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Design of an Underground, Hermetic, Pressurized, Isolated and Automated Medium Voltage Substation

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ABSTRACT This paper presents a new concept in underground medium voltage substations for an optimized operation performance and overall cost reduction. Due to its high-level embedded automation and communication systems, increased standards of reliability, availability and security are reached. Moreover, less expensive IP00 equipment can be used instead of higher IP-rated equipment, since the substation enclosure is hermetic and pressurized. Cost and time of construction works are reduced, as is the inconvenience to the population, especially when it comes to intense traffic areas. In addition, overall personnel labor is downsized, which reduces costs. In this context, the features and design guidelines of the proposed substation concept are presented, along with the methodology developed to address the thermal, structural and electric design issues.

INDEX TERMS Automation, finite elements analysis, reliability, thermal analysis, underground substations.

I. INTRODUCTION

Large metropolitan areas, highly populated city regions and commercial centers are continuously facing complex challenges, with one being the increasing demand for power supply and, consequently, the constant need for the expansion of electric power distribution systems [1]–[2].

In certain cases, the solution involves the construction of underground substations to increase the offer of power, which, despite being the most feasible type in specific situations, still present several drawbacks, such as limited room for the dissipation of the heat generated by the transformer [3]–[5].

Another drawback is the need for employing high-rated IP equipment, usually IP67, able to withstand harsh ambient conditions, such as floods. This adds greatly to the overall cost of equipment and reduces the number of existing brands/models/suppliers, which, in turn, may be a second factor leading to elevations in cost, since the purchase is often performed through public bidding. Besides, in conventional underground substations, the automation level is usually low, despite a growing demand to expand the number of intelligent electronic devices (IED) using the latest communication protocols, such as that defined in the International Electrotechnical Commission (IEC) Standard 61850 [6]. The low automation level increases inspection and operation costs and the required time to put the system back into operation, in case of failure. In addition, several cases of fire and explosion have been reported over time in this type of facility [7]–[10], from all over the world. Furthermore, construction works for its implementation are very time consuming, causing inconvenience to the population, especially in areas of high pedestrian and traffic density. Floods and animal invasion, such as snakes, is also a problem [11]–[12], as illustrated in Fig. 1.

In light of the aforementioned drawbacks, a new concept of underground substation has been developed, which is detailed throughout this paper. However, for an initial insight, its basic characteristics are presented in the following.

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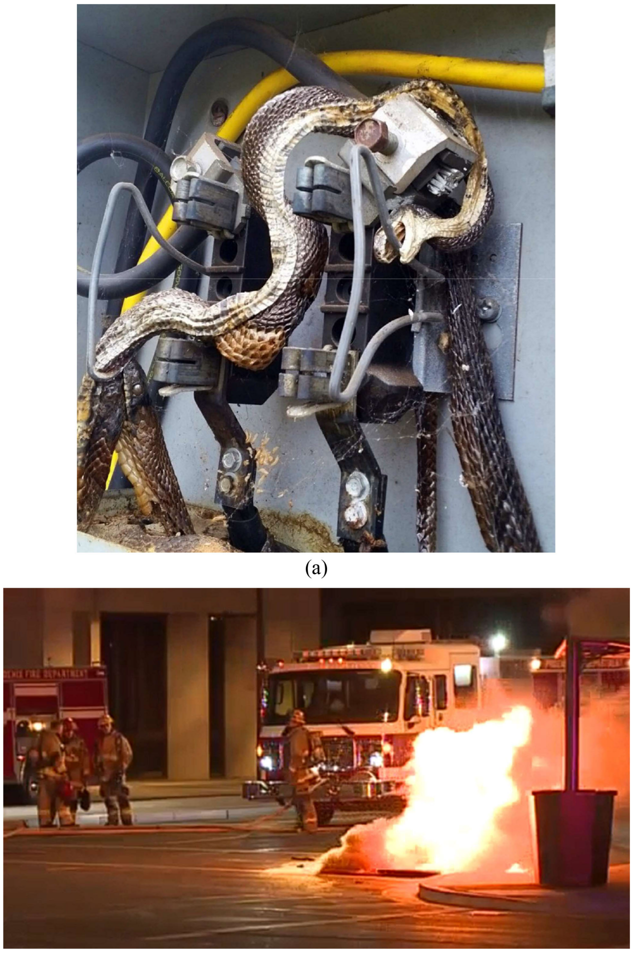

(a)

(b)

FIG. 1. (a) Two snakes entered an electric box and caused a short circuit [11]; (b) Electrical fault explosion killed one worker [8].

The substation ambient is a metallic enclosure, hermetically closed and IP67 rated. To ensure its leak tightness, it is also pressurized to generate an internal positive pressure. All the equipment is thus IP00 and the transformer is of the dry type. The substation is featured with high-level automation and communication systems and with an air-cooling system to keep its internal temperature at the appropriate threshold. The enclosure construction, equipment mounting and connection, cabling and commissioning is all set up prior to its transportation to the operation location, leaving only the power connection to be constructed in loco. This modularity highly reduces the installation time. The prototype under current development is rated for 1 MVA, 13.8 kV / 380 V, and, for such a model, its external measures are 6.0 (length), 2.4 (depth) and 3.2 (height) meters.

In summary, the innovative character of this project can be seen in the use of common equipment, normally destined to conventional systems, now being used in an underground distribution grid, in a safe manner. In other words, through the fact that the substation project ensures that it is airtight,

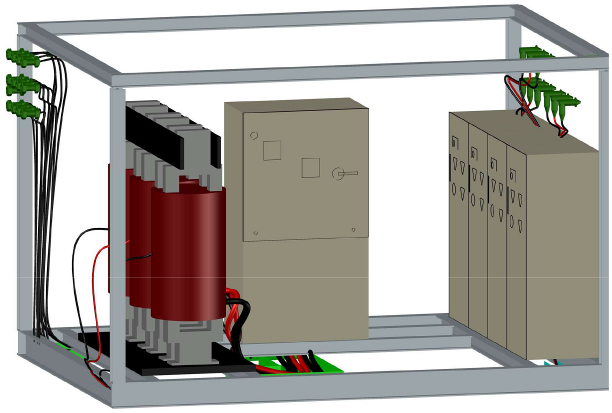

FIG. 2. Illustration of the prototype under development.

equipment with IP00 safety rating can be used in a subterranean application, which generates a generous economy in terms of its acquisition. This is seen not only through its intrinsically lower cost, but also through the fact that there exists a larger number of suppliers for this type of equipment, which contributes toward the reduction in acquisition costs, customarily performed through a bidding process. Noteworthy also is that the airtight attribute results from various solutions adopted throughout the development of the substation, such as the appropriate design and assembly of the enclosure, the characteristics of its sealing and the pressure used, among other factors. In addition, the type of refrigeration system specified for this substation (chiller) is not found in other substations [5], [13], as such this provides a substantially higher service life than more commonly used refrigeration systems, which elevates the reliability indexes. Finally, the level of sophistication of the designed automation and control system is above that traditionally seen in other substations, thus guaranteeing greater safety in operation, availability of equipment and continuity of service, besides compatibility with the Smart Grid concept. Figure 2 presents a preview of the underground substation under study, for which the specific features and design methodology will be discussed in the next sections.

II. MAIN FEATURES OF THE PROPOSED SUBSTATION DESIGN

In the previous section, an overall description of the substation concept was presented as an initial insight. In the following, its main characteristics are further discussed for a broader understanding.

A. SUBSTATION OVERVIEW

Figure 3 provides an external view of the substation structure in focus. It consists of a self-supported galvanized steel structure with anticorrosive coating (1), lifting eyelets (2) and top cover access (3) and hatch (4). On one of the sides, there is the (5) medium voltage box, while, on the other, one finds the

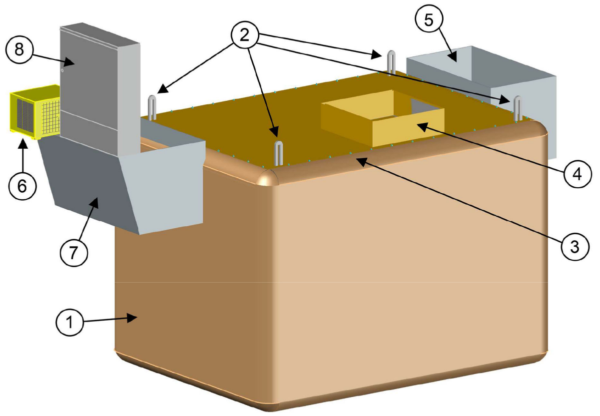

FIG. 3. External view of the enclosure.

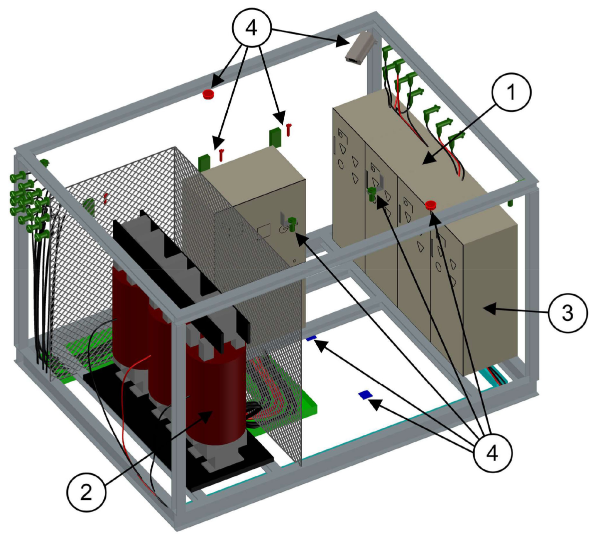

FIG. 4. Internal view of enclosure and the substation equipment.

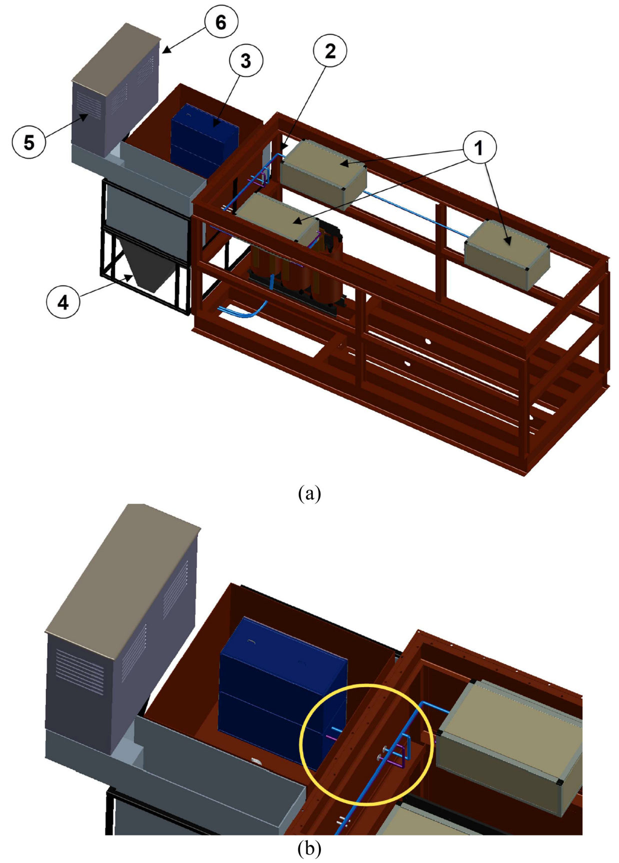

FIG. 5. Main components and design details of the cooling system of the proposed substation.

air-cooling equipment (6), the low voltage junction box (7) and distribution panel (8).

The interior view is depicted in Fig. 4, showing the medium voltage switchgear (1), the dry type transformer (2), the auxiliary service supply system (3) and the automation system with cameras, sensors, and actuators (4).

B. EQUIPMENT DESCRIPTION

The standard equipment that constitutes the substation under development is summarized below:

- Dry type transformer, ranging from 150 kVA to 2 MVA, equipped with RC snubber. In the prototype under development, a 1 MVA transformer was considered.
- Gas insulated and motor driven/remote controlled switchgear, featuring IEC 61850 and DNP3 communication protocols.
- LED interior lighting.
- Cameras (including thermal) for monitoring the enclosure interior.
- Power system for the auxiliary circuits/services featuring a no-break unity able to supply the camera, lighting, automation and communication systems energy demands for eight hours, as well as the switchgear drive/commands and the pressurization system.

C. AIR COOLING AND PRESSURIZATION SYSTEMS

The major source of losses inside the substation is the distribution transformer, whose generated heat must be adequately removed by an air conditioning system to keep the enclosure internal temperature at acceptable levels. A chiller system type was then chosen and dimensioned to ensure a top temperature of 40 °C in the critical regions (where the electronic equipment is placed). Noteworthy here is that this cooling strategy has not been found in underground substation applications, thus representing an innovation for the design. Figure 5(a) shows the most relevant details of the air cooling system that was designed, where (1) indicate the three fan coils installed on the top cover of the enclosure, (2) are the inlet (chilled water) and outlet (hot water) pipes (in blue and purple, respectively), (3) is the evaporator unit, (4) is the air condenser unit, (5) is the ambient air inlet and (6) is hot air outlet. Figure 5(b) highlights the inlet and outlet pipes and the corresponding connections to the evaporator unit and fan

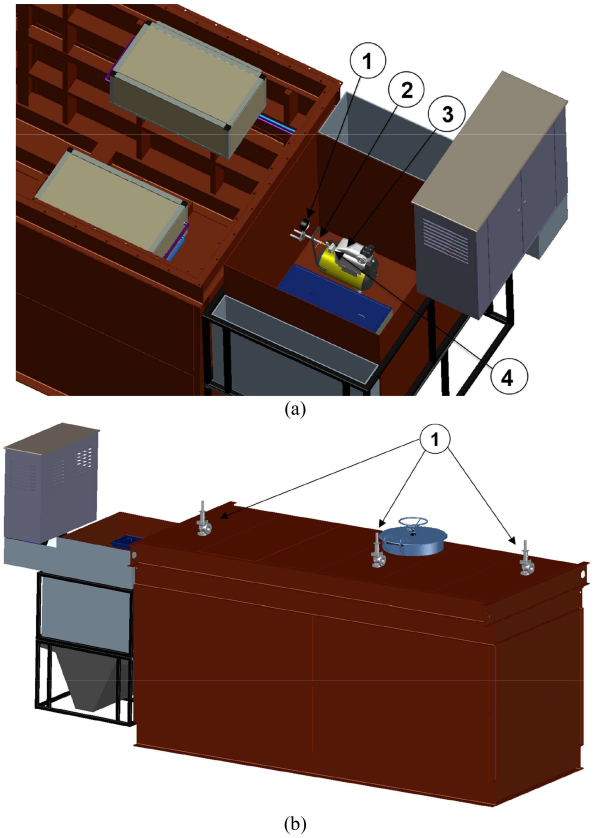

FIG. 6. **Main components of the pressurization system of the substation enclosure.**

coils. A complete thermal analysis is performed in section 3.1, whose results were used for the specification and dimensioning of the air cooling system characteristics and rating.

Along with the appropriate design and mounting of the enclosure structure, the substation leak tightness is aided by keeping an internal positive pressure, provided by an air compression system, at the level of 0.5 bars. A reduction of the measured pressure, below the threshold, or even a continuous operation of the compressor, may be used as a warning alarm for any eventual enclosure lack of sealing. For the sake of security and to prevent hazardous situations, safety valves have been specified to alleviate pressure peaks resulting from abnormal situations, such as the air expansion caused by the occurrence of an electric arc in the interior of the substation, for example.

Figure 6 illustrates the substation enclosure featuring only the components that make the pressurization system. In Fig. 6(a) are illustrated (1) the manometer, (2) the inlet (compressed air), (3) the compressor unit and (4) the pressure switch. Figure 6(b) emphasizes (1) the three pressure relieve and safety valves installed on the top cover of the substation.

D. SENSORS AND ACTUATORS

The operation and security elements of the substation will be largely served by sensors, with redundancy, to increase reliability and help the operation center to make decisions. In addition, it will also feature a number of actuators to provide the largest possible level of remote controllability. A large variety of sensors and actuators play vital roles and are key parts of the substation concept; as such, some are cited below:

- Pressure sensor: by measuring the internal pressure of the enclosure, eventual leakages and liquid entering can be detected. It also works as a second verification for the hatch opening/violation.
- Water blade sensor: along with the pressure sensor, it detects the presence of water inside the enclosure. Water monitoring will be performed on three levels, to indicate the intervention urgency for the maintenance staff. If the third (highest) level is reached, an automatic substation shutdown is commanded.
- Temperature sensors: measure the enclosure internal air temperature and the transformer windings temperature. Appropriate operation of the air conditioning system can be verified by these sensors, as well as possible transformer problems or overload.
- Smoke sensors: installed at different points around the equipment, generate alarm warnings and instant shutdown, depending on the measured level. The internal images from cameras (including thermal) help to identify the problem.
- Inductive sensors: monitor the hatch opening and also the position and status of moving parts of devices (medium voltage panel doors, automation rack door, etc).
- Electric arc detection: the substation will feature optical fiber sensors placed at key points inside the enclosure, connected to a processing unity for arc occurrence identification.

E. AUTOMATION, COMMUNICATION AND SUPERVISION

Regarding the substation automation and communication capabilities, the premises for the system specification are the following:

- Stand-alone operation and alarm warning generation;
- Protocols able to implement smart grid services;
- Ability to connect to the power company supervisory system and its IT infrastructure;
- All communication made through optical fiber and using the IEC 61850 protocol;
- A local PLC to evaluate all operating conditions and to act locally in urgent cases, providing redundancy and automatism if the communication with the power utility operation center is temporarily lost.

An overall view of the automation system structure is depicted in Fig. 7. Noteworthy here is that it enables the prototype to be classified as a “smart substation” [14].

The SE automation project can be summarized according to the architecture exhibited in Fig. 7, in which one readily notes five layers, namely:

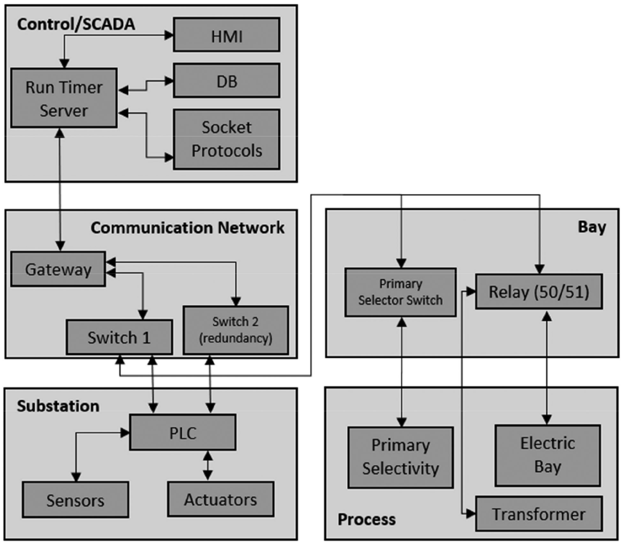

FIG. 7. **Overall structure of the substation automation system.**

- Control/SCADA: refers to the supervisory system, executed at the Operation Distribution Center and which allows for the control of SE resources, remotely.
- Communication Network: this element is physically allocated inside the substation and refers to the communication between the supervisory and the internal components of the substation. The network is basically constituted of switches and a safety gateway which controls access via IP.
- Substation: this has the PLC (Programmable Logic Controller) as its central unit, which, in this project, will take the role of monitoring the operation of the environment variables, such as temperature, pressure, water level, access etc., through the connection of sensors and actuators.
- Bay: at this level one has the electronic devices that monitor the electric variables of the substation in MV or LV; these are basically constituted of disconnection switches, circuit breakers and protection relays.
- Process: this level is constituted of the power equipment, such as electrical busbars, power and measurement transformers, switches (circuit breakers, motorized disconnectors, etc.).

The layers, also called levels, are defined by the standard IEC61850, with exception of the communication network, which was created in this project to attend to the aforementioned objectives, while introducing a desired level of technical innovation in line with modern communication techniques [15], [16].

III. MAIN BENEFITS FOR THE POWER COMPANY RESULTING FROM THE PROPOSED SUBSTATION

The operation of the substation discussed in this paper result both in service quality and financial gains, as explained in the following.

A. PRODUCTIVITY INCREASE

The productivity gains come from personnel labor time lowering in various sectors of the company, as well as contract values reduction of construction and electrical works. More specifically, man-hour savings will take place:

- In the underground substations project team.
- In the works, projects and maintenance staff, due to the shorter time spent in the annual survey for equipment acquisition planning.
- In the personnel responsible for the underground works inspection, since the proposed substation concept requires much less implementation time.
- In the operation team, once the substation disconnection from the grid is fully automatized.
- In the works and maintenance staff, as a result of the shorter waiting time for the substation shut down for the intervention begin.
- In the maintenance personnel, due to the solution of the problems normally related to conventional underground substations, such as floods, low automation level, required time to locate faults, thefts or to replace equipment in underground circuits.
- In the electrical works team, since the overall cost of the equipment mounting is cheaper in the case of the proposed substation.

Aside from the aforementioned, the construction works cost and time are inferior to those related to the underground substations currently in use. In addition, there is a revenue increase, since the asset is put into operation over a shorter period.

B. SERVICE QUALITY

An improvement of the service quality indexes will take place as a result of the high level of automation in the substation, supervision and control, along with the increase in reliability due to a comprehensive protection system. The reasons are as follows:

- Complete internal monitoring of the enclosure, with established security levels, alerts and actions.
- Full remote control of the switchgears and protection devices.
- Monitoring of hot spots using thermal cameras.
- Leak-tightness and measurement of the internal air humidity, temperature and pressure.
- Reduced system recovery time due to the monitoring of the short circuit sensors and the protection/switching devices remote control.
- Less occurrences of system failures due to flood, animal entry, gases, fire and explosions.
- Reduction in theft of cables and internal equipment due to an efficient security system, which comprises remote controlled electromagnetic locks, access monitoring of the hatch and internal panels, as well as of the low and medium voltage junction boxes, with alert generation;

- Improvement in power quality and power continuity indicators.

C. ASSETS MANAGEMENT

The management of the assets becomes simpler because the whole substation can be considered as one single item (if this is convenient for the energy utility), with a single depreciation rate, useful life, replacing time, etc.

Moreover, with the real-time monitoring and storage of the electric quantities by applying a meter data management system (MDMS), the data can be evaluated by qualified personnel, thus enabling a better management of the system use in terms of its demand, operation capability, etc. The result is an optimized deployment of the asset, eventually postponing investments on expansion.

The proposed substation concept is in line with a modern distribution network and will be part of an advanced distribution management system (ADMS). On an ADMS platform, systems are integrated to seamlessly share network models, measurements, database values and control signals, enabling the distribution system operators to efficiently manage the assets, quickly processing near-real-time data and getting ready for the new environment of greater levels of distributed energy resources (DER) penetration and/or transactive loads. Therefore, an ADMS is a combination of outage management systems (OMS), supervisory control and data acquisition (SCADA), distributed energy resources management systems (DERMs) and other mobile and advanced applications from single or multiple vendors [17].

Noteworthy here is that, due to its completely hermetic structure, with internal temperature control and low air relative humidity, the useful life of the equipment will be extended significantly. Finally, once the substation features a comprehensive security system, equipment theft will be substantially reduced, if not eliminated altogether.

D. NON-TECHNICAL LOSSES

The automation system, with monitoring and storage of electrical and other relevant data, allows for greater control of the distributed energy. The company distribution operation center will be able to compare the energy delivered by the substation with the corresponding revenue, quantifying and sectoring the non-technical losses, while allowing for more accurate auditing and more effective measures to be taken against energy theft or frauds.

E. ENERGY MARKET

Benefits regarding the energy market are also expected from the data volume obtained in the substation. Load curves can be derived for each substation, sectoring the energy demand, improving the statistical analyses and enabling more precise predictions for future needs of power expansion and validation.

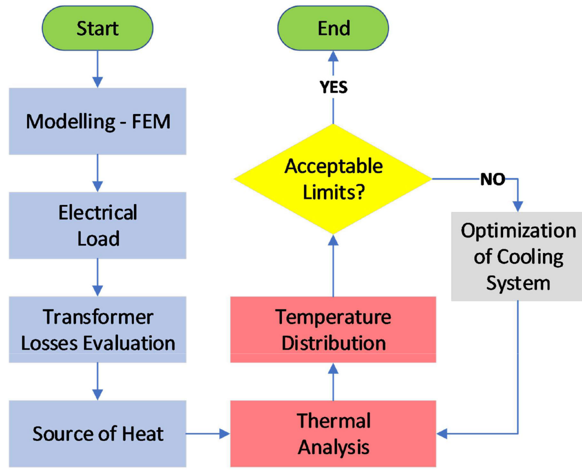

FIG. 8. **Flowchart of the modelling strategy for the thermal analysis.**

IV. DESIGN METHODOLOGY

Among the challenges for the development of the proposed substation concept, the mechanical design of the enclosure and the thermal concerns have been shown to be the most complex ones. Since mechanical issues are out of the scope of this paper, in subsection A the methodology employed for the thermal design is addressed in detail. Considerations on specific electrical design issues and tests are briefly discussed in subsection B.

A. THERMAL ANALYSIS

The thermal analysis of the proposed substation aims at ensuring all equipment operates under favorable temperature conditions, which is desired to be kept at levels lower than 40 °C, as those established in [18] for the dry-type transformers. The modelling and the thermal simulation of the system were performed by employing the finite element method (FEM) [19]–[21], using the software Ansys. Among other investigations, the thermal analysis enabled: (i) the dimensioning of the refrigeration system, (ii) assessment of performance, (iii) the definition of temperature gradients in the environment, and as such the temperature values to which the various types of equipment will be submitted, (iv) the performing of case studies that involve changes in the layout of the substation (internal redistribution of electrical equipment, installation of dividers in order to isolate groups of equipment, etc.), (v) the definition of the need or not for the installation of ventilators on the transformer.

After raising the losses for all the equipment installed within the interior of the substation, it was understood that the transformer would be responsible for around 85% of the heat generated inside the enclosure. For this reason, when the subject falls upon the thermal modeling of electrical equipment that constitutes the system of this study, it will receive special attention. The development of the simulation followed the methodology illustrated by the flowchart of Fig. 8.

TABLE 1. Physical Characteristics of the Windings

Conductivity of the aluminum at 155 ºC	23.8 S/m
Thermal conductivity	205 W/m.k
Specific heat	880 J/kg.k
Cross section (low voltage)	1.3 x 1000 mm^2
Cross section (high voltage)	5 AWG

TABLE 2. Physical Characteristics of the Core

Conductivity	2×10^6 S/m
Thickness of sheet	0.27 mm
Volumetric density	7500 kg/m^3
Thermal conductivity	45 W/m.k
Specific heat	400 J/kg.k

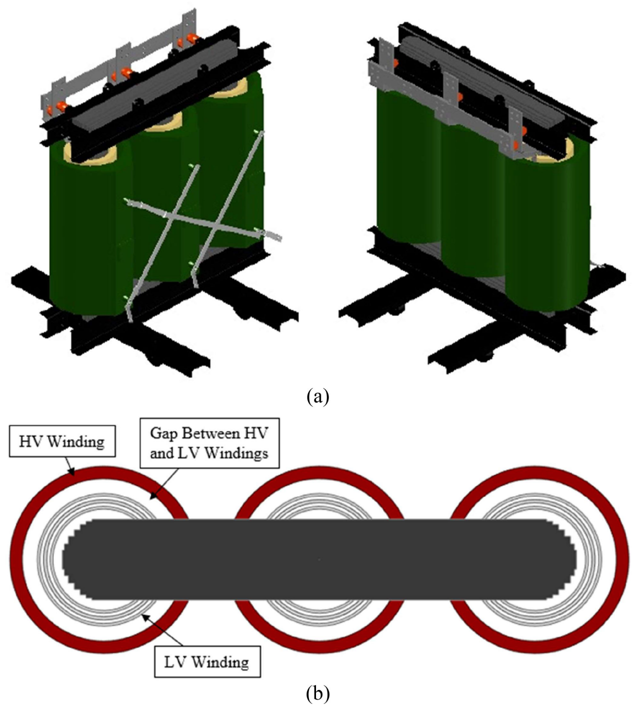

FIG. 9. Physical model of the transformer implemented in the Ansys Maxwell. (a) General view of the model and (b) Top view, illustrating the arrangement of the coils.

According to the previous flowchart, one has the following step-by-step procedure:

- Initially, a purely electromagnetic simulation is developed, using the ANSYS Maxwell tool.
- A load is imposed to the transformer, which will submit the equipment to different operating conditions (nominal and overload, for example).
- Starting out from the operation condition, it is possible to obtain not only the total losses on the transformer, but, in particular, the distribution of the equipment losses, thus identifying the localization of hot points. Noteworthy here is that this simulation is validated for the nominal operating condition, by means of comparing the total losses in the windings and in the magnetic core, along with the magnetic flux value, with the manufacturer data.
- In light of the results for the distribution of losses on the transformer, one thus has the main source of heat in the interior of the substation. These data are then exported to the ANSYS Fluent tool, using the multi-physical environment of the ANSYS (Workbench). The importance of developing electromagnetic simulations of the transformer is thus noted here. This occurs as it is not sufficient only having knowledge of the total losses, being also necessary to know their distribution over the equipment. In this way, one has a more accurate boundary condition for executing the next step.
- By means of the ANSYS Fluent, the data for losses are imported, for the appropriate thermal and fluid analysis.
- From the losses distribution results, the temperature distribution on the transformer is obtained, allowing the identification of hot points on the equipment. The variation of the temperature in the interior of the substation, from the imposed heat source, is also obtained at this point.
- Finally, through the consideration of the cooling system operation, the temperature levels on the transformer and also in the interior of the substation are obtained, to verify if these are acceptable; if not, the cooling system is resized.

- Modeling of the transformer – Losses Analysis

The representation of specific electrical equipment for simulation by means of FEM requires knowledge of the electrical, magnetic and thermal parameters of the material that constitute that specific piece of equipment, in addition to its geometric and structure details. Such information was obtained directly from the manufacturer of the transformer, presented on Tables 1 and 2, which show the characteristics of their windings and ferromagnetic core. The transformer under consideration is of the dry-type, 1 MVA, 13.8 kV / 380 V.

Based on the constructive characteristics of the transformer, the physical model was designed directly on Ansys Maxwell; the results obtained are shown in Fig. 9.

The low voltage winding (internal) is composed of 16 turns, distributed across three layers, among which there exists a space filled by air, as shown in Fig. 9(b). These turns are formed by an aluminum sheet of 1.3 mm in thickness and 1 meter in width (corresponding to the height of the transformer column), wound around the core. After five turns, a separator is placed, thus guaranteeing a space for the air to circulate and, following this, another six turns are performed, where a new separator is placed. Then, a final five turns are performed and the placing of another separator. Over the last five turns, a high voltage coil is wound, which is composed of wires with cross sectional area of 5 AWG, forming a single layer of 12 discs, thus totaling 1006 spirals for the 13.8 kV tap. However, for the aim of the present study, the individual representation of each turn is not necessary; as such, both windings (low and high voltage) were represented by cylinders, for which

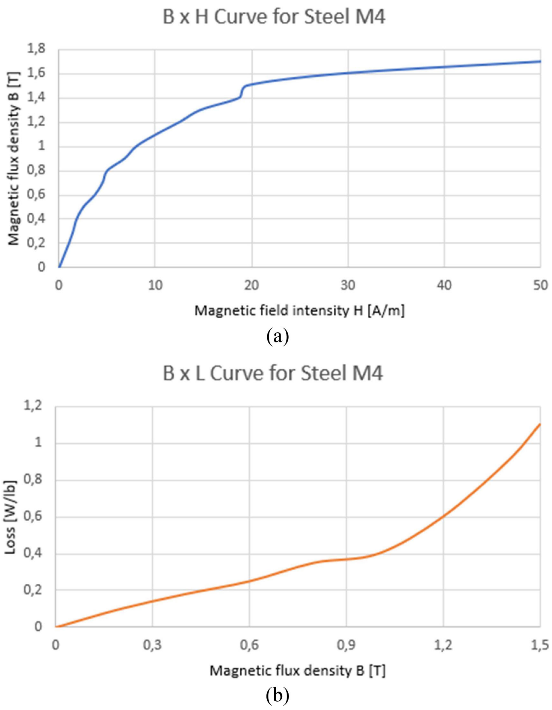

FIG. 10. **Curves (a) B x H and (b) B x L, extracted from [23] and [24], respectively.**

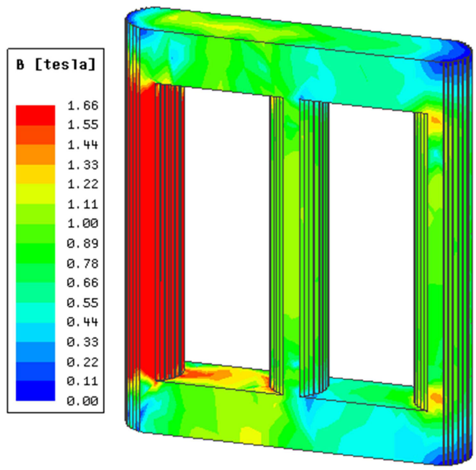

FIG. 11. **Distribution of the magnetic flux density in the transformer core, operating under rated load.**

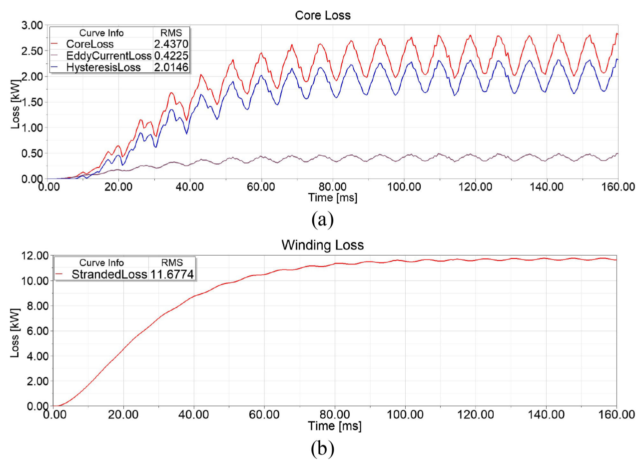

FIG. 12. **Losses (a) in the core and (b) in the windings, obtained in the transformer simulation under rated load.**

the thickness of their walls results in a volume of conducting material equivalent to the respective set of turns.

In addition to the data presented on Table II, the modeling of the transformer requires the B x H curves (flux density versus intensity of magnetic field) and B x L (flux density versus core losses). Through these curves, one can calculate the total losses for the core per unit volume (L_v), using (1), extracted from [22].

$$L_v = L_h + L_{ec} + L_a = K_h f (B_m)^2 + K_{ec}(f B_m)^2 + K_a (f B_m)^{1.5} \quad (1)$$

Where:

- L_h are the hysteresis losses;
- L_{ec} are the eddy current losses;
- L_a are the additional losses;
- K_h, K_{ec} and K_a are, respectively, the coefficients of the hysteresis losses, eddy current losses and additional losses, also known as Steinmetz coefficients, expressed in [W/m^3];
- f is the frequency of the applied voltage (Hz);
- B_m is the magnitude of the sinusoidal wave of the magnetic flux density (T).

The Steinmetz coefficients are determined by Ansys from the insertion of the B x L curve in the software, emphasizing that it is valid for a specific frequency (60 Hz, in this case). Since B x H and B x L curves from the manufacturer were not available, the curves presented in [23], [24] were employed, which are presented in Fig. 10.

After the simulation adjustment (definition of the mesh density, boundary conditions, type of solution, etc), preliminary results were obtained in order to validate the modeling. The first of these concerns the maximum flux density calculation with the transformer operating under rated load, as illustrated in Fig. 11. According to the manufacturer, this maximum value is 1.59 T, while the one found in the simulation was 1.66 T. This demonstrates that even when using a B x H reference curve and not that which is specific to the material employed by the manufacturer, the result can still quite satisfactory.

For the rated load condition, the core and winding losses were calculated, as shown in Fig. 12. In regards to total core losses, the value obtained in the simulation was of 2437 W, while that provided by the manufacturer is 2132 W. Considering that the B x L curve used in the simulation is a typical curve, and not necessarily representing in a specific manner the evaluated transformer, a discrepancy of around

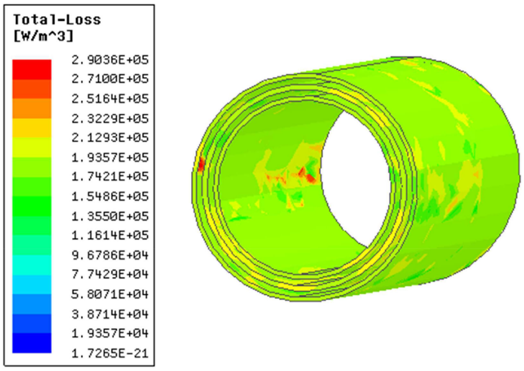

FIG. 13. **Losses distribution in one phase of the high voltage winding.**

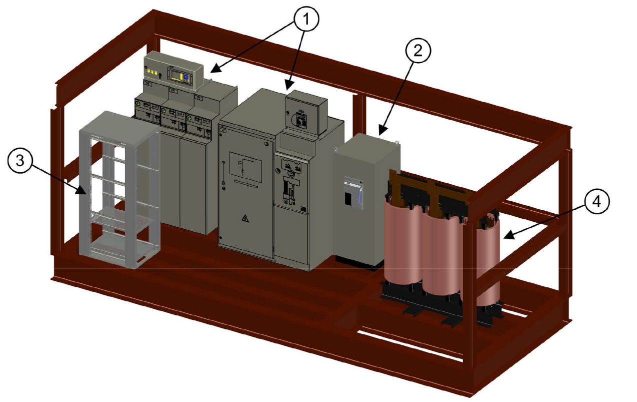

FIG. 14. **Representation of the model for the thermo-fluid simulation of the enclosure, eliminating the sidewalls for the visualization of its internal equipment: (1) medium voltage switchgear and measuring panels, (2) rack with the automation and communication equipment, (3) auxiliary service equipment composed of rectifiers, no-breaks and batteries and (4) dry-type transformer.**

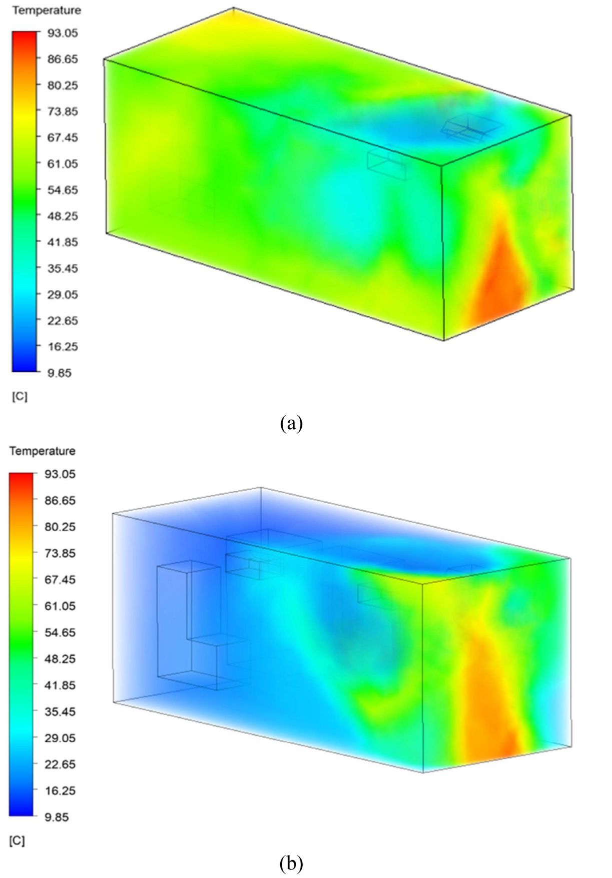

FIG. 15. **Thermal profile inside the enclosure with the transformer operating under rated load and with the use of (a) two and (b) three fan coils.**

14% is imposed. In the case of the winding losses, a simulated value of 11,677.4 W was obtained, while that informed by the manufacturer is 10,846 W, which corresponds to a percentage difference of 7%, and as such is also satisfactory.

By way of illustration, Fig. 13 shows the distribution of the high voltage winding losses in one of the transformer phases.

The losses figures presented above, along with the results related to other operation points of the transformer (not shown here), were analyzed as input data for the thermal simulation of the whole substation system, including the refrigeration system. This study is presented in the following.

- *Thermo-fluid simulations of the substation*

Maintaining the temperature in the interior of the substation at an acceptable level is crucial for guaranteeing the appropriate operation and longevity of its equipment. After a thorough technical and economic, the refrigeration system chosen was of the chiller type, for which the dimensioning was obtained from a thermo-fluid study performed on Ansys Fluent.

As a starting point, the enclosure model was elaborated as shown in Fig. 14, whose interior was filled with the main electrical equipment of the substation, in its final layout.

A case study was performed involving (i) different load conditions for the transformer, (ii) distinct allocation and number of fan coils, (iii) installation of a physical barrier at the side of the transformer to thermally isolate it from the rest of the environment, among other scenarios. Figure 15 illustrates the result obtained for the scenario where the transformer operated with rated power, without the thermal and with the use of (a) two or (b) three fan coils on the enclosure roof.

As previously mentioned, one of the premises of the refrigeration system project is to ensure that the internal temperature of the enclosure does not go over 40 °C at the most critical points. In reality, this objective was reached for practically the whole interior of the enclosure, with exception of localized points in the vicinity of the transformer. Through an analysis of Fig. 15 (a), which refers to the use of two fan coils situated over the transformer, one notes that this temperature level was exceeded in some regions. For this reason, a third fan coil was added onto the opposite side of the transformer, centralized on the region where the medium voltage panels and rack for the automation equipment rack meet. In this case, the temperature was maintained below the desired level throughout the interior of the enclosure, except in the vicinities closest to the transformer.

B. ONGOING ELECTRICAL DESIGN ISSUES

At the present moment, some relevant questions relating to the electrical project of the substation are still under discussion. One such question concerns the design of the grounding system, which presents a degree of complexity due to peculiarities of the proposed substation. One of the challenges refers to the compact dimensions of the grounding grid that can be built. Since one of the premises of the proposed substation is to require faster and simpler construction works for its installation in loco, in addition to a reduced area, the dimensions of the grounding grid cannot exceed the width and length of the enclosure by very much. This therefore limits hugely the amount of vertical rods that may be used, along with the distance between these. As a result, it becomes very difficult to obtain a significantly low value for the grounding resistance. Alternatives, such as treating the soil to reduce resistivity and the use of a non-conventional geometry of the grounding grid are under discussion. However, in regards to the latter, its design and evaluation are not simple, since unusual arrangements are not contemplated, in most cases, by commercial grounding system design software, thus demanding the development of a methodology with specific calculations, resulting in additional complexity and development cost.

Finally, with regard to electrical tests for characterizing the behavior and supportability of the substation, when faced with the diverse electrical demands and thermal, mechanical and dielectric stresses that result from these, various tests have already been defined and established, based on [25]–[27]. Among such, one can cite (i) the measurement of the insulation resistance between different points of the circuit and the enclosure walls, (ii) the evaluation of the effects from electric arcs due to internal failures, (iii) verification into the supportability of the circuits (main and grounding) when faced with a short-circuit current and (iv) verification of the temperature increase of the system at different points, when operating under rated load, among other tests. Tests that refer to the electromagnetic compatibility between the electronic equipment (automation and communication) and the electrical environment into which these are inserted are still under discussion, and should be performed in the next phase of project development.

V. CONCLUSION

In this work, a new underground substation concept was introduced, based on a hermetic metallic enclosure, pressurized and isolated, of compact dimensions, with an easy and rapid installation at the site of operation, which employs electrical equipment with IP00 classification and presents elevated levels of automation and communication. Such a level of supervision and control optimizes the operation of the substation in several aspects, thus generating various technical and financial benefits, while increasing reliability and reducing the global cost of the system, as discussed throughout this article.

In order to maintain the internal temperature of the enclosure at adequate levels, in spite of the heat generated by the electrical equipment confined in its interior, the substation counts on a refrigeration system. The dimensioning of this cooling system was realized employing a methodology of thermal analysis developed in the study, based on FEM and using the software Ansys. From the modeling implemented in the software, there arose the possibility of simulating diverse scenarios, involving different transformer loadings, the use (or not) of a barrier for separating the transformer and the rest of the environment, different layouts regarding the internal distribution of the equipment and the quantity and location of the fan coils. In all cases, the temperature on the most critical points of the enclosure interior were determined to ensure that the equipment is not subject to any type of thermal stress caused by the ambient temperature. After extensive analyses of the obtained results, the definition was made for all the features of the substation project in terms of the internal layout and characteristics of the refrigeration system.

Worthy of note here is that a prototype of this substation concept is under construction and some issues concerning its design are still under discussion. These include the definition of the geometry of the grounding system that will be implemented at its installation site and the electromagnetic compatibility tests, which should be included in the testing phase of the project.

Finally, due to the numerous technical and economic benefits discussed along this article, it is believed that the concept presented herein will be widely accepted in those niches for which this application is intended.

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