Low Voltage Sensing and Control Applied to the Electrical Distribution Grid

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***Abstract*— The overhead distribution transformer is one of the most important and expensive equipment in the distribution grid. Without the proper monitoring of its performance, it can become very difficult to detect possible failures or adverse situations of equipment operation. This article describes a system designed for real-time monitoring and protection of transformers in overhead distribution lines via motorized circuit breakers, installed on the low voltage side. The remote control of the circuit breaker and the calculations of the hot spot temperature and the load of the transformer on the low voltage side will be performed by edge computing. The proposed solution aims to provide protection in the low voltage of the distribution grid and provides more information about the main asset of the utility in the distribution grid. The study is part of an innovation project by Enel Distribuição São Paulo, called "*Urban Futurability*". This project is located in an area with a diversity of grid types, from underground grids with high load density to overhead grids of medium load density. The application of the proposed solution in this article will be carried out in part of the overhead grid of the project region, in the city of São Paulo, Brazil.**

Keywords—Edge computing, hot spot temperature, low voltage measurement, overhead transformer monitoring, predictive maintenance, low voltage distribution protection

I. Introduction

The distribution transformer is the equipment responsible for adjusting the voltage levels for the final consumers. The use of this equipment outside the rated operating conditions - temperature, current or voltage - causes the equipment to accelerate aging or even failures. As a result, it is necessary to carry out costly maintenance and, consequently, impacting the continuity indicators [1], [2], [3], [4].

In Brazil, most of the electricity distribution grid is overhead [5]. This causes the distribution grid in Brazil to be constantly vulnerable to the action of external agents that can cause the interruption of the energy supply [6], [1]. As the cost for building an underground distribution grid is much higher when compared to that of the overhead grid [7], one of the ways to increase the reliability of the distribution grid is by improving the protection system.

The need to improve the quality of the electricity supply and have a robust and reliable system are major challenges for utilities [6], [4], [8], [9], [10]. One way to achieve this goal is through a fast, reliable and cost-effective protection system [4]. Historically, the protection system has been prioritized in the most critical areas, starting with subtransmission, substation and medium voltage distribution [11]. The significant increase in low voltage (LV) sensing and remote control technologies in recent years, with the monitoring of branches, assets and smart meters, helps in the evolution of the protection system in the LV distribution grid.

Normally the protection against overcurrent of the distribution transformers is accomplished through fuses, due to its versatility and low cost [4], [12], [13], [14]. However, when the fuse blows, it is necessary to send a field maintenance team to replace the fuse and restore the service of the electricity distribution grid. Another disadvantage of the fuse is the need for a large amount of equipment stock [12].

According to [13], a study was carried out in Mexico and it was found that 53% of the transformer failures were caused due to overloads or short circuits on the LV side. Thus, in order to reduce the level of failure rate in the distribution transformers, a program was started for the installation of molded case circuit breakers (CB) on the LV side of such transformers. The result is that the failure rate dropped from 4 to 3%. Due to the success achieved, a research project was carried out to assess the feasibility of developing a LV recloser. The operational performance of the reclosers produces 1.31 permanent faults per recloser per year. Comparing this value with the 2 interruptions per year previously reported for the recloser installation, there was an improvement of 34.5% in the continuity of service and a reduction in the same percentage in the sending of maintenance teams to the field after the installation of the LV recloser [13].

Another study carried out in the United Kingdom [14] indicates that 40% of Customer Interruptions (CI) and 75% of Customer Minutes Lost (CML) in urban areas are caused by the LV grid. Another data indicated is that between 50 and 80% of the fuse operations are due to transient faults, indicating that with the insertion of automation in the grid through reclosing action, it would provide benefits and reduction in the maintenance of the distribution grid [14].

Thus, the *Urban Futurability* project seeks to develop a solution with measurement and protection elements to be installed in the LV of the overhead distribution transformers. The monitoring of overhead transformers aims to monitor the load of the transformer, the ambient and internal temperatures and the alarms of the transformers in real time. This information provides subsidies to the operator to schedule preventive maintenance actions, before the failure of transformers [15]. In terms of protection, the objective of the solution is to avoid the unnecessary actuation of the

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transformer protection fuse in eventual transient faults in the LV grid. The solution's differentials lie in the equipment's ability to receive remote commands from the operations center, allowing the operator to open or close the circuit breaker remotely, and to have the reclosure logic embedded in the solution, being able to carry out a reclosure attempt automatically.

The monitoring and control solution uses an RTU applied with edge computing techniques, receiving and processing the data obtained in the field and, later, sending this information to the addressed server.

The objective, when applying such a solution to the ENEL Distribution São Paulo grid, is to reduce maintenance costs and improve continuity rates, generating, for the final consumer, the benefit of a distribution grid with greater reliability and fewer periods of interruptions in the supply of electricity [2], [4], [16].

Two units are being produced for this solution to carry out a Proof of Concept (PoC), consisting of laboratory and field tests. After the PoC period, it is planned to build more units of this solution for its application in the electricity distribution grid of Enel Distribuição São Paulo.

The paper is organized as follows. Section 2 details the description of the system. Section 3 presents the solution methodology. Section 4 presents the expected results for the solution. Finally, section 5 concludes the article.

II. SYSTEM DESCRIPTION

Figure 1 presents the architecture of the solution developed in the *Urban Futurability* project and the data flow. The equipment has measurement, protection and communication components. It is installed on the same pole as the distribution transformer, but on the opposite side. (Figure 4).

The data generated from each unit of the solution will be sent to the SCADA system of Enel Distribuição São Paulo. The technology chosen for data exchange was LTE (Long Term Evolution) and the protocol to be used will be Modbus / TCP. Data of electrical quantities, temperature and alarms that will be programmed in the solution will be sent from SCADA to Universal Virtual Data Lake (UVDL), where they will be available for the Enel team to view the information as it is updated.

The monitoring and control system consists of current sensors, temperature sensor, temperature sensor shelter (avoid distortions in temperature measurements), Remote Terminal Unit (RTU), data concentrator, auxiliary equipment (CB, SPD, fuse, DC power supply and battery) and a motorized LV molded case CB to allow remote commands.

The current sensors to be used are the Rogowski coils. Three sensors are required, one for each phase. According to [17], Rogowski coils have as main advantages the linearity over the entire measurement range, the large frequency bandwidth in which the measurement can be performed and the low weight/volume ratio, due to the lack of a ferromagnetic core.

The panel in Figure 3 has the following dimensions 600x600x300 mm (height x width x depth) and was designed according to the IP-54 protection levels. It is energized directly from the secondary branch of the transformer (Figure 2), from which the Remote Terminal Unit (RTU) collects voltage information.

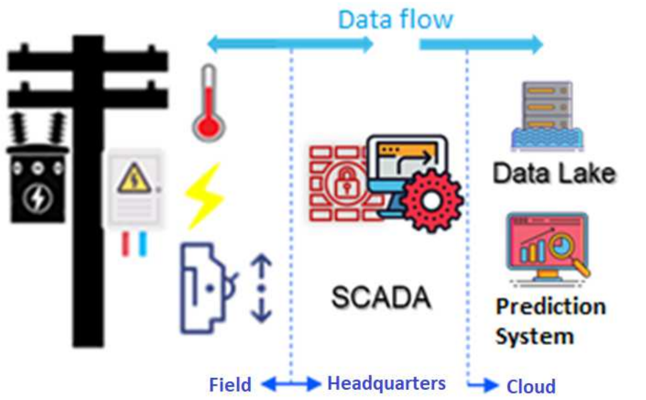

Figure 1 - Monitoring and control system architecture.

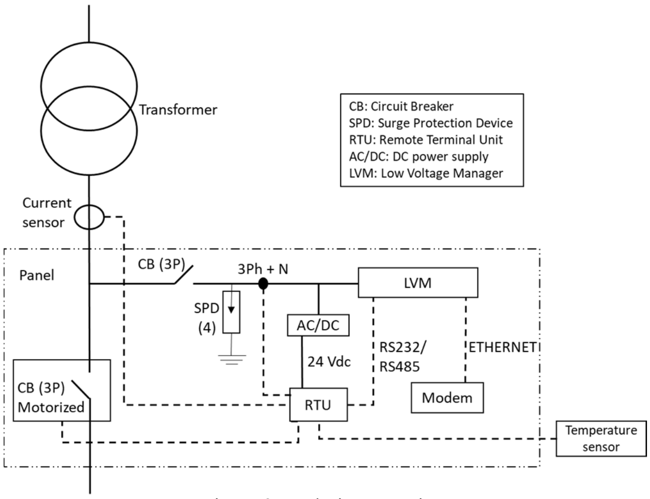

Figure 2 - Solution overview.

All quantities measured in the field - current, voltage and ambient temperature - are collected by their respective sensors and sent to the RTU. The RTU's function is to process this data, perform the necessary calculations and send the information and alarms through the modem. The RTU is also responsible for receiving the remote control signals from the operator and applying them to the motorized circuit breaker.

The solution can be adapted to different power levels of the transformer, as long as the rated current level of the transformer is suitable for the molded case CB installed in the panel. In case of changing the power level of the transformer, just change the CB performance curve to the most suitable for the new scenario and the configuration of the constants in the RTU for the desired transformer model. The constants are: ratio of load losses at rated current to no-load losses; rated temperature and rated current of the transformer.

To measure the ambient temperature, the PT-100 sensor will be used, which will be installed in its appropriate location, as shown in Figure 5.

Auxiliary equipment such as the panel CB, SPD and fuse are used to protect the panel equipment. The DC power supply is used to power the modem, the RTU and the CB motor. Finally, the battery is used to power the DC equipment (modem, RTU and CB motor) in case the panel is without power.

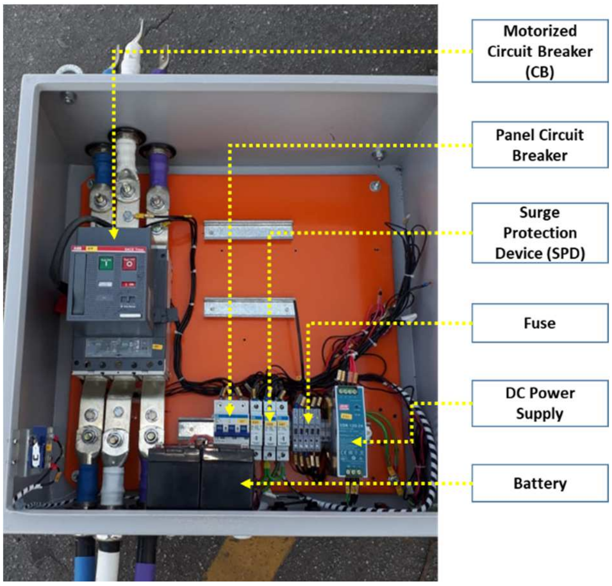

Figure 3 - Inside the monitoring and control panel.

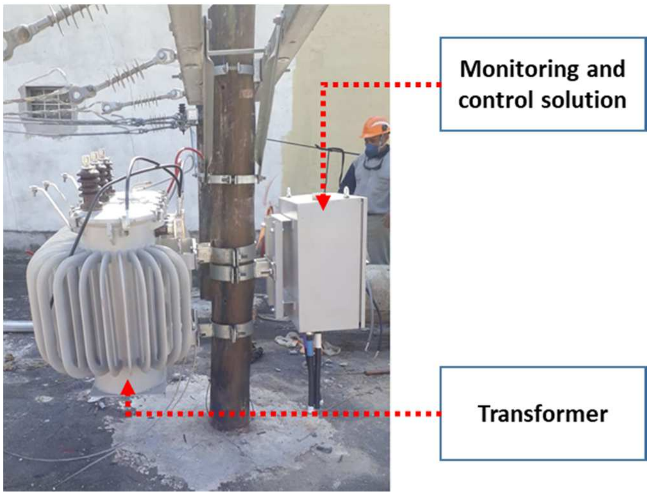

Figure 4 – Example of panel installation.

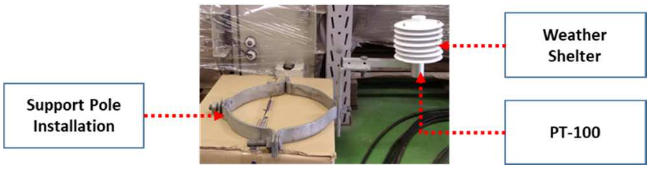

Figure 5 - Ambient temperature sensor shelter.

At the time of writing this article the panels are being developed. Figure 3 shows the panel with an empty space, which is reserved for the installation of the RTU and the modem.

The first version of the solution does not have the frequency monitoring of the LV distribution grid, but it will be a new feature in the next version, in order to assist in monitoring the quality of the electricity supplied through harmonic analysis.

The next section describes the methodology for acquiring and processing data from the electricity grid using the devices described in this chapter. The protection philosophy adopted for the solution will also be discussed.

III. Methodology

The monitoring and control solution will update on the platform, every 5 minutes, the quantities measured and calculated using a moving average of the same time interval. The calculated quantities will be: powers (active, reactive and apparent), energy, hot spot temperature and the loss of life of the transformer. Alarms will also be generated for overcurrent, undervoltage, overvoltage, opening of the panel door, trip of the surge protection device (SPD), CB status (open or closed), battery status (normal, discharging or failure) and overheating of the transformer. The LTE communication modem uses the Modbus/TCP protocol and has two SIM cards that provide communication with redundancy.

A. Hot Spot Temperature Estimation

The overhead transformer's monitoring and control solution estimates the transformer's hot spot temperature using ambient temperature and electrical current data. The calculations used in this estimate are based on Annex I of IEC 60076-7: 2018 [18].

According to [2], [3], [18], the method of solving differential equations presented in the IEC standard is the one that best applies in the case of distribution transformers. The method has no restrictions on the load profile or on the environment with temperature variations. Thus, this method is ideal for the practice of online monitoring.

B. Protection philosophy

The molded case CB for LV will be the element responsible for protecting any faults in the LV distribution grid and, enabling remote commands to restore the grid, without the need for locomotion of maintenance teams in case of temporary faults.

For this to be possible, the molded case CB must be configured in such a way that it presents a selective protection with the medium voltage fuse, located upstream, which performs the protection of the transformer and, a coordinated protection with possible protection equipment that are downstream.

The molded case CB configuration is performed manually, on the front of the CB, as shown in Figure 6. It is possible to configure both the thermal protection (protection against overcurrent with inverse trip time) and the magnetic protection (protection with instantaneous trip) of the CB.

The molded case CB operation was divided into two types of operation, Local or Remote, and in two modes of operation, with and without reclosing.

The Local type operation presents only the operation mode without reclosing and has as characteristics the opening and closing of the molded case CB occurring only on site, through the physical buttons of the CB and the RTU must not send any command to open or close the CB.

The Remote type operation features the operation modes with and without reclosing. If the reclosing mode is selected, the opening and closing commands will be sent by the RTU. If the non-reclosing mode is chosen, the RTU must not execute the CB reclosing process. For the Remote type, in both operating modes, it is possible to open the CB locally only for emergencies.

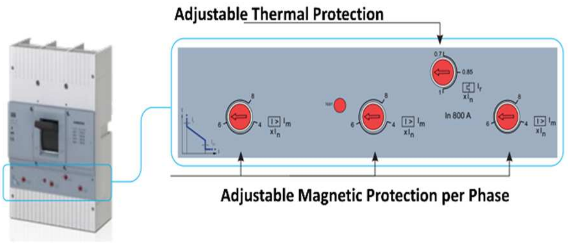

Figure 6 - Configuring the circuit breaker [19].

1) Reclosing process

In the event of a failure in the LV distribution grid, the CB must act for instantaneous or time overcurrent protection, depending on the short-circuit current. The CB will only perform a reclosing attempt and it will be made after 30 seconds of opening the CB. It is possible to find three scenarios for the reclosing process and they will be discussed below.

In the first scenario, the fault in the LV distribution grid persisted after reclosing, so the CB must operate again and must be kept open and blocked, and can only be closed again manually or by the operator's command. Figure 7 presents such a scenario.

If a new instantaneous fault does not occur after reclosing (successful reclosing), the reset process will start. The reset process consists in monitoring the LV distribution grid and the CB for a period of 5 minutes, in the event that a new fault occurs in that period, the CB must operate again and must be kept open and blocked, and can only be closed again manually or by operator command (second scenario). If no new faults occur during the reset period, the reset process is successfully completed and the CB is able to perform the reclosing process again (third scenario).

A flow chart of the reclose operation in the LV distribution grid is shown in Figure 10.

The next section describes the premises of the financial study carried out on the project and the results expected by the solution.

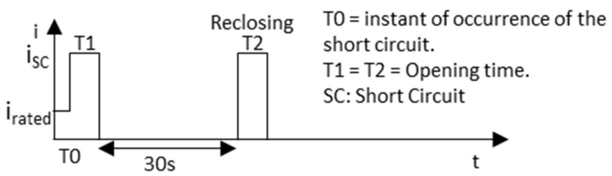

Figure 7 - Reclosing but the fault persisted.

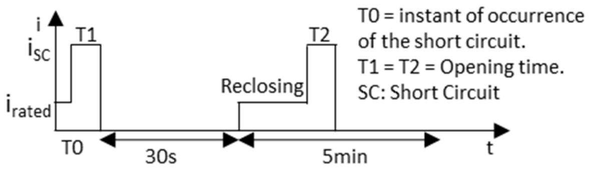

Figure 8 - Reclosing, with fault in the reset process (second scenario).

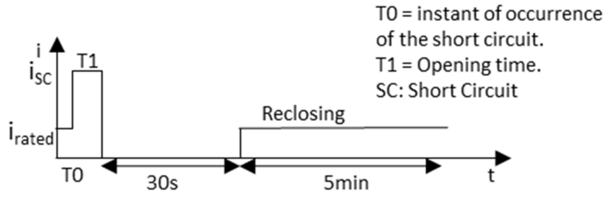

Figure 9 - Successful reclosing (third scenario).

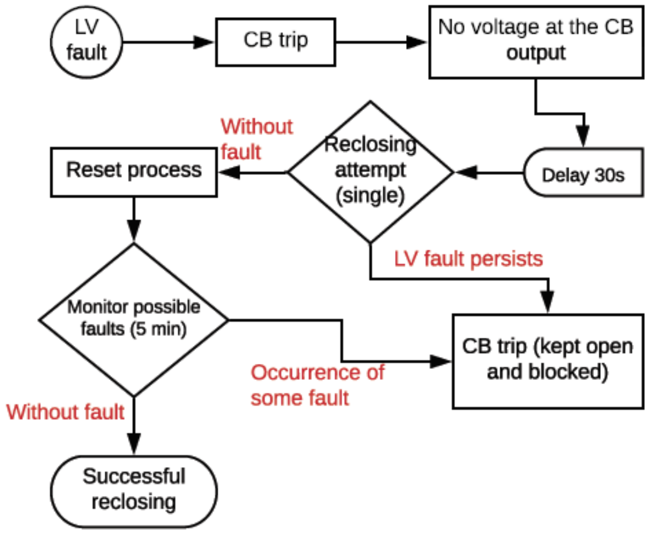

Figure 10 - Flowchart of the reclosing process.

IV. Results

The *Urban Futurability* project has a team responsible for the Cost Benefit Analysis (CBA) of the solution. The CBA team developed a computational tool that considers the defects and failures that occurred in the last year at the Transformer Stations (TSs) and also the technical and economic benefits of the solution and, in possession of these data, the tool indicates which TSs would have more gains from installing the solution.

The technical team of the project together with the business areas of Enel Distribuição São Paulo raised the following technical benefits for the solution: Monitoring of the electrical quantities and temperatures of the distribution transformer; Agility in identifying failures in the distribution grid; Improvement in supply continuity indicators (SAIDI/SAIFI); Protection in the LV distribution grid with remote control; Positive impact on electricity supply; Increased productivity of emergency teams due to reduced unproductive displacements.

The economic benefits of the solution raised by the same teams are related to the tariff readjustment resulting from the improvement of the SAIDI/SAIFI indicators and reduction in compensation payments, due to the significant reduction in overcurrent occurrences, around 70%, and the reduction of approximately 10% of the total duration of occurrences in TSs. In addition to the reduction of unproductive displacements, an increase in revenue from unsold energy and a reduction of 70% of the total transient occurrences on the LV side of TS.

V. Conclusion

Today, the utilities do not have, in the overhead LV distribution grid, equipment that provides information on the transformer (voltage level, current, power...) and, at the same time, protects the LV grid with the option of reclosing and remote opening and closing commands. The equipment developed in the *Urban Futurability* project has a performance similar to the reclosers used in the MV distribution grid, which, also, provide information and protection of the distribution grid, however those of MV, failing to be applied in LV. The data generated by the solution is of great interest to ENEL's areas of Fault Analysis, Engineering and Operation and Maintenance.

The company starts to provide a better service with a reduction in non-technical losses and an improvement in the quality of the energy supplied. In the operation, the information provided by the panel can be used to locate faults, reduce transient faults and unproductive displacement, consequently reducing the SAIDI.

This solution can be replicated for any other power utility that wants to have a more transparent monitoring of its main distribution grid asset (the transformer), the behavior of its distribution grid at LV and, at the same time, provide protection for its LV grid, with the possibility of reclosing. In addition, the solution also provides the operator with information capable of assisting in preventive actions, avoiding possible failures in the transformers and even the possibility of carrying out maneuvers in the LV distribution grid remotely.

At the time of writing this article, the development of two panels of the solution is being finalized for installation by the end of 2020 in the project area. For the year 2021, six more panels will be developed for installation in the concession area of Enel Distribuição São Paulo.

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