that integrate the factory floor to the web, working as an “intermediary”, we can mention protocols like MQTT, OPC DA/UA and CoAP. The MQTT communication protocol is one of the most outstanding, for its ease of implementation, for being widely used, and mainly for being an open technology [15].

In this context, three important technologies that will be used in the development of the proposed work will be presented below, Modbus protocol (OT), MQTT protocol (IoT) and Cloud Computing (IT):

Modbus Protocol

For being simple, free of charge, universal and easy to use, the most popular industrial protocol being used today is Modbus, an open communication protocol developed by Modicon for the interconnection between industrial equipment (e.g., PLCs and IEDs), often used to establish a serial (RS485/RS422/RS232) connection, known as Modbus RTU, based on the master-slave model, allowing a master to control up to 247 slaves in a network, each receiving an address fixed from 1 to 247. It is noteworthy that, by this address, the Modbus Master can both read and write information in slaves [16].

The Modbus TCP, often referred to as Modbus over Ethernet, is simply Modbus packets encapsulated in standard TCP/IP packets, what enables Modbus TCP devices to immediately and easily connect and communicate over existing Ethernet and Fiber networks. It also allows many more addresses than RS485, the use of multiple Masters, and speeds in the gigabit range. While Modbus RTU has a limitation of 247 nodes per network, Modbus TCP networks can have as many slaves as the physical layer can handle [17].

It is worth mentioning that there is also Modbus PLUS, with RS485 physical media, token pass, support for master/slave and peer to peer models, it has several additional features of routing, diagnostics, addressing and data consistency. However, it is still held under Schneider Electric's domain and can only be implemented under license from this manufacturer.

Figure 1 shows a simple example of a Modbus network, with a gateway to convert serial Modbus data into Ethernet.

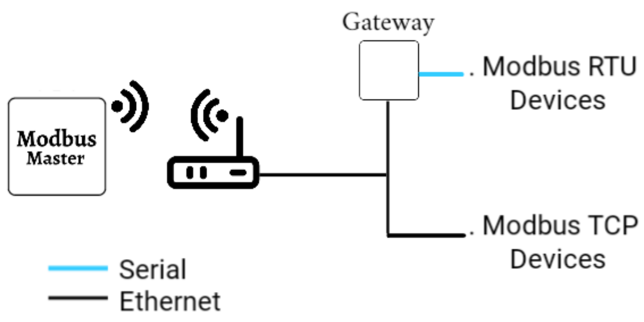


Figure 1: Modbus architecture.

Another advantage of Modbus is that it can run over virtually all communication media, including twisted pair wires, wireless, fiber optics, Ethernet, telephone modems, cell phones and microwave. This means that a Modbus connection can be established in a new or existing plant fairly easily [17]. In fact, as presented in this paper, a growing application for this is the provision of digital communications in older factories, using existing twisted-pair wiring, with the aim of aggregating the necessary data for the new reality of the industry, after which they can be sent to higher levels through IIoT, since the Modbus protocol does not have any mechanism provided for security, i.e., no password, authorization, certificates or any other mechanism and, no least, applications for sending data to cloud services [14].

MQTT Protocol

One of the main IoT technologies used in communication between a network of devices and the cloud is the MQTT protocol (Message queuing telemetry transport). The MQTT architecture is simple to implement, has data security mechanisms and moderate use of network bandwidth. It is a publish/subscribe network protocol for sensors and small mobile devices and its main use is to make machines exchange information, a mode of communication known as Machine-to-Machine (M2M) [18]. This technology was developed by IBM in the late 1990s, and its original purpose was to connect satellite sensors or oil pipelines. Despite having been created some time ago, its applicability is still exceptionally useful today, including in several business branches [14].

In the architecture of the MQTT protocol, the identification of messages takes place through topics. This topic resembles the concept of Uniform Resource Locator (URL), where levels are separated by slashes ("/") [18]. The publish/subscribe message exchange pattern used in MQTT works as follows. When an element of the network wishes to receive certain information, it subscribes to it's topic, making a request to another element of the network capable of managing publications and subscriptions. In MQTT network, this element is known as Broker, the middleware in the communication process. On the other hand, elements that wish to publish information also do so through the Broker, sending the information they have, to pre-established topics [18].

Figure 2 shows an example of the MQTT architecture. In it, clients working only as publishers could be sensors in an automation network, HMIs, PLCs, IEDs or SCADA systems publishing their message to a specific topic for example, while clients both subscribers and publishers, could be cloud databases, data analysis tools, autonomous robots or end users, who could receive and send data to each other.

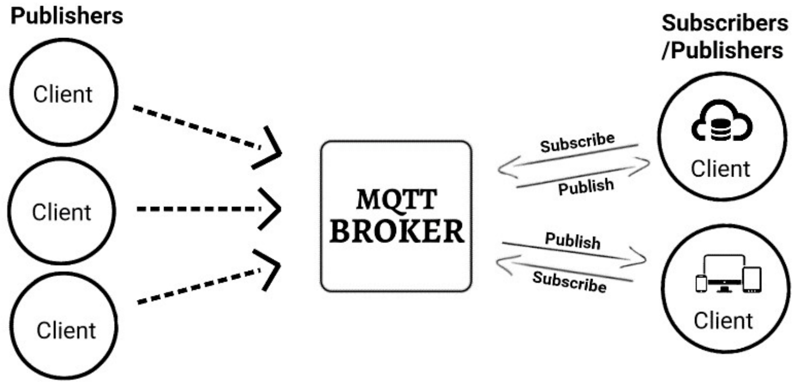


Figure 2: MQTT architecture.

The client's connection to the Broker, be it subscriber or publisher, is originally done via TCP, with login options (i.e. username and password) and use of encryption (SSL/TLS). Every connection process also establishes a desired level of Quality of Service (QoS 0, 1 and 2) indicating how the relationship between the communicating elements should be. Although the Broker seems to represent a weak link in the network when centralizing communications, it can also be optimized to have scalability and availability, in addition to allowing a decoupling between the communicating parties, which is not possible in client/server communication models [18].

Cloud Computing

An existing concept in Industry 4.0 is the Cloud Computing, it refers to a technological concept and a business model that allows the remote use of computing resources through internet connectivity. It allows access to infrastructure, software and information through any device (computer, tablet, cell phone) that is connected to the internet and also allows the storage of large amounts of data (Big Data). This capacity is mainly important to store the data generated during a whole production process. Likewise, Cloud Computing reduces investment in technological resources, allowing the storage space and processing capacity to be contracted on demand, which provides flexibility, agility and adaptability [19].

Cloud storage has several characteristics that make it superior to using dedicated hardware, such as self-service, fast elasticity, broad network access, resource allocation on demand, and pay-per-use, among others. The use of the cloud decentralizes information to a storage where it is possible to access data from anywhere, enabling collaborative and simultaneous access to the information[4].

In terms of functioning, the cloud can be: public, private or hybrid. The public cloud is managed by large companies, where the user installs the software and the administrators take care of the maintenance and security of the information. Examples of this type of storage are AWS (Amazon Web Service), Google Cloud Platform, Microsoft's Azure, Oracle Cloud, among others. In the private cloud, the customer is responsible for data administration and security. Access is via a virtual private network (VPN) and is used by companies that do not want to share space with other users. In the hybrid cloud it involves the use of both public and private network [20].

The Cloud Computing Platform that will be used in this work is the AWS Cloud Platform. But it is noteworthy that, despite some differences in infrastructure, any platform could be used. This will be responsible for running the MQTT Broker in the cloud so that it is not necessary to have a dedicated server for this task, and will also be responsible for storing the database (SQL or NoSQL) in future work.

3 Development Workflow

The architecture of the developed IoT-based industrial remote data monitoring system consists of three modules, namely, IoT Gateway, Remote MQTT Broker, and MQTT Subscriber.

For system tests, a Raspberry Pi provided by the the Automation, Electronic Systems and Control Laboratory (LASEC) was used. The Raspberry Pi is a low cost, credit-card sized computer that plugs into a computer monitor or TV, and uses a standard keyboard and mouse. Robust and affordable, Raspberry Pi technology has been deployed in tens of thousands of applications in a variety of industries across the world. From micro-controllers to ARM-based computers, Raspberry Pi brings every last drop of power to bear in an application [21].

The Raspberry Pi provided by LASEC is a Raspberry Pi 3 Model B, and it will be responsible for being the system's IoT Gateway, by running the developed application. Its main features are: Quad Core 1.2GHz Broadcom BCM2837

64bit CPU; 1GB RAM DDR2; BCM43438 wireless LAN; Bluetooth Low Energy 4.1 (BLE) on board; 100 Base Ethernet and; 5V/2.5A DC power input via Micro USB;

The schematic structure of the proposed work is shown in Fig. 3.

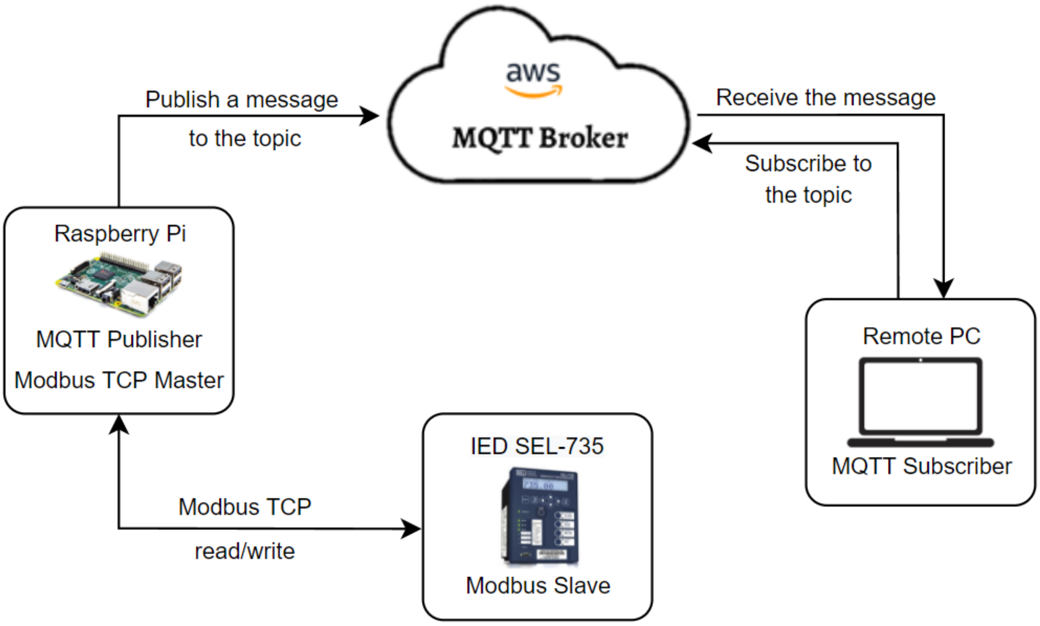


Figure 3: Architecture of the developed project.

Another device provided by LASEC was an Intelligent Electronic Device (IED), for the purpose of working as a Modbus slave. In an industrial environment, an IED refers to multi-function equipment for protection, control, monitoring and measurement, with internal intelligence and the ability to communicate with supervision and data acquisition systems [22].

The IED arranged by LASEC is a SEL-735 Power Quality and Revenue Meter, a fully Class A-compliant to the IEC 61000-4-30 power quality standard produced by the Schweitzer Engineering Laboratories. With reliable Class A measurement, operators can identify power system anomalies and isolate their source with confidence [23].

It is important to emphasize that there are various options for communicating with the SEL-735. The meter communications ports consist of the following [23]: EIA-232; EIA-485; Internal Telephone Modem; 10/100BASE-T Ethernet RJ45 Port; 100BASE-FX or 100BASE-LX10 Fiber-Optic Ethernet LC Port and; Type 2 Optical Port.

3.1 IoT Gateway

In this module, the development of the application responsible for data acquisition, through the Modbus protocol, and publication to higher levels, through the MQTT protocol, will be detailed in two layers respectively.

Modbus TCP

As shown in the previous section, there are different industrial networking protocols currently in the industry. In this project, Modbus TCP was chosen for its ease of implementation, for having some advantages over others, as described in the fourth section, and for being a widely used protocol both in equipment in an industrial process network and in automation and energy systems.

Therefore, this layer is responsible for interfacing with the industrial network that already exists in the industry, aggregating the data obtained through measurement equipment (IEDs) and making them available to higher layers. As main features, this application must have speed and be able to collect data from the various network equipment.

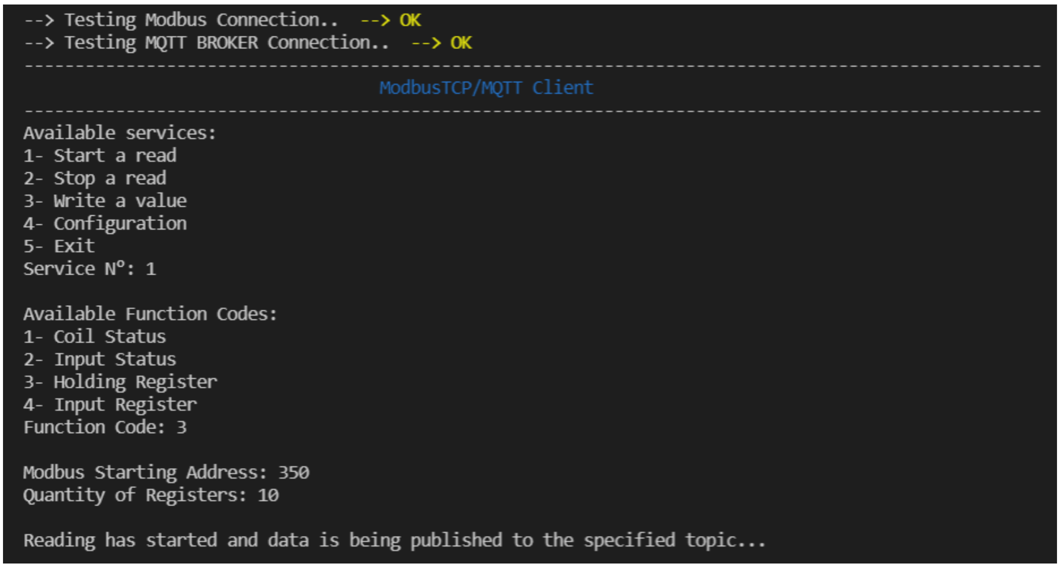
Written in Python and using a library called PyModbusTCP, it was possible to develop the first part of this project, which consisted in the development of a Modbus Master client, with an initial menu for the user, giving him the option to perform reading, writing and configuration services. The application also allows the user to read 4 different function codes (i.e., Coil Status, Input Status, Holding Register and Input Register).

MQTT Publisher

By implementing Eclipse's paho-mqtt library in the same application, it was possible to publish the data, read from the Modbus Master, in the Broker, through the topic specified by the user. Moreover, this app also publishes the data along with its address and function code to the remote Broker. The sampling time referring to the reading could also easily be sent to the broker.

As previously mentioned, MQTT has some features aimed at security and data delivery guarantee, however, in this project none of these have been used yet.

The main menu of the system developed can be seen in Fig. 4, with an example of reading 10 registers starting at address 350.



```
--> Testing Modbus Connection..  --> OK
--> Testing MQTT BROKER Connection..  --> OK
----------------------------------------------------------------------------------------------------
                                      ModbusTCP/MQTT Client
----------------------------------------------------------------------------------------------------
Available services:
1- Start a read
2- Stop a read
3- Write a value
4- Configuration
5- Exit
Service Nº: 1

Available Function Codes:
1- Coil Status
2- Input Status
3- Holding Register
4- Input Register
Function Code: 3

Modbus Starting Address: 350
Quantity of Registers: 10

Reading has started and data is being published to the specified topic...
```

Figure 4: Modbus/MQTT Gateway running in the Raspberry Pi.

3.2 Remote MQTT Broker

In order to have a remote Broker, with high performance and availability, the Amazon Web Service (AWS) cloud computing platform was used. Thereby, an instance was created at the EC2 (Amazon Elastic Compute Cloud) service, a central part of Amazon's Cloud Computing platform which allows users to use the AWS Management Console to configure virtual machines to run personal applications [24]. Finally, an Apache-based server was deployed to host one of the most known and used open source Brokers, the Eclipse Mosquitto [25].

3.3 MQTT Subscriber

This layer is responsible for running an MQTT Subscriber in order to receive and validate the publications sent from the acquisition system. For this, in the Windows Command Prompt (CMD), a Mosquitto-Subscriber was started, subscribing directly to the host (through the public IP generated by AWS "3.134.40.193") of the remote Broker and in the same topic of the IoT Gateway publication. The topic specified for the system tests was "test/status".

There are many options to run the Mosquitto-Subscriber in the CMD. Some examples: "-h" to specify the host to connect to (defaults to localhost); "-p" to connect to the port specified (default to 1883 for plain MQTT or 8883 for MQTT over TLS); "-t", the MQTT topic to subscribe to and; "-u" and "P" for username and password to be used for authenticating with the broker [25].

4 Results and Discussions

For the acquisition tests, the IED, which plays the role of Modbus Slave, was connected to a lamp powered by the electrical network (220V). In Fig. 5 it is possible to see the IED SEL-735 measuring the energy consumption of the lamp. It is also important to point out that it is connected to the local network via Ethernet, so that communication with the Modbus TCP master is possible. This could also be connected via Wi-fi to the same network, however, due to interference and drops, communication via Ethernet cable is preferable when possible.

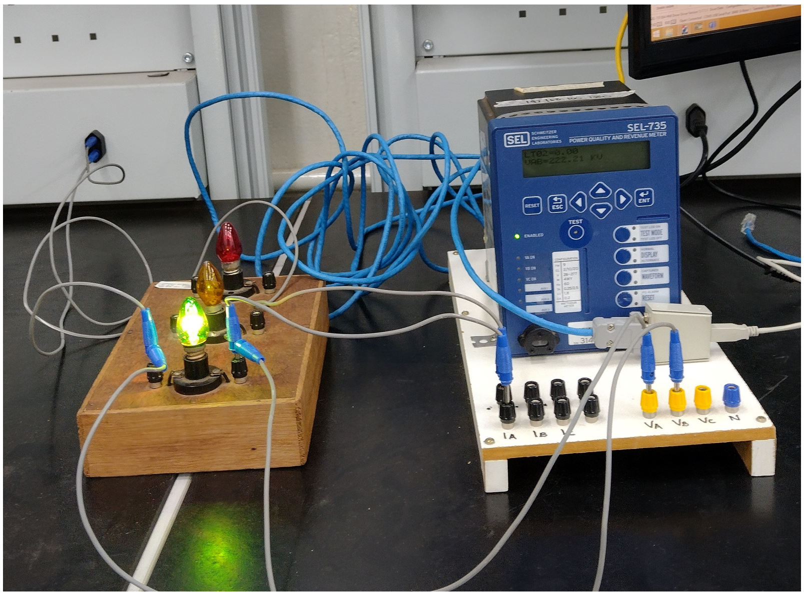


Figure 5: SEL-735 and lamp connected to the power grid.

Table 1: SEL-735 Modbus Register Map Summary [23].

Address		Name	Read (R) Write (W)	Data Types
Decimal	Hex			
350-351	015E–015F	IA	R	LONG100
352-353	0160–0161	IB	R	LONG100
354-355	0162–0163	IC	R	LONG100
356-357	0164–0165	IN	R	LONG100
358-359	0166–0167	VA	R	LONG100
360-361	0168–0169	VB	R	LONG100
362-363	016A–016B	VC	R	LONG100
364–365	016C–016D	VAB	R	LONG100
366–367	016E–016F	VBC	R	LONG100
368–369	0170–0171	VCA	R	LONG100

Table 1 shows a summary of the Modbus Holding Register Map from the SEL-735, which specifies each Modbus register address, the register name, the read/write access, and the data type of the register [23].

In order to confirm the values to be read through the acquisition system, the IED was also connected directly to a computer, where, through the SEL's own AcSELerator QuickSet software, it was possible to see the current values (IA, IB and IC) and voltage (VA, VB, VC, VAB, VBC and VCA) to be remotely monitored. These measured values can be seen, along with some others, in Fig. 6.

Finally, Fig. 7 shows the Mosquitto-Subscriber in the Windows Command Prompt, running as a subscriber of the topic (-t) "test/status", through the Broker (-h) hosted on the AWS server. In this topic, 9 readings of the 10 Modbus registers were published, from 350 to 369, as these parameters use two addresses each, for being "LONG100 type" (Table 1).

It is also possible to compare the values obtained through the developed system with the values shown in the software (Fig. 6) of the equipment itself. It is also worth reaffirming that, with the Broker active in the cloud, it is possible to subscribe to this topic from anywhere in the world, receiving its publications at the exact moment they are published.

With these results, it was possible to verify and analyze the data acquisitions of the IED SEL-735 through the Modbus TCP protocol and also their publication, through the MQTT protocol, in a cloud server, which can be accessed

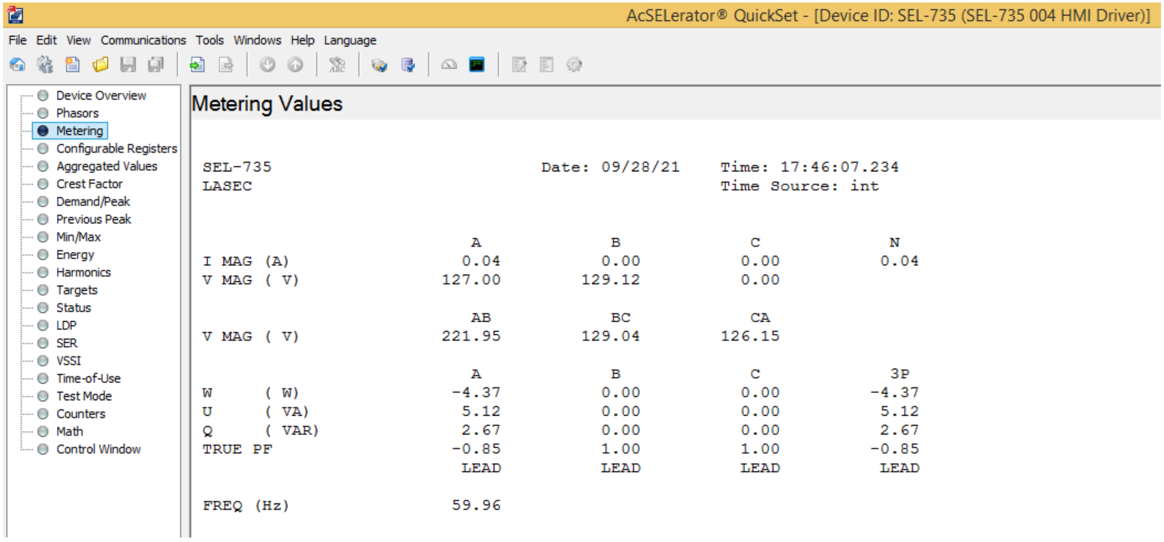


Figure 6: SEL-735 Metering Values (AcSELerator QuickSet).

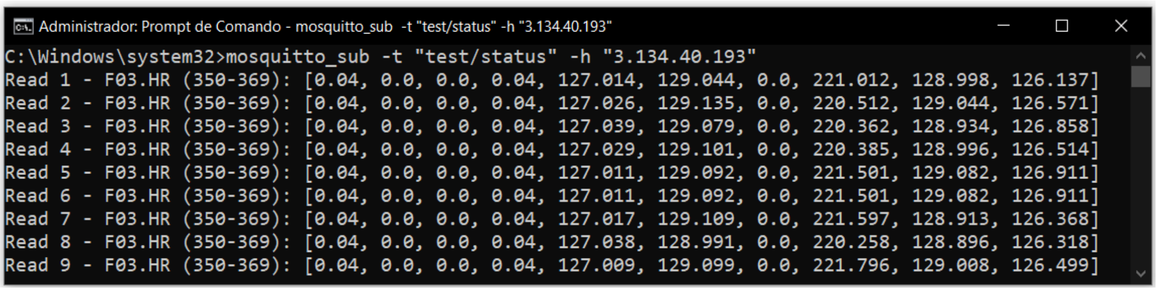


Figure 7: Command Prompt running the MQTT Subscriber.

from anywhere, through the Internet.

5 Conclusions

This paper has presented the integration of an existing and very used industrial technology, Modbus protocol, with an IoT-based technology, MQTT, triggered by this new reality of the fourth industrial revolution, aiming at non-invasive remote monitoring of an industrial process, focusing mainly on the acquisition of electrical variables. The designed system, despite being powerful enough to handle multiple devices at the same time, reliably, securely, and instantaneously, is of very low cost, as only free services were used and a Raspberry Pi that should not go beyond 35 dollars.

Regarding the industrial network used, this project specifically implemented a Modbus TCP client. The use of other network protocols such as DNP3 client could be implemented in the future. In this way, the project would be able to encompass different energy network equipment on the market.

It has a very significant importance, given the relevance of researches under the integration of these different technologies presented in this paper, not only with the intention to improve companies' profit margins, but also to cooperate with sustainability.

As future projects, the integration of other I4.0 technologies, such as the implementation of Machine Learning techniques, will still be studied in order to improve the analysis system, offering predictability and helping in decision making, with a minimum of human intervention. Security aspects of the network at its different levels will also be studied.

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