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SMART GRID SYSTEM PROTOTYPE MODEL WITH LPWAN NETWORK FOR COMMUNICATION

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Abstract: Advances in digital electronics and telecommunications systems have made it possible to integrate a chain of information flow in different sectors of society, and electrical networks are no different. This work aims to build and detail a prototype model of a complete *smart grid system* using LoRa radio as a form of communication, an innovative way. To achieve this, this prototype aims to go through the entire chain of information starting with the collection of data by the *smart meter,* followed by the transmission of this data and ending with its analysis and visualization. Finally, this work aims to detail each of these stages, presenting the equipment used, as well as its advantages and disadvantages.
Keywords: Smart Electric Grid. Smart Meter. LoRa.

INTRODUCTION

The history of humanity can be marked by some innovations, discoveries and scientific inventions that revolutionized the routine and daily life of the entire society, the domain of electrical energy is in fact present on this list (MIRANDA, 2023).

At the beginning of the 20th century, the control of electrical energy facilitated the lighting of external and internal environments in cities, increased security, facilitated work, study and the urbanization of large centers. In the industry, electrical energy, due to its characteristics of transmitting a large amount of energy and also its easy convertibility into movement, light and heat, was one of the main factors responsible for the second industrial revolution (CAROLINO, 2023).

In the modern world, the use of electrical energy is already widespread throughout cities. Therefore, the correct distribution and quality of electrical energy are imperative factors for the economic and social advances of a region (TURCI et al., 2023).

Currently, rapid technological advancement, ease of communication and the population's awareness of environmental issues have caused changes in various sectors of society. With these new paradigms in mind, electrical networks have been updating to more modern concepts and technologies. In this context, the idea of *smart grid or intelligent networks* emerged, which aims to improve energy efficiency, increase automation and facilitate the exchange of information within the electrical system (LINS; RODRIGUES, 2023).

Thus, in this research context, to enable the integrated network that allows communication between concessionaires and consumers, research and improvement of intelligent measuring equipment, which primarily provides readings of electrical network parameters, and the transmission of this data reliably throughout the network, with low implementation costs and high reliability.

Therefore, in this work, we seek to build and test a low-cost prototype of a complete *smart grid system,* using an LPWAN network as a form of communication. Furthermore, adding and exploring features not always explored within the smart meter, such as: calculation of the network frequency and visualization of network parameters (voltage and current) by the consumer. To achieve these objectives, it is necessary to detail some stages of the project, including:

- Construction of a low-cost smart meter prototype with LoRaWAN technology for communication;
- Addition of network frequency calculation functionality to the smart meter prototype;
- Construction of a LoRa *gateway prototype* to receive data sent by the smart meter;
- MQTT server configuration to receive data sent by the LoRa *gateway* ;

- Coding a script or routine that stores data from the MQTT server in a database;
- Construction of a dashboard for visualization and analysis of data measured by the *smart meter* ;

To understand the techniques used in the proposed prototype, it is necessary to examine, initially conceptually, certain aspects of the technologies used.

TECHNOLOGIES AND THE DEVELOPMENT OF SMART GRID

The advent of digital electronics and the advancement of telecommunications have allowed the implementation of sophisticated equipment, so-called *smart meters,* which allow parameters to be read in real time, removing the need for local readings for billing and allowing countless other automations for the electrical system. (F UGITA, 2017).

According to Babayomi et al. (2023), a *smart meter* can be defined as a measuring device based on different operating principles, such as electrical, electronic and mechanical, however, increasingly implemented with electronic and digital systems that make it an interactive tool.

According to Depuru (20 11), a *smart meter* is an energy meter that measures the consumer's electricity consumption, in addition, it provides other additional information to utilities when compared to traditional meters. Therefore, its integration into the electrical grid involves a variety of software techniques, which depend on consumer demand needs. Furthermore, the implementation of a *smart meter* requires an appropriate communication network selection, thus satisfying the security standards of the smart grid.

The use of *smart meters* enables the implementation of *smart grid networks.* By *smart grid networks* or REI (smart electrical grids) understand how those that enable real-time measurement data traffic and offer several benefits for both energy concessionaires and consumers. According to Cabello (2020), the implementation of smart grid network generates main benefits:

- More efficient services at a lower cost;
- Better detection and, consequently, faster response to possible problems;
- Reducing consumption through better management of energy use;
- Consumer with greater control over their expenses;
- Better monitoring of the network allows for a significant drop in losses suffered due to fraud or energy theft;
- Greater space for alternative sources of distributed generation, due to the bidirectionality of the network.

These aspects allow us to state that the implementation of smart electrical grid (REI) represents progress for the electrical sector and, consequently, for society as a whole. Therefore, to facilitate the dissemination of this technology, studies and research related to the topic are necessary, in order to examine, guide and standardize this new technology that is on the rise.

FROM PLC TO LPWAN

smart grid technology Being in the improvement and dissemination phase, there are several technical characteristics to be discussed for its better implementation on a large scale. One of these debated issues is the definition of the most appropriate telecommunications technology for its implementation.

Currently, one of the most promising telecommunications technologies is called Powerline Communication (PLC). PLC technology has the advantage of using the already installed infrastructure of the electrical power system to transport the data necessary for the operation of the smart grid. (ABDULSALAM, 2023).

According to Augusto Matheus (ALONSO, 2014), some of the strongest points of this technology are highlighted by:

- Unlimited access to the entire scope of the energy transmission system;
- Use of the same physical structure as the energy grids, eliminating the need for new cabling;
- Ability to offer high data acquisition rates for establishing communication networks;
- Division of frequency bands for specific data transmission;
- Combination with other types of technology.

Although PLC technology offers several facilities, there are some factors that have made its implementation in REI difficult. Due to the use of SEP for data traffic, the PLC faces an unstable environment, subject to external electromagnetic interference, as well as noise and variations internal to the network.

According to Beshir (2023), there are some disadvantages to using PLC that deserve to be analyzed:

- Attenuation according to frequency: voltage dividers, coupling between phases;
- Delay in communication;
- noise : coming from motors, dimmers, switches;
- Lack of security;
- Electromagnetic compatibility problems, due to the interfacing of electronic circuits with the SEP;
- Unpredictability of parameters of the channel used, such as: impedance, attenuation and noise levels, which fluctuate with time and changes in network load.

Therefore, it is interesting to study other alternative forms of communication to be used in REI. One of these communication technologies that is currently gaining great prominence is the so-called Low Power Wide Area Network or just *LPWAN* (in free translation, Long Distance and Low Consumption Networks).

According to Câmera da Silva (SILVA, 2018), *LPWAN* networks allow connecting devices over long distances (for example: from three to fifty kilometers) at low cost (for example: an end node can cost up to five dollars), with small bandwidth and, consequently, low relative battery consumption.

Therefore, because *smart grid systems do not require high data traffic and LPWAN* networks provide low cost and long range, they make them a viable candidate as a telecommunications technology within an REI system.

LPWAN NETWORKS

LPWAN networks *(Low Power Wide Area Network),* or in free translation, long distance and low consumption networks, are networks that are characterized by the ability to have large coverage areas, low data transfer rates and low equipment energy consumption.

LPWAN networks can reach a distance of 5 km in urban areas and 15 km in rural areas. This is possible due to the new physical layer design, which is designed to have high receiver sensitivity (CENTENARO, 2015).

According to Patel (2018), *LPWAN networks* achieve their long communication distance with modulation techniques that focus on waveforms with high energy per bit rather than waveforms with high bit rate. Therefore, modulation rates are reduced with the aim of putting more energy into each bit or symbol transmitted. This way, the receiver is able to decode even the weakest signals without errors.

LoRa AND LORaWAN

LoRa is a physical layer technology that modulates the signal in *Sub Ghz ISM band* using a proprietary spread spectrum technique (SFORZA, 2010), developed and commercialized by *Semtech Corporatio*n (SEMTECH, 2022). Bidirectional communication is provided by the *chirp spread spectrum* (*CSS)* technique, which spreads the narrow band of an input signal into a larger bandwidth channel. The result is a signal with properties similar to noise. Thus, making the signal difficult to detect. Furthermore, the processing gain allows for greater resilience to interference and noise (RAZA, 2017).

The LoRaWAN protocol defines the system architecture, communication parameters, security, quality of service and power adjustment used by LoRa technology. This protocol allows operation in bands 433, 868, 915 MHz depending on the region. The channel width is set to 125 kHz. The modulation generally used is *CSS,* and it is also compatible with *FSK* and *GFSK*. The supported data rate is between 0.3 kbps and 50 kbps (ANDREADOU, 2016).

LoRa technology uses *half-duplex* x communication, that is, a bidirectional connection is established between the parties, however, only data flow is allowed in one direction at a time. In other words, there is no simultaneous transmission, at one time only radio A transmits, at another time only radio B transmits.

Due to this limitation of the *half-duplex characteristic, although uncommon, some applications with LoRa radio that require full duplex* communication, use two pairs of parallel radios, allowing one channel only for transmission and another channel only for receiving data. This way, simultaneous bidirectional communication is established between the devices.

MQTT - MESSAGE QUEUING TELEMETRY TRANSPORT

In 1999, engineers Andy Stanford-Clark (IBM) and Arlen Nipper (Cirrus Link, Eurotech) developed the first version of the *MQTT (Message Queuing Telemetry Transport) protocol.* This aims to provide low network and bandwidth consumption, as well as to carry out communication without the need for many software resources. Although the protocol was developed at the end of the 90s, its free release was only made available in 2010 (SANTOS, 2022).

MQTT protocol, or Message Queuing Telemetry Transport, is a message transport protocol in Client/Server format. This enables *M2M (Machine to Machine)* communication and has been widely used for system connectivity with *IoT (Internet of Things) solutions.*

In an *MQTT protocol,* sending and receiving messages is carried out through an intermediary server called *a Broker.* Its form of communication follows a publication and subscriber standard (*Publisher / Subscriber)*, where customers can be *Publishers* and/or *Subscribers.* When acting as a *Publisher,* the client sends data to the *Broker* on a specific topic, while when acting as a *Subscriber,* the client subscribes to receive data from one or more topics (SOARES, 2021).

PROTOTYPING

When simulating a *smart grid network* using the LoRaWAN communication protocol, it is necessary to: measure the voltage and current values of the electrical network (*smart meter)*, transmit these measurements to a receiver connected to the internet (*gateway)*, serialize and transfers of this data to an *MQTT* server, adequate storage of these measurements in a database server and a platform that allows easy visualization of this data (*dashboard*). The complete schematic of the system can be seen in figure 1.

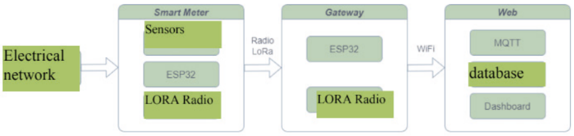

Figure 1 - System Schematic.

Source: Author

For prototyping the *smart meter device,* the following components are selected:

- ESP32 DOIT Devkit v1: The ESP32 development board selected for the system's microcontroller is based on *Espressian* 's *Do It version,* considered the most reliable, low-power and cost-effective microcontroller available for connecting to clouds, according to Talbi et al. al. (2023). Figure 2 illustrates the ESP32 board used.

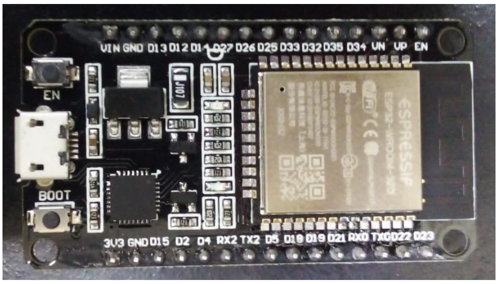

Figure 2 - ESP32 Devkit v1 board.

Source: Author

- LoRa E32-433T20D: Radio for data transmission - low consumption *LPWAN standard and limit range of tens of kilometers.* This allows the transmission of data collected by the smart meter. The manufacturer is *Ebyte* and it has the SX1278 chip from *Semtech Corporation,* 433 MHz frequency, 10 to 20 dbm of power and *UART communication interface.* The image of the plate can be seen in figure 3.

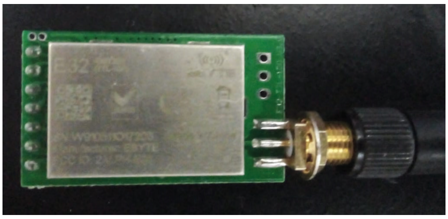

Figure 3 - E32-433T20D LoRa board.

Source: Author

- 16x2 LCD Display: Screen for viewing instantaneous voltage and current data;

Figure 4 - 16X2 LCD Display

Source: Author

- ZMPT101B: Sensor for measuring the electrical voltage of the network - accuracy of 0.3%, voltage limit of 1000Vac (MICRO, 2022). The image of the component can be seen in Figure 5.

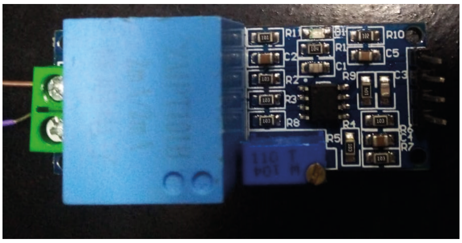

Figure 5 - ZMPT101B Voltage Sensor.

Source: Author

- ACS712T: Sensor for measuring electrical current in the network - accuracy of 1.5%, current limit of 5A (ELECTRONIC, 2022). This sensor works invasively, that is, it needs to be in series with the load that you want to measure the current values. The sensor image can be seen in figure 6.

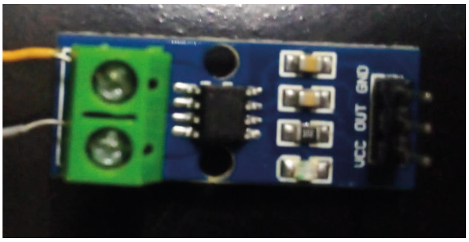

Figure 6 - ACS712T Current Sensor.

Source: Author

The schematic of the smart meter device can be seen in Figure 7.

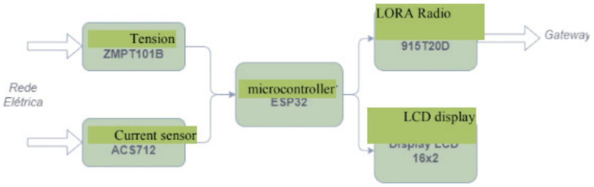

Figure 7 - *Smart Meter schematic.*

Source: Author

The image of the smart meter prototype can be seen in Figure 8.

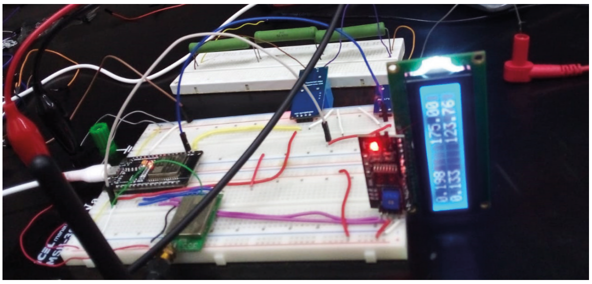

Figure 8 - Image of the *Smart Meter Prototype.*

Source: Author

For prototyping the gateway device, the following components were selected:

- ESP32 DOIT Devkit v1: The selected ESP32 development board for system microcontroller;
- LoRa E32-433T20D: Radio for data reception.

The complete schematic of the device can be seen in Figure 9.

Figure 9 - *Gateway Schematic.*

Source: Author

The image of the device prototype can be seen in Figure 10.

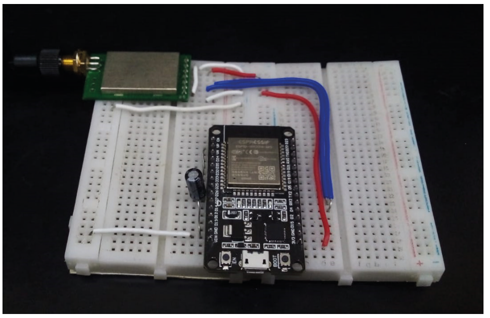

Figure 10 - Image of the *Gateway Prototype.*

Source: Author

The analysis of the voltage calculation algorithm, current calculation, frequency calculation and data sending via LoRa implemented in the *smart meter firmware* can be found in full on the project github (DELSIN, 2023).

The code relating to receiving data via LoRa and sending it to a *web server* implemented in the *gateway 's firmware,* can be found in full on the *github page* (DELSIN, 2023).

To connect the data sent by the gateway to the *MQTT server, a Python* algorithm was used, which can be executed at a certain regular time interval. The complete code of the MQT T server connection algorithm can be found on the *MQT* T server page. *github* (DELSIN, 2023).

Initially, the algorithm makes a request to the web server routed through the *gateway* to collect measurement data. After the request, the data received is organized and serialized. This excerpt of the code can be seen in Figure 11.

```python
x = 0
while(x == 0):
    try:
        # Recebe o body da pagina web
        response = req.get(url, headers=headers)
        # Divide o body do html em uma string por espaçamento.
        parametro = response.text.split()
        print(response.text.split())
        x = 1
    except:
        x = 0
```

Figure 11 - Request *Loop to the Web Server Routed by the Gateway.*

Source: Author

After data serialization, date and time values are assigned to the packet. Afterwards, with the package complete and organized, the connection and sending of this data to the *MQTT* server begins. This code snippet can be seen in Figure 12.

```python
# Adiciona data e hora no pacote
horario = str(datetime.datetime.now())
parametro.append(horario)

# Realiza a publicação no tópico "smartmeter1".
client1.publish(
    "smartmeter1",
    parametro[0] + " " +
    parametro[1] + " " +
    parametro[2] + " " +
    parametro[3]
    )
```

Figure 12 - Adding Date/Time and Sending the Package to the *MQT* T Server

Source: Author

To store the values from the *MQTT server* in a database, a Python algorithm was used, programmed to remain in an eternal loop waiting for publications on the subscribed topics. The complete code of the data storage algorithm on a database server can be analyzed on the github page *(*DELSIN, 2023).

To allow visualization of the data stored on the database server, a Python script was used together with the matplotlib graph construction library. The full script code can be analyzed on the project's github page (DELSIN, 2023).

RESULTS AND DISCUSSION

Initially, in order to verify the accuracy of the ZMPT101B measurements, the voltage sensor output voltages were measured using a digital oscilloscope. For this, the ZMPT101B sensor was connected to the 127 V RMS and 60 Hz frequency power supply with 3.3 V and 5.0 V supplies.

In Figure 13 you can see the output voltages of the ZMPT101B sensor for a 5 V supply. In Figure 14 you can see the output voltages of the ZMPT101B sensor for a 3.3 V supply.

As it can be seen in Figures 13 and 14, the voltages are consistent with the *datasheet specifications*. In the case of a 5V supply, the average output voltage was 2.54 V, approximately half the supply voltage. In the case of a 3.3 V supply, the average output voltage was 1.69 V, approximately half the supply voltage.

The value of 0.8 V from peak to peak was defined using the adjustment potentiometer integrated on the ZMPT101B board. Using the minimum and maximum values, it is possible to identify that approximately 0.4 V was assigned above for the average voltage values and 0.4 V below the average voltage values for the power supply analyzes with 5.0 V and 3.3 V This way, it is possible to verify that the system behaves as expected when measuring the sine wave supplied by the electrical network.

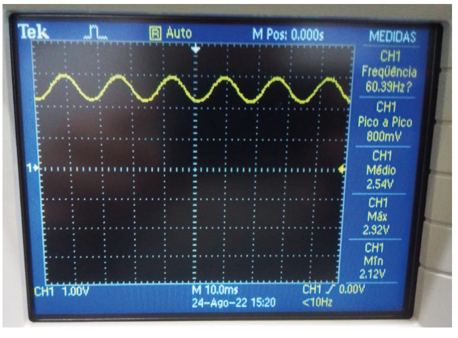

Figure 13 - ZMPT101B Accuracy Test with 5.0V Power Supply.

Source: Author

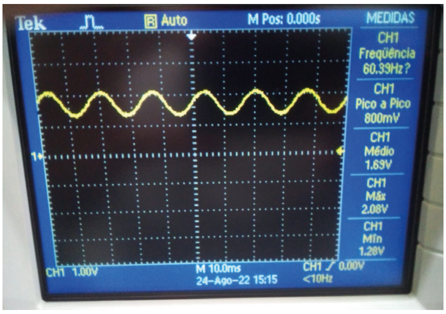

Figure 14 - ZMPT101B Accuracy Test with 3.3V Power Supply

Source: Author

To establish the reference values of the ZMPT101B output voltage after the analog-to-digital conversion of the ESP32 microcontroller, a signal reading analysis was used at the microcontroller's serial port. As can be seen in Figure 15, the average voltage value of the sine wave was around 1870 and the maximum value was 2200, being equivalent to the values 0 V and 180 V, respectively.

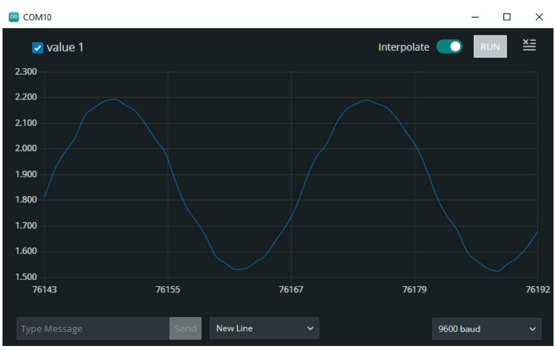

Figure 15 - Analog-Digital Converter of the ESP32 Microcontroller

Source: Author

For the complete operation of a smart grid network with LoRa communication, a long process was carried out that involves data acquisition, serialization, processing, storage and analysis. The details of this process can be divided into a few steps:

- Acquisition of data by the *smart meter*;
- Transmission of data from the smart meter and reception of data by the *gateway* via LoRa radio;
- Forwarding of data received by the *gateway to an MQTT* server via *Wifi* ;
- Storage of data received by the *MQTT server* in a SQL database;
- Monitoring of data stored in the *SQ* L database through a graphical display;

For data acquisition, as previously mentioned, a smart meter prototype was built that has voltage and current sensors, in which the data from these sensors are converted into digital values by the system's microprocessor through an ADC. Figure 16 shows an example of reading data from the smart meter through the serial port of the ESP32 microcontroller.

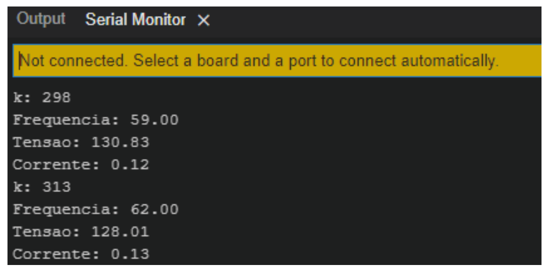

Figure 16 - Data *Log through the Series Monitor.*

Source: Author

As previously mentioned, a LoRa radio was used to transmit and receive data between the *smart meter* and *gateway prototypes*. The complete code can be found on the github page (DELSIN, 2023).

To forward the data received by the *gateway to an MQTT server, it was necessary* for the gateway to establish a *Wi-Fi connection.* Figure 17 illustrates an example of the *Wifi connection* made by the *gateway.*

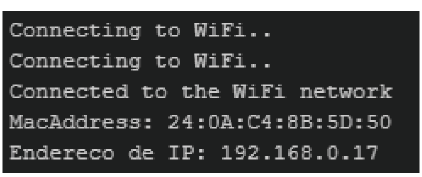

Figure 17 - Example of *Gateway Wifi Connection.*

Source: Author

Wifi connection, it was necessary to establish a web server to make the data available via HTTP. The snippet of the gateway code responsible for this process can be seen in Figure 18.

```
WiFiClient client = server.available();
if (client) {
  Serial.println("New Client.");
  while (client.connected()) {
    if (client.available()) {
      client.println("HTTP/1.1 200 OK");
      client.println("Content-type:text/html");
      client.println();
      if (recebido != ""){
        client.print(recebido);
      }
      break;
    }
  }
}
```

Figure 18 - Code Responsible for Establishing the *Web Server.*

Source: Author

With the web server established, the Python code is responsible for publishing this data to the *MQTT server.* In Figure 19 you can see an example of a Python code log performing publications on the *MQTT server.*

```
C:\Users\Vinicius\Desktop\ScriptsPython>python pub_mqtt.py
Aguardando conexao com o servidor.
['248.23', '0.15', '42.00']
Dados Publicados

C:\Users\Vinicius\Desktop\ScriptsPython>python pub_mqtt.py
Aguardando conexao com o servidor.
['250.35', '0.01', '46.00']
Dados Publicados

C:\Users\Vinicius\Desktop\ScriptsPython>python pub_mqtt.py
Aguardando conexao com o servidor.
['255.30', '0.05', '54.00']
Dados Publicados

C:\Users\Vinicius\Desktop\ScriptsPython>python pub_mqtt.py
Aguardando conexao com o servidor.
['255.30', '0.05', '54.00']
Dados Publicados
```

Figure 19 - Message *Log in MQTT Publication.*

Source: Author

To store the data published on the *MQTT server* in a SQL database, as previously mentioned, a Python script was used. This is responsible for subscribing to the desired topic on the *MQTT server* and inserting messages into the database whenever a publication occurs. Figures 20 and 21 show examples of the subscription log on all *MQTT* server topics via Mosquitto (*open source software* for message *broker)* and the storage script log.

```
C:\Program Files\mosquitto>mosquitto_sub -p 1884 -t #
127.30 0.13 59.00 2022-08-09 16:49:53.967405
126.40 0.13 58.00 2022-08-09 16:54:15.691516
126.70 0.13 59.00 2022-08-09 17:00:51.045712
127.30 0.13 60.00 2022-08-09 17:01:27.458185
```

Figure 20 - Subscription *Log* on All Topics via Mosquitto.

Source: Author

```
C:\Users\Vinicius\Desktop\ScriptsPython>python armazenaBD.py
creating new instance
connecting to broker
Subscribing to topic smartmeter1
message received  126.40 0.13  58.00  2022-08-09 16:54:15.691516
message topic= smartmeter1
message qos= 0
message retain flag= 0
message received  126.70 0.13  59.00  2022-08-09 17:00:51.045712
message topic= smartmeter1
message qos= 0
message retain flag= 0
```

Figure 21 - Data Storage Script Log in SQL Database.

Source: Author

To perform monitoring and graphical visualization of data stored in the SQL Bank, a Python script was developed responsible for performing data visualization. The full code can be reviewed on the github page.

Figures 22 and 23 show the results of some example visualizations, illustrating graphs of voltage by time and current by time, respectively.

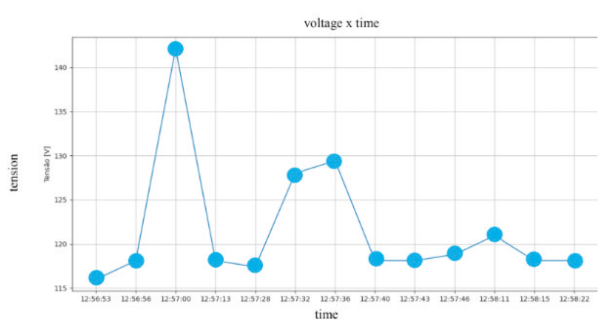

Figure 22 - Voltage by Time Graph.

Source: Author

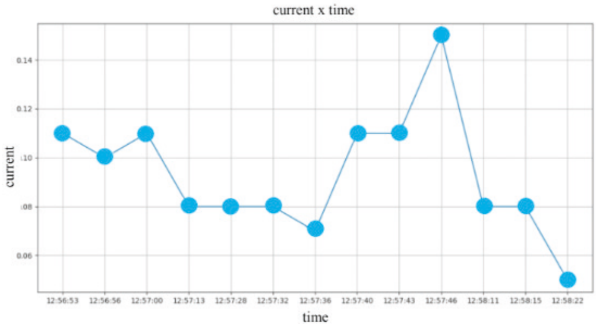

Figure 23 - Current Graph by Hour.

Source: Author

Smart meter project is linked to the choice of sensors and their precision adjustments. The sensors need to be calibrated in practical tests, which is only feasible after the construction of the *smart meter prototype.* This difficulty occurs due to the characteristic that the output signal of the voltage and current sensors offers as an *offset* half of their supply voltage, a voltage that was supplied by the microcontroller and can change according to the number of components supplied.

Another characteristic of the prototype is that the definition of the network frequency was established by the *smart meter* using an algorithm for counting the times that the voltage sinusoid reached the value of 0 V. This way, the value after the analog-to-digital conversion carried out by the microcontroller referring to 0 V of the network had to be obtained experimentally, as well as the error range for a sample to be considered as 0 V. In this case, the exceptional harmonic formation of the signal could harm the frequency reading, with the proposed algorithm.

Finally, two cost tables for the prototype were created, one for the cost of the *smart meter* and the other for the cost of the *gateway.* This way, it is possible to estimate the price for a prototype *smart grid network* with several *smart meters* and *gateways*. The cost tables can be seen in Figure 24.

Smart Meter	Cost (R$)
ESP32	R$ 58,00
LoRa	R$ 150,00
Display LCD	R$ 37,00
Sensor ZMPT	R$ 23,00
Sensor ACS712T	R$ 9,00
Antena	R$ 26,00
Total	**R$ 303,00**

Gateway	Cost (R$)
ESP32	R$ 58,00
LoRa	R$ 150,00
Antena	R$ 26,00
Total	**R$ 234,00**

Figure 24 - Prototype Costs

Source: Author

FINAL CONSIDERATIONS

For real applications of the *smart grid* model with LoRa communication presented, a broader analysis of voltage and current sensors is suggested, specifically in the case of the current sensor, in which the use of a non-invasive sensor is desirable due to the ability to operate at higher currents and also the greater physical robustness of the component.

Furthermore, for a practical application of the prototype, a micro source can be used with or without a battery to use the *smart meter.* In both cases, but especially if the choice is a switched source, it is necessary to pay attention to the generation of harmonic distortions in the electrical network, an effect that can interfere with the quality of the network, and consequently the accuracy of measurements (DECKMANN, 2010).

Therefore, when dealing with harmonic distortions for a professional application of the model, it is appropriate to use filters between the electrical network and the voltage and current sensors, with the aim of minimizing measurement errors (VICIANA et al., 2023).

For a practical application of the model with LoRa communication and LoRaWAN protocol, it is necessary to research the approved communication frequency spectrums allowed for LoRa communication in each country in the world.

Finally, for a more reliable cost estimate in a real field scenario, it is worth a cost study for the development of a professional board, without the use of development kits, with isolated components purchased in larger quantities and the development of a proprietary PCB (Printed Circuit Board).

This way, by surveying the cost per *gateway* and an estimate of its coverage area, it is possible to carry out a precise study on the economic advantages and disadvantages of using a private LoRa network or subscribing to a public LoRa network service to forward messages from of *smart meters.*

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