Comparative performance analysis of AIS and GIS substations: A case study

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ABSTRACT
This work addresses the comparison between the performance of AIS and GIS Substations, in which a case study is used as a basis. The constructive aspects are highlighted when analyzing the characteristics of SF6 gas-insulated substations and conventional substations, detailing their structure and evaluating the performance of two real installations that fit into this context. The document presents a comparative analysis, in which parameters such as equipment downtime considering the repair of failures, incidence of occurrences and the defect presented in the equipment of each construction are raised. On the basis of the information obtained from the samples analysed, any conclusions will be drawn about the performance of these installations.

Keywords: SF6 Gas, Substations, GIS, AIS, Substation Performance.

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INTRODUCTION

According to the report by the International Energy Agency (IEA), there is a projected growth of 2% in global electricity demand this year, and projections for 2024 are 3.3% (BRASIL, 2023). Based on studies such as the IEA, it is understood that industrial expansion, global growth and other factors tend to drive the increase in electricity demand. Soon, the efficient and reliable transmission of electrical power became a concern. Substations are vital hubs of the power distribution network, they play a crucial role in ensuring the continuous flow of electricity from generating plants to end consumers. Among the various types of substations, Air Insulated Switchgear (AIS) and Gas Insulated Switchgear (GIS) substations emerge as two distinct technological solutions, each with its own set of advantages and limitations.

Throughout history, electrical substations have demonstrated durability, with many of them remaining unchanged from their original design. This scenario is even more evident when considering gas-insulated substations, as this technology, based on the use of SF6 gas for electrical insulation, was developed in the 1960s and 1970s. However, in just five years after the research began, this technology was already adopted in approximately 20% of the new substations built in locations with spatial constraints. (DE JESUS, M; YOKOGAWA, R; DE OLIVEIRA, T, 2017)

Thus, this article proposes to explore and examine the multifaceted aspects of AIS and GIS substations, focusing on their performance and the inherent disparities between the two technologies, taking into account the case study on the comparison between SE A (AIS) and SE G (GIS). As the energy industry faces the pressing need to improve grid reliability, reduce environmental impact, and optimize resource utilization, it is imperative to critically evaluate these alternatives.

DEFINITION OF ELECTRICAL SUBSTATIONS

Electrical Substations are physical installations that have a set of equipment, which can be for maneuvering, transforming and compensating reagents, which have the purpose of guiding the flow of electrical energy in the power systems and enable the variability of alternative paths. As a result, they are equipped with protection instruments capable of identifying the various types of failures that may occur in the electrical system, in order to isolate the section to which the failure occurs (MONTEIRO, 2023).

CLASSIFICATION OF SUBSTATION TYPES

According to Monteiro (2023), substations have their types defined according to function and installation. Substations can have the function of being:

- **Transformer:** They raise or decrease the level of voltage, which is why they are called Elevator or Lowering Substation. The SE's close to generation centers are called step-up substations. The SE's in the vicinity of the load centers are step-downs.
- **Disconnector, Maneuver or Switching**: These are substations that connect circuits to which they have the same voltage level and that can maneuver the flow of power, allowing the supply of energy to smaller stretches of the network.

As previously discussed, substations can be classified according to the installation, which can be:

- **Time Substations:** The equipment in these facilities is allocated to the weather, which is exposed to adverse weather conditions, which interfere with their properties, such as insulation quality and useful life.
- **Sheltered Substations**: In these the equipment is installed inside buildings, which can be a building or an underground vault. They can be built in metal cubicles or insulated by sulfur hexafluoride (SF6) gas.

According to Monteiro (2023), the choice of voltage of a substation can be estimated through equation (1):

$$V_{se} = 18\ x\ \sqrt{P_c} \qquad (1)$$

$$V_{se} - nominal\ system\ voltage\ in\ kV;$$

$$P_c - load\ power\ in\ MW$$

According to Mamede (2021), transformer substations have a subclassification according to their voltage level. Thus, it is possible to classify the installation as follows:

- **Level I medium voltage substation:** Whose voltage level is between 2.3 kV and 25 kV, with the vast majority of installations being 13.8 kV.
- **Level II medium voltage substation:** In these installations the voltage level is between 34.5 k V and 46 kV. They are more common in industrial and intermediate-sized enterprises.
- **High voltage substation:** The 72.5 kV and 145 kV substations are used in most of the distribution companies in the country while the 230 kV substations are used in the basic network of the SIN. These voltages are also used in the input substations of large industries, such as the oil and gas sector.
- **Extra high voltage substation:** These are substations with a voltage greater than 230 kV and have their highest composition in the basic network of the SIN. It also encompasses a voltage level of 800 kVdc.

When analyzing the types of installations based on the insulating medium of the equipment, the main focus of the work is the air-insulated substations (AIS) and the SF6 gas-insulated substations (GIS).

AIR-INSULATED SUBSTATION (AIS)

The most widely employed substations are AIS, due to their reduced cost compared to other types of substations isolated by alternative insulating media. Generally, these substations occupy more extensive spaces compared to other types of substations (MAMEDE, 2021).

The standards of the Brazilian Association of Technical Standards (ABNT) contemplate temperature and altitude to determine the level of insulation of equipment arranged in AIS. The standardised insulation levels consider a temperature between -40º and 40º C, and an altitude of up to 1000 meters. (MUZY, 2012).

At high altitudes, the air has a lower density, thus decreasing the dielectric strength (electric field over the thickness of the insulating material). Therefore, technical standards tend to reduce the insulation rating at high altitudes, taking into account a correction factor for altitudes greater than 1000 meters. Since the air, it has a lower capacity to cool the equipment, which heats up due to pressure losses. (DE JESUS, M; YOKOGAWA, R; DE OLIVEIRA, T, 2017)

SF6 ISOLATED SUBSTATION (GIS)

SF6 GAS

Since the objective of this work is to compare the performance of an AIS and a GIS, it is necessary to understand what are the properties that SF6 gas (sulfur hexafluoride) has, in order to understand why it is used in the electrical sector as an insulating material.

SF6 gas, a synthetic material, is an octahedral molecule, made up of eight faces and six vertices, as shown in figure 2. Under normal pressure and temperature conditions it is a non-flammable, colorless, odorless, and non-poisonous gas. It is chemically stable, in addition to having an excellent insulating property, thus suppressing possible electric arcs. Its sublimation temperature is 63.8 ºC and its liquefaction temperature is 50.8 ºC, with a vapor pressure of 22.8 atm. and a dielectric constant of 1.002026 at 20 ºC and 0.101 Mpa (MARQUES, 2023).

Dielectric strength refers to the ability to conduct electricity without showing conductivity, while dielectric strength indicates the ability to withstand high stresses without suffering damage. Electronegativity, in turn, represents the ability to attract free electrons, with fluorine being the most electronegative element recognized on the planet. As previously discussed, SF6 contains six fluorine molecules that can dissociate from sulfur, capturing electrons during an arc and subsequently returning to their original state. The gas's pronounced electronegativity and high dielectric strength are the reasons why it stands out as an insulating gas that is widely used in power transmission and distribution equipment. (MARQUES, 2023).

According to Marques (2023), when switching or opening an electrical circuit with more than 250 volts, as the contacts begin to separate, an arc forms between them. This arc can reach temperatures in excess of 2,000 °C (3,632 °F), which is enough to fuse and cause the metal contacts to bond. The ability of SF6 gas to capture free electrons contributes to reducing the effects of arcing.

A negative aspect of the gas is that it was pointed out at the 1997 Kyoto conference as one of the six greenhouse gases, it has a great capacity to retain heat. (DE JESUS, M; YOKOGAWA, R; DE OLIVEIRA, T, 2017)

GIS

Relating SF6 gas to the SE, according to Mamede (2021), compact installations housed with high voltage level (GIS) have high voltage equipment installed inside metal cylinders, which are filled with SF6 gas, under pressure.

According to Muzy (2012), the maximum pressure levels for GIS metal cylinders are defined by substation standards, which are defined by design, cost, and through standard tests established by standards that differ according to the country of manufacture, the main ones being: IEC 603776, IEC 62271, IEC 60480, IEC 60068 and NBR 16902:2020.

Despite the cheapness in the construction of GIS over the last few years, it is still a more expensive technology to implement. Therefore, it should be installed in places where there is little space for construction, such as near large Metropolis. This theory is proven, since for his analysis, an AIS in a region farther from the metropolis is 97% cheaper than a GIS, while in the capital, GIS was 66.62% cheaper. (DE JESUS, M; YOKOGAWA, R; DE OLIVEIRA, T, 2017)

METHODOLOGY

The literature review is the activity of researching scientific works related to the area of objective of the work, researching scientific works and standards that were within the scope of the object of study, which are mentioned in the theoretical foundation. Books, articles, term papers and dissertations on substations, electrical equipment, SF6 gas and regulatory sanctions were used. This material was used to point out the constructive and structural differences of the substations and the equipment present in them, in order to compare AIS and GIS.

Data analysis is based on the process of applying statistical and logical techniques to evaluate information. This process includes the inspection, investigation, storage and follow-up of information. In this study, an extraction was carried out in the asset management software of the company to which the case study is focused, more specifically in the maintenance module. As the main objective of the work is to analyze the performance of a GIS substation and an AIS pointing out their differences, it was raised through the SAP – PM system, which according to the SAP company, responsible for its development and commercialization, is a module for maintenance management that encompasses all essential tasks, such as inspections, warnings, preventive and corrective maintenance, repairs and other actions to preserve the proper functioning of technical systems. SAP-PM has some transactions intrinsic to it, in which IH08 and IH03 were used to raise which problems happened that left the equipment unavailable and in which equipment they happened, respectively.

These data were concatenated in a database, which was used to generate the graphs through Microsoft Excel presented in the following sections.

CASE STUDY SUBSTATIONS

For this work, two substations belonging to a power distribution and generation company in Brazil were chosen. The choices were made taking into account some criteria. The first of these was the voltage level at which both companies work, both SE A and SE G, have 138 kV and 500 kV busbars. The second criterion was location, which facilitates the need to travel during any technical visits that may be necessary during the study. Another criterion taken into account was that both are in a similar climate, as well as the date of energization and manufacture of the equipment of both are close and finally the most important criterion, one is AIS (A) and the other is a GIS (G).

All these characteristics allow the equipment to be analyzed on an equal footing, and the main defects that apply in both are surveyed and analyzed.

STRUCTURAL ANALYSIS

SUBSTATION A:

The SE A shown in figure 1 is located in the state of Rio de Janeiro. It covers a total area of 321,677.63 m² (Measurement obtained by Google Maps), with the courtyard having 184,279.75 m² (Measurement obtained by Google Earth). It has a total of 1161 pieces of equipment (Information Taken from SAP-PM).

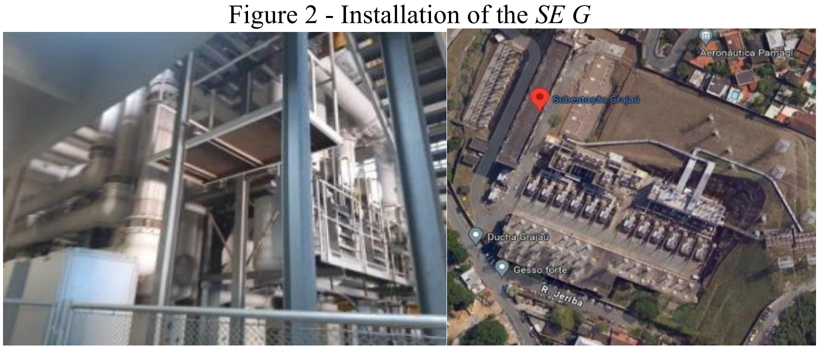
Figure 1 - Installation of *SE A*

Source: Author

SUBSTATION G

The SE G presented in figures 36 and 37 is located in the city of Rio de Janeiro and in the state of Rio de Janeiro. It has a total area of 33,195.55 m² (Measurement obtained by Google Earth), with a total patio of 11,043.68 m² (Measurement obtained by Google Earth). Having a total of 834 pieces of equipment (Information Taken from SAP-PM).

Figure 2 - Installation of the *SE G*



Source: Author

When structurally analyzing, it can be seen that substation G has a much smaller area compared to substation A, as shown in table 1.

Table 1 - Structural Analysis of the Substations Studied

Substations	Patio Area (%)	Equipment (%)
G	18	70
A	100	100

Source: Author

a) **Yard Area (%):** Represents the ratio of the substation yard area to substation A.

b) **Equipment (%):** Represents the proportion of the number of equipment in substation G in relation to substation A. In this case, it is indicated that G has approximately 70% of the amount of equipment in A.

This disproportion between area and amount of equipment exists because of SF6 Gas, since it allows more equipment to be installed in a smaller area.

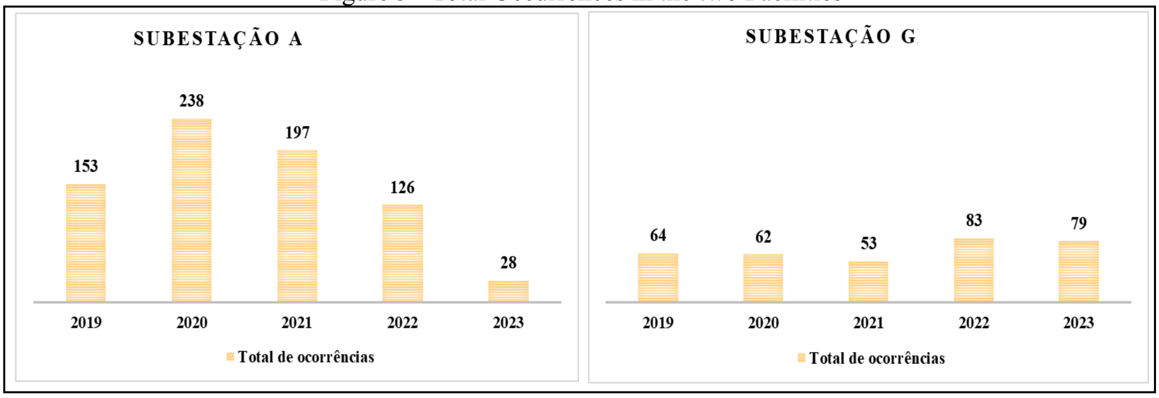
This allows SE GIS to take advantage of aspects related to the footprint. Because it is smaller, it provides a lower visual impact.

ANALYSIS OF RESULTS

In order to determine the result, an analysis of the quantity referring to the annual occurrences related to the equipment to be unraveled in a following comparative analysis of the substations was carried out.

As a result, within the time horizon of 5 years, taking into account the cases raised until November 2023, the AIS substation presented a higher number of occurrences in all years compared to the G substation, as shown in the figure below.

Figure 3 - Total Occurrences in the two Facilities



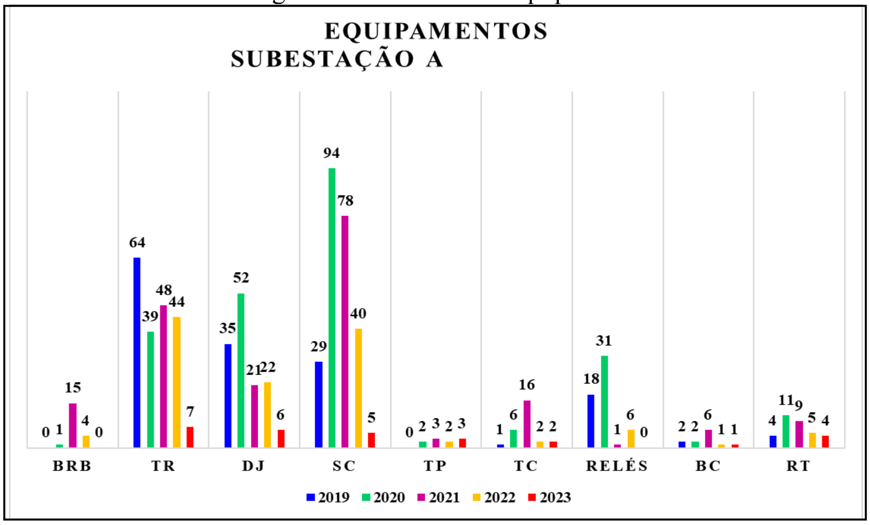
Source: Author

By deepening the analysis, it is necessary for this case study to identify the guiding equipment of these occurrences. For this purpose, the information from the data analysis was collected with the objective of unraveling the quantity referring to the number of occurrences of each type of equipment from the annual perspective previously analyzed of each substation.

Thus, the entities used for this analysis are: busbar (BRB), transformer (TR), circuit breaker (DJ), disconnect switch (SC), potential transformer (TP), current transformer (TC), synchronous compensator (CS), capacitor bank (BC), reactor (RT) and relays, as shown in figure 4. The distribution of this quantity by equipment is of paramount importance to identify the points to be taken into account in the performance of the substation and the existing performance.

From this perspective, when it comes to substation A, the criticality of the transformer (TR), circuit breaker (DJ), disconnect switch (SC) equipment is observed, with a jump in the disconnect switch (SC) in 2020, which boosted it to be the year with the highest number of occurrences if it is observed in an accumulated way in the previous graph.

Figure 4 - Substation A Equipment



Source: Author

It can be seen from the graph that in 2019 the transformer (TR) presented a marked number of occurrences, which decreased in the following year and remained stable in the two following years, unlike the disconnect switch (SC), which went the opposite way until it presented a considerable drop in 2022, but still with a relevant quantity.

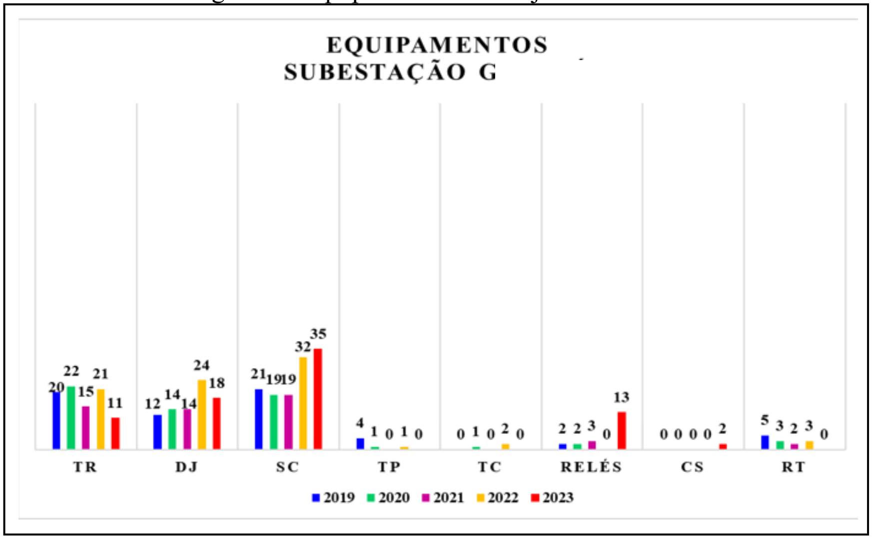
When it comes to circuit breakers (DJ), the number is accentuated in the years 2019 and 2020, which was later stabilized over the years.

The current transformer (CT) and the bus (BRB) in 2021 showed an atypical behavior related to the number of occurrences, and the same can be observed for the number of relays in the years 2019 and 2020.

However, when the analysis starts to encompass the results obtained by the study of the information related to substation G, it is observed that, according to the graph below, the busbar type equipment (BRB) becomes non-existent in the calculation of the quantity of occurrence.

When it comes to atypical years, unlike substation A in which the year 2020 presented non-linear results, in substation G 2022 was the year referring to the emergence of occurrences of increasing number, as shown in figure 5.

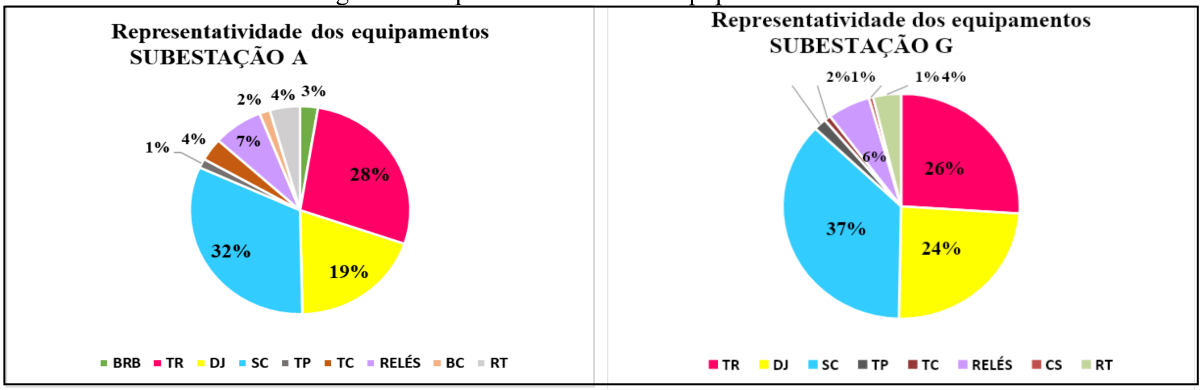
Figure 5 - Equipment of the Grajaú Substation



Source: Author

The equipment of transformer (TR), circuit breaker (DJ), disconnect switch (SC) as well as in substation A, in substation G were also the types in which most occurrences appeared. As below:

Figure 6 - Representativeness of Equipment in the Ses



Source: Author

Thus, it is necessary for the development of the case study to identify the main causes of unavailability of the occurrences of the equipment that most affected the substations.

With the help of the database worked, the author was able to study and perform analyses according to the transformer (TR), circuit breaker (DJ), disconnect switch (SC) equipment of both substations and identify the respective problems that affected the performance over the years, they are:

AIS A SUBSTATION:

Table 2 - Main Problems for the Performance of SE A

Transformer (TR)	**Disjuntor (DJ)**	**Chave Disconnect Saw (SC)**
Alarm Malfunction	Leaks (oil and air)	Failure to close the disconnector contacts
Problems with the drain	Discrepancies measured between phases	Electrical control fault
Problems with the display	Low pressure in the stages	Deficiency of signage on the dashboard
Pump malfunction	System failure to accept commands	Hot spot
Oil leak	Alarms fail	Alarm Failed
Monitoring system failure	Problems with the led	X
Ventilation Failure	Low hydraulic oil level	X
Related Problems Insulating Oil Chromatography	X	X

Source: Author

GIS G SUBSTATION

Table 3 - Main Problems for the Performance of the SE G

Transformer (TR)	**Disjuntor (DJ)**	**Chave Disconnect Saw (SC)**
Problems in the chromatography of insulating oil	Close Command Failures	Low pressure of SF_6 in equipment and phases
Faulty temperature monitor	Failures in the automatic control	Remote control failure
Faulty oil level monitoring	Faults in the operation command	Problems with Electrical Control Acceptance
Oil leak	X	X
Shorted lighting	X	X

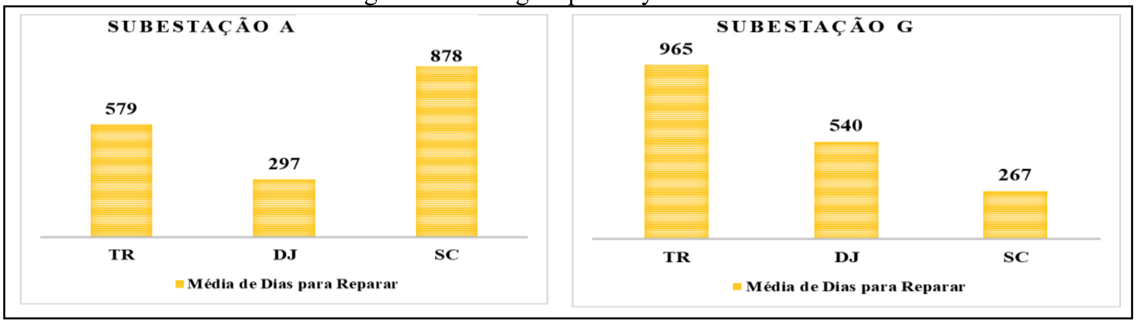
Source: Author

To understand how these problems are being taken into account and the appropriate actions to solve these causes and the impacts of the consequences on the substations, the author spoke with experts in the area in which they are assigned in the company responsible for maintaining the substations and providing services, who stated that strategic studies are being developed to mitigate these effects. to improve the service and reduce the number of occurrences, through preventive and predictive maintenance plans.

Although the current work does not discuss what these actions are, some examples to which the experts went were: reducing the periodicities between oil analysis in transformers, using special cameras to detect hot spots and SF_6 leaks.

Another aspect that was analyzed was the average number of days that the problems take to be solved, taking into account the switches, circuit breakers and transformers for the two substations. Below is the figure which represents this:

Figure 7 - Average repair days of both SEs



Source: Author

As seen in the graphs, we have that the average number of days to solve the problems is relative, but as the average is being done, some problems were solved faster, while others took longer. It is observed that the average repair time for transformers and circuit breakers is shorter in SE A compared to SE G, this is due to the fact that the parts of SE G are of higher unit cost and more difficult to obtain, since it is a shielded substation and less common in relation to an AIS. The scenario is reversed for the disconnect switches, but this happens due to the large number of maneuvers that the disconnectors of the SE A make in relation to the SE G, this generates more problems and ends up causing a greater number of changes of such equipment.

CONCLUSION

In this work, two technologies related to electric power substations were compared. The AIS was addressed, which is the most commonly used substation in the SIN – National Interconnected System, to which the equipment is exposed to the weather and its effects. The second SE analyzed was GIS, in which the equipment is pressure-insulated in pipelines filled with SF6 gas.

Both were compared, verifying their equipment, arrangements and construction characteristics, defects that occur in the equipment, based on two real substations.

It was observed that regarding the constructive characteristics, the GIS substation needs a smaller area compared to the conventional one, since the insulating properties of SF6 gas allow this to be implemented in places that have little space. This has a constructive advantage over conventional ES. This characteristic makes it possible for GIS to provide less visual pollution and interfere less with the area around it.

Another aspect verified is the performance, throughout the study, it was noticed that, in general, the AIS SE studied presented a greater number of defects in relation to GIS, at a rate of 50% more over these five years studied. This is due to the fact that GIS is sheltered, and runs fewer risks related to factors external to the system, such as weather, pollution, or accidents. Another important point is that, as it was found throughout the study, the equipment that gave the most defects in both SE's were, Power Transformer, Circuit Breaker and Disconnector. This is because the circuit breaker and the disconnector are switchgear and are constantly in use in order to make maneuvers for load control by the ONS – National Electric System Operator. Regarding the transformer, they work most of the time at their limit and often exceed their useful life, this means that the technical specifications to which they were built are no longer respected, since they are most of the time working under high stress and generate more problems. An example is the high level of problems detected from insulating oil chromatography tests. Finally, in order to verify their performance, the repair times were analyzed for these three main pieces of equipment that present failures, so that the defects can be corrected. It was observed that apart from the disconnector, the repair times for circuit breakers and transformers in substation G take longer to be corrected, since because they are part of the SF6 shield, it is more difficult and more expensive to obtain these parts in the market, this is a big problem, since the unavailability of some of this equipment can generate a loss in PV (Variable Plot) and possible fines.

Linked to the survey of the average time to correct defects in the main defective equipment, the major causes of unavailability of this equipment for the two substations in this five-year horizon were raised. It was found that oil leakage is a major problem for the transformers and circuit breakers of both facilities. As for the disconnectors, in SE A there were a large number of problems related to the closure of their contact, to solve a problem like this the company often needs a relative time, since it can be mechanical problems in the activation, which require the replacement of key components, for example. On the other hand, for SE G, the main cause of unavailability over this time was the loss of SF6 pressure, this is a problem that is often generated by another that appeared in the survey of unavailability, which is the leakage of SF6.

Therefore, it is observed that both installations have positive and negative points, which must be taken into account for their implementations.

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