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Original Article

Analysis of Supply Interruptions by Disconnections of Transformers of Power

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Abstract *- Operation is a fundamental process for companies engaged in power transmission, especially when it comes to the operation of power transformers, which are one of the main components of the electric power system and represent a large part of the investment required to implement these systems. To improve the quality of the operation of power transformers and ensure their reliability and safety, it is essential to monitor power supply interruptions and the electrical parameters that comprise them. Therefore, the objective of this research is to improve operating practices to minimize the impact of power supply interruption events on the consumer due to disconnections of 22.9 kV, 60 kV, 138 kV and 550 kV power transformers operated and maintained by ISA REP, one of the largest electric transmission companies in Peru. The results of this study, i.e. the analysis of technical operating indicators over 4 years (from 2018 to 2021), the review of the documentation of the company's operating practices in force during this period and the proposal of best operating practices based on the previous results, aiming to improve the operation of the transmission system, are expected to contribute to the knowledge of this field of electrical engineering.*

Keywords *- Power interruptions, Technical operating indicators, Operating practices, Power transformers, Case studies.*

1. Introduction

Efficient and reliable operation of power transformers is essential to ensure the stability and quality of power supply in transmission systems. These critical components represent a significant investment for power transmission companies and play a fundamental role in the electrical infrastructure [1]. However, supply interruptions due to transformer disconnections can seriously affect consumers, industries and the grid [1-4]. In this context, Red de Energía del Perú SA (ISA REP), one of Peru's main energy transmission companies, was involved in 84 power interruption events due to disconnection of power transformers that it operates and maintains in 2018-2021. Therefore, the company must improve its operating practices to make its service more reliable and secure. Given this situation, the following question arises: How can operating practices be improved to minimize the impact of power interruption events on consumers due to disconnections of power transformers? So, this research paper aims to analyze the interruption events in a 4-year period (from 2018 to 2021) caused by power transformer disconnections at a leading transmission company in Peru. By examining technical indicators, historical data, and operational practices, we seek to propose improved strategies to increase the reliability and safety of electric transmission systems. In recent years, the scientific community and practitioners have focused on understanding and improving the operation of power transformers. Several studies have investigated consumer outage events, technical indicators, and best practices related to this equipment. Some notable contributions are presented below.

- Advanced health monitoring and diagnosis. The reference work explores novel techniques for monitoring and diagnosing transformer health, emphasising real-time analysis of operational data [4].
- Impact of the disconnections of transformers. The recent study investigates interruption events caused by transformer disconnections, shedding light on their impact and possible mitigation strategies [2].
- Historical challenges and safety. Pioneering work addresses maintenance, reliability and safety challenges in transformer operation [6].
- Power quality and robust design. Research examines power quality issues associated with transformer operation, highlighting the need for robust designs [7].
- Technical indicators and operational practices. The comprehensive analysis of technical indicators and operational practices directly affects system reliability [5]
- Performance under extreme conditions. The study focuses on the performance of transformers during adverse weather conditions, highlighting the importance of preventive measures [1].

- Transformer protection and control. Research explores protection and control mechanisms to improve system resilience [3].

2. Methodology

This study recorded 84 interruptions in the energy supply to consumers from January 2018 to December 2021 caused by disconnections of power transformers.

The following electrical parameters have been recorded for each power interruption event:

- Power interrupted (MW)
- Duration of interruption (hours)
- Energy not supplied (MWh)
- Primary side voltage level of the power (kV)

The study consists of three main parts. Figure 1 shows the procedure to be followed graphically. According to this figure, first, technical operating indicators will be calculated from the records of electrical parameters of supply interruptions to analyze the quality of the operation. Second, the documentation on the company's operating practices will be reviewed. Finally, improvements to the reviewed operating practices will be proposed, prioritizing the practices that are considered to have the greatest impact on reducing technical indicators to improve the quality of the operation.

In addition, based on the evaluation of the details of each event, one of the types of causes will be assigned, as shown in Table 1. By the way, the following causes will not be considered because they cannot be mitigated by improvements in the company's operating practices:

- Scheduled or unscheduled rationing
- External failures
- Load rejection

2.1. Technical Operating Indicators

The following technical operating indicators proposed by the company will be calculated and analyzed by the Commission of Regional Energy Integration (CREI). https://www.cier.org/es-uy/Paginas/Que-es-CIER.aspx.

2.1.1. Index of Non-Supplied Energy – INSE

The objective of this indicator is to measure the magnitude of the power cut to connected consumers relative to the total energy demanded by end consumers. (1) is used to calculate it.

$$IENS_{a,T,k} = \frac{\sum_{i=1}^{N_{a,T,k}} ENS_{a,T,k,i}}{DE_a} \tag{1}$$

Where $IENS_{a,\ T,k}$ Index of energy not supplied for the year a, due to tension level T, due to the cause k. $ENS_{a,\ T,k,\ I}$ is the Energy not supplied to the consumers of the transmission system due to the event that occurred during the year a, due to Tension level T, due to the k cause [MWh.] DE_a Energy demand during the year of the consumers of the transmission system for their supply [MWh].

2.1.2. Equivalent Interruption Frequency –FEI

The objective of this indicator is to monitor the continuity of supply to final consumers. (2) will be used to calculate it.

$$FEI_{a,T,k} = \frac{\sum_{i=1}^{N_{a,T,k}} PI_{a,T,k,i}}{DP_a} \tag{2}$$

Where $FEI_{a,T,k}$ is the Equivalent frequency of supply interruption to transmission system users during the year due to stress level events and the cause k [times per year]. $PI_{a,T,k,I}$ is the power interruption to the transmission system user due to the event that occurred during the year a, due to tension level events, due to the cause k [MW].DP_a is the Maximum demand of consumers who require the company's transmission system for their supply during the year a [MW].

2.1.3. Equivalent Duration of Interruption – EDI

The objective of this indicator is to monitor the duration of power outages to transport system users.

$$DEI_{a,T,k} = \frac{\sum_{i=1}^{N_{a,T,k}} PI_{a,T,k,i} * DI_{a,T,k,i}}{DP_a} \tag{3}$$

Where $DEI_{a,T,k}$ is the equivalent duration of interruption of supply to transport system users during the year of the tension T, caused by k[hours]. $PI_{a,T,k,i}$ is the power interruption to the transmission system user due to the event i that occurred during the year a due to stress level T caused by k [MW].$DI_{a,T,k,i}$ is the duration of interruption of supply to the consumer due to the event i occurred during the year a, due to the cause k, tension T level [hours].DP_a is the Maximum demand of consumers who require the company's transmission system for their supply during the year a [MW].

2.1.4. Annual Interruption Rate – TAI

The objective of this indicator is to monitor the rate of supply cuts or interruptions to final consumers.

$$TI_{a,T} = \frac{8760 * \sum_{j=1}^{NT_{a,T}} PI_{a,T,j}}{\sum_{j=1}^{NT_{a,T}} HS_{a,j}} \tag{4}$$

$TI_{a,T}$ is the Annual rate of interruptions in supply to transmission system users at the tension T level during the year a [breaks/year]. $NI_{a,T,j}$ is the number of interruptions in supply to the user of the transport system due to events in the element j of the tension T level during the year a. [number].$HS_{a,j}$ is hours during the year a and the element j [hours].

2.2. Operating Practices

The following topics for this research were studied for the outcomes.

- Operational Policies
- Operation planning and scheduling
- Operation optimization
- Replacement and modernization of assets
- Coordination of electrical protections
- Telecommunications
- Computer programs, systems and devices
- Contingency plans
- Postoperative analysis

3. Results

For reference, Table 2 shows the quantities and characteristics of the power transformers operated by REP during the study period. As can be seen, the majority (45%) of the transformers are 220 kV, while the minority (2%) are 22.9 kV.

3.1. Analysis of Technical Operating Indicators

Figures 2, 3, 4, 5 and 6 show the distribution of the causes of supply interruptions throughout the study period 2018-2021 and for 2018, 2019, 2020 and 2021, respectively. For reference, Table 1 indicates the group of each type of cause. As shown in Figure 2, in the 2018-2021 study period, of the 84 interruptions recorded, the majority were scheduled, while the minority were due to failure in power equipment. Note that all types of causes considered occurred in the study period. As shown in Figure 3, 2018, of the 26 interruptions recorded, the majority were scheduled, while the minority were due to failure in protection and control equipment.

Fig. 1 Main parts of the study

Table 1. Cause of events

Group	Cause	Description
1	Established / Programmed	Regular Maintenance
2	Natural disaster	Natural discharge, wind, animals
3	Humans Mistakes	Accidents and errors in operations
4	Failures on High Power Equipment	Failures in transformers and transformer cell switching equipment
5	Failure to save equipment and control equipment	Failures in protective equipment, failures of protective equipment
6	Others	No determined causes

Table 2. Characterization of the transformation equipment

Tension (kV)	# Equipment	Capacity (MVA)	
		Minimum	Maximum
22.9	2	3.4	4.0
60	4	37.5	5.5
66	1	3.0	3.0
132	11	30.0	7.0
138	25	6.5	60.0
210	9	50.0	100.0
220	45	30.0	150.0
225	4	30.0	50.0
500	11	200.0	250.0
Total	112		

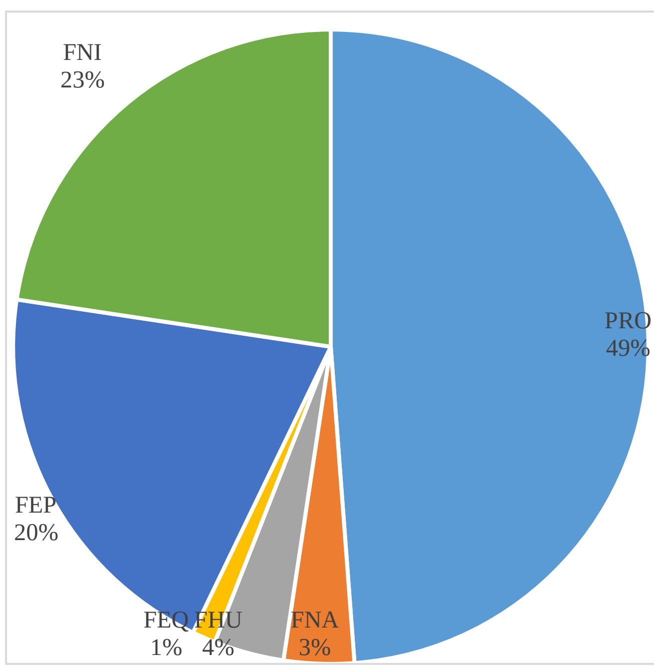

Fig. 2 Distribution of types of causes – 2018-2021

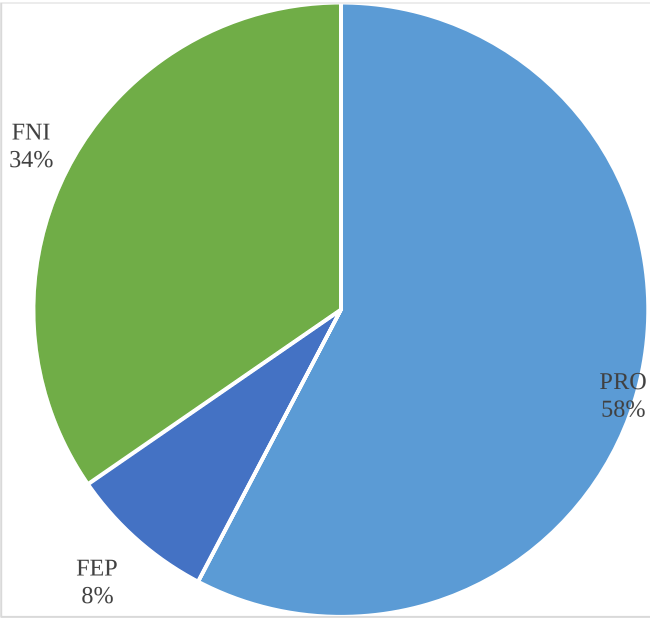

Fig. 3 Distribution of causes - 2018

As shown in Figure 4, 2019, of the 27 interruptions recorded, the majority were scheduled, while the minority were due to human error. As shown in Figure 5, in 2020, of the 21 interruptions recorded, the majority were scheduled, while the minority were due to failures in power equipment. As shown in Figure 6, in 2021, of the 10 interruptions recorded, the majority were due to failures in protection and control equipment, while the minority were due to natural and environmental phenomena.

3.1.1. IENS Indicator – Index of energy not supplied

Figure 7 shows the results of the IENS indicator. Only 2018, with the maximum value of 1.8E-05, exceeds the 75th percentile, while only 2021, with the minimum value of 6.6E-06, is below the 25th percentile. The resulting values for the median were 1.3E-05 and the average 1.3E-04, which are expected values in the operation of transmission systems. A downward trend and low values are observed for the indicator.

3.1.2. FEI Indicator – Equivalent Frequency of Maximum Demand Interruption

Figure 8 shows the results of the FEI indicator. Only 2019, with the maximum value of 0.06 interruptions per year, exceeds the 75th percentile, while only 2021, with a minimum value of 0.01 interruptions per year, is below the 25th percentile. The resulting values for the median were 0.03 interruptions per year and an average of 0.03 interruptions per year, which are expected values in the operation of transmission systems. The most predominant events that cause interruptions are those due to scheduled maintenance and undetermined causes. An increase is observed from 2018 to 2019, then the behavior is downward, and the values are low for the indicator.

3.1.3. DEI Indicator – Equivalent Interruption Duration

Figure 9 shows the results of the DEI indicator. Only 2018, with the maximum value of 0.13 hours per year, exceeds the 75th percentile, while only 2021, with the minimum value of 0.03 hours per year, is below the 25th percentile. The resulting values for the median were 0.10 hours per year and the average 0.09 hours per year, which are expected values in the operation of transmission systems. The most predominant events that cause interruptions are those due to scheduled maintenance and undetermined causes, and those that took the longest to be addressed were interruptions due to scheduled maintenance. A downward trend is observed, and the values are low for the indicator.

3.1.4. TAI Indicator - Annual Interruption Rate

Figure 10 shows the results of the TAI indicator. Only 2018, with a maximum value of 3.21 interruptions/year, exceeds the 75th percentile, while only the year 2021, with the minimum value of 0.19 interruptions/year, is below the 25th percentile. The resulting values for the median were 1.45 interruptions/year and the average 1.58 interruptions/year, which are expected values in the operation of transmission systems. A downward trend is observed, although 2020, there was an increase in interruptions/year compared to 2019, and the values are low for the indicator.

3.2. Category Review of Operating Practices

Below are the results of the review of operating practices according to the categories proposed in point 2.2.

3.2.1. Review of Operational Policies

The company has developed and documented a strategy for the next decade, focusing on enabling operational efficiency of processes and effective decision-making through new management platforms. In addition, its policies and guidelines are based on current certifications in international standards.

3.2.2. Review of Operation Planning and Programming

The company has developed procedures to provide the necessary resources to operate the elements of the transmission system (substations and complementary equipment) with quality, availability and safety criteria. In addition, it has procedures for daily, weekly, monthly and annual programming. Due to this, it is considered that the company's operating practices with respect to this category have been adequately developed but can be improved.

3.2.3. Operation Optimization Review

The company has developed and documented strategies and procedures to perform the electrical studies required to determine the behavior of the transmission system under different operating states and conditions. Due to this, the company's operating practices with respect to this category are considered to have been adequately developed but can be improved.

3.2.4. Review of Asset Replacement and Modernization

The company has developed and documented replacement and modernization plans that indicate adequate procedures for managing the life cycle of assets such as the power transformer. In addition, these plans are based on current certifications in international asset management standards such as ISO 55001. Due to this, the company's operating practices in this category are considered to have been widely developed.

3.2.5. Review of Electrical Protection Coordination

The company has developed and documented strategies and procedures to conduct electrical studies to coordinate electrical protections. With respect to power transformers, the protection that can be coordinated is overcurrent protection, which is adjusted to guarantee the availability, safety and quality of the transmission service. Due to this, it is considered that the company's operating practices in this category have been widely developed.

3.2.6. Telecommunications Review

The company has developed and documented strategies and procedures to ensure the availability of telecommunications that allow remote access to the information from each substation for supervision and control. Until recently, the telecommunications service was provided by a third party. However, a project was carried out to renew the operational network with new equipment managed by the same company. Due to this, it is considered that the company's operating practices in this category have been widely developed.

3.2.7. Review of Computer Programs, Systems and Devices

The company has arranged for the implementation of monitoring and control systems. The control centre has modern technology that complies with international standards such as IEC 60870-5-104. However, at a more local level, some substations still have old systems that work but fail constantly. In addition, the company has updated licenses for transmission system simulation programs to study and analyse the operation and coordination of electrical protections. Due to this, the company's operating practices with respect to this category are considered to have been adequately developed but can be improved.

3.2.8. Review of Contingency Plans

The company has developed and documented multidisciplinary contingency plans for different emergency scenarios. In addition, it keeps these plans updated following changes in the transmission system. Due to this, the company's operating practices in this category are considered to have been extensively developed.

3.2.9. Postoperative Analysis Review

The company has developed and documented failure analysis procedures. In addition, the power systems area meets weekly with the maintenance area to analyze failures and take corrective actions. Due to this, it is considered that the company's operating practices with respect to this category have been adequately developed but can be improved.

4. Discussion

From the results of the IENS indicator, it can be deduced that the company has the operation well controlled, minimizing scheduled interruptions or openings and quickly responding to unscheduled interruptions of power transformers, in turn allowing for better conditions for the provision of the service. The company's transmission system has high reliability and safety behaviors in the operation of its electrical infrastructure.

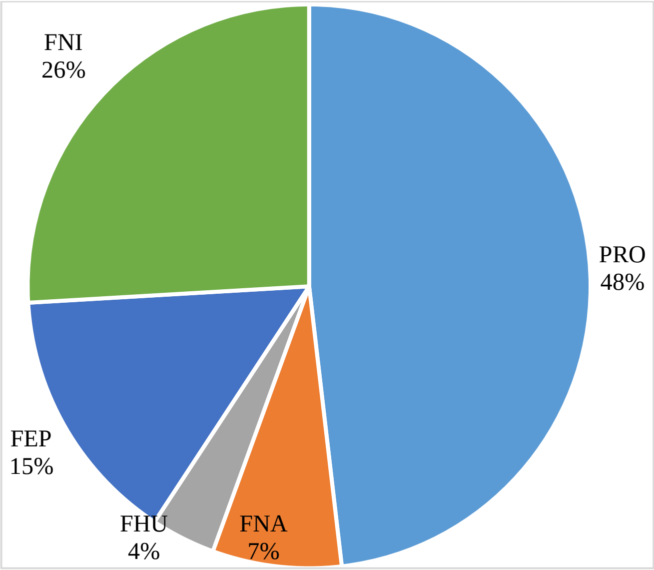

Fig. 4 Distribution of causes - 2019

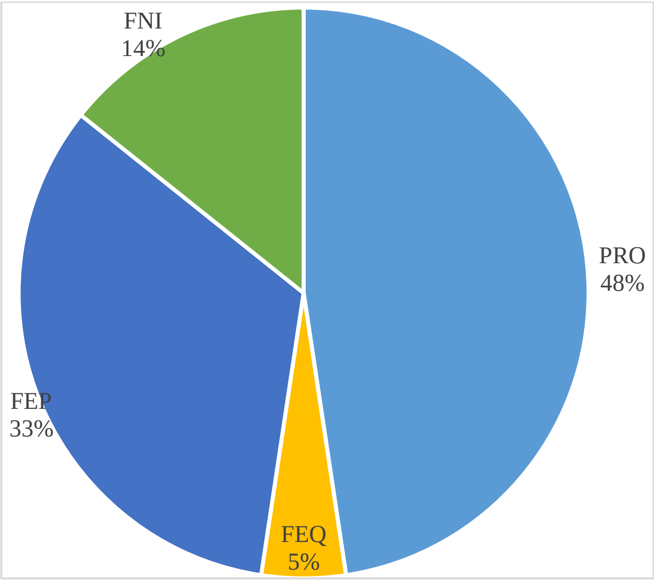

Fig. 5 Distribution of causes - 2020

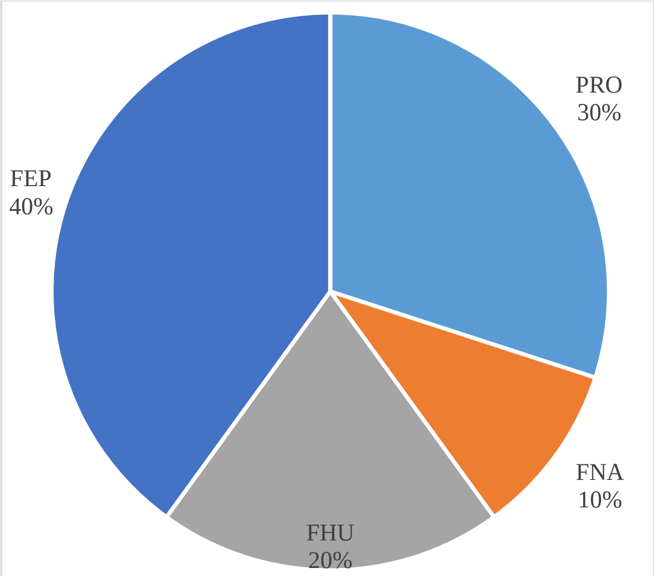

Fig. 6 Cause distributions - 2021

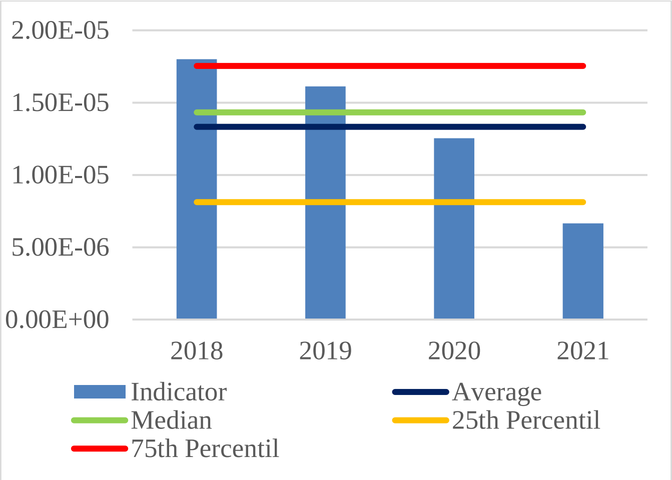

Fig. 7 IENS indicator - 2018-2021

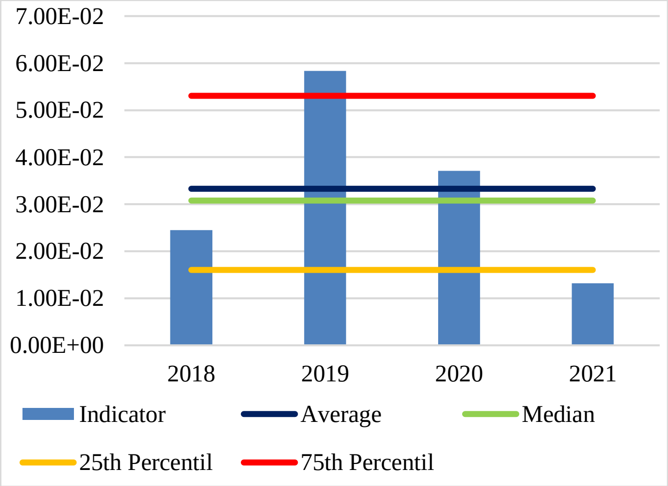

Fig. 8 Results of the FEI indicator - Number of times per year (2018-2021)

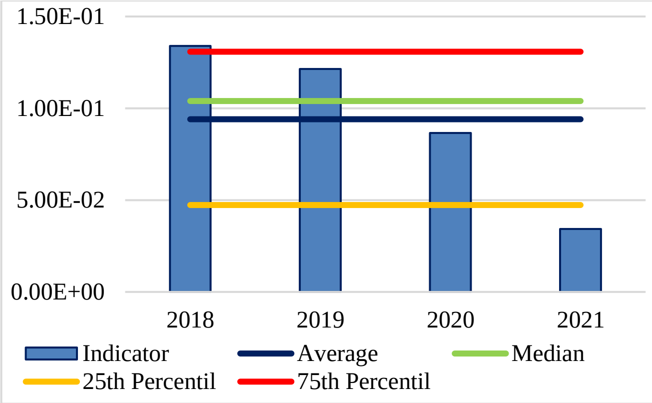

Fig. 9 Results of the DEI indicator - Hours - 2018-2021

From the results of the DEI and TAI indicators, it can be deduced that the company applies good management and use of the resources necessary for operational tasks, especially in dealing with events that cause service interruptions. In general, the technical operating indicators show that the company has improved the operation of power transformers over time. However, some points need to be addressed. For example, it is noteworthy that almost all interruptions were due to three causes: scheduled, failures in protection and control equipment, and undetermined.

The results of the indicators show that the causes that had the greatest impact were scheduled and undetermined. In addition, it is important to mention that a more exhaustive review revealed that failures in protection and control equipment caused the interruption events, and there were many failures in the trip circuits due to failure in the insulation of the connection boxes. Therefore, priority should be given to improving operating practices that help minimize the impact of these causes. From the results of the review of operating practices documentation, it is deduced that the company could improve in the following categories:

- Operation planning and scheduling
- Operation optimization
- Computer programs, systems and devices Post-
- Operative analysis

4.1. Proposal for Best Operating Practices

Below, some improvements in operating practices are proposed taking into account the results of the technical operating indicators and the review of the documentation on the company's operating practices.

4.1.1. Best Practices for Planning and Scheduling Operations

The following are some practices that the company could apply to improve the planning and scheduling of the operation:

- Information flow service agreements with other company areas are formalized, documented and updated.

- Standardized procedures taking into account the operating code and electrical regulation.
- Equipment operating instructions and good engineering practices.

4.1.2. Best Practices for Operation Optimization

The following are some practices that the company could apply to improve the operation optimzation:

- Have a specific work area that carries out technical studies and is equipped with the necessary tools to perform high-precision simulations of the demand behavior of the transmission system.
- Have information applications or optimization models (deterministic or probabilistic) that allow simulations of demand behavior in such a way that the system's operation can be optimized with the electrical infrastructure of the existing transmission system.

4.1.3. Best Practices for Computer Programs, Systems and Devices

The following are some practices that the company could implement to improve computer programs, systems and devices:

- Have databases that are fully interrelated with other key processes in the company so that all operational information is recorded, stored and protected with greater security.
- Provide management tools to plan the operation, carry out planning studies for the operation of the transmission system, analyze the power system, and study and simulate electrical protections applied to the transmission system.
- Updated procedures and sufficient specialized resources for adequate maintenance of the information systems database for electrical studies of the transmission system.

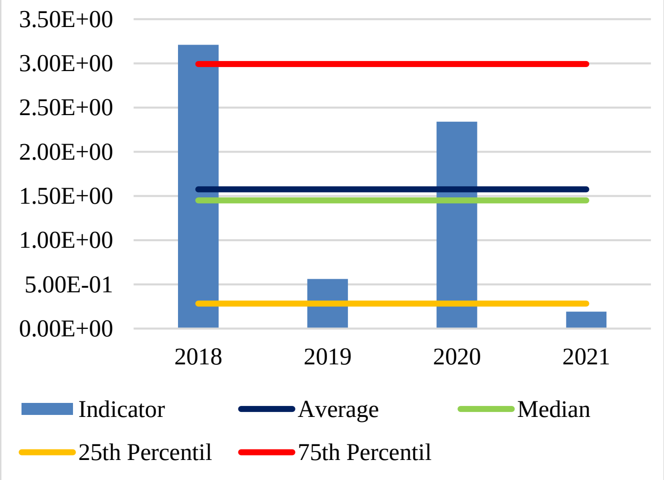

Fig. 10 Results of the TAI indicator - Interruptions/year (2018-2021)

4.1.4. Post-Operative Analysis Best Practices

The following are some practices that the company could implement to improve post-operational analysis:

- Have defined, documented and updated procedures with criteria and guidelines that guide the statistical analysis of performance in the operation of the transmission system.
- Have the following documented and updated procedures defined: for reports and results, for calculations and periodicity, for the preparation of statistical studies, for performance indicators and applied with criteria and guidelines that guide the statistical analysis of the operational process for the operation of the company's transmission system.
- Provide criteria and guidelines for statistical analysis of the performance of electrical protections applied to forced power transformer trips; actions of electrical protections of power transformers; acquisition and processing of data and system disturbances. Hold weekly meetings to analyze and draw conclusions on the effect of faults. Review statistics on the performance of electrical protections in the form of an indicator through monthly reports.

4.2. Limitations and Suggestions

Regarding the limitations of this study, it can be mentioned that the study period was intended to be longer, at least 10 years. However, it was not possible to obtain records of events prior to 2018. In addition, a more thorough and enriching study would consider, for example, other equipment, such as transmission lines, operation and maintenance costs, maintenance and administration, and, in general, all the company's processes, to propose comprehensive improvements. However, greater resources would be required for this undertaking. Regarding suggestions, a large-scale study could be conducted to compare the performance of different companies in the sector. However, this would require even greater resources.

5. Conclusion

84 events of supply interruption to consumers that occurred over 4 years were analyzed due to disconnections of power transformers of a company dedicated to electrical transmission that has 112 of these devices with nominal electrical voltages of 22.9, 60, 138, 220 and 550 kV. First, the technical operating indicators IENS, FEI, DEI, and TAI were calculated and analyzed using the interrupted power, the duration of the interruption, the energy not supplied for each event, and the causes of the events were categorized. Thus, it was found that the company adequately controls the operation, minimizing scheduled interruptions or openings and quickly responding to unscheduled interruptions. In addition, it has high reliability and safety behaviors in the operation of its electrical infrastructure and applies good management and use of resources. Despite this, opportunities

for improvement were found. Priority should be given to planning and scheduling scheduled maintenance, investigating interruption events to avoid undetermined causes, and inspecting protection and control equipment. Second, the company's operating practices documentation was reviewed according to a categorization. Thus, it was found that the company has opportunities for improvement in operation planning and scheduling, operation optimization, computer programs, systems and devices, and post-operational analysis. Finally, improvements to operating practices were proposed, prioritizing them according to the calculation and analysis results of the indicators and the review of the operating practices documentation. Among the most important aspects, it was proposed that the documentation and management of operational information be improved and the failures be statistically analyzed.

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