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Expansion of production capacity and vulnerability in the electrical connection to the National Interconnected System: case of a refinery focused on diesel.

José Fernando Neto

DEE, Universidade Federal de Pernambuco, Brazil. E-mail: josefernando.silvaneto@ufpe.br

Thais Campos Lucas

DEP, Universidade Federal de Pernambuco, Brazil. E-mail: thais.lucas@ufpe.br

Given the growing demand for petroleum derivatives and the expansion of production, an investment of approximately US$ 1.5 billion is planned for 2027 to expand a refinery in Brazil, with a focus on diesel oil production. This scenario brings the need to ensure the reliability and safety of the refinery's electricity supply, which is connected to the Sistema Interligado Nacional (SIN) through the Abreu e Lima substation. This substation plays a crucial role in the continuity of the electricity supply, transforming and distributing energy, and must be prepared to operate safely and efficiently. In this context, it is vital to conduct contingency simulations to assess the electrical system's security requirements and identify potential vulnerabilities, especially considering the projected increase in production. The analysis of these contingencies, along with the consideration of critical scenarios in the production process, will allow the identification of points of failure in the energy supply, ensuring greater system robustness. Based on reports from the system operator and other planning organs of the SIN, this study proposes to evaluate the vulnerability of the Abreu e Lima substation through power flow simulations. These simulations will be carried out for both the current refinery scenario and the future scenario after the expansion project is completed. The goal is to provide a quantitative basis for planning a more resilient Brazilian electrical system, helping to identify vulnerabilities and propose solutions that ensure the security and robustness of the energy supply, which is essential for the operation of the interconnected system.
Keywords: Vulnerability, Power Flow, Eletric Power System.

1. General Appearance

It is undeniable that the Brazilian Electric System (SEB) has undergone rapid expansion in recent years, driven especially by the growth of wind and solar generation, particularly in the Northeast region. However, this expansion of the high-voltage transmission network has faced significant challenges in delivering large volumes of renewable generation to the Southeast/Central-West region, the country's main load center. In this context, developing methodologies to assess the impacts of expansion and increased electricity production in SEB planning is essential.

To achieve this, it is crucial to understand and analyze the minimum operational requirements, from an electrical perspective, that come with the expansion of an electric system. In this regard, power flow analysis [1] is one of the most widely used computational tools in the planning and operation of a Power System (SEP), enabling the assessment of a network's operational state—whether in its full or degraded topology—across different time horizons. However, it is also essential to consider the specific demands of key sectors of the national economy, such as the refinery industry, which plays a vital role in petroleum derivative production.

Given the growing national demand for petroleum derivatives and the need to increase production, it is worth noting that industrial, residential, and public sectors are among the world's largest electricity consumers [2]. To meet this demand, an estimated investment of US$ 1.5 billion will be allocated to the implementation of the second set of refining units [3] at a refinery located in Ipojuca, Pernambuco.

Currently, the world's primary electricity sources are non-renewable and have high CO_2

emission levels [4]. In this sense, diversifying the energy matrix has been a strategic approach to meeting the country's growing demand, ensuring better utilization of regional resources, and increasing the reliability of the power generation sector [6].

Given the above, this study aims to conduct a vulnerability analysis through power flow modeling of the substation (SE) that connects the Abreu e Lima refinery to the National Interconnected System (SIN), as well as the substation after the refinery's production capacity expansion. The power flow modeling will be carried out using the ANAREDE software.

The study will analyze the 2023 and 2027 scenarios, considering the expansion outlined in Petrobras' 2023-2027 Strategic Plan. The analysis will cover both the network in its full configuration and under contingency conditions, allowing for a detailed assessment of the expansion’s impact on the electrical system's performance.

2. Vulnerability analysis in the service of the Abreu e Lima substation

According to [7], vulnerability is a concept related to system security and is characterized as a weakness in the system's structure or topology that can be exploited by a threat. In this context, system changes or the progressive increase in loads can pose threats to the Power System (SEP), potentially making it unstable concerning voltage and its acceptable operating range [8].

Given this, the commissioning of the refinery’s second set of units, scheduled for 2027, and the consequent expansion of the load supplied by the Abreu e Lima substation (SE) highlight the need for detailed studies to identify potential weaknesses at the refinery’s connection point to the National Interconnected System (SIN). To address this, an analysis of the electrical region in which the Abreu e Lima SE is located was conducted through power flow modeling, considering both the network in its full topology and under contingency conditions.

To enhance the understanding of the system’s operation and SEB planning, the concept of resilience was also explored. A literature review revealed a lack of consensus on its definition, as well as the absence of standardized metrics in the context of power systems. However, some common aspects can be identified, such as the attributes of absorption, adaptation, and recovery capacity [9], which are described through the resilience triangle concept proposed in [10] (Figure 1).

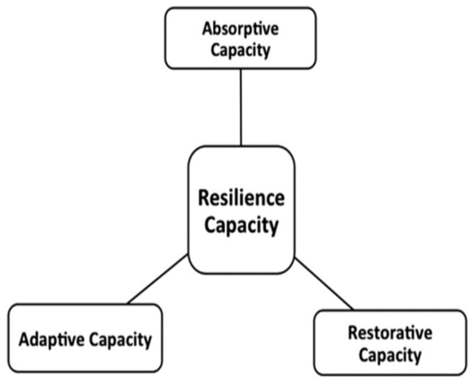


Fig. 1. Resilience Triangle.

Based on these concepts, this study adopted the definition of resilience as established by [10] and [11], structured into three main capacities:

- **Absorptive Capacity:** The extent to which a system can absorb disturbances and minimize their consequences with minimal effort. It includes the ability to anticipate, mitigate, and withstand the effects of disruptions;
- **Adaptive Capacity:** The system's ability to reconfigure itself in adverse situations. Unlike absorptive capacity, adaptive capacity involves system changes in response to negative impacts, particularly when absorptive capacity is exceeded. This ability is enhanced by anticipating disruptive events, recognizing unforeseen occurrences, reorganizing after adverse events, and preparing for future contingencies [10];

- **Restorative Capacity:** The speed and ease with which the system returns to normal operation after a disturbance;

In the context of resilience, studies conducted by the National Electric System Operator (ONS)—responsible for operating the National Interconnected System (SIN)—and the Energy Research Company (EPE)—which carries out studies supporting the planning of the Brazilian Electric System (SEB)—are essential in addressing solutions to mitigate the impacts of the system's expansion.

Using these data, the network states, the long- and short-term operational flows in each case, and the loading capacity of the remaining elements under contingency conditions were analyzed by the authors. Therefore, the cases studied were:

- Scenario 2023, Winter, Medium Load;
- Scenario 2027, Winter, Net Limit Load (120 MVA);
- Scenario 2027, Winter, Net Limit Load (240 MVA) and Addition of One Transformer;
- Scenario 2027, Winter, Net Limit Load (360 MVA) and Addition of Two Transformer.

3. Power Flow Simulation of Abreu e Lima Substation

For the power flow modeling of the system to which the Abreu e Lima Substation (SE Abreu e Lima) is connected, the *Análise de Redes* software, version 11.06.02 - ANAREDE, was used under a usage license granted to the Federal University of Pernambuco (UFPE). Developed by the Electric Energy Research Center (Cepel), ANAREDE is the main computational program used in Brazil by utilities and regulatory bodies responsible for planning and operating the expansion of the country's power grids. The software enables various analyses, including power flow, network equivalence, contingency analysis, voltage sensitivity analysis, active power redispatch, and continued power flow analysis of electrical networks [13].

To obtain the modeling data, the SINtegre platform was used. This portal was developed by the National System Operator (ONS) to integrate information management and improve interaction with electricity sector agents. The data is provided in a format compatible with ANAREDE. The access cases from November 2023 were used, considering a horizon aligned with the Medium-Term Electrical Operation Plan of the SIN (PAR/PEL) for the 2024-2028 cycle.

Thus, the steady-state power flow problem was modeled for the entire electrical system connected to SE Abreu e Lima using the network equivalence tool for the years 2023 and 2027. Based on this model, a comparative evaluation of the power grid was conducted before and after the commissioning of the second set of refining units.

3.1. *Scenario 2023, Winter, Medium Load*

In this case, the net limit load is defined by the contingency of one of the two transformers, totaling 120 MVA (100 MVA nominal plus 20% overload). Under normal conditions, the system still operates within acceptable limits, though with lower safety margins compared to the previous scenario (Figure 2).

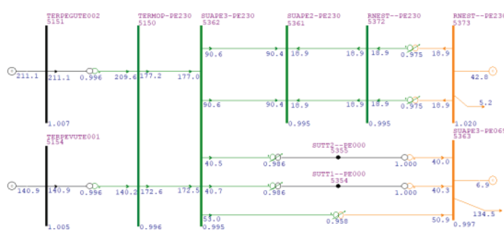


Fig. 2. Modeling in ANAREDE of the electrical system that serves SE Abreu e Lima in 2023.

3.1.1 *N-1 Contingency: Transformer TR1 230/69 kV Out of Service*

The loss of one transformer in this scenario has a more severe impact, as the remaining transformer must handle the entire load. Even with the permitted 20% overload, the network operates at risk, with the potential for voltage drops and instability if another failure occurs or an unexpected demand increase takes place (Figure 3).

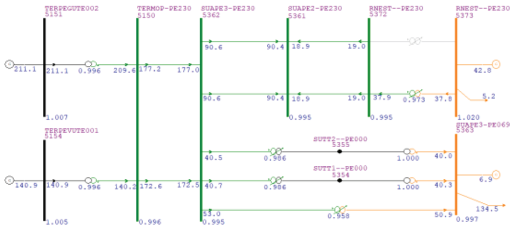


Fig. 3. Simulation of the loss of transformer TR1 230/69 kV 100 MVA (Contingency N-1).

3.1.2 *N-1 Contingency: Transmission Line LT 04M1 Out of Service*

The unavailability of LT 04M1 compromises load distribution and may overload other lines. Additionally, the increased power flow through alternative lines can lead to voltage stability variations, making the system more susceptible to oscillations (Figure 4).

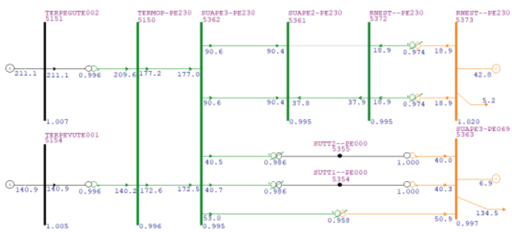


Fig. 4. Simulation of the loss of LT 04M1 at SE Abreu e Lima (Contingency N-1).

3.1.3 *N-2 Contingency: LT 04M1 and TR1 Out of Service*

In this scenario, the network operates in a critical state, requiring load shedding to prevent system failures. Expanding cogeneration can help mitigate this issue by reducing reliance on the external grid. However, the lack of complete redundancy in transformers still compromises supply security under N-2 criteria (Figure 5).

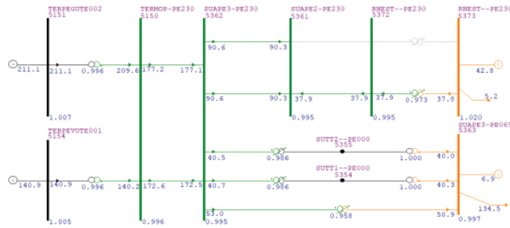


Fig. 5. Contingency of the 230 kV Abreu e Lima - Suape II LT and the 230/69 kV 100 MVA TR1 transformer (Contingency N-2).

3.2. *Scenario 2027, Winter, Net Limit Load 120 MVA*

With the addition of a third transformer, the net limit load increases to 240 MVA. This expansion improves load distribution and reduces individual equipment loading levels, providing greater operational margin and stability (Figure 6).

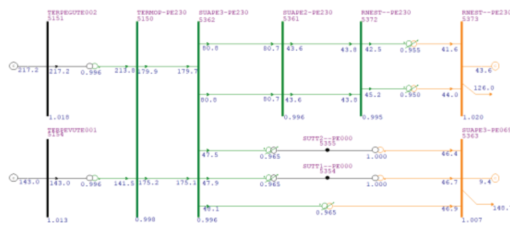


Fig. 6. Modeling in ANAREDE of the electrical system that serves SE Abreu e Lima in 2027.

3.2.1 *N-1 Contingency: Transformer TR1 230/69 kV Out of Service*

The loss of one transformer is now better absorbed by the two remaining transformers, ensuring that the load is supplied without exceeding operational limits. The system exhibits greater security compared to previous scenarios (Figure 7).

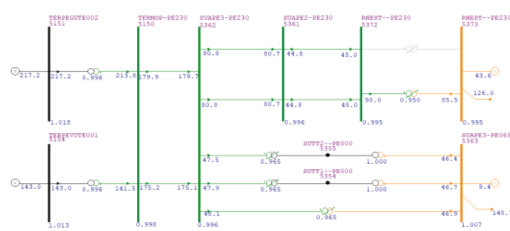


Fig. 7. Simulation of the loss of transformer TR1 230/69 kV 100 MVA (Contingency N-1).

3.2.2 *N-1 Contingency: Transmission Line LT 04M1 Out of Service*

In this case, a significant increase in loading on remaining lines and transformers is observed. However, the system still operates without the need for load shedding, albeit with higher stress on the equipment (Figure 8).

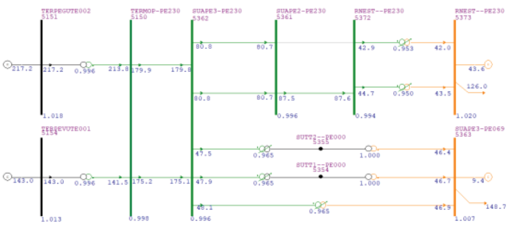


Fig. 8. Simulation of the loss of the LT 230 kV Abreu e Lima - Suape II circuit (Contingency N-1)

3.2.3 *N-2 Contingency: LT 04M1 and TR1 Out of Service*

The introduction of the third transformer enhances operational security, reducing the need for emergency measures during contingencies. However, transmission capacity remains a limiting factor in ensuring safe operation under N-2 criteria (Figure 9).

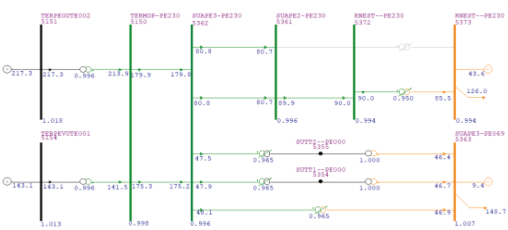


Fig. 9. Contingency of the 230 kV Abreu e Lima - Suape II LT and the 230/69 kV 100 MVA TR1 transformer (Contingency N-2).

3.3. *Scenario 2027, Winter, Net Limit Load 240 MVA*

Sections, sub-sections and sub-sub-sections are numbered uniformly in Arabic numerals. Leave two spaces after the end of the numbering and beginning of heading text. Flush left all paragraphs that follow after section headings. Subsequent paragraphs should be indented (Figure 10).

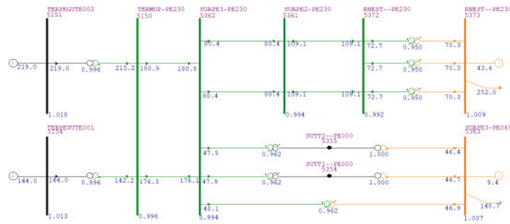


Fig. 10. Modeling in ANAREDE of the electrical system that serves SE Abreu e Lima in 2027 with an added transformer and a net load of 240 MVA.

3.3.1 *N-1 Contingency: Transformer TR1 230/69 kV Out of Service*

The loss of one transformer in this scenario has a more severe impact, as the remaining transformer must handle the entire load. Even with the permitted 20% overload, the network operates at risk, with the potential for voltage drops and instability if another failure occurs or an unexpected demand increase takes place (Figure 11).

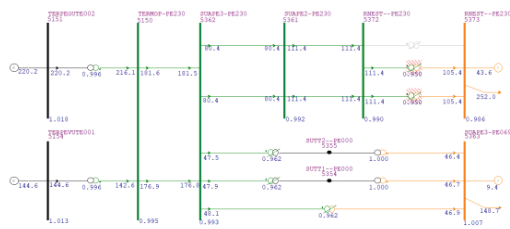


Fig. 11. Simulation of the loss of transformer TR1 230/69 kV 100 MVA with an added transformer and a net load of 240 MVA (Contingency N-1).

3.3.2 *N-1 Contingency: Transmission Line LT 04M1 Out of Service*

The unavailability of LT 04M1 compromises load distribution and may overload other lines. Additionally, the increased power flow through alternative lines can lead to voltage stability variations, making the system more susceptible to oscillations (Figure 12).

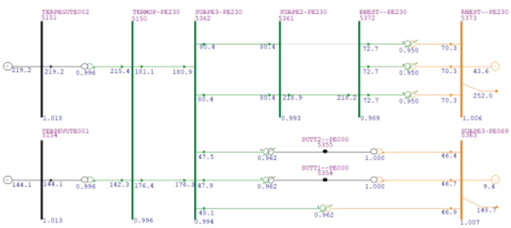


Fig. 12. Simulation of the loss of LT 04M1 at SE Abreu e Lima with an added transformer and a net load of 240 MVA (Contingency N-1).

3.3.3 *N-2 Contingency: LT 04M1 and TR1 Out of Service*

In this scenario, the network operates in a critical state, requiring load shedding to prevent system failures. Expanding cogeneration can help mitigate this issue by reducing reliance on the external grid. However, the lack of complete redundancy in transformers still compromises supply security under N-2 criteria (Figure 13).

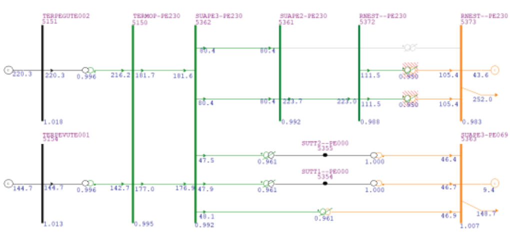


Fig. 13. Contingency of the 230 kV Abreu e Lima - Suape II LT and the 230/69 kV 100 MVA TR1 transformer with an added transformer and a net load of 240 MVA (Contingency N-2).

3.4. *Scenario 2027, Winter, Net Limit Load 360 MVA*

This scenario considers the installation of a fourth transformer, increasing total capacity to 360 MVA. The expansion of transformation capacity improves operational reliability and significantly reduces the individual loading of each transformer under normal conditions (Figure 14).

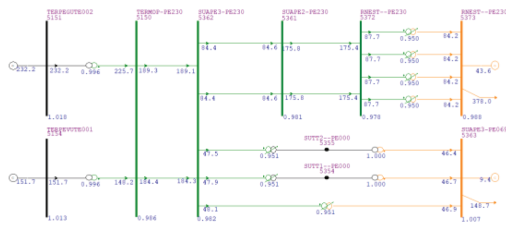


Fig. 14. Modeling in ANAREDE of the electrical system that serves SE Abreu e Lima in 2027 with an added transformer and a net load of 360 MVA.

3.4.1 *N-1 Contingency: Transformer TR1 230/69 kV Out of Service*

With four operational transformers, the system can handle the contingency of one unit without critical overloads. This redundancy enhances system resilience (Figure 15).

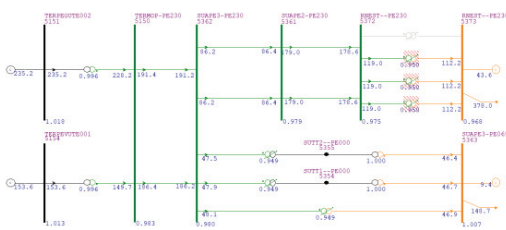


Fig. 15. Simulation of the loss of transformer TR1 230/69 kV 100 MVA with an added transformer and a net load of 360 MVA (Contingency N-1).

3.4.2 *N-1 Contingency: Transmission Line LT 04M1 Out of Service*

The failure of LT 04M1 remains a challenge as it may compromise load distribution. However, the availability of additional transformers reduces the overall impact on the refinery (Figure 16).

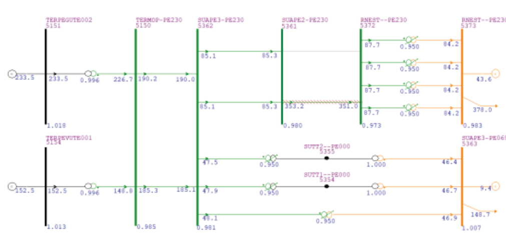


Fig. 16. Simulation of the loss of LT 04M1 at SE Abreu e Lima with an added transformer and a net load of 360 MVA (Contingency N-1).

3.4.3 *N-2 Contingency: LT 04M1 and TR1 Out of Service*

Even with a fourth transformer, the simultaneous loss of a transformer and a transmission line still represents a significant operational risk. The need for transmission reinforcement becomes evident (Figure 17).

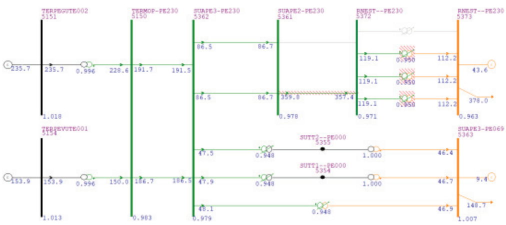
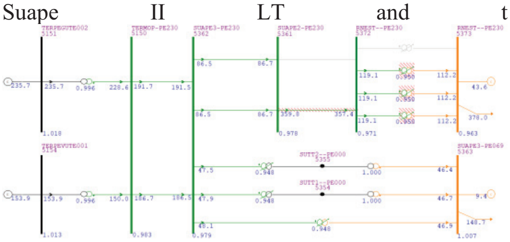


Fig. 17. Contingency of the 230 kV Abreu e Lima - Suape II LT and t



he 230/69 kV 100 MVA TR1 transformer with an added transformer and a net load of 360 MVA (Contingency N-2).

4. Final Considerations

The simulations carried out for different scenarios in 2027 provided a detailed analysis of the refinery's electrical system operation under various load and contingency conditions. The results highlight that the expansion of cogeneration can significantly reduce the refinery's dependence on the external grid, enhancing system resilience. However, despite this mitigation, the analysis revealed that transmission infrastructure remains a critical factor for operational security.

In the scenario with a net limit load of 120 MVA, the network remains operational but with reduced safety margins, emphasizing the need for structural reinforcements to ensure stability under severe contingencies. The addition of a third transformer, increasing the load limit to 240 MVA, demonstrated a significant improvement in fault absorption, reducing the need for load shedding in N-1 contingencies. However, the simultaneous loss of a transmission line and a transformer (N-2 criterion) still posed a high risk, underscoring the need for additional investments in transmission infrastructure.

The expansion to four transformers and a load capacity of 360 MVA provided greater redundancy and operational capacity, enabling a more efficient response to isolated failures. However, the tests indicated that even with this expansion, transmission infrastructure remains a critical bottleneck. The lack of reinforcement in transmission lines could compromise the refinery's energy supply under adverse conditions, reinforcing the need for an integrated approach between generation and transmission to ensure system security.

Thus, the study concludes that the expansion of cogeneration can reduce dependence on the external grid. However, transmission reinforcement is necessary to meet the N-2 criterion. The evolution of transformation and transmission capacity is essential to ensure the safe operation of the refinery's electrical system in future scenarios.

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