Development of an Automated Distribution Grid With the Application of New Technologies

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ABSTRACT With the advancement of technology and the application of new sensors in the electric distribution grid, in order to increase its automation, meeting the idea of smart grids, a concept that has been expanding through the years. This article describes some of the solutions and results that ENEL Distribution São Paulo has achieved, through its R&D (Research and Development) Urban Futurability project, to make its electricity distribution grid automated and in line with trends and future technologies. The project includes the installation of sensors for monitoring and protecting both the overhead and underground electricity distribution grid and medium and low voltage, digitalization of the primary substation and improvements in the communication infrastructure, seeking their complete automation. The project was applied in one of the largest urban centers in the world, the city of São Paulo, Brazil, with a diversity of load profiles, both residential and commercial, being a great place to test new technologies in different scenarios. With the increased application of automation in the electricity distribution grid, ENEL Distribution São Paulo seeks to provide its customers with a better service, with a safer and more reliable electricity distribution grid, monitored practically in real time and with state-of-the-art technologies. Therefore, the end consumers benefit from an electric distribution grid with greater availability and decreased number of interruptions.

INDEX TERMS Distribution transformer sensing, fiber optic communication, fuse sensing, grid automation, primary substations digitalization, protection in the low voltage grid, underground fault tracking.

ABBREVIATIONS

ANEEL	Agência Nacional de Energia Elétrica
AWS	Amazon Web Services
CBA	Cost-Benefit Analysis
CIT	Customer Interrupted Time
COMTRADE	Common format for Transient Data Exchange for power systems
DNP3	Distributed Network Protocol 3
DTS	Distribution Transformer Sensing
ENEL	Ente nazionale per l'energia elettrica
GDS	Global Digitalization System
GIS	Geographic Information System
GOOSE	Generic Object Oriented Substation Event
IEC	International Electrotechnical Commission
IED	Intelligent. Eletronic Devices
IPH	Inductive Power Harvester
LTE	Long Term Evolution
LV	Low Voltage
LVC	Low Voltage sensing and Control
MCCB	Molded Case Circuit Breaker
MMS	Manufacturing Message Specification
MQTT	Message Queuing Telemetry Transport
MV	Medium Voltage
PoC	Proof of Concept
RAM	Reliability, Availability and Maintenance
R&D	Research and Development
REP	Resilient Ethernet Protocol
RTU	Remote Terminal Unit
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index

SCADA	Supervisory Control and Data Acquisition
SLA	Service Level Agreement
SNMP	Simple Network Management Protocol
STP	Spanning Tree Protocol
TS	Transformer Station
UVDL	Universal Virtual Data Lake

I. INTRODUCTION

The electricity distribution grid is one of the most vulnerable points in the electricity supply process [1], [2]. In some countries, approximately 80% of power outages occur due to failures in the distribution system [2]. This is due to its large extension and numerous derivations, consisting of various devices and exposed in an environment that can cause defects, such as trees and vehicle accidents. The insertion of new automation elements in the electric energy distribution grid has as main objective the reduction in the restoration time in the electric energy supply in these unexpected moments of failure in the electric energy distribution grid [1], [3].

Many of these new automation elements are made possible through direct tests on the grid itself. Therefore, performing tests in a faster way and searching for greater accuracy, thus avoiding possible human errors and the possibility of carrying out tests in parallel, in different scenarios, are characteristics of automation [1], [4]. Another very interesting alternative is to carry out simulations of the electricity distribution grid, which is a very important activity, especially in some areas within a utility, such as, e.g, the processes of: operation, planning, projects and others [4], [5]. These points, mentioned above, emphasize the importance of innovation in automation in electricity distribution grids today, for the purpose of taking better advantage of the investments made in the development of new equipment and technologies [1], [2], [6].

In order to extract all the potential that automation can provide for the electricity distribution grid, it is important to take this concept also to primary substations [2], [7]. Many substations nowadays are outdated, with obsolete equipment installed, such as electromechanical relays, and it is necessary to modernize it to meet the new demands of the electricity sector [8]. As it is still new, the automation and digitalization of primary substations present a very high cost of implementation, however, some countries are gradually starting to show themselves adept to new ideas for innovation and subsequent implementation of this new model of primary substation [2], [9]–[11]. The automation of primary substations is based on the modernization of their equipment, using Intelligent Electronic Devices (IEDs), together with a more robust and reliable communication system, with protocols that allow the interaction between field equipment and IEDs. So that the system detects and eliminates faults in the fastest and most assertive way, also enabling the assistance with predictive and preventive maintenance studies with the extraction of operational data obtained by the equipment instantly [2].

A protection system of the electric power distribution grid is considered well configured, when it, in failure situations, performs the isolation of the section of the electric power distribution grid only on the components that are defective,

optimizing for the smallest number of unattended consumers and keeping the rest of the electricity distribution grid stable and with energy supply [6], [7]. There can be many reasons for failures in the electricity distribution grid, from adverse weather conditions and collisions of vehicles on distribution poles, even failure in the electricity distribution grid equipment due to overload or operation outside the nominal levels of voltage and frequency [6]. One of the ways to avoid these events is by monitoring the electrical quantities of the electricity distribution grid, in order to help protect and preserve the functioning of assets in the electricity distribution grid [6], [11], [12]. The monitoring and control of substations and their distribution transformers is also very important, in addition to helping reduce occurrences and duration of failures, it is an essential activity for studies and future predictive analysis, through the large number of data generated by the digitalized substations [2], [11].

The communication network infrastructure plays a fundamental role for the correct functioning of the automated electricity distribution grid together with the substation. It is in this layer that the exchange of information between the equipment and the transmission of field data to the control center takes place, as well as the sending of operation commands, so that the electricity distribution grid operates as planned [4], [7], [12], [13].

To guarantee the interoperability between the substation equipment and the electric energy distribution grid, the application of IEC 61850 standard protocols was started, such as GOOSE (Generic Object-Oriented System-wide Events). The use of these protocols together with the IEDs, which in addition to performing their basic protection function, also perform very well the functions of automation, control and communication, making the operation of the system as a whole more efficient and intelligent [7], [13].

In general, the effective integration among automation, protection and communication in the electric energy distribution grid, provides gains in several areas of the utility, such as greater productivity through optimal dispatches from the field team and greater flow of information available to the operators make more assertive decisions; planning for optimal installation of the equipment in the field, after carrying out several simulations; provide an optimization of the electricity distribution grid, being able to optimally reconfigure it in adverse situations, such as failures or overload. Added to all these benefits, the utility now has a reduction in operating and maintenance expenses [4], [12], [14]. First-world countries, where the application of automation in the electricity distribution grid reaches expressive levels, present excellent regulatory levels, such as Germany, which in 2016 presented the SAIDI (System Average Interruption Duration Index) of 12.8 minutes [4]. As a result, the country has a safer, more reliable and more qualified electricity distribution grid for its consumers [4], [7], [14].

Through the *Urban Futurability* project, ENEL Distribution São Paulo seeks to implement these innovations in part of its concession area. The project includes the installation
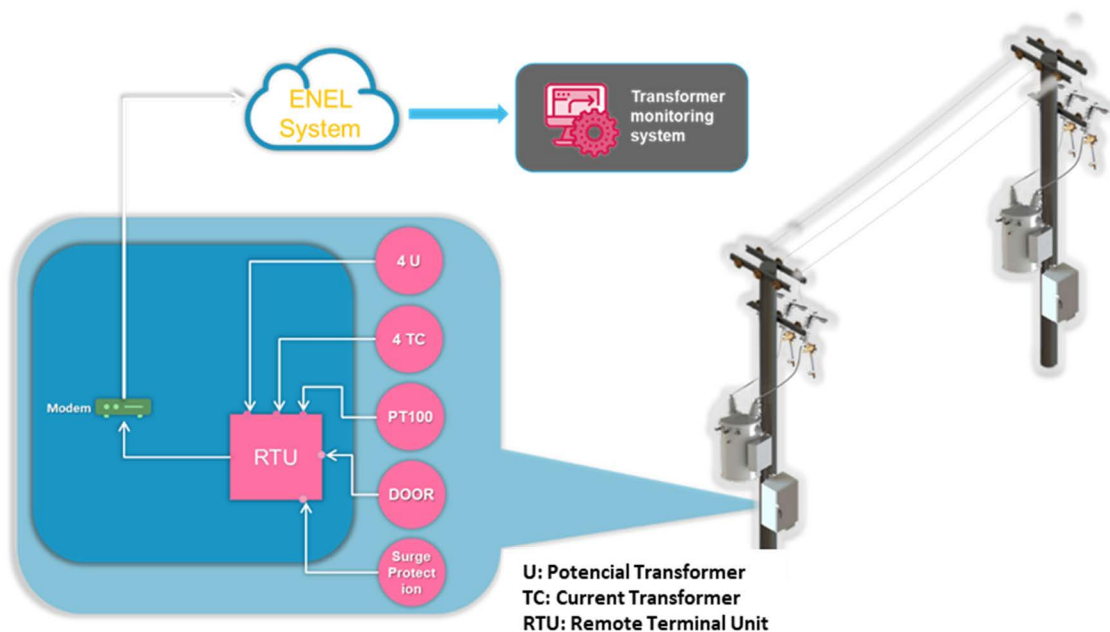
FIGURE 1. Schematic of the solution's operation in the overhead electricity distribution grid.

of sensors for monitoring and protecting both the overhead and underground electricity distribution grid and medium and low voltage, digitalization of the primary substation and improvements in the communication infrastructure, seeking complete automation in its electricity distribution grid. The region that is receiving the improvements is Vila Olímpia, a place with both residential and commercial load profiles, being a great place to test new technologies in different scenarios, because of its diversity of types of grids (overhead and underground) and also of consumers, is an excellent place to apply a living lab.

The paper is organized as follows. Section 2 presents the solutions applied in the project. Section 3 presents the expected and collected results and, finally, section 4 concludes the paper.

II. SOLUTIONS APPLIED IN THE PROJECT

A. DISTRIBUTION TRANSFORMER SENSING (DTS)

The Distribution Transformer Sensing solution is designed to permanently and in practically real-time monitor the loading of transformers, as well as the ambient temperature and the hot spot temperature of the transformer, providing subsidies for scheduling maintenance operations prior to the occurrence of failures in the transformers. These are the main features that differentiate the solution described in this paper from the one presented in paper [3]. The DTS seeks to monitor and collect data from the distribution transformer, with a focus on solving specific distribution transformer operation problems, while the paper [3] describes a solution focused on the final consumer and the use of smart meters.

The operating structure of the transformer monitoring system in the overhead electricity distribution grid, through a simplified view, is presented in Figure 1.

All components shown in Figure 1 are installed in a panel, and this panel is installed on the same pole as the transformer. Current and ambient temperature sensors are used to measure the quantities. Voltage levels are measured through the derivation for the panel supply.

The Remote Terminal Unit (RTU) receives field measurements and performs the necessary calculations (power, energy, hot spot temperature and loss of life of the transformer), in addition to monitoring the values of the measured and calculated quantities and, if any of them exceeds the established limits, the equipment sends the alert, whether due to magnitude values or equipment failure (surge protection actuation, panel door open, among others). The RTU information is sent to the Dual Band modem installed inside the panel, and then, via LTE (Long Term Evolution) and using the MQTT (Message Queuing Telemetry Transport) communication protocol to the ENEL Distribution São Paulo cloud system, the UVDL (Universal Virtual Data Lake), which hired Amazon's AWS for the *Urban Futurability* project.

In order to develop the best solution for the utility, PoCs (Proof of Concept) were carried out with 4 different suppliers, with 10 units of each supplier being installed (40 units in all). For the PoCs, the suppliers were allowed to use their own platforms to view the data and alarms generated by the equipment in the field, the paper [15] presents in more detail the PoCs carried out in the project. However, to extend the amount of devices installed in the field, the companies must be able to integrate their platforms with the UVDL developed in the *Urban Futurability* project and the other monitoring systems of ENEL Distribution São Paulo, such as GIS (Geographic Information System) and PowerOn. The equipment updates the values of the magnitudes every 5 minutes and the alarms
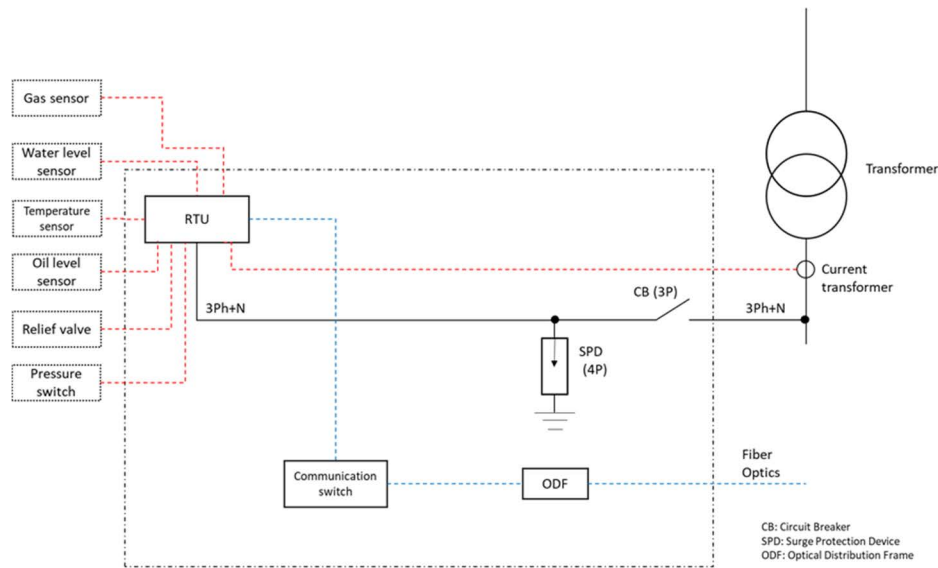
FIGURE 2. Overview of the solution in the underground electricity distribution network.

are generated immediately after the occurrence. The PoCs were carried out with the objective of developing the best version of the solution, collecting feedback on the operation of the equipment in the field, installation process and from different areas of the company, which used the data provided by the equipment, such as Operation and Maintenance, Fault Analysis, Engineering, among others.

For the application of the DTS in the underground electricity distribution grid, the operating principles used will be the same mentioned previously, changing only the types of sensors, since the environment has a greater number of variables to be monitored. Another point is that there is no need to use a modem in the solution, as the underground vaults (place where the underground distribution transformer is installed) will be equipped with optical fiber for communication (Fiber Optics Communication Network solution, to be presented later in this paper). Figure 2 presents a schematic that allows an overview of the solution for the underground electrical distribution grid.

In summary, the DTS solution seeks to provide data to the utility regarding the operating conditions of the distribution transformer, such as power flow, voltage level, phase loading and hot spot temperature, information that is increasingly important due to increased inclusion of renewable energy sources in the distribution grid [3].

B. LOW VOLTAGE SENSING AND CONTROL (LVC)
The monitoring and control solution for overhead transformer stations has as its scope to create a panel with measurement and protection elements to be installed in the low voltage (LV) of overhead distribution transformers. Like the DTS solution, the LVC also monitors the loading of the distribution transformer and its electrical quantities and temperatures. The main differential of the LVC solution is that it is able to act in the protection of the LV electrical distribution grid, avoiding the unnecessary actuation of the transformer protection fuse in eventual transient faults in the LV electrical distribution grid. The operating structure of the transformer monitoring and control system in the overhead electrical distribution grid. Its operating structure, through a simplified view, is presented in Figure 3.

As with the DTS solution, the voltage measurement in the LVC solution is done by derivation of the panel power supply. The measurement of current and ambient temperature is done through suitable sensors to record these quantities. The other components of the solution shown in Figure 3 are installed inside a panel, with the panel and sensors being installed on the same pole of the distribution transformer.

To carry out the protection in the LV electrical distribution grid, a motorized MCCB (Molded Case Circuit Breaker) is used, adding automation to the LV electrical distribution grid. With the circuit breaker motorization, it starts to receive remote commands and, in the case of this initiative, the reclosure function was added, so that it performs a reclosure cycle, protecting the distribution transformer against transient faults.

As in the DTS solution, RTU is an important component, being responsible for sending alerts when the limits established for the quantities are exceeded or when there is failure in any of the components (surge protection actuation, panel door open, among others). RTU is also responsible for receiving the quantities measured in the field and treating these data with the necessary calculations being carried out (power, energy, hot spot temperature and loss of life of the transformer) for the LVC solution. For the Low Voltage Sensing and Control solution, the RTU is also the equipment responsible for sending the commands to the motorized MCCB, as well as informing its status. It is also equipped
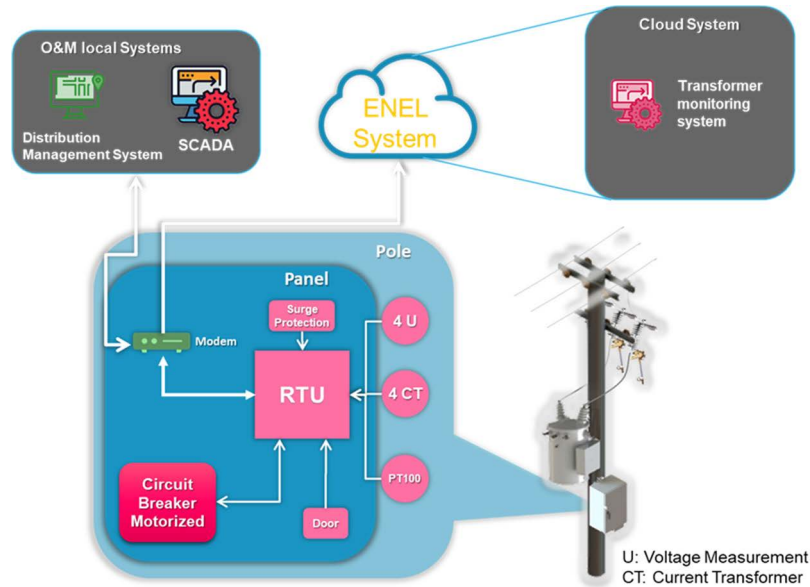
FIGURE 3. Schematic of the solution's operation in the overhead network.

with circuit breaker reclosing logic, so that it automatically recloses when this function is enabled. The data generated in the RTU are sent to the communication modem and then the information is transmitted to both the transformer monitoring platform that will be integrated with the UVDL developed in the Urban Futurability project (previous chapter), and also to SCADA, responsible for the commands of the motorized MCCB.

As with the DTS solution, PoCs were carried out in order to assist in the development of the best version of the solution. In the PoC, the RTUs suppliers were allowed to use their own platforms to visualize the data and alarms generated by the equipment in the field. However, to extend the amount of equipment installed in the field, companies must be able to integrate their platforms with the UVDL developed in the *Urban Futurability* project and with the SCADA of ENEL Distribution São Paulo. The equipment updates the values of the quantities every 5 minutes and the alarms are generated immediately after the occurrence.

C. FUSE AND BRANCH SENSING

The solution for monitoring the status of the protection fuse of the medium voltage electricity distribution grid sought to develop an electronic device that allows monitoring the fuse in real time, capable of monitoring the status of the fuses through a sensor with an accelerometer, signaling when it undergoes a change of state (Figure 4). The operating structure of the fuse base monitoring system, through a simplified view, is presented in Figure 5.

The solution will be used for monitoring legacy protection devices that do not have sensing and communication technology, providing customers with faster service and lower costs
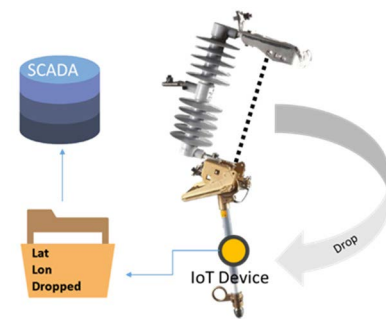

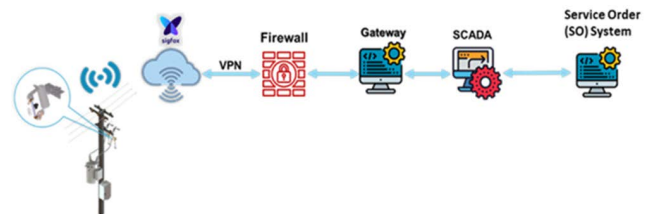**FIGURE 4.** Operating principle of the device.

FIGURE 5. Schematic of the solution's operation.

for utilities with reduced SAIDI and unproductive displacements. As an example, we can mention: the locomotion of the field team to locate the defect in the electricity distribution grid, when the customer reports a power outage to the utility, the field team travels, in their vehicle, the path of the faulty electrical circuit, in order to locate the fault. The solution proposes the development of sensors with IoT communication and a system that allows the integration of devices in the supervisory system.
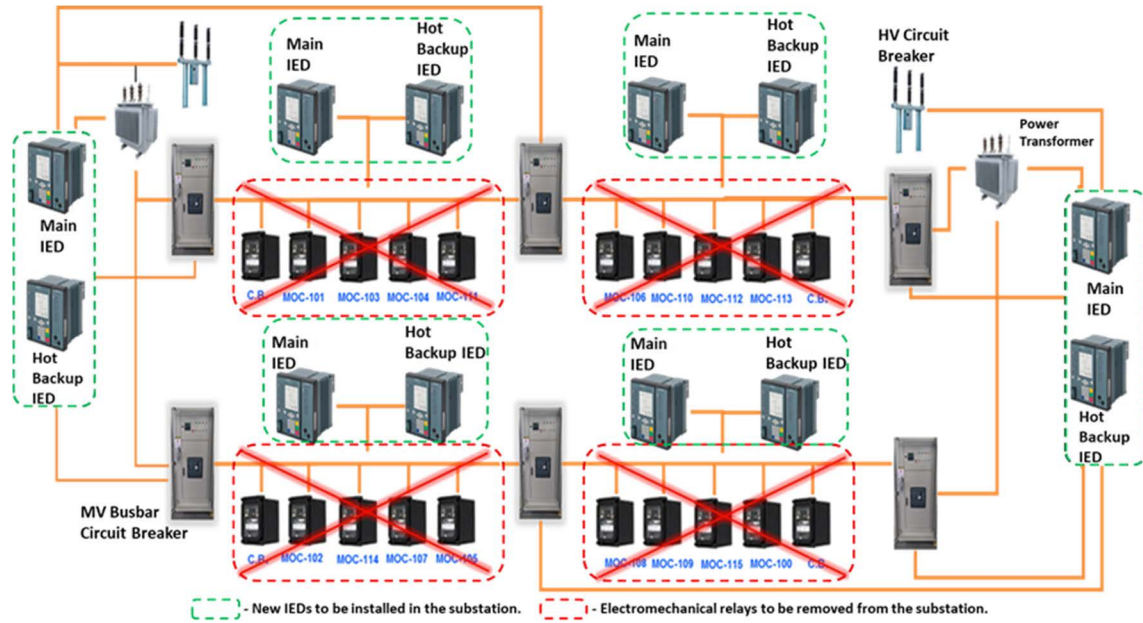
FIGURE 6. Proposed modernization architecture.

The equipment has a degree of protection suitable for field operation subject to bad weather, as well as an operating temperature between −20 and 85°C. The equipment is powered by an integrated battery, which is independent from the electricity distribution grid.

With the monitoring of the state of the fuse, it is possible to detect its actuation more quickly, not depending on customers calling to complain of power outage or other equipment indicating the problem.

D. PRIMARY SUBSTATION DIGITALIZATION

The operating philosophy proposed for the digitalization of the MONÇÕES substation, the primary substation that feeds the entire *Urban Futurability* project area and which is located next to Vila Olímpia, is based on the reduction in the number of IEDs used in bus protections. In the current architecture, there is one IED per feeder, totalizing five IEDs per bus, while in the proposed architecture, only two IEDs per bus are used, one main and the other hot backup, as can be seen in Figure 6.

The current communication architecture is shown in Figure 7 and has two separated networks, one being the operative network and the other one the local network. The operational network is responsible for carrying out the communication between the control center and the MiniSCADA devices where there is a software to collect the COMTRADE files and then make them available to the control room. The communication between the supervisory system and the feeder IEDs is done via the local network. In the current architecture, it is not possible to access IED devices through the operating network. In addition, the status indication and some interlocks are made by input/output contact of the IEDs, i.e,
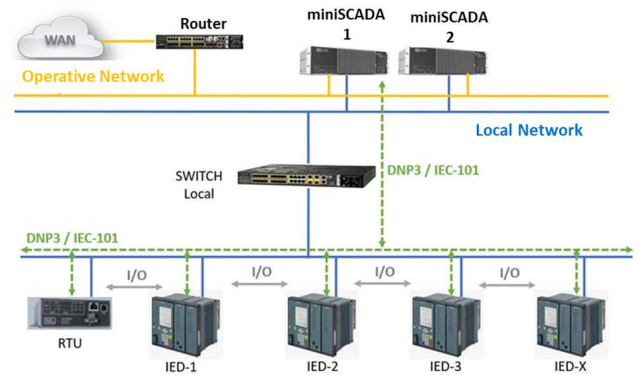

FIGURE 7. Current communication logic scheme.

a physical connection among the IEDs for these to communicate with each other is necessary. Analog values collected are sent using the DNP3 protocol or IEC 101/104. There is no redundancy of protective IEDs in the high or medium voltage bus, only in the transformer bay or in the transmission line bay there are IEDs with a main function (Differential protection) and a backup function (Overcurrent protection). Each substation has 2 local supervisors (MiniSCADA) being them main and the hot backup.

The communication logic scheme for digitalizing the MONÇÕES substation is shown in Figure 8. The communication will be carried out horizontally for status indication and some interlocks and will be done using the IEC 61850 GOOSE protocol, which considerably reduces the amount of cables needed for communication among the IEDs. The GOOSE protocol will also be used in protection functions,
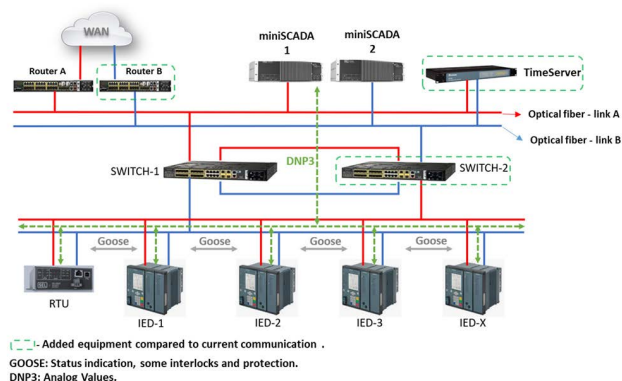
FIGURE 8. Proposed logical communication scheme for the primary substation MONÇÕES.

FIGURE 9. Solution diagram.

such as in the 50BF protection. Analog values will be sent through DNP3, this protocol will be used instead of MMS because the existing miniSCADA in the substation is not capable of working with the MMS protocol. The MiniS-CADA equipment performs the interface between the IED and the Central SCADA. It is important to emphasize that in this configuration it is possible to access the IEDs using the same network as the control center, differing from the architectures previously used by ENEL.

ENEL, through its GDS (Global Digitalization System) department, uses centralized supervisory systems that enable the monitoring and control of IEDs connected to the company's corporate and operational telecommunications networks.

These systems use open protocols, such as syslog and SNMP (Simple Network Management Protocol), which allow real-time monitoring of the status of monitored elements. With the use of these systems, it is possible to accurately identify, for example, the failure of a substation communication link or the disconnection of an ethernet network interface of a field-installed protection relay. The use of these resources has enabled preventive actions and reduced correction time in the event of a fault.

This architecture for the modernization of the MONÇÕES primary substation aims to increase the reliability of the electricity distribution grid, since the modernization of protection equipment promises a faster and more assertive fault detection and elimination system. In addition, the data that will circulate in the communication network will assist in predictive and preventive maintenance studies.

Regarding the system's RAM (Reliability, Availability and Maintenance) performance, for the first two topics, the entire communication system has redundant equipment (routers, switches, communication ports, fiber optic cables, etc.). This guarantees the high reliability and availability of protection, automation and communication installed in the substation. It is also expected that substation digitalization will contribute to increased productivity, reducing the amount of work to be carried out within a substation, with a view to reducing
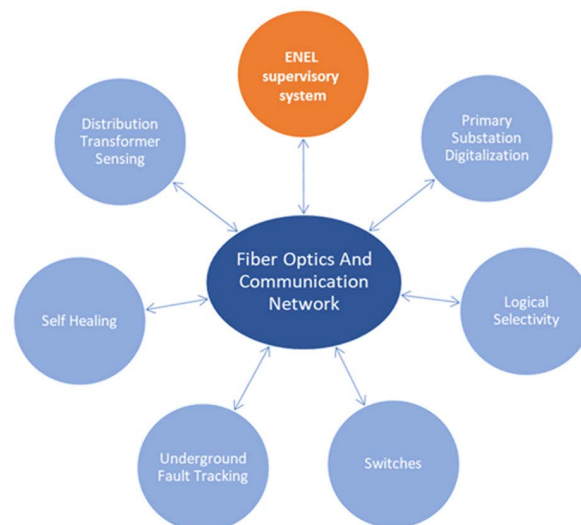
equipment and increasing the level of data availability with regard to predictive and preventive maintenance, thus reducing maintenance costs at the substation.

In summary, the digitalization takes place at the bay level, through the use of the GOOSE protocol for the communication between the IEDs, removing the need to use wires for this type of communication, and the concentration of protection functions in the same IED, reducing the total amount of equipment in the substation. The digitalization of an existing substation occurs due to the need for evolution of the equipment used in the substation, over the years the equipment becomes obsolete and it is no longer possible to retrofit it. Digitalization makes it possible to use more modern equipment, with new protection functions, the possibility of using a redundant and faster communication network, and greater equipment processing capacity, making it possible to add more protection functions in the same IED.

E. FIBER OPTICS COMMUNICATION NETWORK

The Fiber Optics Communication Network solution consists of the infrastructure for data traffic generated by other solutions of the *Urban Futurability* project, as well as managing the information and making the data available to the utility operations center. The solution will allow the implementation and communication of several smart devices in ENEL Distribution São Paulo's electricity distribution grid.

The main objective of the solution is to establish a safe and fast environment for data communication among smart devices and the ENEL system, through the use of optical fiber. Figure 9 presents the schematic diagram of the proposed solution.

As characteristics of the new communication network, we can mention: high reliability, redundancy, due to the ring topology, low latency and SLA (Service Level Agreement)

of 99.98%, in order to fully meet the other solutions of the *Urban Futurability* project [16].

Another differential of the Fiber Optics Communication Network solution is the use of the REP (Resilient Ethernet Protocol) to integrate the primary substation with the electric distribution grid, represented in orange in the diagram in Figure 9.

REP is a Cisco proprietary protocol that provides an alternative to Spanning Tree Protocol (STP). REP provides a way to control communication network loops, handle link failures, and improve convergence time. This protocol, controlling a group of ports connected on the same segment, ensures that the segment does not create switching loops and responds to link failures within the segment [16], [17].

The use of the REP protocol as an alternative to STP contributes to technological advancement due to the fact that this protocol has a shorter convergence time in Layer-2 Ethernet networks, which leads to a faster restoration of services and also allows SLA rates high [16].

Another standard that will be applied in the solution is the IEC 61850 standard. It was developed with the purpose of ensuring interoperability among the substation devices, however, it is also currently used for industrial automation and distributed automation in electric distribution grid. The standard has some protocols, but GOOSE will be the main one to be used, mainly in the Primary Substation Digitalization solution. It is a multicast protocol (multiple sites, but with targeted information), used mainly in activities to protect the electricity distribution grid, since it sends sporadic information of high criticality [18], being applied to the communication among the IEDs of the digitalized substation.

F. UNDERGROUND FAULT TRACKING

The Underground Fault Tracking solution aims to locate faults in the underground distribution grid, reducing the consumers' power outage period. Fault location equipment is installed in underground manholes, where they will monitor the underground electricity distribution grid. Furthermore, the product communicates with the utility's system through integration with SCADA.

As they are measuring equipment, it is necessary to be careful in relation to the environment where they will be installed. Thus, in addition to performing their basic fault location function, they also have the ability to monitor the environment where they are installed. Thus, through measurements of temperature, humidity, water levels and gas levels, they ensure that the fault locator will be working in their ideal conditions.

With current and voltage measurements, the product is able to detect the directionality of the fault that occurred in the system. From the fault location, the customer service process is vastly improved, making it more efficient and objective. Therefore, the utility guarantees to provide a better service to its customers.

Although the main objective of the equipment is the ability to indicate the fault directionality in the underground system,
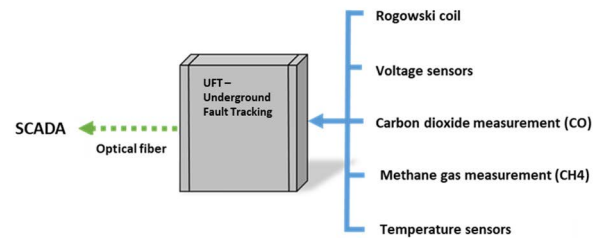

FIGURE 10. Simplified schematic of the Underground Fault Tracking solution.

its competence to measure environmental factors is of great value for the solution. Through the measurements of electrical quantities of the system, together with the measurements of environmental factors, the developed product provides reliability and quality of energy delivered to consumers. So that, through constant monitoring, the utility is able to act quickly and effectively, preventing the end consumer from being without energy supply for long periods.

For this solution, equipment is being developed with the ability to monitor, at the same time, up to 4 different circuits, being a fully integrated product, capable of realizing electrical quantities and environmental conditions. The communication with the central system is via optical fiber through the DNP3 protocol. The equipment is shown in Figure 10.

Details of the components and functioning of the second generation of this equipment can be seen in the paper [19]. A unit of this generation of equipment was installed in the city of São Paulo and the necessary improvements were collected (Results chapter of Underground Fault Tracking) so that the next generation of equipment can fully meet the demands of ENEL Distribution São Paulo.

III. RESULTS

A. DISTRIBUTION TRANSFORMER SENSING (DTS)

Between 2019 and 2020, ENEL Distribution São Paulo carried out the installations of the first DTS units in the overhead electricity distribution grid. In paper [20] the development, installation and data visualization on the platform of the first 10 units of the developed prototype was presented. In total, four models of equipment, from different suppliers, were installed, so that each of them could carry out an assessment of the most adherent model for the infrastructure that ENEL Distribution São Paulo has [15].

Through the data visualization platform, it is possible to follow the behavior of the electrical quantities in the distribution transformer. With the installation of the DTS, 7 types of anomalies have already been detected in the electricity distribution grid (Figure 12). One of the examples can be seen in Figure 11, with a graph showing a distribution transformer operating at overload.

The data presented in Figure 11 refer to a 45 kVA three-phase transformer. It is possible to notice that phases A and B, on every day, presented current levels higher than the nominal value of 118.1 A for each phase, with
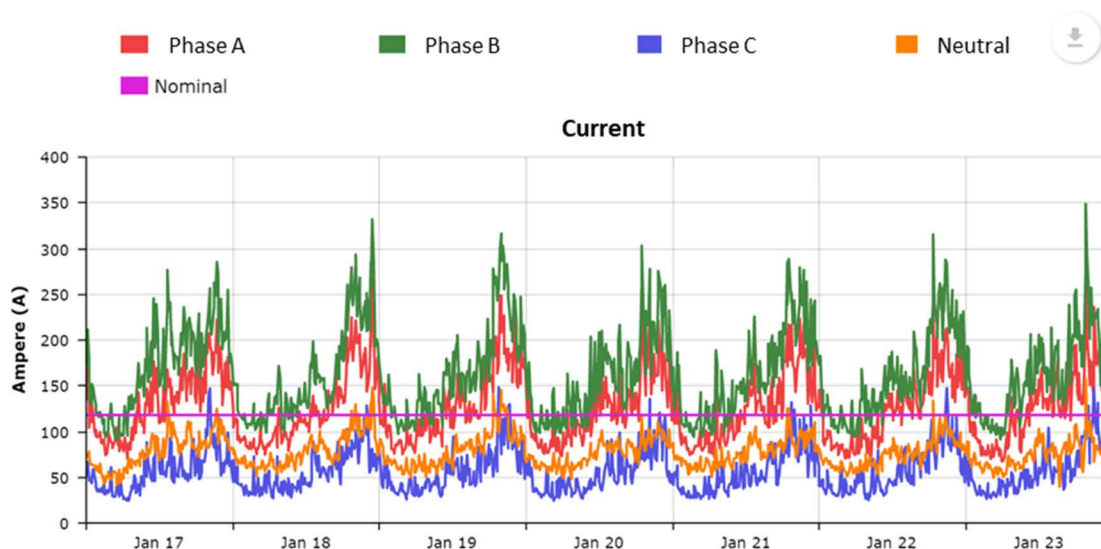
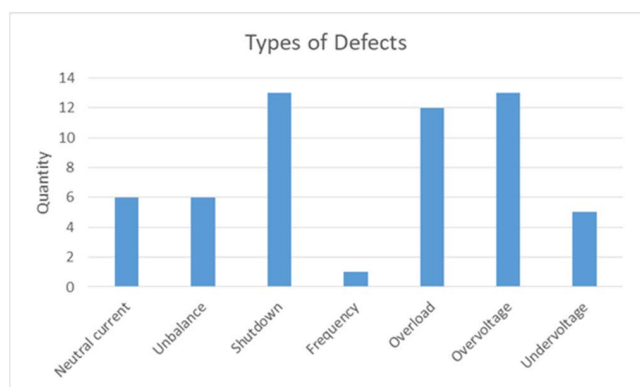**FIGURE 11.** Example of a distribution transformer in overload.

FIGURE 12. Types of defects.

FIGURE 13. Internal view of the panel with MCCB WEG and RTU WAGO.

phase B at times reaching values greater than 300 A. When phases A and B presented higher levels, phase C reached the nominal value for the phase, demonstrating an overload behavior in the transformer, with one phase at nominal value and two other phases with values much higher than the nominal, in the same instant.

This type of information is very important for the utility, especially for its maintenance area. A report is sent monthly indicating the anomalies presented, so that the maintenance team can plan the correction of the defect.

With the application of this equipment in the field, the project's technical team expects a 90% reduction in electrical grid failures due to overload in the distribution transformer and a 10% reduction in the total duration of failures, since the DTS assists in locating faults in the electrical distribution grid.

For the overhead electricity distribution grid, ENEL Distribution São Paulo already has 40 units of this equipment installed in the field since January 2021. For the underground elec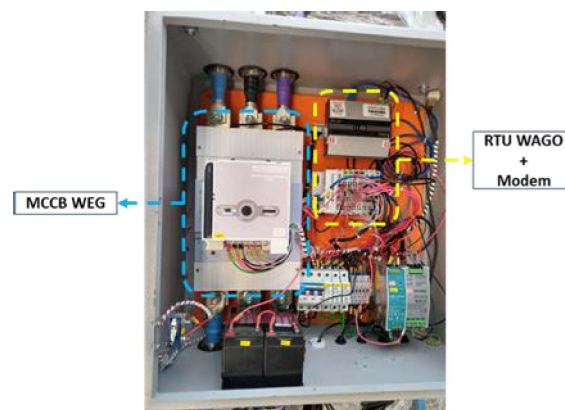tricity distribution grid, it is expected that by the end of the second quarter of 2022 the first 10 units of the solution will be installed.

B. LOW VOLTAGE SENSING AND CONTROL (LVC)

In March 2021, the first LVC unit was installed. Like the DTS, it performs the monitoring of electrical quantities in order to help detect possible anomalies in the low voltage electricity distribution grid. For this PoC, two panels were manufactured, one with MCCB from WEG and RTU from WAGO, and the other with MCCB from ABB and RTU from ME Consulting. Regarding the MCCBs, devices with the same nominal current value, 630 A, were used, with the advantages of ABB equipment being the greater range of options to parameterize the MCCB and for being more compact than the WEG equipment. Regarding the RTUs, in both it was possible to insert the reclose logic and they were able to send the opening and closing commands to the MCCB. As an advantage, the ME Consulting equipment proved to be much more compact than the WAGO one.
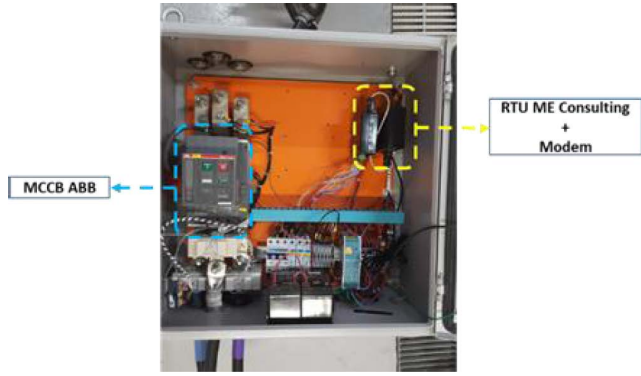
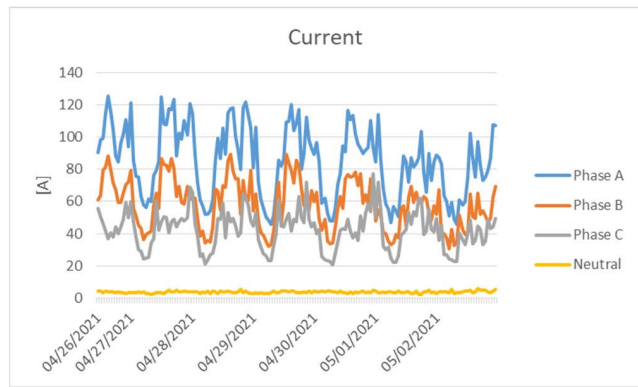**FIGURE 14.** Internal view of the panel with MCCB ABB and RTU ME consulting.

FIGURE 15. Current measured by an LVC unit.

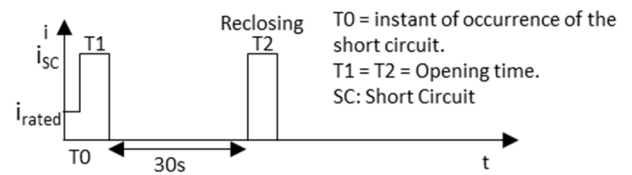**FIGURE 16.** LVC field installed.

FIGURE 17. Reclosing process with permanent fault.
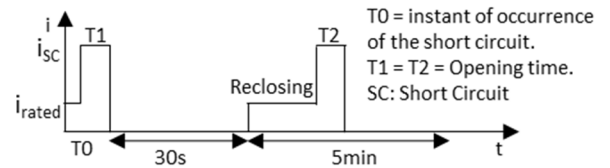
FIGURE 18. Reclosing with fault in the reset process.
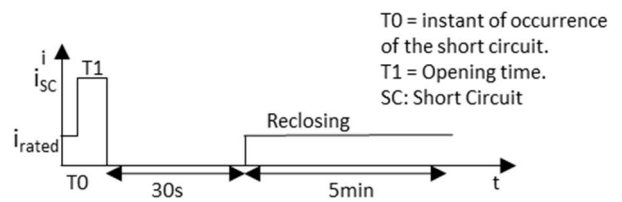
FIGURE 19. Successful reclosing.

From the moment the devices were installed until the writing of this article, no anomalies were detected by the LVC. Figure 15 shows a week-long sampling of currents from one of the installed equipment.

The main differential of this solution is its ability to perform automatic reclosing at low voltage, as it is programmed to perform a reclosing attempt. So far there was no need to carry out the reclosure, but if the reclosure comes to work, it can find 3 scenarios. The first one is permanent fault (Figure 17), in which after the 30-second interval, that is the interval between the breaker actuation and the first reclosure attempt, the fault persists, the breaker will actuate again and will be blocked. The second one is fault in the reset process (Figure 18), when performing the reclosure attempt and the circuit breaker does not actuate, the reset process will start, which has a time of 5 minutes to indicate that the fault has not occurred again. If in this period a fault occurs, the circuit breaker will trip and stay locked. Finally, successful reclosure (Figure 19), which is in case no faults occur during the reset process.

Thus, both the DTS and LVC solutions have as operating philosophy the monitoring and control of the main asset in the electricity distribution grid, the transformer, as well as the behavior of the electricity distribution grid on the LV side, in which ENEL Distribution São Paulo does not have

any monitoring and protection nowadays. Providing a better service to its customers, with fewer interruptions and, in case of power interruption, greater assertiveness and agility in correcting the problem.

ENEL Distribution São Paulo has installed 2 LVC units and by the end of 2021 intends to acquire other 8 units of the solution. When comparing it with the solution mentioned above, the DTS, the LVC is installed in places where there is a certain frequency of occurrence of transient faults in the LV of the electricity distribution grid, especially regions with trees close to the electricity grid. The DTS has as a reason for

FIGURE 20. Average preparation time of field teams.

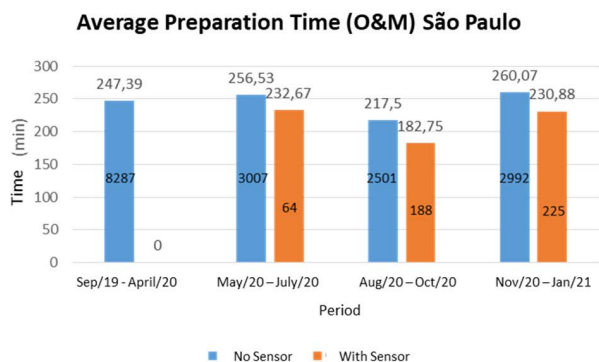**TABLE 1.** Comparison between the current substation and the proposed digitalization.

Item	Today	Proposed Digitalization
N° of electromechanical	12	0
N° of IEDs	27	12
Transformer control	Decentralized	Centralized
Parallelism control	Decentralized	Centralized
Main and Hot Backup with same protection parameters	No	Yes

installation, places with frequent complaints about the quality of electricity, non-technical losses and overload problems.

The application of LVC in the field, as well as the DTS, seeks to reduce overload failures in distribution transformers and the total failure duration time, with the same values presented in the DTS chapter, 90% and 10%, respectively. The differential that LVC presents is the protection on the LV side of the distribution transformer, with a 70% reduction in transient failures in the LV distribution grid being expected.

The DTS and LVC projects have similar functionalities and benefits, differing only in the item of protection and remote control in the LV distribution grid presented by LVC. Thus, the project team responsible for the Cost-Benefit Analysis (CBA) of the solution developed a tool capable of indicating which Transformer Stations (TSs) to use DTS and which to use LVC, since it is not necessary and would not have benefits use both equipment on the same TS. The analysis tool developed considers the technical and economic benefits of each project (DTS and LVC) raised by the business areas of ENEL Distribution São Paulo, and thus calculates which equipment will bring the greatest return to the company in that particular location.

C. FUSE AND BRANCH SENSING

After carrying out laboratory tests and a PoC, activities described in paper [21], the Operation and Maintenance area of ENEL Distribution São Paulo acquired 2500 units of the sensor. The use of these sensors in fuse bases showed immediate gains. We can see in Figure 20 that from the moment of using the sensors, we have already obtained a reduction in the preparation time of the field teams. In the graph, the numbers in the middle of the bar indicate the number of fuse actuations, while the numbers in the top of the bar indicate the average preparation time. The fuses that have the sensor always had an average preparation time lower than the unmonitored fuses. On average, the gain was equivalent to a reduction of approximately 34 minutes in the preparation time, during the monitored period.

The Fuse and Branch Sensing solution proved to be simple to install, due to no need to adapt the electricity distribution

grid (the sensor is connected externally to the fuse), simple application functionality and low processing requirements. Furthermore, it presented immediate feedback for both the utility and the final consumer, with a better and faster service provided by the utility.

Regarding the CBA of the solution, it was verified that, by staggering the installation of the devices for the entire concession area of ENEL Distribution São Paulo, the financial performance of the indicators was positive, resulting in a viable project. The main reason for this is the high value of CIT (Customer Interrupted Time) which, when reduced, impacts on a lower SAIDI, and as a consequence, an increase in revenue. Therefore, the economic analysis supports the decision-making for the installation of Fuse Sensing in points where there is a higher CIT, on average the solution proposes to reduce the prediction time by 90 minutes, that is, when the prediction time is greater than 90 minutes, considering the history of occurrence of the site, it is feasible to install the device.

D. PRIMARY SUBSTATION DIGITALIZATION

One of the objectives of the primary substation digitalization solution is to modernize the substation, replacing obsolete equipment, such as electromechanical relays, for equipment with greater processing and functions consistent with current technologies. Table 1 presents a comparison of equipment and functions of how the substation meets the proposed digitalization.

With the insertion of these new devices and functionalities, the implementation of self-healing between overhead and underground feeders is facilitated due to the ability to concentrate data and make decisions. Managing these field captured data also makes it simpler to apply adaptive protection logic and logical selectivity.

Adaptive protection is a philosophy that allows and seeks to make adjustments to the protection system to make it more suited to the changing conditions of the electrical system. Opposing to the classic protection philosophy that has fixed parameters, adaptive protection aims to constantly adjust its

parameters in an autonomous and resonant way with the natural changes of the grid. In relation to logical selectivity, it is a philosophy that allows evaluating the ideal sequence for the actuation of trip commands of relays/IEDs of the electrical grid, in order to promote assertiveness in the decision of which elements should have their circuit breakers commanded to open and disconnect the grid. Such assertiveness is defined as protection selectivity, where only equipment belonging to the faulty protection zone must act. This setting prevents the opening of circuit breakers outside the fault zone, i.e, it avoids undue load shedding. Furthermore, selectivity mitigates the fault location as it acts incisively on the equipment closest to the fault. In the *Urban Futurability* project, both solutions will be applied to the five overhead feeders of the MONÇÕES primary substation.

Another differential point in the proposed architecture is the use of the directional relay for protection. Another important point to consider is the change in the form of the transformer control and the parallelism function, which used to be decentralized, with the functions in an IED for each power transformer, and now it is centralized, with an IED with the functions for the two power transformers.

Finally, we can see in Figure 8 that all communication systems have redundant equipment (routers, switches, communication ports, fiber optic cables, etc.). This guarantees the high reliability and availability of protection, automation and communication in the substation.

Protection and communication equipment with state-of-the-art technologies will be used. The importance of a safe substation can be seen in the recent accident that occurred in November 2020 in a Brazilian state, in the northern region of the country, where an accident in the substation transformer left practically the entire state without power for more than 20 days [22]. The digitalization of the substation seeks to avoid these types of accidents, providing consumers with a distribution substation with greater reliability, safety and availability of the electricity distribution grid.

In comparison with paper [23], in this paper we address the issues of system performance through RAM, the challenges for ENEL Distribution São Paulo in relation to the communication network at the substation and even the case of an accident that may occur if the substation is obsolete.

E. FIBER OPTICS COMMUNICATION NETWORK

The optical fiber used in the construction of the communication network will be of the single-mode type. The topology chosen to be applied in the solution was the ring topology, which consists of the cable leaving the primary substation and going along the path of the designated circuit and returning to the primary substation through a path different from its circuit, as shown in Figure 21.

This topology provides redundancy in the communication network and, using priority techniques, it can have a recovery time of 5 milliseconds per switch or hub. According to [24], this solution has the best cost-benefit ratio.
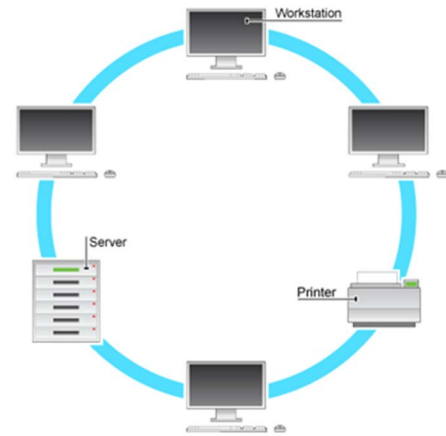

FIGURE 21. Ring Topology [18].
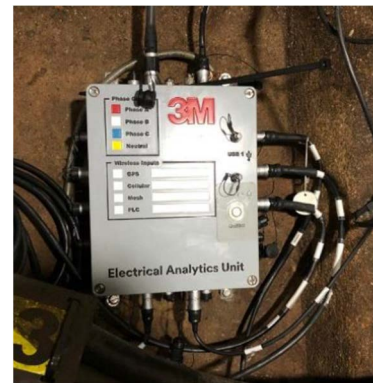
FIGURE 22. Equipment for fault location in the underground electricity distribution grid.

FIGURE 23. Current sensors in underground distribution grid, Underground Fault Tracking.

The infrastructure provided by the Fiber Optics Communication Network solution is essential for other solutions of the project, such as DTS, Primary Substation Digitalization and Underground Fault Tracking, to operate as planned through a secure and fast communication system. The solution also makes the region ready to receive future solutions that may need such communication features.

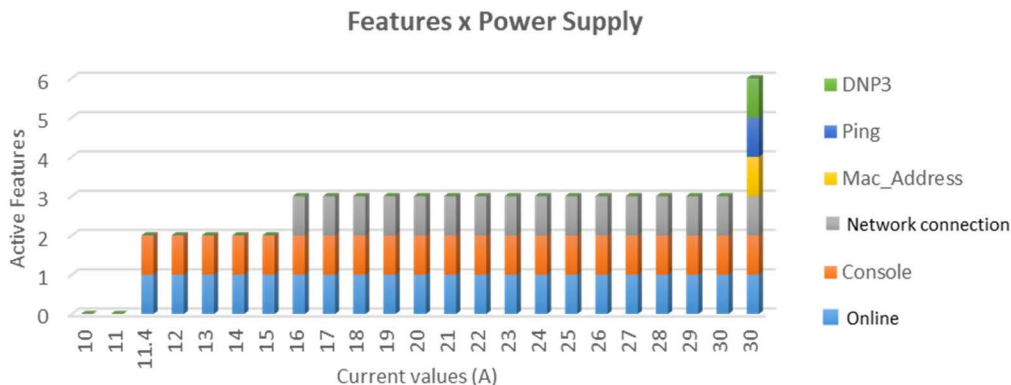**FIGURE 24.** Power supply current comparison tests with communication problems.

F. UNDERGROUND FAULT TRACKING

In order to validate the equipment's robustness and functioning, a PoC was carried out in the central region of São Paulo, at the Paula Souza substation feeders. The region was chosen because it already had the fiber optic infrastructure, the communication system necessary for the solution to operate correctly and to be able to integrate with the SCADA of the utility. Another highlight of the region is the high load concentration, making it possible to test the measurement of the electrical quantities by the equipment, as well as the location of the fault in case it occurs.

The equipment consists of current, voltage, temperature, gas and water level sensors, in addition to the electrical analysis unit. To install the equipment it is necessary to de-energize the feeder, as the solution is capable of monitoring 4 feeders at the same time. To minimize the impact of feeder shutdown for end consumers, this activity is carried out only at night (11:00 pm to 06:00 am) and only 1 feeder is turned off per night, taking four nights to completely install the equipment.

The PoC was carried out with the installation of only one unit, as the equipment is still in development, so the necessary improvements were collected and sent to the supplier, to be applied in the next versions. Improvement feedbacks include:

- Voltage sensors: In the first version, the calibration of the sensors is done manually. ENEL Distribution São Paulo requests that the voltage sensors start to have an automatic calibration or that this activity can be performed remotely by the operations center;
- Grounding: In the process of installing the equipment, all its parts must be grounded. This step is essential for the safety of the installation team and the proper functioning of all parts of the system. Such grounding instructions must be provided and emphasized in the installation manual;
- Redundant power supply: The equipment has redundant power supply inputs, so the device can be powered by two IPH (Inductive Power Harvester) or two connections for a low voltage source. However, it is not possible to merge device power supply between IPH and low

voltage source. This redundancy of different power supplies would ensure greater applicability, e.g, in feeders that have current intermittency in the primary circuits, causing the IPH to work intermittently, and the low voltage source providing backup energy. This is necessary because it was found, through laboratory tests, that for the equipment to operate correctly, a current of 30A is needed to enable all its functions, as shown in Figure 24.

With the application of these improvements in the next version of the equipment, it is expected to reduce the time to locate defects in the underground electricity distribution grid, a fact that contributes to the reduction of the restoration time of services provided by the utility. Therefore, customers connected to the circuits affected by the fault will have electricity available in their homes and businesses for as long as possible.

Thus, the application of the Underground Fault Tracking solution in ENEL Distribution São Paulo's underground electricity distribution grid not only represents an increase in the efficiency of the utility's current processes, but also has a positive impact with the improvement in the quality of services provided to the society, which culminates in the reduction of complaints rates, increased customer satisfaction and mitigation of the SAIDI and SAIFI (System Average Interruption Frequency Index) indexes.

IV. CONCLUSION

Aiming to advance the process of digitalization and automation of the electricity distribution grid, ENEL Distribution São Paulo, through the *Urban Futurability* project, seeks to improve the monitoring of assets, as well as the protection system in the distribution grid of electric power MV (medium voltage) and LV. So that all these improvements can be implemented, a communication network is developed for the communication between the field equipment and the operations center.

All solutions presented in the paper seek to bring great innovations to the electricity sector, especially for utilities. Equipment that are installed on the LV was presented for

real-time monitoring of the operation of the distribution transformer and its protection with remote commands and automatic reclosing. The fuses, which are equipment widely used by the utility, now have real-time monitoring of their performance, showing results in the field of faster service provided by the company at the time of maintenance of the electrical grid. Regarding the substation, the modernization of its equipment will be carried out, as well as its protection logic, with new communication protocols, protection redundancy and reduction in the number of equipment. Finally, equipment capable of locating faults in the underground distribution grid and monitoring up to 4 different circuits with the same equipment, optimizing the time of the utility's field staff in locating the fault and repairing the defect.

With the application of all these solutions mentioned in the paper, ENEL Distribution São Paulo seeks to provide its customers with a better electric energy distribution service, with a safer, more reliable electricity distribution grid, monitored practically in real time and with technologies of the latest generation. Therefore, the end consumers benefit from an electricity distribution grid with greater availability and decreased number of interruptions.

From the point of view of the utility, the Grid Automation front of the *Urban Futurability* project, which encompasses all the solutions mentioned in this paper, provides the company with a reduction in continuity rates, SAIDI and SAIFI, in addition to avoiding possible fines from agency regulators due to the quality of the electrical energy supplied. It is estimated in the Vila Olímpia region a reduction of approximately 50% in SAIDI and 42% in SAIFI, arising from the equipment that will be implemented in *Urban Futurability*. The company also starts to prevent possible theft of electricity and illegal connections by monitoring distribution transformers. Finally, much of the data generated by all these solutions will be used as inputs in the predictive maintenance system that has been developed by ENEL Distribution São Paulo [25], making maintenance less costly for the company, since the performance of predictive maintenance, in a planned way, generates less expenses for the utility.

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