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**STRUCTURAL DESIGN OF AN UNDERGROUND HERMETIC AND
PRESSURIZED SUBSTATION FOR TRANSFORMING ELECTRIC
ENERGY**

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Abstract. *This work proposes the use of computational thermo-fluid simulations to estimate the psychometric conditions of the indoor air of a modular and hermetic substation of electrical energy transformation. The design of the substation foresees the installation of an external auxiliary operational module, located at ground level, which has a refrigeration system (Chiller) able to guarantee safety conditions for the operation of the 1000 kVA power transformer, located inside the underground substation. The analyzes were performed at the computational software ANSYS®, the simulations of thermo-fluid and electromagnetic problems were made simultaneously. As results, the thermal profile of the substation's indoor air was estimated for two cooling strategies. The most suitable scenario has a refrigeration system with three fan coils units; at this condition the air temperature presented values below 40 °C in the critical regions. Parallel to the main objective, computational structural simulations of the metallic structure were performed and the main parameters as equivalent tensions of Von-Mises, total deformation and buckling were estimated. The conception of the idea of this underground hermetic substation is recent and the patent application is already regularized in the INPI (National Institute of Industrial Property of Brazil).*

Keywords: *underground substation, computational simulations, refrigeration.*

1. INTRODUCTION

Generally, the underground electrical substations have problems with the insufficiency of their seals. This generates high costs in the construction and maintenance of substation's equipment, due to their vulnerability to external interferences such as animals or floods that can damage the system. However, in this case the substation project considers the importance of seals, and consequently need to carry out additional studies of its structure and thermo-fluid analysis of equipment.

In the last years scientific studies are being oriented towards the improvement of other factors that involve the underground substations. *Loo and Ukil (2017)* developed a structural design of a grounded substation resistant to external factors. This model designs a substation to withstand earthquakes, but this work is neither seals nor hermetic, in addition to not being equipped with a high level of automation. In a case study in Alaska, *Miranda et al. (2017)* developed an underground substation project subject to weather inclement weather. Can observe the problem of lack of indoor air heating of the substation, which may compromise the operation of the components. In this work the thermal problem is about the cooling of the air inside the substation.

Nair et al. (2016) studied some propositions of safety measures and operation in underground substations. Although, this project does not provide for hermetic insulation and the monitoring system is restricted to electrical variables. Otherwise, *Shkrabets and Ostapchuk (2013)* approached a new underground substation model with monitoring of operating parameters. The study focuses on applications in large mines, where high-class IP equipment is used. The authors show that the difficulty of access and maintenance is very considerable in their model.

On thermal analysis of the substation, *Dawood et al. (2017)* studied a three-phase transformer of 1.25 MVA doing analytical analysis and finite element in 2D and 3D dimensions. Dispersion reactance, magnetic flux density and energy were calculated using a program ANSYS Maxwell and the analytical methodic. Transformer prototype was building about the results of FEM. Analytical and numerical results of different parametric of transformer were compare with

experimental results also. The results show that FEM can be a great tool, with a biggest efficacy for calculations of different transformer parameters. The difference between experimental and FEM results was not be more than 5 %.

Loucaides et al. (2010) evaluated the thermal behavior of a distribution substation in order to simulate various ambient and load temperature scenarios, as well as investigating the effect of design parameters such as aperture size and construction materials. The substation transformer is 1000 kVA with losses of approximately 10 kW. From this work it is possible to evaluate the ideal air conditions for the equipment that makes up a substation of this capacity (1000 kVA) is 40 °C.

The main objective of this work is to create a realistic version of the substation concept using finite elements techniques of simulation to estimate the temperature profile of the indoor air of a modular and hermetic electrical substation with capacity of 1000 kVA. The substation depends on an external auxiliary operational module equipped with a chiller system, located at underground level. The purpose of this system is to achieve a sufficient heat exchange rate by the fan coil units to maintain internal air volume in the condition of dry bulb temperature and relative suitable for the operation of the transformer and other electrical equipment. In addition, the finite element model also aims at the structural analysis of the substation, and the main parameters such as equivalent tensions of Von-Mises, total deformation and buckling were estimated.

2. MATERIALS AND METHODS

The idea of a new electrical substation is presented in Figure 1. It consists in a self-supporting structure made of galvanized steel, with coating, equipped with an access cover, an access hatch and lifting eye. There is a medium voltage box with medium voltage disconnect terminals, a low voltage pass-through box, a low voltage distribution panel and finally, the item, which symbolizes the equipment related to the refrigeration system, which was studied throughout this work.

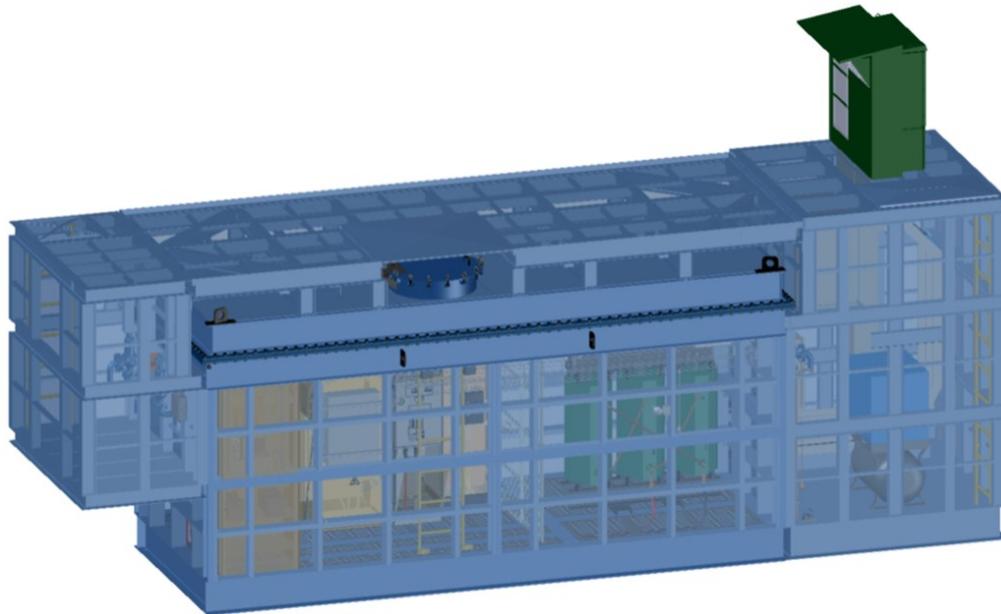


Figure 1. Concept model of the substation. External components, a. internal components, b. Simplified substation model used for computational analysis, c.

The use of ANSYS® requires that a strategy is adopted for the design, optimization and analysis of an electromagnetic device. In general, the methodology employed consists of three phases: pre-processing (modeling of device geometry, definition of physical properties), processing (problem-solving) and post-processing (analysis of results).

The computational simulation of thermal problems is an indispensable tool for the modeling of the heat exchanger of this substation in order to estimate its specifications. In addition, computational models of heat exchangers help to define the optimal positioning inside the substation. This positioning is related to the operation characteristics of the power transformer and to the influence on the thermal effectiveness of the refrigeration system.

The software used to thermal simulation of the substation is the ANSYS®, through your tool Fluent. This tool allows the use of a variety of control volumes and flow conditions. More general and simplified conditions were used, which are sufficient for the generation of satisfactory results for thermal analysis of the substation without the need for experimental studies.

The dry transformer, as a rule, dissipates more heat to the environment than other types of transformers, after initial analysis, the refrigeration system chosen to compose the future substation is a 5 TR water chiller. The cooling effect on the air inside the substation will be done by fan coil units, or hydronic heat exchangers. So, cold water, with a mass flow rate of 1 kg s⁻¹, will enter at 5 °C at the heat exchange. Therefore, the refrigeration system will remove approximately 16 kW of energy that is dissipated by the power transformer, maintaining the operating temperature of the air at 40 °C near the electrical and electronics components.

Figure 2 shows the equipment and accessories that make up the cooling system. The red line represents the direct expansion refrigeration system. The refrigerant flows inside the copper tubes (items 1 to 9), where: (1) is the refrigeration compressor; (2) pressure sensor; (3) air-cooled condenser; (4) liquid viewfinder; (5) dryer filter; (6) electronic expansion valve, EEV; (7) plate heat exchanger; (8) pressure sensor; and (9) temperature sensor. The blue line represents the secondary fluid circuit, or cold water, this will be composed of stainless steel or copper tubes (items 10 to 13), where: (10) is the thermal isolated reservoir of cold water; (11) centrifugal pump for cold water; (12) temperature sensor and (13) hydronic heat exchanger, fan coil unit.

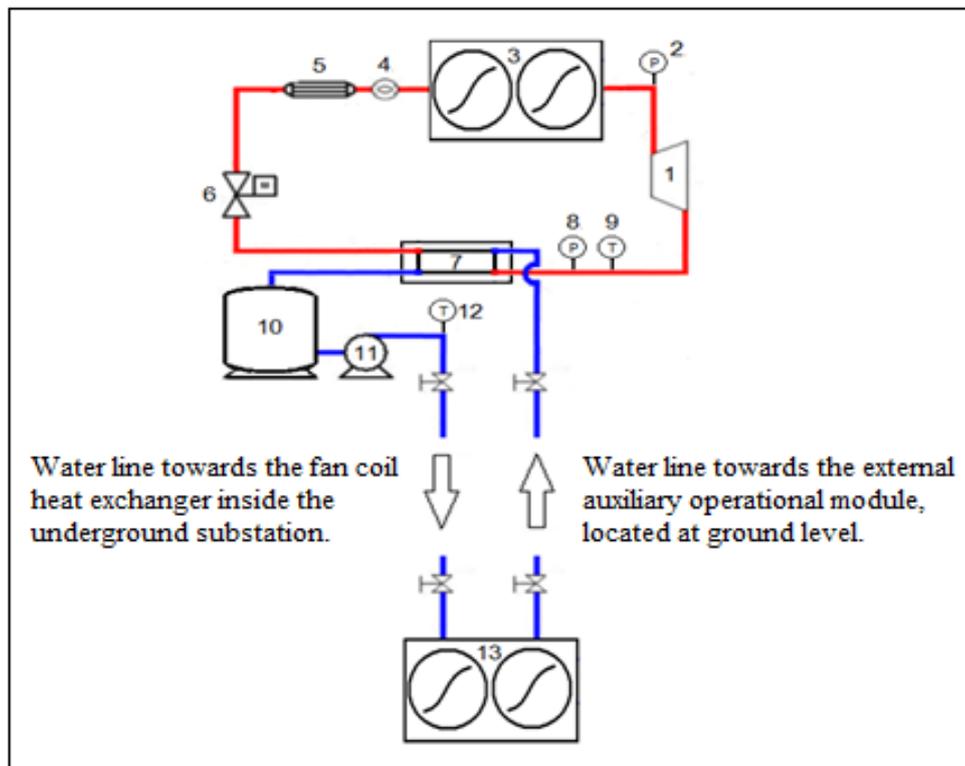


Figure 2. Schematic operating of the cooling system.

The cooling system has 3 heat exchangers, mentioned above. The water passes through the hydronic heat exchanger and performs the absorption of heat present in the indoor air of the substation. Otherwise, the plate heat exchanger is responsive to the transfer of heat between the primary fluid (refrigerant) and the secondary fluid (distilled water), in this way the refrigerant receives the heat from water. Finally, in the air-cooled condenser occurs the rejection of the heat present in the refrigerant to the external ambient.

It is important to emphasize that the substation construction, as well as its installation and operation, is scheduled for 2020. So, Fig. 1 and Fig. 2 are illustrative and were presented only with the objective of defining the concept of the substation. The layout of the electrical equipment and the geometry of the metal structure can be altered according to the needs of the general design of the substation.

The first group of simulations was then performed to verify the thermal profile of the substation's indoor air for two cooling strategies. Figure 3 (a) shows the simplified model of the substation with two fan coil units, and Fig. 3 (b) represents the model with a metal partition and three fan coil units.

(a)

(b)

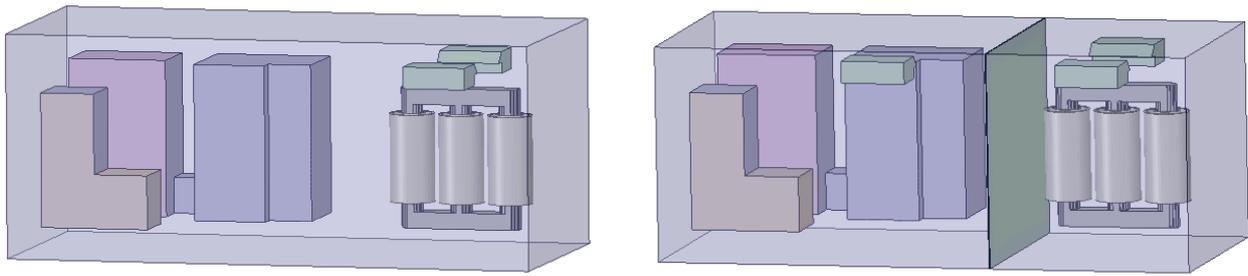


Figure 3. Simplified model of the substation with two fan coil units, a. Simplified model of the substation with the metal partition and three fan coil units, b.

Preliminary electromagnetic simulations of the transformer generated a set of hot spots, and the maximum temperature found was 125 °C at the top of the equipment. By means of a conservative strategy, this maximum value was adopted as a boundary condition on the entire surface of the transformer reels, and thereafter thermo-fluid simulations were started, simultaneously with the electromagnetic problem.

The fan coil units (heat exchanger) provide heat transfer between the indoor air and the chilled water, each unit blow cooling air at 1.5 ms⁻¹ and 10 °C, these values were adopted as boundary conditions. The substation walls were considered adiabatic; they have complete contact with the ground. For the other components, thermal dissipations were not considered, since the transformer heat dissipation is much higher.

Then the simulations were directed to optimize the thermal profile of the substation's indoor air for the critical regions, for this purpose a 4 mm metal plate was inserted inside the substation in order to contain the thermal dissipation of the dry transformer for the other components. In addition, a new fan coil unit has been added to ensure temperature control in the critical regions where the battery box and instrumentation module are located, Fig. 3 (b). The addition of the fan coil unit represents, in practice, an increase in the capacity of the ground-level Chiller.

The simulations using the finite element method were also performed in order to verify the effectiveness of the structure to support the loads applied on it. The stress and strain were simulated in such a way as to guarantee the strength of the structure and the full operation of the installed equipment. Optimizations were performed from this model in order to achieve it is ideal configuration.

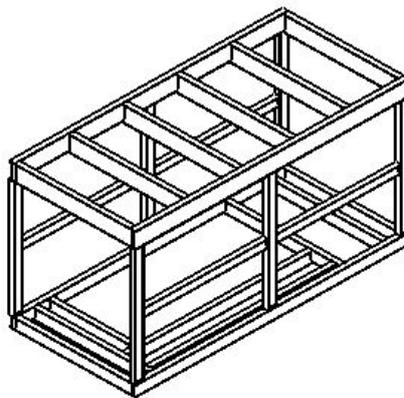


Figure 4. Model of the substation for the structural analysis.

Figure 4 represents the model used for the simulations of the substation structure. Firstly, the beams and columns to be used in the metal structure were defined by analytical methods, considering that the substation cover is 1 meter below the ground. This would result in 26920 Kgf of Earth above the structure. In addition, it was considered 24000 Kgf of cargo vehicles passing over the substation. On the base beams, only the weight of the power transformer was considered (4000 Kgf).

3. RESULTS AND DISCUSSIONS

The use of the Fluent tool enables the realization of indoor air substation simulations of different scenarios. The first cooling strategy is justified by the need to know the most critical conditions, i.e. the operating limits of the cooling system. And thus ensure full control of the temperature limits in the indoor environment. Therefore, the simulations occurred with

the maximum operating conditions of the dry transformer, the temperature of 125 °C was adopted on all surface of this equipment.

Figure 5 shows the thermal profile of the air inside the enclosure for the scenario described in Fig. 3 (a), i.e. with the installation of two fan coil units, operating with airspeed and temperature of 1.5 ms⁻¹ and 10 °C, respectively.

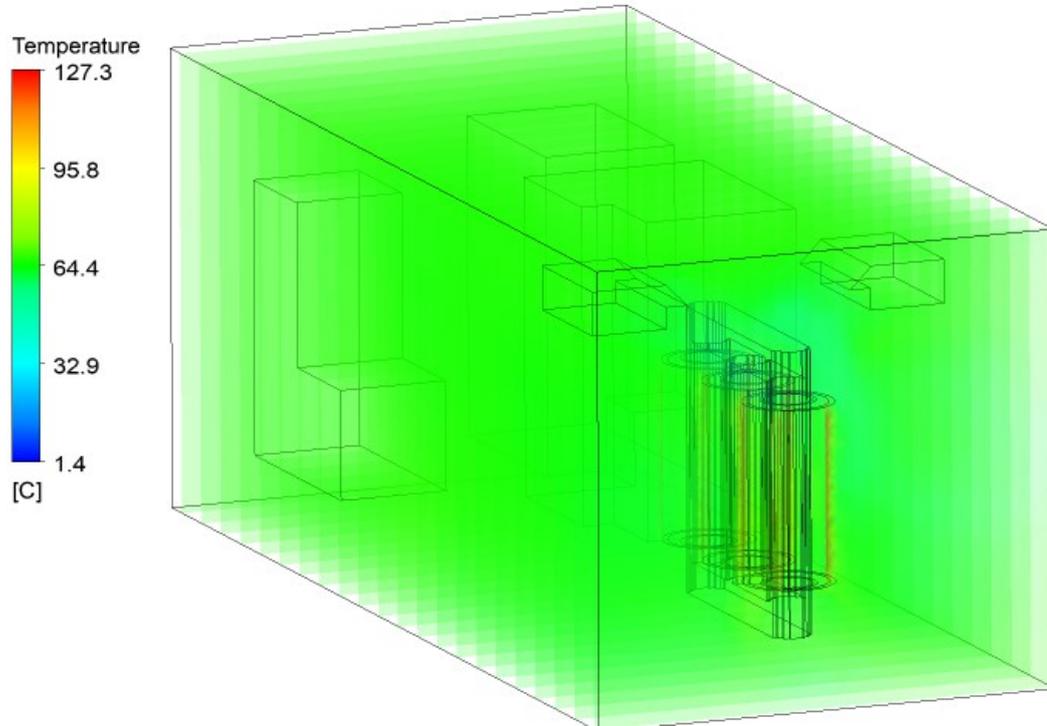


Figure 5. Thermal profile of the air inside the enclosure for the first scenario.

In this situation it is observed that the units are capable of cooling the air practically homogeneously throughout the substation volume. Temperature values were in the range of 60 to 70 °C, which is above the desired 40 °C. The main concern here is with the instrumentation module and the battery box, equipment that according to the manufacturer's information has a shortened service life when working at such high temperatures.

The second cooling strategy was designed to achieve a heterogeneous indoor air thermal profile. This optimization is justified by the need to protect the most sensitive components at high temperature levels. Thus, a 4 mm thick sheet metal was added in an attempt to control the air flow of the fan coil units, and consequently this shield optimizes heat transfer in these two distinct regions, a region close to the dry transformer, and another region where the most heat sensitive components are installed. In addition, another fan coil unit was added over the battery box and instrumentation module. The boundary conditions described in the materials and methods were maintained and Fig. 6 shows the thermal profile of the air within the enclosure for the scenario described in Fig. 3 (b).

Heterogeneous temperature profile of the enclosure indoor air is observed, the two fan coil units near the transformer are capable of effectively cooling the air with temperature values in the range of 60 to 100 °C. The main effect of optimization can be observed at the left extremity of the enclosure where the most sensitive components are located, in this critical region the temperature values remained close to the desired 40 °C. The main concern in this case is with the instrumentation module and the battery box, equipment that according to the manufacturer's information has a reduced service life when working at high temperatures.

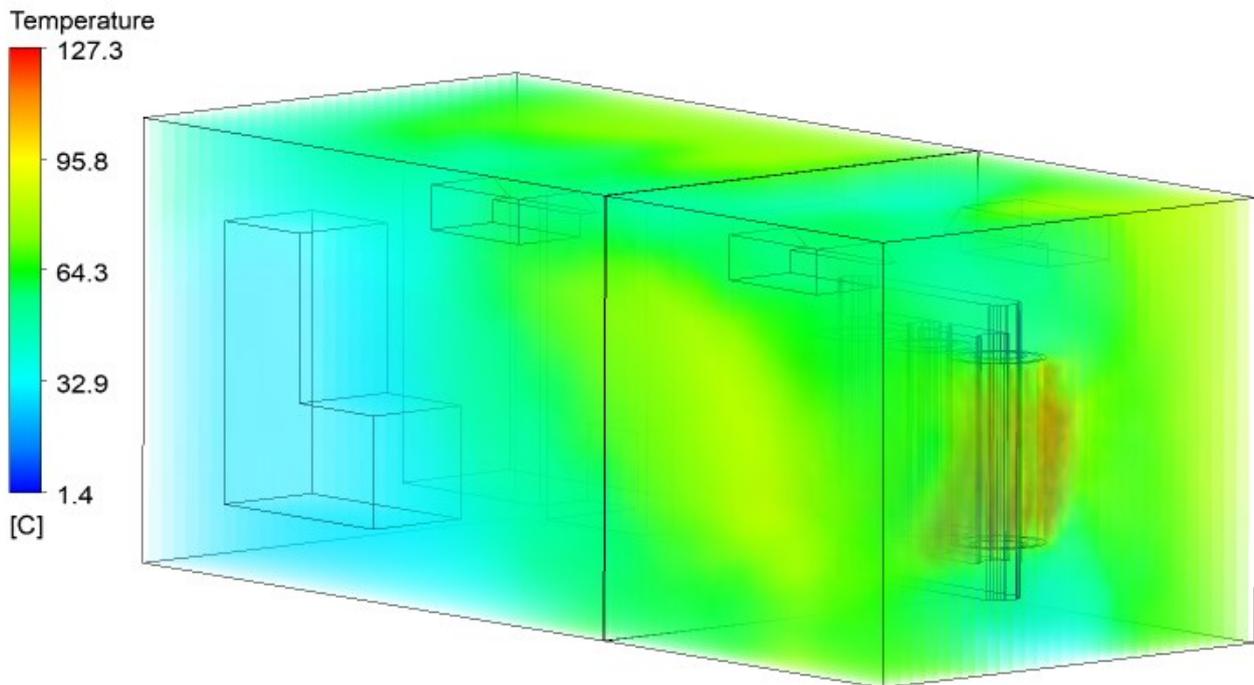


Figure 6. Thermal profile of the air inside the enclosure for the second cooling strategy.

The next step was the structural analysis from the model of Fig. 4. At this point a load was defined distributed along the area of the substation cover. The loads located on the sides of the structure were disregarded, since the project considers the use of retaining walls. The model was drawn in the ANSYS® and obtained the stress and strain distributions.

The analysis of the substation model was subdivided into two main parts: the substation basis and the elements group formed by the side pillars, the structural roof and the solid cover. Symmetry-related techniques could have been used, but this simplification was not chosen. Therefore, the model is a faithful representation of the structure.

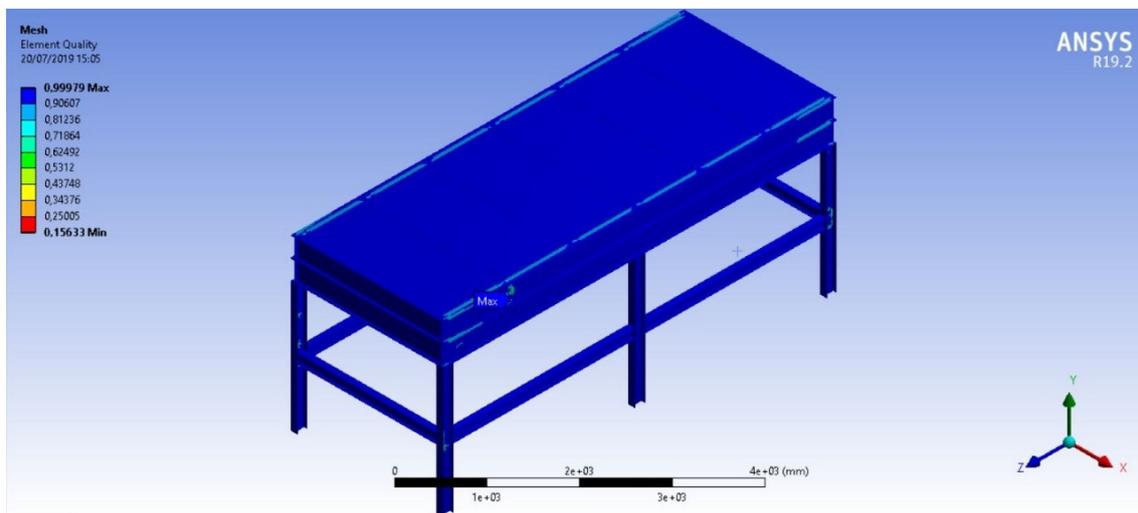


Figure 7. Element quality values for the mesh of the elements group (side pillars, roof and cover).

From the range of possibilities for mesh treatment, the advantage of treating the model in question as a shell rather than a solid model has been proven, since the set, formed by many parallel faces and plates have a smooth surface before the geometry. The predominantly used element was the hexahedral, which reached the quality of adequacy in the great majority above 98%. Figure 7 represents the element quality of mesh control for the elements group. In this case the element size tool set at 20 mm was used.

The first results shown in the Fig. 8 represent the Von-Mises equivalent stresses for the elements group (side pillars, roof and cover). Convergence techniques with relative error criteria of less than 1% were applied and the maximum value of stress found was 217.81 MPa, value below the resistance limits.

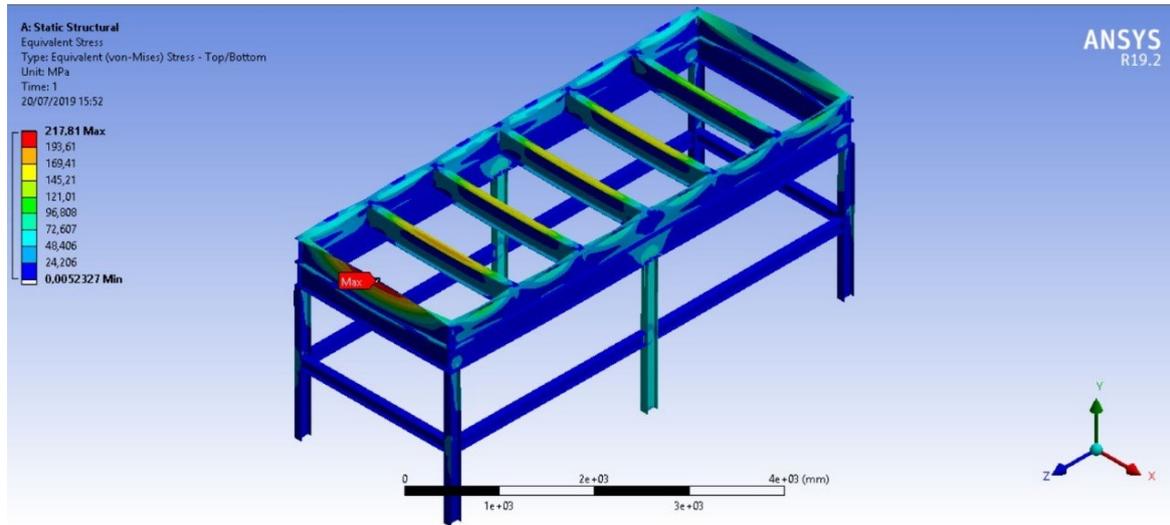


Figure 8. Von-Mises equivalent stresses for the elements group (side pillars, roof and cover).

In addition, the elements group was analyzed for buckling by parallel analysis of flexural stresses and displacement. A primary analysis of the situation of the pillars surrounding the sides of the structure revealed that sizing initiatives could still be used to improve the model situation in the face of buckling. The pillars were then locked in half by welding additional beams, resulting in a reduction in buckling length.

Figure 9 represents the total strain results for the elements group, in which case the structure would need a load 12 times greater than that to which the structure is subjected to collapse. Since the base of the substation is already protected under this type of request, the most dangerous zone for the phenomenon is located in the core of the upper ceiling beams, with a safety coefficient of three. The critical point regarding the buckling effect is highlighted.

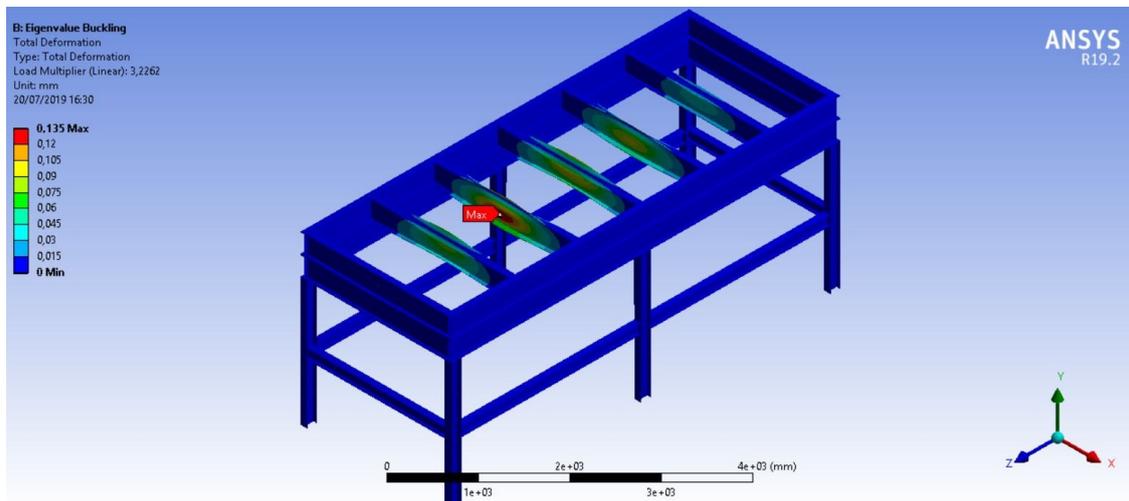


Figure 9. Buckling effect for the elements group (side pillars, roof and cover).

Subsequently, the substation basis was simulated, focusing on the support beams of the dry transformer. Once described the loading that the dry transformer support beams should support, the design of the most suitable section for use in the model was performed. The weight of this equipment was represented as concentrated loads in four points, two of them for each beam, applied under the upper face of the beams, with modulus equal to a quarter of the total loading.

The results presented in Fig. 10 confirm that the higher bending propensity in the analyzed model occurs due to the transformer loading, since this is the heaviest internal equipment. Taking into account the effect of the twisting that this loading could have on the beams at the base of the structure, it was decided to consider welding the transformer beams only on the lower tabs, which gives a conservative and safe scenario. The maximum value of total deformation was 1.3438 mm.

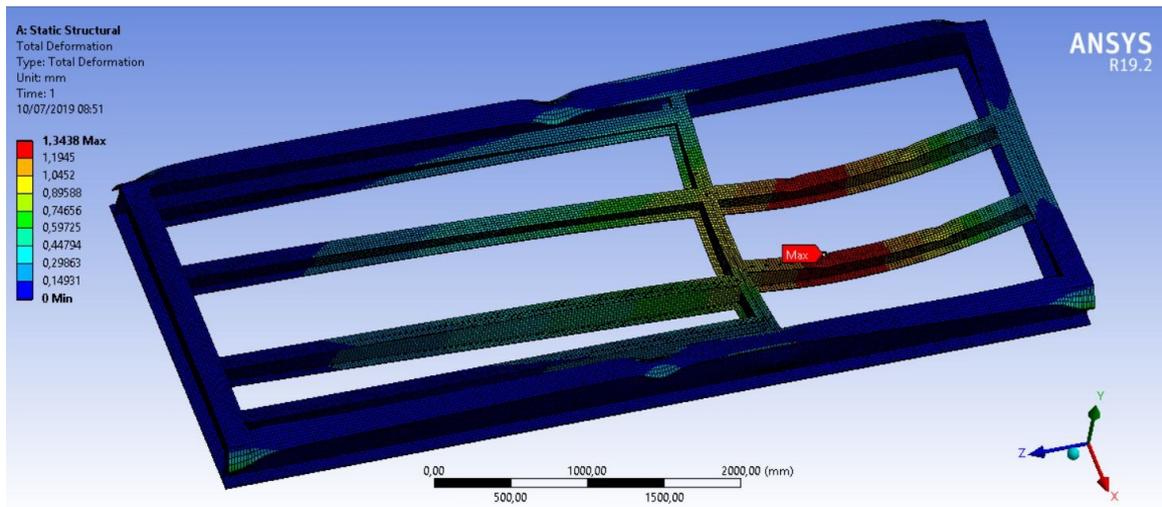


Figure 10. Total deformation for the basis.

Considering as crimped beams, they could deflect without torsional effects propagating to the rest of the structure. According to NBR 6118 (ABNT, 1978), the estimated maximum deflection found in the analysis of the transformers would be 6.6667 mm, so the beams for supporting the transformers are also protected against deformation. Figure 11 shows the values of Von-Mises equivalent stresses in the transformer support beams. The most critical points are the concentrated load application points.

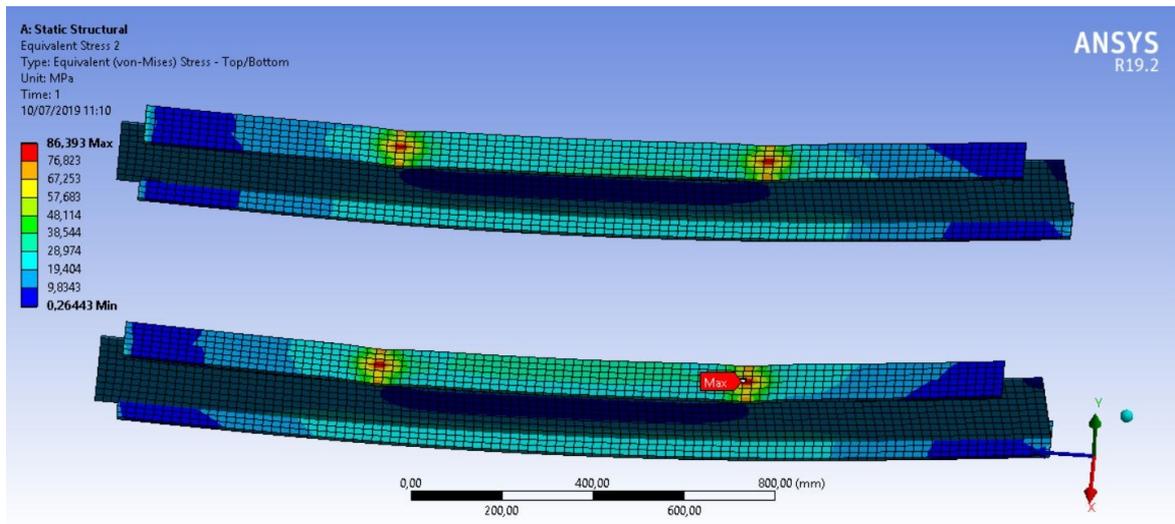


Figure 11. Von-Mises equivalent stresses for the basis.

4. CONCLUSIONS

Computational modeling and implementation of the main components of the substation were carried out, aiming at raising structural and thermal interferences inside the involucre. These studies were necessary to assess the possible impacts caused by electrical components (transformer, circuit breaker, electrical switch, etc.), which allows the construction of the substation more optimally and with greater reliability and safety of operation.

The first simulations resulted in a homogeneous temperature profile throughout the substation volume. In that situation it was observed that the units were not capable of providing sufficient cooling effect. Temperature values were in the range of 60 to 70 °C, which is above the desired 40 °C.

Heterogeneous temperature profile of the enclosure indoor was obtained after an optimization process. Two fan coil units near the transformer were capable of effectively cooling the air with temperature values in the range of 60 until 100 °C. The main effect of optimization could be observed at the left extremity of the enclosure where the most sensitive components were located, in this critical region the temperature values remained close to the desired.

Computational structural simulations of the metallic structure were performed and the main parameters as Von-Mises equivalent stresses, total deformation and buckling were estimated. The substation basis was simulated, focusing on the support beams of the dry transformer. The results showed that the structure would support the loads to which the substation is subjected and its total deformations agreed with the safety standards.

It is important to emphasize that the substation construction, as well as its installation and operation, is scheduled for 2020. However the present work was necessary to predict the behavior of the structural parameters and to establish a strategic temperature profile capable to provide the operational conditions of all electrical components present inside the substation.

5. ACKNOWLEDGEMENTS

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