

SIMPLE CONTINGENCY ANALYSIS, PARALLEL COMPENSATION, AND DETERMINATION OF THE LOADING MARGIN IN TRANSMISSION LINES

ANÁLISE DE CONTINGÊNCIA SIMPLES, COMPENSAÇÃO PARALELA E DETERMINAÇÃO DA MARGEM DE CARREGAMENTO EM LINHAS DE TRANSMISSÃO

ANÁLISIS DE CONTINGENCIA SIMPLE, COMPENSACIÓN EN PARALELO Y DETERMINACIÓN DEL MARGEN DE CARGA EN LÍNEAS DE TRANSMISIÓN

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ABSTRACT

The electrical system needs to be reliable and capable of withstanding contingencies to guarantee energy demand without overloading electrical equipment. In this research, the voltage stability of the STB-33 test system was analyzed in three situations: base case, after simple transmission line contingency simulation, and after applying parallel compensation in cases of contingency with voltage violations. The ANAREDE software was used to simulate contingencies and seek solutions using the Newton-Raphson method, discarding cases where line removal would cause isolation of network elements, resulting in 26 simulated contingency cases. Seven cases did not obtain an initial solution for the load flow, mainly in area A, which is not able to supply its demand alone, resulting in an exchange of energy with area B. As a means of forcing a solution to the load flow, three methods were used: turning off the ANAREDE controls, representing the load at 75% active power, and defining the buses that interconnect the contingency lines as a reference. The last option resulted in the convergence of all cases and the lowest severity indices. These cases were disregarded in the compensation studies due to simplifications to achieve convergence. Contingency cases with flow violations in the lines are mainly in area B, where area A imports energy due to its demand exceeding supply. Cases with voltage violations in the busbars are mostly found in area A, as the buses in this area are unable to support all their demand, resulting in voltage drops. For these cases, parallel compensation was applied, which is important for controlling reactive power in the network and improving the performance of transmission lines. Therefore, FLUPOT was used to perform the optimal power flow calculations, determining the amount of reactive power to be allocated and the buses that should receive parallel compensation. Cases 18 and 22 were chosen to receive compensation due to their high

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severity indices, where the compensation proved effective, recovering the voltages of the contingent and peripheral busbars. Voltage stability studies identify vulnerable points in the system, and a common method is the PV curve. Using the continuation method through ANAREDE to determine the PV curve and analyze the load margin of cases 18 and 22, a load increase of 0.2% was performed. Some buses did not remain stable in terms of voltage, even after compensation. These buses are considered critical because they presented undervoltage during emergencies. The base case had the highest load margin and voltage safety margin, respecting the minimum limit pre-established by ONS, of 7% for complete systems. Cases 18 and 22, after the contingency, presented a load margin and voltage safety margin below the 4% limit, which is the minimum limit for incomplete systems. After compensation, cases 18 and 22 had an increase in load and voltage indices, with a safety margin of 4.8446% for case 18 and 6.2976% for case 22.

Keywords: Electrical Power Systems. Electrical Power Transmission. Stability. Electrical Energy.

RESUMO

O sistema elétrico precisa ser confiável e capaz de suportar contingências para garantir a demanda de energia sem sobrecarga em equipamentos elétricos. Nesta pesquisa, foi analisada a estabilidade de tensão do sistema-teste STB-33 em três situações: caso base, após a simulação de contingência simples de linhas de transmissão e após a aplicação da compensação paralela nos casos de contingência com violações de tensão. Foi utilizado o software ANAREDE para simular as contingências e buscar soluções utilizando o método de Newton-Raphson, descartando casos em que a retirada da linha causasse isolamento de elementos da rede, o que resultou em 26 casos de contingência simulados. Sete casos não obtiveram solução inicial para o fluxo de carga, principalmente na área A, que não é capaz de suprir sua demanda sozinha, o que resulta em um intercâmbio de energia com a área B. Como meio de forçar a solução do fluxo de carga, foram utilizados três métodos: desligamento dos controles do ANAREDE, representação da carga em 75% de potência ativa e a definição das barras que interligam as linhas contingenciadas como referência. A última opção resultou na convergência de todos os casos e nos menores índices de severidade. Esses casos foram desconsiderados nos estudos de compensação devido a simplificações para obter a convergência. Os casos de contingência com violações de fluxo nas linhas estão principalmente na área B, onde a área A importa energia devido à sua demanda maior que o fornecimento. Já os casos com violação de tensão nos barramentos se encontram, em sua maioria, na área A, pois as barras dessa área não são capazes de suportar toda a sua demanda, resultando em quedas de tensão. Para esses casos, foi aplicada a compensação paralela, importante para controlar a potência reativa na rede e melhorar o desempenho das linhas de transmissão. Sendo assim, foi utilizado o FLUPOT para realizar os cálculos do fluxo de potência ótimo, determinando a quantidade de reativos a serem alocados e as barras que devem receber a compensação paralela. Os casos 18 e 22 foram escolhidos para receber a compensação devido aos seus altos índices de severidade, onde a compensação se mostrou eficaz, recuperando as tensões dos barramentos contingenciados e periféricos. Estudos de estabilidade de tensão identificam pontos vulneráveis do sistema, e um método comum é a curva PV. Utilizando o método da continuação através do ANAREDE para determinar a curva PV e analisar a margem de carregamento dos casos 18 e 22, foi realizado um acréscimo de carga de 0,2%. Algumas barras não se mantiveram estáveis em termos de tensão, mesmo após a compensação. Essas barras são consideradas críticas, pois apresentaram subtensão em emergências. O

caso base teve a maior margem de carregamento e margem de segurança de tensão, respeitando o limite mínimo preestabelecido pela ONS, de 7% para sistemas completos. Os casos 18 e 22, após a contingência, apresentaram margem de carregamento e margem de segurança de tensão abaixo do limite de 4%, que é o limite mínimo para sistemas incompletos. Após a compensação, os casos 18 e 22 tiveram aumento nos índices de carregamento e tensão, com uma margem de segurança de 4,8446% para o caso 18 e de 6,2976% para o caso 22.

Palavras-chave: Sistemas de Energia Elétrica. Transmissão de Energia Elétrica. Estabilidade. Energia Elétrica.

RESUMEN

El sistema eléctrico debe ser fiable y capaz de soportar contingencias para garantizar el suministro de energía sin sobrecargar los equipos. En esta investigación, se analizó la estabilidad de tensión del sistema de prueba STB-33 en tres situaciones: caso base, tras una simulación simple de contingencia en la línea de transmisión y tras aplicar compensación en paralelo en casos de contingencia con violaciones de tensión. Se utilizó el software ANAREDE para simular las contingencias y buscar soluciones mediante el método de Newton-Raphson, descartando los casos en los que la desconexión de la línea provocaría el aislamiento de elementos de la red, lo que resultó en 26 casos de contingencia simulados. En siete casos no se obtuvo una solución inicial para el flujo de carga, principalmente en el área A, que no puede abastecer su demanda por sí sola, lo que provoca un intercambio de energía con el área B. Para forzar una solución al flujo de carga, se utilizaron tres métodos: desactivar los controles de ANAREDE, representar la carga al 75 % de potencia activa y definir los buses que interconectan las líneas de contingencia como referencia. Esta última opción resultó en la convergencia de todos los casos y los índices de severidad más bajos. Estos casos se omitieron en los estudios de compensación debido a las simplificaciones necesarias para lograr la convergencia. Los casos de contingencia con violaciones de flujo en las líneas se concentran principalmente en el área B, donde el área A importa energía debido a que su demanda supera la oferta. Los casos con violaciones de tensión en las barras colectoras se encuentran mayormente en el área A, ya que las barras en esta área no pueden soportar toda su demanda, lo que provoca caídas de tensión. Para estos casos, se aplicó compensación en paralelo, lo cual es importante para controlar la potencia reactiva en la red y mejorar el rendimiento de las líneas de transmisión. Por lo tanto, se utilizó FLUPOT para realizar los cálculos óptimos de flujo de potencia, determinando la cantidad de potencia reactiva a asignar y las barras que debían recibir compensación en paralelo. Los casos 18 y 22 se seleccionaron para recibir compensación debido a sus altos índices de severidad, donde la compensación resultó efectiva, recuperando las tensiones de las barras colectoras contingentes y periféricas. Los estudios de estabilidad de tensión identifican los puntos vulnerables del sistema, y un método común es la curva PV. Utilizando el método de continuación a través de ANAREDE para determinar la curva PV y analizar el margen de carga de los casos 18 y 22, se realizó un incremento de carga del 0,2%. Algunos buses no mantuvieron la estabilidad de tensión, incluso después de la compensación. Estos buses se consideran críticos debido a que presentaron subtensión durante las emergencias. El caso base presentó el mayor margen de carga y margen de seguridad de tensión, respetando el límite mínimo preestablecido por la ONS del 7% para sistemas completos. Los casos 18 y 22, tras la contingencia, presentaron un margen de carga y un margen de seguridad de tensión inferiores al límite del 4%, que es el límite mínimo para sistemas incompletos. Después de la compensación, los casos 18 y 22 experimentaron un incremento en los

índices de carga y tensión, con un margen de seguridad del 4,8446% para el caso 18 y del 6,2976% para el caso 22.

Palabras clave: Sistemas de Energía Eléctrica. Transmisión de Energía Eléctrica. Estabilidad. Energía Eléctrica.

1 INTRODUCTION

Currently, the geographic area occupied by the country is growing rapidly and unevenly for economic and environmental reasons. The expansion of the physical structure of the National Interconnected System (SIN) does not proportionally follow the additional demand caused by the activities of a growing population. In this scenario, the electrical system, which previously operated maintaining energy transfer without loss of voltage stability, now operates at the safety limit to fully satisfy the energy needs of consumers (PINTO, 2013; COELHO, 2018).

There are several studies that allow keeping the power grid stable and in good working order, involving the management and implementation of strategies to repair disturbances in power transmission, verifying the state of operation of the grid and whether its performance is adequate. Through Submodule 23.3 of the Network Procedures, the National Electric System Operator (ONS) has responsibilities and elaborates guidelines and criteria to be implemented in electrical studies (ONS, 2018).

The system's security analysis integrates the verification of the behavior of the electrical network in the face of the loss of elements, such as busbars, generators and transmission lines (LT), detecting areas at risk of blackouts and enabling their prevention. The contingency analysis verifies situations immediately after the shutdown of one or more elements of the grid, observing changes in the operational characteristics of the Electric Power System (SEP). These contingencies can be simple, or N-1 criterion, where the analysis is made from the disconnection of a single element, or multiple, where more than one element is disconnected at the same time, and may follow N-2, N-3 and so on criteria (DELGADO, 2019).

From a contingency, there may be voltage instabilities in the system's busbars and, with this, the need for studies aimed at monitoring this parameter arises. The loading margin makes it possible to assess the imminence of voltage drops, making it possible to analyze the voltage of the system under normal operating conditions and in the face of a disturbance (ZEFERINO, 2011).

One way to analyze SEP voltage is by determining the PV curve. This method makes it possible to observe the voltage level in a bar as the active power increases, allowing the observation of voltage variation in various operating situations. The most used means to delimit this curve is the continuation method, or Continuous Charge Flow (FCC), which,

through successive load increments, makes it possible to find solutions for the flow of power at the Maximum Loading Point (PMC) (DELGADO, 2019).

Another situation that can lead the electrical system to voltage instability is the lack of control of reactive in the network. In this aspect, parallel reactive compensation becomes a more economically viable alternative, establishing a better system performance and control of operational parameters (CHAVES, 2007).

In order to improve the voltage profile of the busbars, it is sought to determine the best places for the application of compensation and the most appropriate amount of reagents to be allocated, performing analyses through the Optimal Power Flow (FPO), which is common in studies aimed at managing the operation in the face of disturbances (ONORIO, 2022). According to Dahlke (2010), the calculation of the FPO consists of obtaining the optimal operating point of a SEP, meeting a group of constraints, seeking to improve some performance index.

At the national level, the Optimal Power Flow Program (FLUPOT), developed by the Electric Energy Research Center (CEPEL), which seeks to optimize a pre-established objective function through selected controls (CEPEL, 2018), is widely used. Regarding contingency analysis, CEPEL has the Network Analysis Program (ANAREDE), which makes it possible to carry out several studies, such as simulations of the occurrence of contingencies, that is, the output of various elements of the network, seeking a new solution for the flow of power and monitoring the operational state of the simulated system (CEPEL, 2011).

Problems related to voltage instabilities can occur in highly stressed systems, where a voltage collapse can be related to a deficit in the supply of reagents or to the emergence of a contingency, with the subsequent problem being the fragility of the electrical system (KUNDUR, 1994).

Thus, starting from the initial operating point of the system, the need arises to know the PMC, as it determines if the system has the capacity to maintain its voltage levels stable. A widely used method to determine the PMC is by defining the PV curve, performing successive load increments and finding new solutions for the load flow. However, the Newton-Raphson method has problems regarding its convergence as the calculated points approach the PMC, and it is necessary to find new methods to solve the problem (PINTO, 2013; DELGADO, 2019).

In order to maintain the reliability of the system and increase the resistance against contingencies, the construction of a new TL emerges as one of the alternatives, as it would increase the robustness and redundancy of the system. However, in addition to the environmental impact that can be caused by the construction of a transmission line, building a system that is totally resistant to contingencies would require a high financial investment, thus emerging the compensation of reagents as a more financially viable and effective means (PIRES, 2005; JÚNIOR, 2019).

In order to achieve an appropriate level of reliability, the electrical system must have the ability to withstand certain contingencies in order to sustain the energy demand without overloading other equipment in the system, such as transmission lines and transformers. For this reason, the SIN is designed adhering to the N-1 reliability criterion, because when a simple contingency occurs, the system must be prepared to sustain it (JÚNIOR, 2019).

Studies focused on voltage stability become extremely important, because from them it is possible to determine vulnerable points in the system. The method of determining the PV curve is one of the most used means today when it comes to analyzing the loading margin and voltage stability of the electrical system. From power flow solutions by the continuation method, it is possible to delimit the PV curve and analyze the stability of the system under normal operating conditions and in cases of contingency (DELGADO, 2019).

In order to obtain reactive control and better performance of transmission lines, whether short, medium or long, parallel compensation methods are applied in order to obtain control over the reactive power in the grid (STEVENSON, 1986).

Often, carrying out studies focused on SEP manually can be unfeasible due to mathematical complexity when it involves systems composed of a large number of elements. In Brazil, the Department of Electroenergetic Systems (DSE) develops computer programs in order to assist in studies aimed at the planning and operation of the SEP, such as ANAREDE, which is a program aimed at SEP analysis in steady state, such as load flow and contingency analysis, and also FLUPOT, which is applied in studies such as the optimal allocation of reactive power (CEPEL, 2022).

This work carried out a voltage stability analysis study in a test system under normal operating conditions, after simulations of simple contingencies of transmission lines and the application of reactive compensation, in order to first verify and, subsequently, eliminate or reduce the impacts of contingencies. The specific objectives of this work consisted of:

- Simulate contingency cases with criterion N-1 lines in the Brazilian 33-Bar Test System (STB-33) using the ANAREDE program, disregarding cases that result in islanding;
- Simulate parallel compensation in cases that result in stress violation in the bars and present the optimal connection points, through the FLUPOT program;
- Determine the PV curves of the system members under normal operating conditions, after contingencies and after reactive compensation, presenting the analysis of the stress profile of the bars and the *ranking* of the bars according to their loading margins.

2 LITERATURE REVIEW

2.1 POWER FLOW

Stevenson (1986) conceptualizes the study of power flow as the determination of voltage, current, power and power factor or reactive power in various locations of an electrical network, whether in real or ideal operating conditions. Therefore, the study of load flow becomes necessary for the increase of the system, as it covers the effects of the interconnection of new loads, generating units, transmission lines and even other systems.

The power flow study is carried out to determine the steady-state performance of electrical grids. For a given network configuration and a given load and generation condition, it is evaluated whether the voltage levels on the busbars and the loads on the lines, transformers and other components of the network meet the pre-established criteria (ONS, 2018).

Monticelli and Garcia (2011) describe the basic formulation of power flow by associating each bar of the network to four variables, where two are provided and two are unknown, as demonstrated in the **Table 1**.

Table 1

Types of bars

Bar	Given variables	Unknowns
WHY	P_K and Q_K	V_K and θ_K
PV	P_K and V_K	Q_K and θ_K
Slack	V_K and θ_K	P_K and Q_K

Source: Adapted from Monticelli and Garcia (2011, p. 206)

Where:

- V_K : magnitude of nodal tension;

- θ_K : nodal tension angle;
- P_K : net active power generation;
- Q_K : reactive power liquid injection.

To represent the load and generation bars, the bars of the PQ and PV types are used, respectively. The reference bar, slack or V θ , has two uses: to provide the reference of voltage magnitude, which is the ground itself; and close the balance of power (Monticelli; Garcia, 2011).

Specific computational means are also used to determine the power flow. At the national level, the Network Analysis Program is the most used computer program by companies, both public and private, in the generation, transmission and distribution of energy. This is a program that aims to analyze the SEP in steady state, making it possible not only to calculate the power flow, but also the continuous power flow, contingency analysis, network equivalent, voltage sensitivity analysis and active power redispatch (CEPEL, 2022).

2.2 NEWTON-RAPHSON METHOD

When it comes to nonlinear equations, the most common method of solving is the Newton-Raphson method. Based on an unknown initial estimate and using the Taylor expansion series, this method makes a successive approximation of the desired value (SAADAT, 1999).

The obtaining of the power flow solution can be achieved through the Newton-Raphson method algorithm, which consists of (STEVENSON, 1986):

1) Through the values of nodal stress modulus and its suggested angle for the first iteration ($i = 0$), determine the value of the Equation (1) and Equation (2).

$$P_{km} = g_{km}V_k^2 - V_kV_m(g_{km}\cos\theta_{km} + b_{km}\sin\theta_{km}) \quad 1)$$

$$Q_{km} = (b_{km} - b_{km}^{sh})V_k^2 - V_kV_m(g_{km}\cos\theta_{km} + b_{km}\sin\theta_{km}) \quad 2)$$

2) Calculate and $\Delta P \Delta Q$ for each bar, which is given in the Equations (3) and (4), respectively.

$$\Delta P^{(i)} = P_k^{esp} - P_k^{calc} \quad 3)$$

$$\Delta Q^{(i)} = Q_k^{esp} - Q_k^{calc} \quad 4)$$

3) Determine the Jacobian matrix. $(J^{(i)})$

4) Solve the nonlinear system from the Equation (5).

$$\begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix}^{(i)} = \begin{pmatrix} H & N \\ M & L \end{pmatrix}^{(i)} * \begin{pmatrix} \Delta \theta \\ \Delta V \end{pmatrix}^{(i)} \quad 5)$$

5) Calculate the new values for and $\theta_K V_K$

6) Go back to item 1 and repeat the process using the new values of the modulus and angle of the tension until the values of e are equal to or less than the chosen tolerance. $\Delta P \Delta Q$

2.3 OPTIMAL POWER FLOW

In order to meet a set of constraints of equality or inequality, the FPO seeks to increase or decrease some performance index (DAHLKE, 2010). Through a series of calculations, sought to meet the operational and physical delimitations of the electrical network, the FPO becomes an important instrument, leading operators to manipulate the system within their delimited safety margins. This means that the energy demand of the electricity grid is satisfied and that the operational and physical constraints of the system are not violated (ROSAS, 2008).

Rosas (2008) represents the problem of the POF being the minimum of the objective function (Equation ((6))), subject to the equality restriction (Equation (7)) and the inequality restriction (Equation (8)).

$$\min = f(x) \quad (6)$$

s. a.

$$g(x) = 0 \quad 7)$$

$$h_{min} \leq h(x) \leq h_{max} \quad 8)$$

The Equations (1) and (2), described in subsection 0, indicate the balance of active and reactive power in the grid, composing the FPO equality constraint vector. Depending on the issue at hand, some system controls can be changed or added to existing ones, rather than being modified within a specific range. On the other hand, the inequality vector can represent the maximum load on transmission lines and transformers, maximum and minimum limits of the modulus of the voltages in the busbars, as well as maximum and minimum limits of active and reactive power generation (ROSAS, 2008; SESSA, 2013).

Through computer programs, it is possible to establish the optimal point of operation of a system based on a pre-established objective function and its constraints of equality and inequality. FLUPOT, a program developed by CEPEL, is widely used for the study of optimal power flow, with the minimization of active losses, load shedding, optimal allocation of reactive power support and maximization of active power transfer between areas or in a set of circuits.

2.4 CONTINGENCY ANALYSIS

For a better functioning of the SEP, security analyses are carried out of a cluster of contingencies most likely to occur in the network, as well as the verification of its operating and emergency limits (MONTICELLI, 1983).

The goal of operating the system is for it to be in a safe state. Under steady-state operating conditions, it is subject to load restrictions, which are related to load balance and generation; the operating restrictions that represent the limits imposed on the magnitudes of the voltages in the busbars, the apparent power flows in the transmission lines and transformers, and the reactive power injections in the generation bars; and, finally, the safety constraints that define the safe operation of the system under a list of possible contingencies, such as loss of line, generators and capacitors. (PATACA, 2012, p. 34-35).

Pataca (2012) defines contingency as the disconnection or shutdown of a system component, which can be the disconnection of transmission lines, loads, transformers and/or generators, caused by disturbances or faults. These contingencies can be single (criterion N-1), when only one component of the system is disconnected from the grid, or multiple (criterion N-2, criterion N-3...), when several outputs of system components are considered.

Through the use of computer programs, contingency analysis is carried out. By defining a point in the system and applying simulations of a series of contingencies, the impact on the network is observed and evaluated (PATACA, 2012).

According to CEPEL (2011), in order to find severe operational difficulties, ANAREDE performs the simulations by processing a sequence of contingencies, where in each case a new solution is made for the power flow and monitoring of the operational state of the simulated system.

This research will perform the analysis of simple contingencies through simulations of the shutdown of transmission lines in the STB-33 test system.

2.5 PARALLEL REACTIVE COMPENSATION

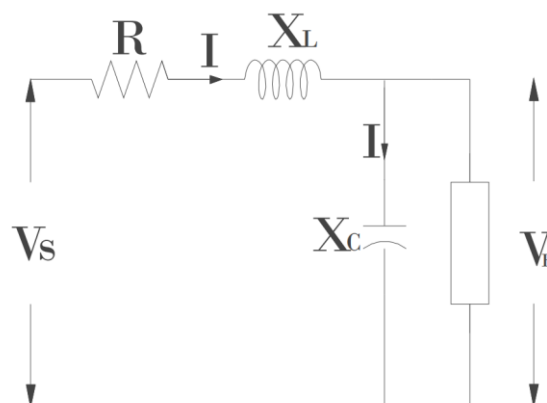
In order to obtain better performance in transmission lines, whether short, medium or long, reactive compensation methods are applied. When there is a need to supply or absorb reactivities in the network, capacitor banks or reactors are added, respectively, thus applying parallel compensation, or *shunt* (REZENDE et al., 2013).

The

Figure 1 demonstrates an equivalent circuit with capacitive parallel compensation, through a capacitor bank (JESUS; SUNTAN; COGO, 2018).

Figure 1

Equivalent circuit with parallel compensation



Source: Jesus, Tan and Cogo (2018).

Where:

- V_S : voltage at the emitting end;
- V_R : voltage at the receiving end;
- R : LT resistance;
- X_L : reactance of the LT;
- X_C : bank of capacitors in shunt.

According to Rezende *et al.* (2013), the compensation of a transmission line is directly related to the natural property of the lines, which require reactive energy in greater or lesser quantities to carry out the flow of active power. The ideal condition for the flow of energy through a line is one in which it carries an active power of value corresponding to the *Surge Impedance Loading* (SIL).

Saadat (1999) describes SIL as all reactive energy generated by the line being absorbed by it, with no losses in this line and with constant active power at the transmitting and receiving terminals. Demonstrated by the Equation ((9), where represents the nominal voltage of the line and is the characteristic impedance. $V_L Z_C$

$$SIL = \frac{|V_L|^2}{Z_C} \quad (9)$$

The lack of reactive control in transmission lines can cause two scenarios: when the active power transported by the line is lower than the SIL, therefore, the line will generate a greater number of reactive than necessary; and when the reactive power is greater than the SIL, indicating that there is a need to supply reagents to the line (REZENDE *et al.*, 2013).

Thus, this research will apply parallel reactive compensation in cases of contingencies that result in voltage violation in the busbars of the STB-33 test system.

2.6 LOADING MARGIN

In order to analyze places in the system that are more vulnerable to changes in operating conditions, studies related to voltage stability provide guidance for the control and optimal structuring of the electrical system (DELGADO, 2019). In order to assess the imminence of a voltage decrease, the loading margin is determined, defining the level of change from a disturbance in the system, which can be a variation in load and/or generation or a contingency (ZEFERINO, 2011).

From the perspective of voltage analysis, the SEP is considered stable when it is possible to maintain the voltage level in normal operating conditions or when it is subjected to some disturbance. In cases where the network suffers some gradual and disoriented loss of voltage, due to the removal of a transmission line and an increase in load, voltage instability is qualified, which can be caused, mainly, by the inability to supply reactive power (KUNDUR, 1994).

A SEP is considered safe when it has the ability to continue operating normally in the face of contingencies; however, no system is completely resistant to contingencies, because, in reality, the system is designed to sustain a finite number of generation, transmission and load contingencies (RESENDE, 2007).

Regarding voltage safety, ONS (2018) determines that studies focused on voltage stability must have the system's stability margin defined through simulations and compared with the predefined safety standards. The ONS also emphasizes a Voltage Safety Margin (MST), which is the minimum value of the stability margin that can be evaluated in a system. The MST for incomplete networks is at least 4%, and for complete networks it is 7%.

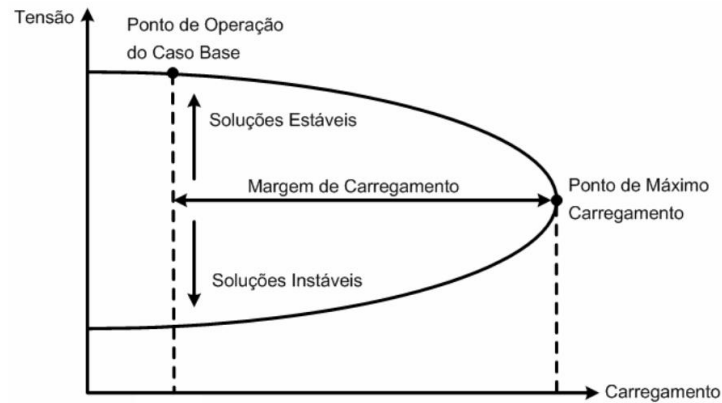
According to Delgado (2019), a complete network is one in which the original system is in normal operation, while an incomplete network occurs when there is a lack of some element of the system, such as substations and transmission lines.

2.7 PV CURVE AND THE FOLLOW-UP METHOD

One of the most used means to analyze voltage stability in SEP is through the PV curve. The PV Figure compares the voltage level in a bar as a function of the power increased in a given direction, and can analyze the proportion of variation between the system operating under normal conditions and cases of instability (DELGADO, 2019).

In **Figure 2**, it is possible to observe that the loading margin is given by the distance between the operating point of the base case and the PMC of the current case. The PMC, or critical point, is the place where the system loses the ability to retain admissible voltage levels, presenting instabilities (DELGADO, 2019).

Figure 2
PV Curve



Source: Resende (2007).

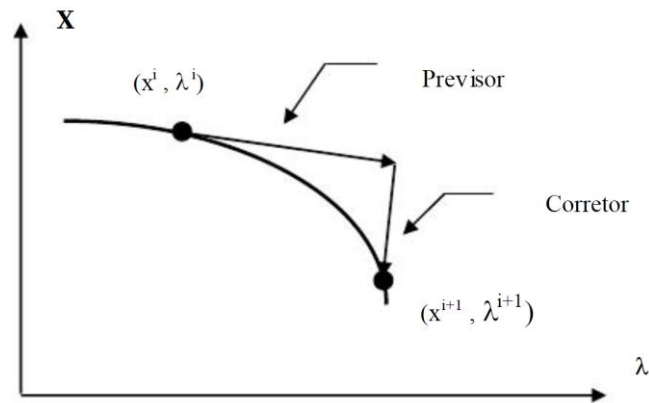
However, in order to trace the PV curve and reach solutions for the power flow in the PMC, other mathematical methods are needed, as the Newton-Raphson method becomes unusual due to the contrariety in relation to convergence when the studied points are close to the collapse point of the system (PINTO, 2013).

Soon, the continuation method, or Continuous Load Flow (FCC), emerges, which rewrites the power flow equations and, through the prediction and correction of the Figureic points, circumvents problems related to convergence, making it possible to reach power flow solutions in the PMC and draw the PV curve (DELGADO, 2019).

The **Figure 3** demonstrates the forecast-correction process used in the FCC solution, where, starting from the initial operating point, it is possible to observe the direction of load growth, from a new estimated operating condition. Thus, the resulting point is corrected by calculating the usual power flow, enabling an equilibrium point (KRAUER, 2007).

Figure 3

Predictor-broker scheme



Source: Krauer (2007).

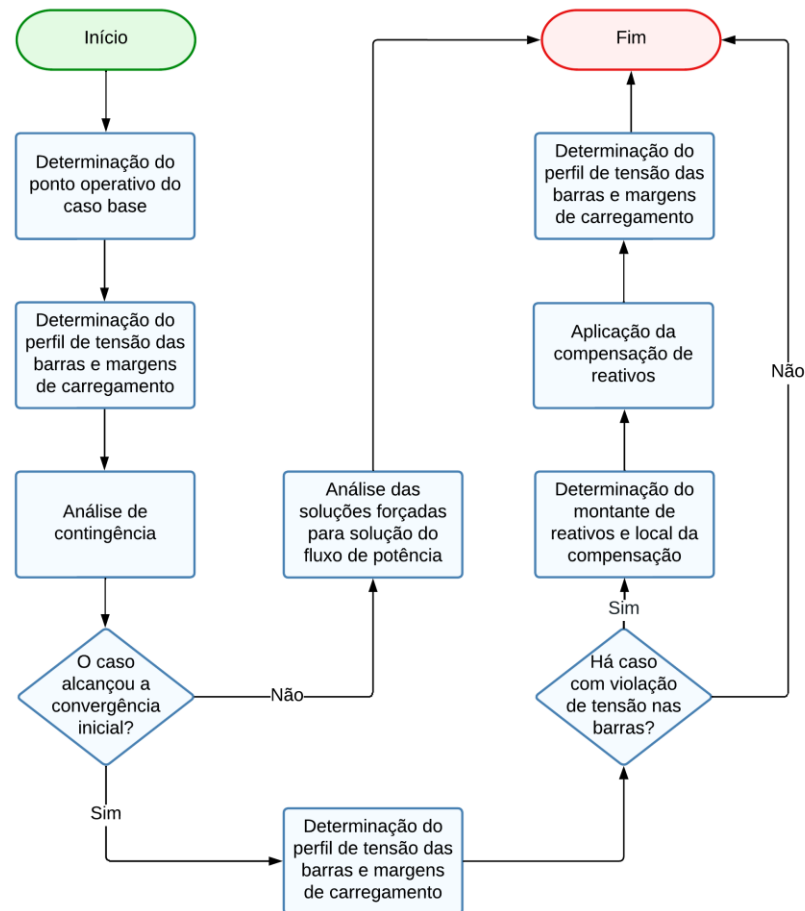
Through the determination of the PV curve by the continuation method, the present research will evaluate the loading margin of the STB-33 test system in three moments: under normal operating conditions, after contingency and after reactive compensation. In this stage, ANAREDE's Continued Power Flow Program will be used.

3 METHODOLOGY ADOPTED IN THIS STUDY

Seeking a better understanding of the methodology to be followed, the flowchart represented in the **Figure 4**, which demonstrates the step-by-step of the proposed methodology.

Figure 4

Flowchart of the research methodology



Source: The authors.

The analyses developed in this work were performed using the STB-33 test system. This and other test systems were developed by Alves (2007) through data taken from the Brazilian SEP, allowing studies through computer programs to have scenarios closer to reality, highlighting parameter violations, collapses, instabilities, oscillations, and other electrical disturbances.

To perform the calculations of the power flow, the contingency analysis and the creation of the PV curves, the *ANAREDE software* was used, which has tools aimed at the studies of the SEP in the steady regime. To carry out the studies aimed at parallel compensation, the *FLUPOT software* was used, together with *ANAREDE*, which allows the planning and allocation of reactive compensation.

Both programs are projects of the Department of Electrical Systems (DSE) and make up the group of Planning and Operation Programs for the Electrical Area of CEPEL, created

with the intention of filling the lack of computational tools aimed at the planning and operation of SEP in Brazil (CEPEL, 2022).

It should be noted that all the studies carried out in this research followed Submodule 23.3 of the Network Procedures, which dictates the guidelines and criteria for electrical studies proposed by ONS (2018).

3.1 DETERMINATION OF THE OPERATIVE POINT

The first step of this work was the determination of the operative point of the base case. For this, the calculation of the power flow was carried out through the Newton-Raphson method, through the EXLF execution code and the NEWT execution control, provided by ANAREDE. The aim was to obtain the voltage profile of the system and the load on the transmission lines to make comparisons with the results of the subsequent analyses.

3.2 SIMPLE CONTINGENCY ANALYSIS OF TRANSMISSION LINES

In order to analyze each contingency case separately, the Automatic Contingency Analysis execution code was used, provided by the Contingency Analysis Program of ANAREDE. For each contingency of a TL, the program performs a new calculation of the power flow by the Newton-Raphson method, monitoring the operational state of the network.

The contingency program provides monitoring reports that display lists of the critical busbars of contingency cases, detailing those that have violations of voltage, power flow, and reactive power generation parameters. This information is made available through the MOCT, MOCF, and MOCG options, respectively. The *software* details critical cases using the severity index, which is used to order contingency cases based on the mean square deviation in relation to the limits of each quantity that will be monitored (ONS, 2018).

ANAREDE also provides a list of controls and, based on the methodology of Alves (2007), three of them were selected:

- CAP: controls the voltage by transformer with automatic variation of TAP under load;
- QLIM: controls the limit of reactive power generation;
- CREM: Remotely controls voltage by reactive power sources.

Together with the voltage monitoring report, the emergency operating voltage levels pre-established by ONS (2018), presented in the **Table 1**.

Table 1

Permissible phase voltages at 60Hz

Rated operating voltage	Normal operating condition		Emergency operating condition	
(kV)	(kV)	(PU)	(kV)	(PU)
<230	...	0.950 to 1.050	...	0.900 to 1.050
	Pages		Pages	
230	218 to 242	0.950 to 1.050	207 to 242	0.900 to 1.050
345	328 to 362	0.950 to 1.050	311 to 362	0.900 to 1.050
440	418 to 460	0.950 to 1.046	396 to 460	0.900 to 1.046
500	500 to 550	1,000 to 1,100	475 to 550	0.950 to 1.100
525	500 to 550	0.950 to 1.050	475 to 550	0.900 to 1.050
765	690 to 800	0.900 to 1.046	690 to 800	0.900 to 1.046

Source: ONS (2018).

For contingency cases that did not obtain a solution for the power flow, that is, that did not achieve its convergence, the methodology of Alves (2007) was followed. The proposed procedure consists of three steps:

- 1) Shutdown of execution controls.
- 2) Relaxation in the load representation at 75% of the active power and 100% of the reactive power, varying with the square of the voltage.
- 3) Establishment of the bus that interconnects the contingency transmission line as a reference.

3.3 APPLICATION OF PARALLEL COMPENSATION

As a solution for the elimination of voltage violations after the contingency of a TL, the application of parallel reactive compensation was established. For this, the *FLUPOT* and *ANAREDE* software were used.

First, FLUPOT was used in order to obtain the most appropriate amount of reagents and bars for the allocation of compensation. For the objective function, Voltage Control

(CLTN) was used. This option sets a reactive adjustment based on the busbar voltage limits. DVLB and DCAQ functions were also required, which receive the data of voltage limits per bar and delimit the maximum amount of reagent injection in MVar, respectively. ANAREDE was used to carry out and evaluate the effectiveness of this compensation in relation to voltage violations in the case of contingency.

In this stage of the research, contingency cases that resulted in power flow violation in the TLs were discarded, as it was not the objective of this work to carry out studies of reactive series compensation.

3.4 DETERMINATION OF THE PV CURVE

According to ONS (2018), in order to carry out studies that cover voltage safety, it is necessary to obtain the stability margin through simulations and make comparisons in different scenarios, in which the power factor must be kept constant during the process.

In this work, through the plotting of the PV curve and the continuation method, the loading margin of the system was determined in three distinct cases: base case, after contingency and after the application of parallel compensation. For the analysis of the loading margin, the Continuous Power Flow Program was used, which allows plotting the PV curve through successive increments of loads, attributing an increment of 0.2% to both active and reactive power, which, according to Delgado (2019), ensures a constant power factor for the same curve.

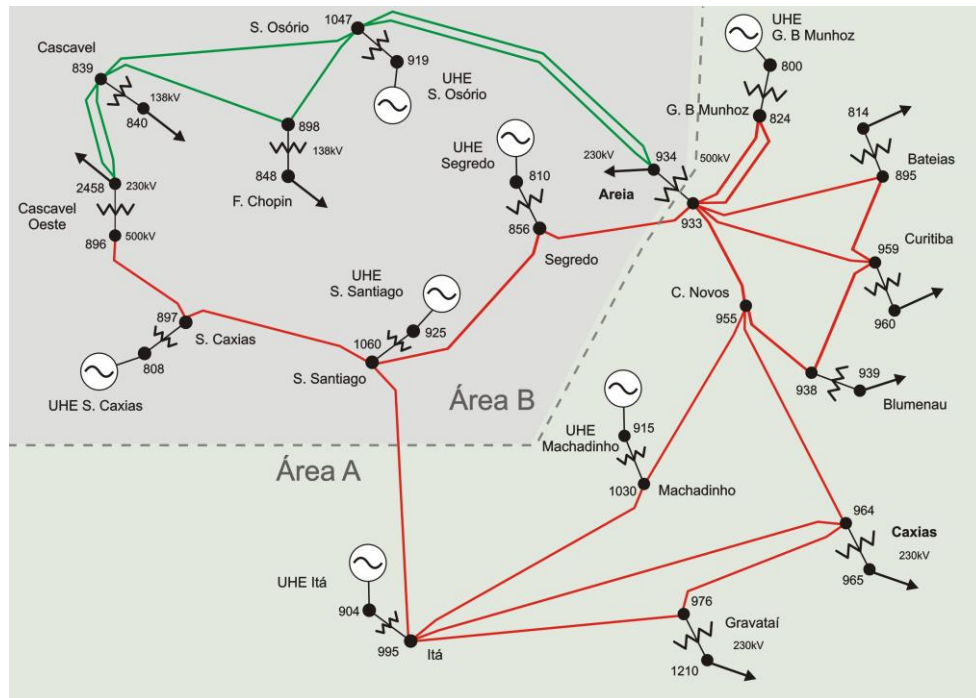
4 RESULTS AND DISCUSSIONS

4.1 SIMPLE CONTINGENCY OF STB-33 TRANSMISSION LINES

The test system chosen to receive the analyses of this work was the STB-33 test system, also known as the Reduced South System. It was prepared from data taken from the 230kV and 500kV grids of the southern region of Brazil, as can be seen in the **Figure 5**.

Figure 5

Brazilian 33-Bar Test System



Source: Alves (2007).

The system represents 33 bars and 7 large generators, totaling a maximum demand of 5.085MW and a total generation capacity of 8.912MW. The network was divided into two geoelectric areas, A and B, which are interconnected by two TLs and a transformer. Area A has a higher concentration of load and is unable to meet its demand, thus arising the need to import energy from area B.

The system has a topological characteristic of a mottled arrangement, forming a ring that connects the plants in the region. This results in a robust and structured drivetrain. Therefore, the removal of a TL does not cause the isolation of any other element of the network, resulting in 26 simulated contingency cases, as provided for in the **Table 2**.

Table 2
Contingency cases

Case	From	Towards	Name	Voltage (kV)	Circuit	Area
1	824	933	Gov. Bento Munhoz – Areia	500	1	A
2	824	933	Gov. Bento Munhoz – Areia	500	2	A
3	839	898	Cascavel – Foz do Chopin	230	1	B
4	839	1047	Cascavel – Salto Osório	230	1	B
5	839	2458	Cascavel – Cascavel Oeste	230	1	B
6	839	2458	Cascavel – Cascavel Oeste	230	2	B
7	856	933	Secret – Sand	500	1	A → B
8	856	1060	Secret – Salto Santiago	500	1	B
9	896	897	Cascavel Oeste – Salto Caxias	500	1	B
10	898	1047	Foz do Chopin – Salto Osório	230	1	B
11	933	895	Sand – Bateias	500	1	A
12	933	955	Areia – Campos Novos	500	1	A
13	933	959	Sand – Curitiba	500	1	A
14	934	1047	Sand – Salto Osório	230	1	B
15	934	1047	Sand – Salto Osório	230	2	B
16	938	955	Blumenau – Campos Novos	500	1	A
17	938	959	Blumenau – Campos Novos	500	1	A
18	955	964	Campos Novos – Caxias	500	1	A
19	959	895	Curitiba – Bateias	500	1	A
20	964	976	Caxias – Gravataí	500	1	A
21	976	995	Gravataí – Itá	500	1	A
22	995	964	Itá – Caxias	500	1	A
23	995	1030	Itá – Machadinho	500	1	A
Case	From	Towards	Name	Voltage (kV)	Circuit	Area
24	995	1060	Itá – Salto Santiago	500	1	A → B
25	1030	955	Machadinho – Campos Novos	500	1	The
26	1060	897	Salto Santiago – Salto Caxias	500	1	B

Source: The authors.

Using the Automatic Contingency Analysis function, ANAREDE performs simple contingencies of TLs, finding new solutions to the problem of power flow through the Newton-Raphson method, in view of the contingency and its interference with the parameter of voltage, power flow and reactive generation of the test system. Next, ANAREDE displays the

monitoring reports, detailing whether the contingency case has achieved its convergence and whether there have been parameter violations.

According to Alves' (2007) methodology, to facilitate the convergence process, the procedure of blocking the tap value in the first solution was adopted, deactivating the CTAP control at first, and then the analysis was carried out considering this control, but no difference was obtained in the results. The results of the simulations can be found in the

Table 3.

Table 3

Result of contingency simulations

No Violation	With violation			Non-convergent
...	Tension	Power Flow	Voltage and Power Flow	...
10	2	5	2	7

Source: The authors.

The results of the simulations can be summarized in three situations: of the 26 simulated cases, 10 did not present parameter violations, 7 cases did not reach their convergence, that is, it was not possible to find a solution for the power flow, and in 9 cases there was a violation of some network parameter. Of these, 2 resulted in voltage violation, 5 resulted in power flow violation, and in 2 cases there was voltage and flow violation. The

Table 4 details the contingency cases that resulted in voltage violations.

Table 4

Contingency cases with voltage violations

Case	From	Towards	Name	Voltage (kV)	Circ.	Area
7	856	933	Secret – Sand	500	1	A → B
18	955	964	Campos Novos – Caxias	500	1	The
Case	From	Towards	Name	Voltage (kV)	Circ.	Area
22	995	964	Itá – Caxias	500	1	The
24	995	1060	Itá – Salto Santiago	500	1	A → B

Source: The authors.

It can be observed that the busbars where voltage violations occurred are not limited only to the dams of the contingency TLs, but also to the busbars in their vicinity. All violated busbars are located in area A, as this area presents an excess of demand, resulting in

undervoltage in the critical busbars which, according to Pinto (2013), are prone to induce the entire system to a voltage collapse.

In

Table 5, the contingency cases that resulted in flow violations in the TLs are presented.

Table 5

Contingency cases with flow violations

Case	From	Towards	Name	Voltage (kV)	Circ.	Area
3	839	898	Cascavel – Foz do Chopin	230	1	B
4	839	1047	Cascavel – Salto Osório	230	1	B
7	856	933	Secret – Sand	500	1	A → B
10	898	1047	Foz do Chopin – Salto Osório	230	1	B
14	934	1047	Sand – Salto Osório	230	1	B
15	934	1047	Sand – Salto Osório	230	2	B
24	995	1060	Itá – Salto Santiago	500	1	A → B

Source: The authors.

It is possible to observe that the cases of flow violations occurred in lines that are entirely in area B and in the only two cases in which the exchange of energy between areas occurs. This is due to the fact that area A does not have enough generation to supply its loads, supplying only 52.8% of its demand, resulting in the need to import energy from area B.

Cases 7 and 24 were the only cases that resulted in the violation of both voltage and flow. By analyzing the single-line diagram of the system, presented in the **Figure 5**, it can be seen that, if one of these lines is lost, areas A and B are interconnected only by a single TL, which hinders the exchange of energy between the areas. The cases in which it was not possible to achieve initial convergence are listed in the **Table 6**.

Table 6

Contingency cases that did not converge

Case	From	Towards	Name	Voltage (kV)	Circ.	Area
9	896	897	Cascavel Oeste – Salto Caxias	500	1	B
11	933	895	Sand – Bateias	500	1	The
13	933	959	Sand – Curitiba	500	1	The
16	938	955	Blumenau – Campos Novos	500	1	The
20	964	976	Caxias – Gravataí	500	1	The

21	976	995	Gravataí – Itá	500	1	The
26	1060	897	Salto Santiago – Salto Caxias	500	1	B

Source: The authors.

The first step to find the load flow solution consisted of turning off the execution controls of ANAREDE. In this first attempt at convergence, only cases 9 and 26 were resolved; however, they resulted in high levels of violation in the parameters of voltage, reactive generation and power flow. In the second stage, a relaxation of the representation of the loads was carried out. According to Alves (2007), this measure favors convergence, because the current required by the load will be lower, reducing the voltage drop. Thus, all cases of **Table 6** reached their convergence, resulting in a violation of some parameter, with the exception of case 26, which did not converge.

The third and last attempt consisted of establishing busbars that interconnect the contingency TL as a reference, seeking to obtain the solution of the power flow, even if the voltage is corrupted. At this stage, all cases have achieved solutions for cargo flow; However, case 26 was the only one that did not present any violation in its parameters.

The

Table 7 details case 9 in the three attempts to search for the forced solution of the problem, resulting in large variations of violations of the voltage, reactive generation and flow parameters, regardless of the method.

Table 7

Case 9: Severity indices in forced load flow solutions

Forced solution	Severity Index		
	Tension	Reactive generation	Power Flow
...			
Switching off controls	502,1	120,9	9,9
Load relaxation	50,1	11,3	5,0
Reference bar	49,7	10,9	5,0

Source: The authors.

With regard to studies related to the compensation of reactives, cases that converged from the forced solution of the power flow will not be considered, due to the number of simplifications used to achieve their convergence.

4.2 PARALLEL COMPENSATION AND VOLTAGE VIOLATION CASES

After the contingency analysis, there were four cases that resulted in voltage violations, with case 18 obtaining the highest severity index. It is through the severity index that ANAREDE determines the classification of critical contingencies.

To define the appropriate amount of reactive for allocation, FLUPOT's CLTN objective function was used, which determines an adjustment in the reactive controls, in order to maintain the voltage of the busbars within the limits that were specified (CEPEL, 2018). The selection criterion for the application of reactive compensation was based on choosing the bars where the voltage violations occurred, not only those belonging to the contingency TL.

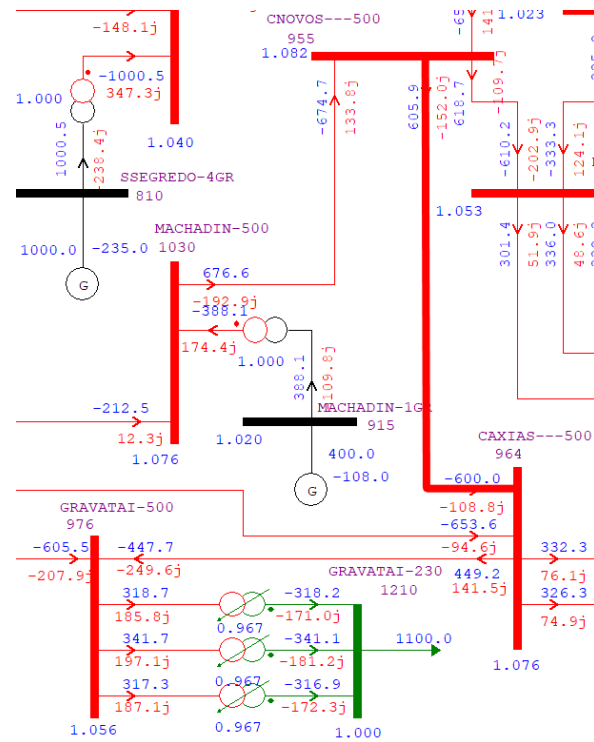
As mentioned in the section 0, for the application of parallel reactive compensation, cases that presented power flow violations were disregarded, since the objective of parallel compensation is to improve the voltage profile of the busbars of a system. Therefore, cases 18 and 22 were chosen to detail the corresponding studies.

4.3 CASE 18

The contingency of case 18 occurs due to the disconnection of the Campos Novos – Caxias line, delimited by dams 955 and 964, respectively. This line has a voltage of 500kV, is located in area A and is the only connection between these busbars. It is possible to observe in the **Figure 6** that the voltage levels of the busbars belonging to the TL and the peripheral buses are within the normal operating limits pre-established by the ONS for 13.8kV, 230kV and 500kV busbars.

Figure 6

Case 18: Campos Novos (955) – Caxias (964)

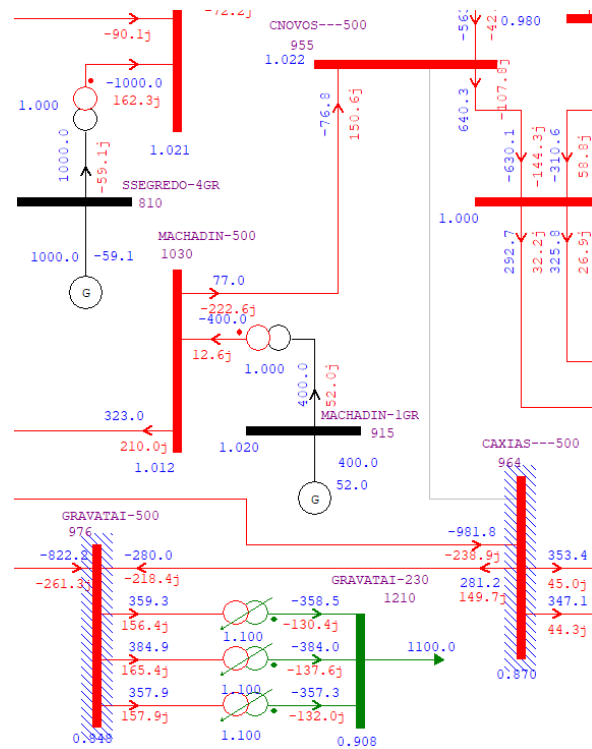


Source: The authors.

The result of the simulation of the contingency of case 18 can be found in the **Figure 7**.

Figure 7

Case 18: after the contingency



Source: The authors.

Then, the simulation of the loss of the transmission line was carried out through ANAREDE. The result of the monitoring report provided by the *software* is in the

Table 8.

Table 8

Case 18: Voltage monitoring report

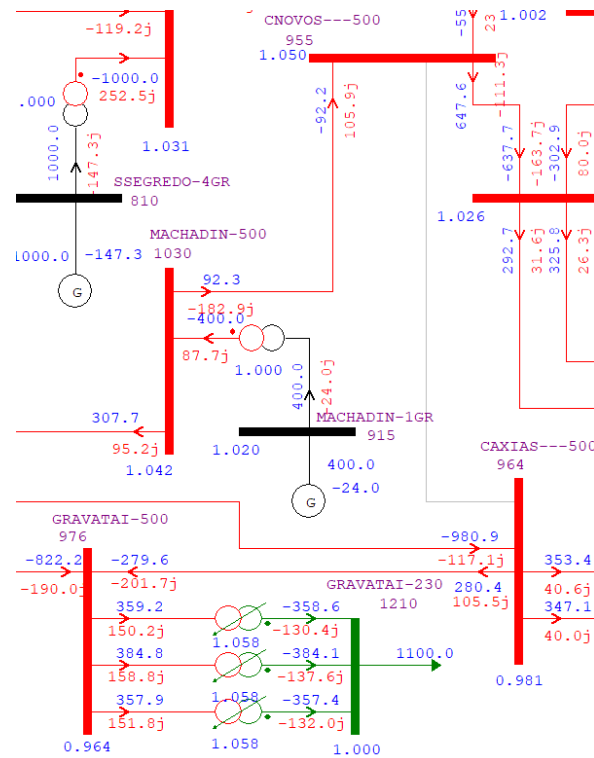
Bar	Name	Area	Voltage (PU)			Violation (pu)	Severity
...	...	...	Minim	Monitored	Maxim	...	...
964	Caxias	The	0,950	0,870	1,100	-0,080	168,0
976	Gravataí	The	0,950	0,848	1,100	-0,102	

Source: The authors.

After the contingency, voltage violations occurred in the 964 and 976 buses, both of 500kV. It is possible to observe that the Gravataí dam (976) is a neighboring element. Therefore, for this case, not only the bars belonging to the contingency transmission line were chosen to receive the compensation, but also the bar 976, as shown in the **Figure 8**.

Figure 8

Case 18: after compensation



Source: The authors.

The FLUPOT program was used to determine the appropriate amount of reagents for compensation. The

Table 9 refers to the results of the number of reagents allocated to the **Figure 8**.

Table 9

Case 18: Allocated reactive power report

Bar	Name	Allocated Power (MVar)
955	New Fields	16,63
964	Caxias	71,78
976	Gravataí	74,40

Source: The authors.

Finally, the system was compared under normal operating conditions with the two prominent situations of this case: after the contingency and after the application of parallel compensation. For such detailing, the **Table 10**, which presents the stresses of the members of the contingency transmission line and neighboring lines.

Table 10

Case 18: Voltage comparison

Bar	Name	Voltage (PU)		
		Base case	After the contingency	After clearing
...	...			
933	Sand	1,045	1,020	1,033
938	Blumenau	1,053	1,000	1,026
955	New Fields	1,082	1,022	1,050
964	Caxias	1,076	0,870	0,981
976	Gravataí	1,056	0,848	0,964
995	Italy	1,071	0,986	1,027
1030	Hatchet	1,076	1,012	1,042

Source: The authors.

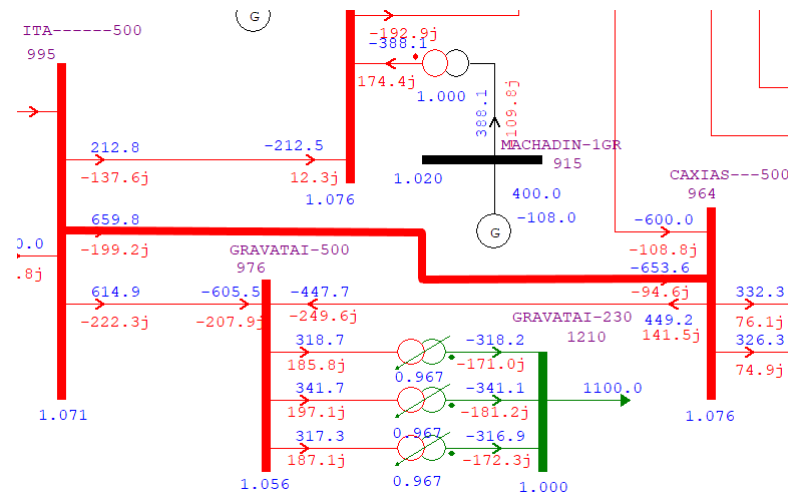
With the data presented, it is possible to observe that, after the simulation of the contingency, there was a significant voltage drop, not only in the busbars of the contingency TL, but also in the neighboring busbars. As for compensation, it proved to be effective, as the stress levels of the violated bars returned to the emergency limits stipulated by the ONS.

4.4 CASE 22

The second case studied was case 22, which addresses the analysis of the Itá (995) – Caxias (964) line, represented by the **Figure 9**. This 500kV line plays a fundamental role in interconnecting the busbars and is located in area A. In the figure, it is possible to observe the normal operation of the line, operating within the limits established by the ONS. This interconnection is extremely important to ensure the stability and reliability of the electrical system, supporting the flow of energy necessary to meet regional demand.

Figure 9

Case 22: Itá (995) - Caxias (964)



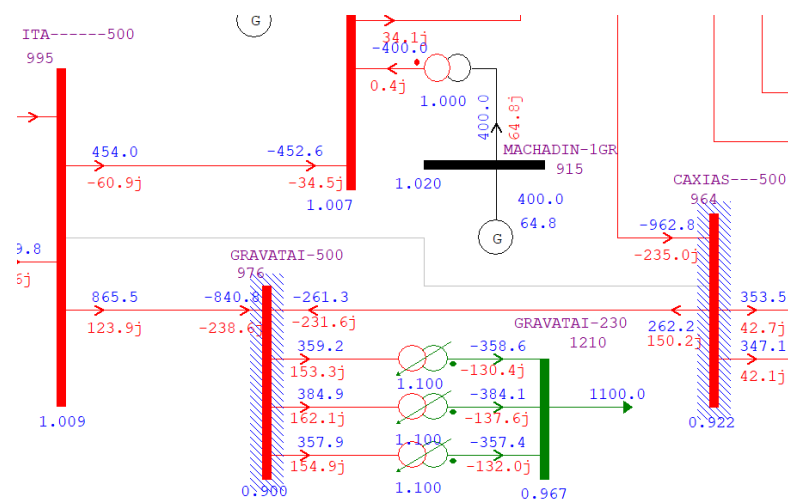
Source: The authors.

The

Figure 10 presents in detail the case studied, taking into account the disconnection of the specific line.

Figure 10

Case 22: after the contingency



Source: The authors.

The monitoring report is detailed in the



Table 11.

Table 11

Case 22: Voltage monitoring report

Bar	Name	Area	Voltage (PU)			Violation (pu)	Severity
			Minim	Monitored	Maxim		
...	...	...				...	...
964	Caxias	The	0,950	0,922	1,100	-0,028	32,6
976	Gravataí	The	0,950	0,900	1,100	-0,050	

Source: The authors.

After the contingency, voltage violations occurred in the 964 and 976 buses, both of 500kV. In this case, due to the fact that the severity index was lower, only the violated bars were chosen to receive compensation and, based on the definition of the bars, FLUPOT returned the report from the

Table 12, which specifies the most appropriate amount of reactive power for compensation *Shunt*.

Table 12

Case 22: Allocated reactive power report

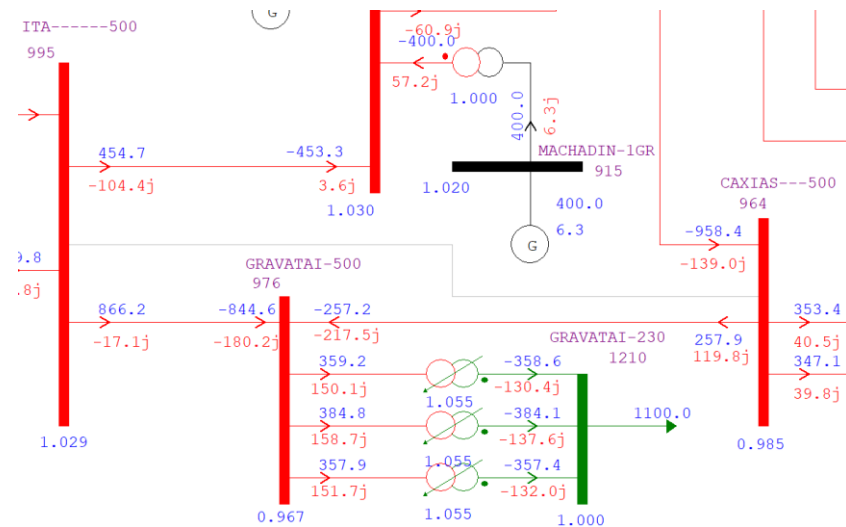
ar	Name	Allocated Power (MVar)
64	Caxias	62,99
76	Gravataí	67,15

Source: The authors.

The result of the application of the compensation can be seen in the **Figure 11**.

Figure 11

Case 22: after the compensation of reactive agents



Source: The authors.

In addition, it was detailed in the

Table 13 the comparison of stress levels in the three scenarios: base case, after contingency and after reactive compensation. It is possible to observe that, even after compensation, the voltage of the busbars did not reach the same values as in the base case, but still falls within the emergency operational limits.

Table 13

Case 22: Voltage comparison

Bar	Name	Voltage (PU)		
		Base case	After the contingency	After clearing
955	New Fields	1,082	1,000	1,029
964	Caxias	1,076	0,922	0,985
976	Gravataí	1,056	0,900	0,967
995	Italy	1,071	1,009	1,029
1030	Hatchet	1,076	1,007	1,030
1060	Salto Santiago	1,050	1,030	1,037

Source: The authors.

4.5 LOADING MARGIN ANALYSIS

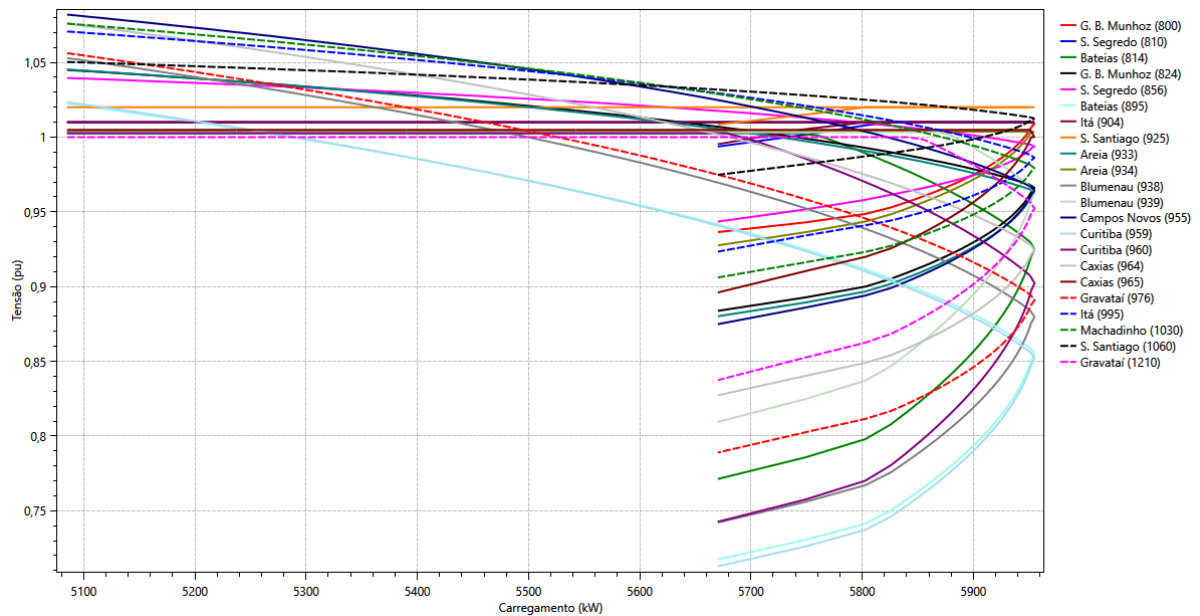
Regarding the studies related to voltage stability, the PV curves were determined using the Continuous Power Flow Program, available at ANAREDE. The program performs successive load increments, and it is possible to observe the maximum charging point (PMC) that the system can maintain safe voltage levels. For this, a load increase of 0.2% of active

and reactive power was carried out for each iteration, which, according to Delgado (2019), guarantees a constant power factor for the same PV curve.

Figure 12 shows the PV curves of the base case buses.

Figure 12

Base case: PV curves



Source: The authors.

The base case has a loading margin of 5.9550MW and a voltage safety margin (MST) of 17.1086%. The ONS (2018) determines that, for complete systems, the MST is at least 7%, which makes the test system within the accepted criteria. However, it is possible to observe that not all busbars were able to maintain voltage levels above the minimum limits established by ONS. The **Table 14** Shows the voltage levels at the maximum loading point of the complete test system.

Table 14

Base case: voltages monitored in the PMC

Bar	Name	Tension (kV)	Minimum Emergency Voltage (PU)	Tension in the PMC (PU)
800	Gov. Bento Munhoz	13,8	0,900	1,009
810	Secret Jump	13,8	0,900	1,010
814	Bateias	230	0,900	0,925
824	Gov. Bento Munhoz	500	0,950	0,966
856	Secret Jump	500	0,950	0,994
895	Bateias	500	0,950	0,855
904	Italy	13,8	0,900	1,010
925	Secret Jump	13,8	0,900	1,020
933	Sand	500	0,950	0,963
934	Sand	230	0,900	1,004
938	Blumenau	500	0,950	0,880
939	Blumenau	230	0,900	0,962
955	New Fields	500	0,950	0,964
959	Curitiba	500	0,950	0,852
960	Curitiba	230	0,900	0,902
964	Caxias	500	0,950	0,925
965	Caxias	230	0,900	1,000
976	Gravataí	500	0,950	0,891
995	Italy	500	0,950	0,986
1030	Hatchet	500	0,950	0,979
1060	Salto Santiago	500	0,950	1,012
1210	Gravataí	230	0,900	0,952

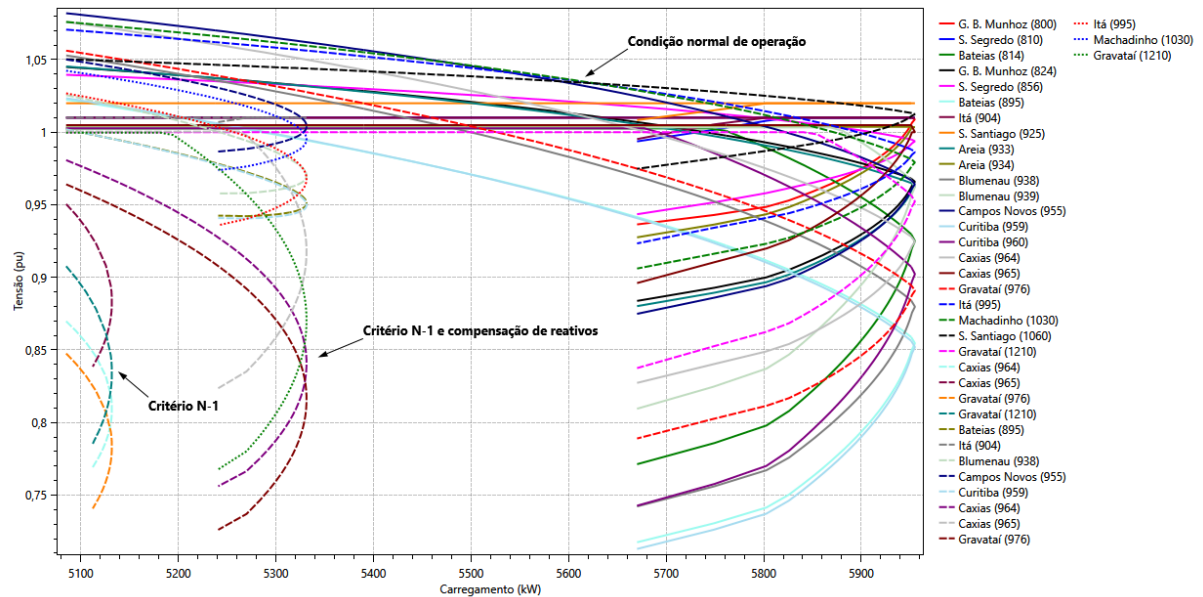
Source: The authors.

By analyzing the diagram of the test system, it is possible to observe that the bars that are unable to support the increase in load are substations interconnected to high loads. This interconnection with high demands makes such bars highly critical when confronted with events of this type.

Figure 13 shows the PV curves of the base case and of case 18, taking into account the contingency suffered and the measures adopted for the compensation of reactivities. This Figureical analysis allows a complete visualization of the effects of these occurrences and the solutions implemented to mitigate the resulting imbalances.

Figure 13

Case 18: comparison of all PV curves

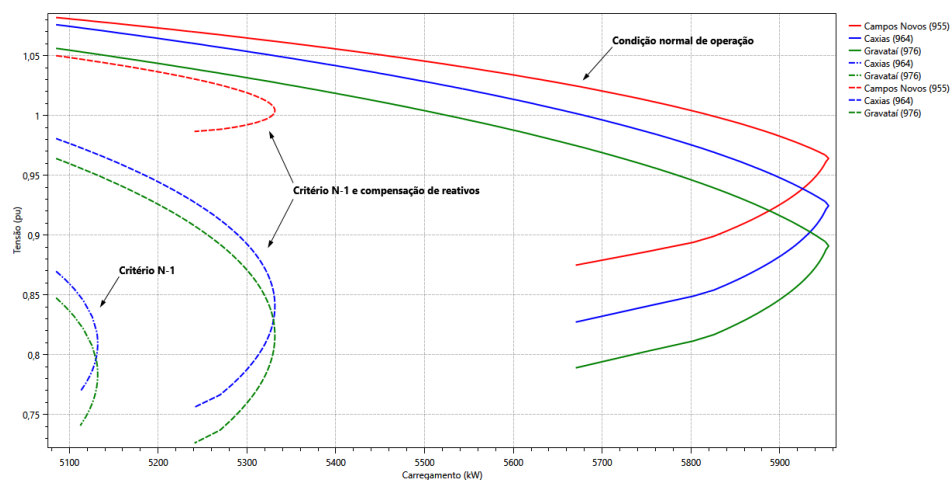


Source: The authors.

For a clearer and more objective visualization, Figure 14 was elaborated, which shows only the busbars of the contingency line of case 18 and the bar that presented the voltage violation.

Figure 14

Case 18: comparison of PV curves of bars 955, 964 and 976



Source: The authors.

The **Table 15** details the stresses on the members at the point of maximum loading in the three situations of Figures 2 and 3.

Table 15

Case 18: Tensions in the CMP after contingency and compensation

Bar	Name	Voltage (PU)		
		Base case	Criterion N-1	Criterion N-1 and Compensation
...	...			
895	Bateias	0,855	...	0,952
904	Italy	1,010	...	1,010
938	Blumenau	0,880	...	0,971
955	New Fields	0,964	...	1,005
959	Curitiba	0,852	...	0,950
964	Caxias	0,925	0,812	0,842
965	Caxias	1,000	0,886	0,920
976	Gravataí	0,891	0,786	0,818
995	Italy	0,986	...	0,969
1030	Hatchet	0,979	...	0,996
1210	Gravataí	0,952	0,837	0,872

Source: The authors.

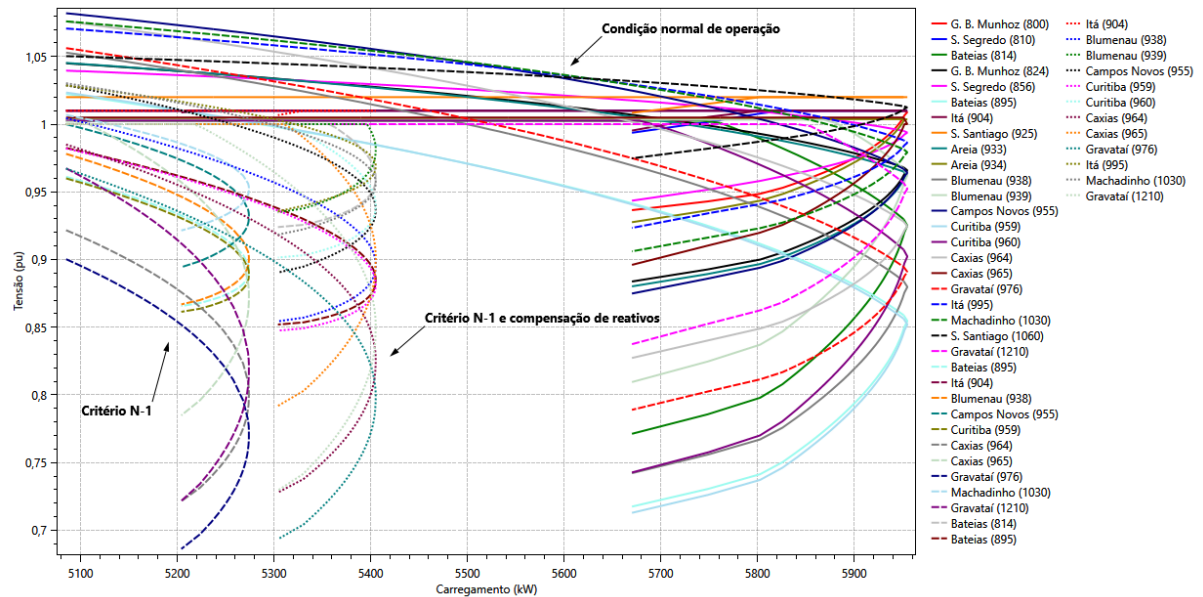
When it comes to incomplete systems, that is, after the loss of some element, the minimum margin of voltage stability established by the ONS must be 4%. Case 18 is the most critical contingency case of STB-33, obtaining a loading margin of 5.1318MW and an MST of 0.9209%, making the system unstable from the point of view of voltage stability.

After the compensation of reactives, there was an increase in the PMC to 5.3313MW and the MST to 4.8446%, making this case within the minimum limit of 4%. However, some busbars did not reach the minimum emergency limit, because when the load is increased, the electric current in the line increases and, consequently, the voltage drop in the line increases and the voltage of the critical bus decreases.

Figure 15 presents a comprehensive set of information on the PV curves in the scenario of case 22, considering all possible simulations after the occurrence of the contingency on the Itá – Caxias line. In addition, the chart also demonstrates the bar curves after the implementation of reactive compensation. These curves offer a complete view of the changes that have occurred in the system, allowing for more in-depth analysis and a clearer understanding of the effects of contingency and compensation.

Figure 15

Case 22: comparison of all PV curves

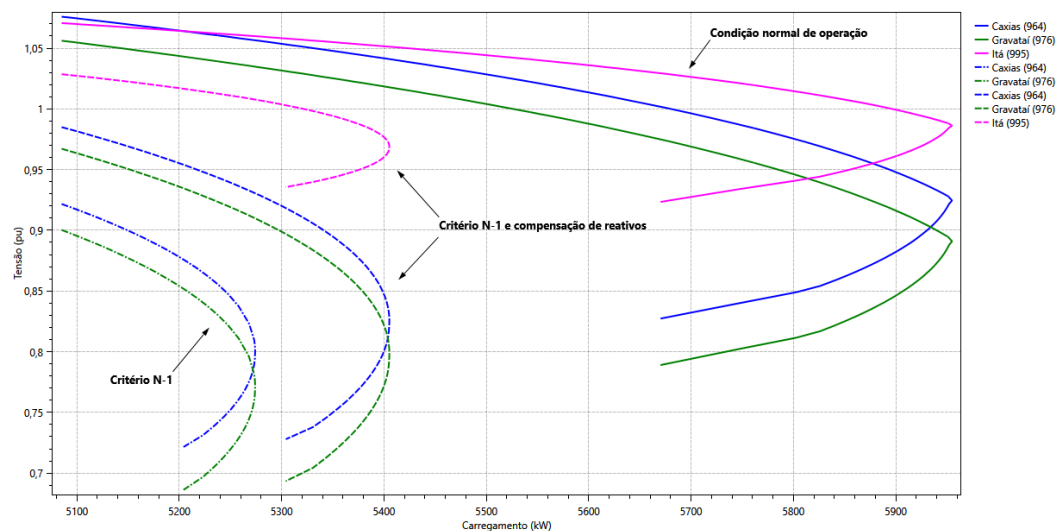


Source: The authors.

Figure 16 presents case 22 in order to detail the PV curves of the members belonging to the contingency TL, as well as the bus where the voltage violation occurred.

Figure 16

Case 22: comparison of PV curves of bars 964, 976 and 995



Source: The authors.

The PMC of case 22, after the disconnection of the line, was 5.2741MW and the MST of 3.7185%, which makes the system unstable considering the voltage stability, as the MST is less than the minimum limit of 4%. However, when parallel compensation is applied, the PMC is 5.4052MW and the MST is 6.2976%.

Table 16 that, even after the application of reactive compensation, the violated busbars remain critical, because, due to the increase in load, there was undertension in the bars close to the highest load amounts.

Table 16

Case 22: Tensions in the CMP after contingency and compensation

Bar	Name	Voltage (PU)		
		Base case	Criterion N-1	Criterion N-1 and Compensation
...	...			
814	Bateias	0,925	...	0,960
895	Bateias	0,855	0,893	0,885
904	Italy	1,010	...	1,010
938	Blumenau	0,880	0,902	0,896
939	Blumenau	0,962	...	0,981
955	New Fields	0,964	0,933	0,937
959	Curitiba	0,852	0,890	0,882
960	Curitiba	0,902	...	0,940
964	Caxias	0,925	0,802	0,825
965	Caxias	1,000	0,874	0,900
976	Gravataí	0,891	0,773	0,798
995	Italy	0,986	...	0,969
1030	Hatchet	0,979	0,953	0,957
1210	Gravataí	0,952	0,821	0,849

Source: The authors.

In order to obtain a more general view of the loading margins and MST after the contingencies, the **Table 17**. It contains the base case and the contingency cases, except for the cases that did not reach the initial convergence.

Table 17

Loading margin classification after contingency

<i>Ranking</i>	<i>Case</i>	<i>From</i>	<i>Towards</i>	<i>Tension (kV)</i>	<i>Circ.</i>	<i>Area</i>	<i>Upload (MW)</i>	<i>MST (%)</i>
First	Base	...	...	...	...	...	5,9550	17,1086
2nd	5	839	2458	230	1	B	5,9544	17,0982
Third	6	839	2458	230	2	B	5,9543	17,0963
4th	3	839	898	230	1	B	5,9449	16,9101
5th	14	934	1047	230	1	B	5,9347	16,7090
6th	15	934	1047	230	2	B	5,9346	16,7089
7th	10	898	1047	230	1	B	5,9333	16,6833
8th	2	824	933	500	1	The	5,9321	16,6591
<i>Ranking</i>	<i>Case</i>	<i>From</i>	<i>Towards</i>	<i>Tension (kV)</i>	<i>Circ.</i>	<i>Area</i>	<i>Upload (MW)</i>	<i>MST (%)</i>
9th	1	824	933	500	2	The	5,9318	16,6526
10th	8	856	1060	500	1	B	5,8945	15,9194
11th	23	995	964	500	1	The	5,8802	15,6387
12th	19	959	895	500	1	The	5,8359	14,7674
13th	25	1030	955	500	1	The	5,6997	12,0889
14th	12	933	955	500	1	The	5,6138	10,3991
15th	4	839	1047	230	1	B	5,4973	8,1080
16th	7	856	933	500	1	A → B	5,3145	4,5131
17th	24	995	1060	500	1	A → B	5,3024	4,2761
18th	22	995	964	500	1	The	5,2741	3,7185
19th	17	938	959	500	1	The	5,2122	2,5024
20th	18	955	964	500	1	The	5,1318	0,9209

Source: The authors.

The base case has the best loading margin and MST, as it is the complete system and is operating under normal conditions. There were contingency cases in which the system is well prepared to receive them, such as cases 5 and 6, because they are located in an area (B) where the energy demand is lower than its generation.

It is possible to observe that the most critical contingency cases, that is, those that presented the highest severity indexes, are found lower in the *ranking* indicating a lower loading margin, as well as MST. The **Table 18** presents the *ranking* with updated data from cases 18 and 22 after reactive compensation.

Table 18

Loading margin classification after compensation

<i>Ranking</i>	<i>Case</i>	<i>Fro m</i>	<i>Tow ards</i>	<i>Tension (kV)</i>	<i>Circ.</i>	<i>Area</i>	<i>Upload (MW)</i>	<i>MST (%)</i>
First	Base	...	...	...	...	...	5,9550	17,1086
2nd	5	839	2458	230	1	B	5,9544	17,0982
Third	6	839	2458	230	2	B	5,9543	17,0963
4th	3	839	898	230	1	B	5,9449	16,9101
5th	14	934	1047	230	1	B	5,9347	16,7090
6th	15	934	1047	230	2	B	5,9346	16,7089
<i>Ranking</i>	<i>Case</i>	<i>Fro m</i>	<i>Tow ards</i>	<i>Tension (kV)</i>	<i>Circ.</i>	<i>Area</i>	<i>Upload (MW)</i>	<i>MST (%)</i>
7th	10	898	1047	230	1	B	5,9333	16,6833
8th	2	824	933	500	1	The	5,9321	16,6591
9th	1	824	933	500	2	The	5,9318	16,6526
10th	8	856	1060	500	1	B	5,8945	15,9194
11th	23	995	964	500	1	The	5,8802	15,6387
12th	19	959	895	500	1	The	5,8359	14,7674
13th	25	1030	955	500	1	The	5,6997	12,0889
14th	12	933	955	500	1	The	5,6138	10,3991
15th	4	839	1047	230	1	B	5,4973	8,1080
16th	22	995	964	500	1	The	5,4052	6,2976
17th	18	955	964	500	1	The	5,3313	4,8446
18th	7	856	933	500	1	A → B	5,3145	4,5131
19th	24	995	1060	500	1	A → B	5,3024	4,2761
20th	17	938	959	500	1	The	5,2122	2,5024

Source: The authors.

Parallel compensation proves to be effective, causing cases 18 and 22 to increase their loading margins and MSTs, being within the minimum limits stipulated by the ONS and increasing their respective positions in the *ranking*.

5 FINAL CONSIDERATIONS

The electrical system needs to be reliable and able to withstand contingencies to ensure the demand for energy without overloading equipment, such as generators, transformers, and LTs. It is important to carry out voltage stability studies to identify the vulnerable points of the system, and a widely used method for this is the PV curve. The

application of parallel compensation is essential for the control of reactive power in the network and better performance of transmission lines, regardless of their length.

The objective of this research was to analyze the voltage stability of the STB-33 test system in three different situations: the base case, after the simulation of the simple contingency analysis of transmission lines and after the application of parallel reactive compensation in contingency cases that had voltage violations in their busbars, as a solution for such violations.

To perform the contingency analysis, the *ANAREDE software* was used, which seeks a new solution to the power flow problem through the Newton-Raphson method in each contingency simulation. For this stage, cases in which the removal of the TL caused the isolation of some element of the network were discarded, resulting in 26 contingency cases.

There were seven cases in which the initial solution was not found, most of them belonging to area A, where there is a greater exchange of energy with area B. Among the solutions presented, establishing the bars that interconnect the contingency TL as a reference resulted in convergence of all cases and the lowest severity indexes. It is important to understand the power flow solution to assess whether the system can maintain voltage stability during emergencies, so these cases have been disregarded from studies related to reactive compensation, due to the amount of simplification made to achieve convergence of these cases.

The contingency cases that resulted in the initial convergence of the problem, but with power flow violations on the lines, are mainly in area B of the test system. Due to the fact that area A is unable to generate enough power to meet its demand, the need arises to import power from area B. Among the four cases that resulted in voltage violations in their busbars after the contingency, two cases are entirely in area A, which has a demand greater than the power supply, resulting in drops in the magnitude of tension of the contingency bars and neighboring busbars.

Using FLUPOT and calculating the POF, the amount of reactive to be allocated and the bars that should receive parallel compensation were determined, thus avoiding a poorly dimensioned compensation. In cases 18 and 22, compensation proved to be assertive, recovering the stresses of the busbars, not only where the compensation was allocated, but also in peripheral busbars.

To determine the PV curve and to be able to analyze the loading margin, the ANAREDE continuation method was used. In cases 18 and 22, when the load increase is

carried out, it is possible to observe that not all busbars are considered stable from the point of view of tension, as is the case of busbars violated after contingencies. These bars, even before compensation, are considered critical, as an undervoltage occurs when placed under a state of emergency, not being able to remain stable in the face of an increase in load after compensation.

The base case obtained the highest loading margin with 5.9550MW and an MST of 17.1086%, which makes the test system above the minimum limit established by the ONS for complete systems, making it stable from a voltage point of view.

Cases 18 and 22, after the contingency, presented PMCs of 5.1318MW and 5.2741MW and MSTs of 0.9209% and 3.7185%, respectively, obtaining an MST of less than 4%, as predetermined by the ONS. After the application of the compensation, cases 18 and 22 achieved an increase in the loading and voltage indexes, where case 18 obtained a loading margin of 5.3313MW and MST of 4.8446%, and case 22 presented a PMC of 5.4052MW and an MST of 6.2976%, presenting positive results in the variables studied.

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