DOI: 10.48011/sbse.v1i1.2226

Thermoelectric generation re-dispatch through Online Stability Assessment in altered grid conditions

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Abstract: This article presents the design, algorithms, and results obtained situations not foreseen by the operating procedures, through the use of a real-time assessment analysis tool to perform change of generation of thermoelectric plants in a configuration denominated as an altered grid, which may impact the excellent performance of Systemic Special Protection Schemes implemented by power system operation planning. Thus, through the analysis of the security region, control center operators may have the adequate allowance, in real-time, to perform a new and precise generation request and thus avoid instabilities as well as overload in the electric system under analysis, especially prolonged interruptions of electricity for consumers.

Keywords: altered grid; assessment region; Brazilian Interconnected System; dynamic analysis; power system security; online stability assessment; real-time operating thermoelectric generation re-dispatch.

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1. INTRODUCTION

Operational safety assessments quantify power systems' vulnerability to disturbances (Kundur et al.) and designate the adoption of preventive practices to keep them operational when subjected to component failures (Wood et al.) (Kundur et al.). These practices are well documented in the operating instructions and also implemented in special protection schemes (SPS) (ONS). Traditionally, Traditionally, extensive offline studies bases these assessments, whose simulation tools consider a list of some (the most severe) contingencies applied to an approximate network model (Lyon et al.; Thappetaobula et al.), because the problem of dimensionality makes it impossible to scan all contingency combinations within a reasonable timeframe (Diao et al.), which would require greater computational complexity.

Thus, as good as the system planning may be, it is not possible to evaluate all operating conditions likely to occur in real-time operating (Savulescu). Furthermore, it is not possible to build a 100% reliable electrical system, given the complexity and size of modern interconnected power systems. Not only must the contemporary power system control provide for reliability, but it must also ensure system survivability (Litvinov). Thus, considering the uncertainties of prediction of future operating conditions, several studies confirm the need for online safety assessment (Savulescu), especially stability parameters, to reduce the risk of blackouts in system operation (Savulescu), which is called Dynamic Safety Assessment (DSA) (Jardim).

Therefore, the challenge of DSA is to continually determine the current stability condition and safety margin associated with a given system operating point as well as the safe operating region. Thus, online stability analysis (OSA) enables real-time operators to perform preventive actions in enough time to ensure electrical system safety. In the Brazilian Interconnected System (BIS), the implemented OSA system (Savulescu) can provide information on preventive measures or corrective actions, being able to perform stability assessment: transient, voltage, frequency, and small signals.

On the other hand, generation redesign is an optimization problem that includes constraints such as thermal limits of the lines and transformers, generation limits, and the dynamic safety of the electrical system. Several techniques have been proposed based on particle swarm, differential evolution, and genetic algorithms (GAs) to solve these optimization problems (Corrêa et al.). Besides, the design of the increasingly competitive deregulated electricity market (Kirschen and Strbac) introduced economic criteria in the planning of the operation, intending to operate the system at the lowest possible operating cost.

In Brazil, hydrothermal programming optimization is being performed by a new model that can use mixed-integer linear programming (MILP), linear programming (LP), or by applying a Dynamic Dual programming algorithm (DDP) (MME). Despite the improvement in the accuracy of the dispatch using this methodology, there is still the possibility of thermal generation dispatches outside the order of merit indicated in the model for maintaining electrical safety. For example, when the operation planning wishes to inhibit the operation of SPS's that have preconfigured load cuts in a given electrical area. In this case, the amount dispatched considers the worst case for the offline safety analysis, being as conservative as possible. This type of dispatch is called Electricity Dispatch (ED) (ANEEL). The ED considerably increases charges costs for consumers.

Thus, there are still intrinsic inaccuracies to the modeling performed in operation planning that ratify the need for real-time operative actions, which become more effective when performed based on OSA tools, for example, in order to maximize transmission utilization and therefore avoid operating costs associated with offline limits (Thappetaobula et al.). On the other hand, given the complexity of the Brazilian system generation dispatch problem, operators do not have the autonomy to carry out a redesign, especially of thermal plants, unless if this kind of action is well-documented in operating instructions (OI's): they must strictly follow the generation program. There is no resolution of the problem of dynamic economic dispatch (DED) (Attaviriyanupap et al.;Han et al.;Xiao and McCalley).

This paper presents real-time ED thermal generation redispatch based on safety regions calculated for a given electrical area by the DSA tool in service at ONS control centers. This methodology is validated by analyzing the performance of an SPS against re-dispatch actions, especially in the critical case of the altered grid. Section II provides an overview of the electrical system studied and the particularities of the implemented SPS. Section III provides details of the online safety assessment with the methodology used and the real-time verified results for stability studies performed by operation planning. Section IV presents the case study focusing on the advantages of using the online stability assessment tool, with quantitative and qualitative examples. Comparing the results obtained from the operation planning with the revalidation performed by the real-time operation reveals that not only are operating costs mitigated but also to prevent the total loss of the integrity of the studied electrical area. Section V presents the conclusion.

2. RIO AREA ELECTRICAL SYSTEM OVERVIEW

2.1 Generation and consumption of the Rio Electric Area

The Rio Electric Area System (Rio area) is part of the Brazilian interconnected system (BIS) and serves the entire state of Rio de Janeiro. Table 1 presents the average annual generation and consumption data (EPE;BEN). Table 2 presents levels of load discretization considered in this article that also usually performs by the operation planning. In this area, there is a substation called Grajau. The SPS considers this Grajau's substation.

Table 1. Generation and consumption of the Rio Electric area

Electric Area Rio de Janeiro	**Average electrical data**[a]	
	Total	Partipation (%)
1.Generation Capacity	8,916 MW	5.7[b]
2. Consumption	38,882 GWh	8.3[b]
3. Total Power Generation	57,965 GWh	12.3[b]
3.1 Hydro	5,310 GWh	9.16[c]
3.2 Wind	78 GWh	0.13[c]
3.3 Solar	11 GWh	0.02[c]
3.4 Nuclear	15,739 GWh	27.15[c]
3.5 Thermal	36,827 GWh	63.53[c]

[a] Reference:year 2017; [b] Refers to country participation;
[c] Refers to state participation

Table 2. Discretization of loading levels of the Rio area

Loading Level	**Total demand**	
	MW	MVAr
Light	3,050.0	650.0
Average	4,575.0	975.0
Heavy	7,625.0	162.0

2.2 Criticality of Grajaú Substation for Rio area

Grajaú substation connects the 138kV distribution system services loads of the entire commercial center and Zona Sul (for example Copacabana's beach) of the city of Rio de Janeiro, Sambadrome Marquês de Sapucaí, Journalist Mário Filho (Maracanã) and Olímpico Nilton Santos stadiums, as well as service to Tom Jobim International Airport. This is because, this substation is approximately 5 km away from Maracanã stadium, 8 km away from Sambódromo and 10 km away from Rio's commercial center. This 138kV distribution system is outside the operation's grid of the ONS.

2.3 SPS of Grajaú Substation

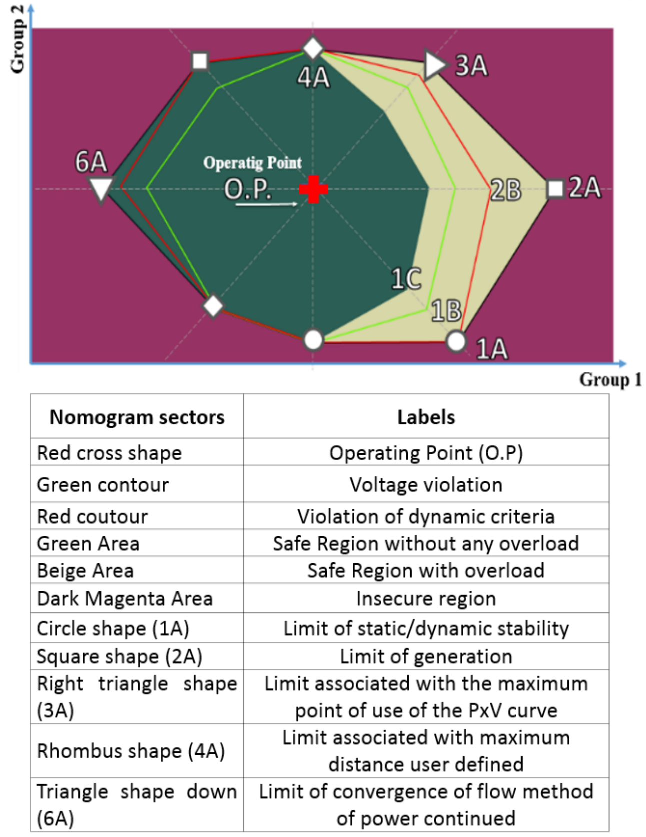
The purpose of the SPS of Grajaú Substation (SPS Grajaú) is to eliminate inadmissible overload in the 138 kV system as well as a sharp drop in the voltage profile of the Rio area when it occurs double shutting down of the connected 500 kV lines to this substation. Thus, to avoid transformer shut down due to overload protection, as well as to eliminate overloads on transmission lines and to reestablish the affected regions, this scheme automatically changes the grid configuration and performs load cuts, sequential and coordinate. In quantitative terms, in the case of double loss in the Grajaú substation, taking into account the performance to the last stage, this scheme can cut 700 MW of load from the Rio area (ONS).

3. BIS ONLINE STABILITY ASSESSMENT TOOL

3.1 User Interface

The DSA graphic interfaceSavulescu allows data input and editing through dialog boxes. Data output is displayed in report tables, single-line diagrams, and nomograms (2-dimensional plotting), as seen in Fig. 1(Neves).

The security region visualization presented in Fig. 1 is one of the most potent visualizations tools for security assessment. Systems Operators can see if an operating point in



Nomogram sectors	Labels
Red cross shape	Operating Point (O.P)
Green contour	Voltage violation
Red coutour	Violation of dynamic criteria
Green Area	Safe Region without any overload
Beige Area	Safe Region with overload
Dark Magenta Area	Insecure region
Circle shape (1A)	Limit of static/dynamic stability
Square shape (2A)	Limit of generation
Right triangle shape (3A)	Limit associated with the maximum point of use of the PxV curve
Rhombus shape (4A)	Limit associated with maximum distance user defined
Triangle shape down (6A)	Limit of convergence of flow method of power continued

Figure 1. Example of Nomogram

generation coordinates lies in the secure (green) or alert (yellow or dark red) region (Savulescu). Fig. 1 provides a label of the other relevant information that makes up this kind of visualization so that system operators can quickly identify whether the current operating point, as well as its time-domain excursion, is safe or not.

3.2 Benefits of Online Safety Region Calculation

The use of DSA Online in ONS processes (Penna et al.) provides many benefits, including (Savulescu):

- The only tool for effectively, accurately, and computationally performing dynamic simulations that can be graphed by safety regions. Currently monitoring dynamic security from various transmission corridors (at least one nomogram per corridor)
- Analysis of transmission bottlenecks in operational planning;
- Fast computation of transmission constraints for unexpected network configuration and definition of operational orders;

3.3 Offline security limits validation by online DSA tool

The results presented in this section consider the case of the operation in real-time for the limits obtained by the offline security analysis by the operation planning. The situation “a” (Fig. 2) represents the case that the planning of the operation wants the Grajaú SPS to act, performing load cuts equivalent 400 MW in the city of Rio de Janeiro (about 10%), in stages and in a timed manner (Fig. 3), as predicted ONS. The red cross in the green hatched area means that the point of operation is safe by SPS performance.

On the other hand, the situation “b”(Fig. 4) represents the case of inhibition of Scheme actuation. For example, during 2016’s Olympic Games or currently Carnival periods in Rio’s city. The red cross away from the green hatched area means that the operating point is safe without SPS performance. For this, there is a dispatch of Barbosa Lima Sobrinho thermoelectric plant (BLTP) at maximum (350 MW).

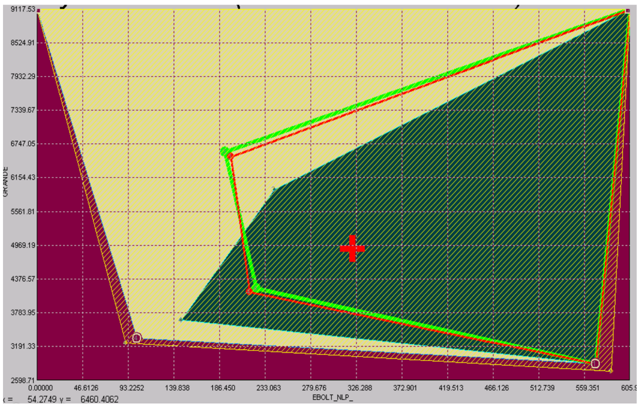


Figure 2. Nomogram situation (a)

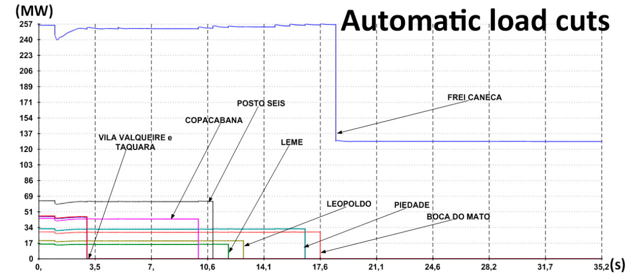


Figure 3. Load cuts in substations of the 138 kV system by Grajau’s SPS

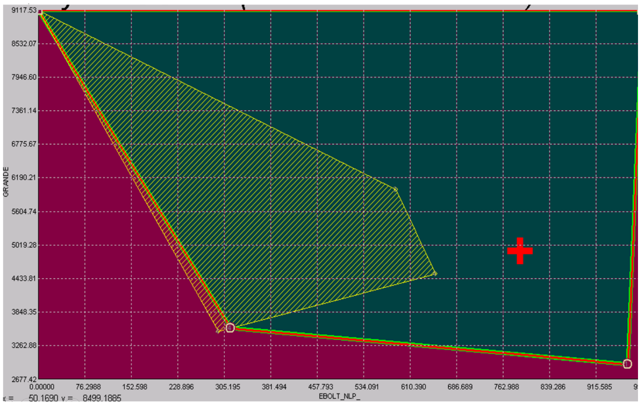


Figure 4. Nomogram situation (b)

4. THERMOELECTRIC GENERATION RE-DISPATCH THROUGH DSA ONLINE TOOL

This section presents the case study to illustrate the benefits of implementing a thermal generation re-dispatch process through an online stability assessment tool, especially in the analysis of transmission bottlenecks in operational planning.

4.1 Algorithm of thermoeletric generation re-dispatch process

Fig. 5 presents the algorithm of the proposed methodology, which allows a practical and reliable analysis of the reality of the operation in real-time. Operative actions consist primarily of assessing network security around a given operating point from data acquired directly from the real-time state estimator to obtain the maximum accuracy possible. Depending on this assessment, it occurs a simulation of the variation of the generation of a plant under different grid conditions and system loading until obtaining adequate dispatch, considering not only the safety aspect but also the economic one. Fig. 5 presents the algorithm of the proposed methodology, which allows a practical and reliable analysis of the reality of the operation in real-time. Thus, when there is a representation of thermal limit violation means, in fact, overload in equipment because of the configuration of emergency limits provided by the proprietary agents inside the DSA tool.

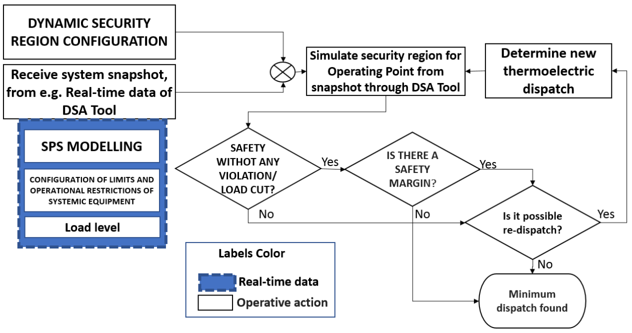


Figure 5. Algorithm for solving thermoelectric re-dispatch problem using DSA tool

4.2 Methodology application case study

The evaluation of the application will consist of the application of this methodology in the Rio area considering the influence of BLTP thermal re-dispatch for performance or not of Grajau's SPS in the dynamic simulation of the occurrence of double shutting down that should sensitize this scheme. Firstly, in the reasonable operating condition (complete grid). Secondly, in altered grid condition for three load levels (light, average, heavy load), for analyzing the most critical case of the Rio area.

Generation Groups for Nomograms - Table 3 presents the configuration of the generation groups of each axis of nomograms. Thus, the safety region nomograms of the axes formed by Groups 1 and 2 will support results, whose units of measurement are megawatt (MW).

The altered grid configuration - Despite the reinforcements and modifications that occurred in the Rio Area transmission system, this study considered a base case of the year 2017 since it is the last data consisted and made available for public consultation (EPE; BEN). Thus, it is possible to carry out the studies in a more fragile network configuration than the current condition, being also the closest configuration to that existing during the international events that took place in the city of Rio, especially the 2016's Olympic Games.

Table 3. Configuration of the dynamic safety region generation groups

Tag Group	**Power Plant**	**Pmax [MW]**	**Pmax/ Group [MW]**
#Group1: EBOLT_NLP_PPS_FT	Nilo Peçanha	380	962
	Fontes	132	
	Pereira Passos	100	
	Barbosa Lima Sobrinho	350	
#Group2: GRANDE	Luis Carlos Barreto	1049	11430
	Furnas	1216	
	Mascarenhas de Moraes	492	
	Emborcação	1192	
	Nova Ponte	510	
	Jaguara	400	
	São Simão	1680	
	Volta Grande	380	
	Guilman Amorim	140	
	Itumbiara	2280	
	Corumbá	381	
	Serra da Mesa	1260	
	Cana Brava	450	
#Group3: SP	Marimbondo	1488	9017
	Henry Borden 88 kV	194	
	Henry Borden 230 kV	482	
	Água Vermelha	1396	
	Três Irmãos	807	
	Jupiá	1552	
	Capivara	679	
	Porto Primavera	1540	
	Taquaruçu	525	
	Chavantes	414	

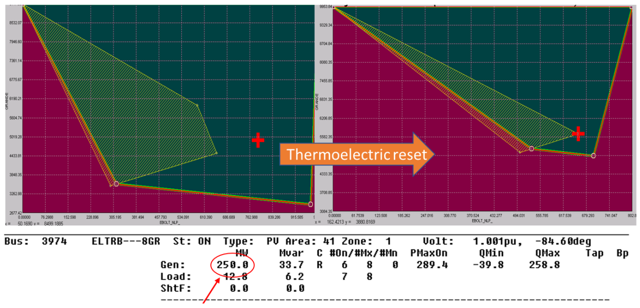
For this base case, the altered grid scenario will be represented by the unscheduled unavailability of the 138 kV "Cascadura 1 / Jacarepaguá" circuit, belonging to the distribution system connected to the Grajaú substation. The value of the electric current of this circuit is one of the sensitization parameters of Grajau's SPS. However, this circuit does not belong to the BIS operating network (ONS), so it is under the responsibility and autonomy of the distribution agent.

4.3 Results

Improved operating cost without compromising safety under complete grid conditions - The application of the methodology considering the situation shown in Fig. 4 obtained a 30% reduction in the thermal dispatch indicated by the operation planning. Fig. 6 presents a minimum of 250 MW was reached from the BLTP to ensure that the SPS did not operate, considering one determined at the same full grid operating point. For understanding the avoided operating cost, Table 4 shows the results.

Table 4. Costs Savings

Dispatch [MW]		**Regulated market amount**	**$/MWh (Aug/2016)**	**Cost [$/h]**	**Savings (A-B) [$/h]**
A	350	321	96,131	30,858.00	9,613.08
		29	76,212	2,210.14	
B	250	221	96,131	21,244.92	
		29	76,212	2,210.14	



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Bus:  3974    ELTRB---8GR  St: ON  Type:  PV Area: 41 Zone:  1     Volt:   1.001pu,  -84.60deg
                                          MW      Mvar  C #On/#Mx/#Mn  PMaxOn     QMin      QMax     Tap  Bp
                          Gen:      250.0      33.7  R   6   8   0   289.4    -39.8     258.8
                          Load:      12.8       6.2      7   8
                          ShtF:       0.0       0.0
                          --------------------------------------------------------------------
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Figure 6. Comparison of the nomogram presented in Fig.4: BLTP minimum dispatch for non-performance of SPS

Definition of new operational actions after analysis of transmission limitations unplanned by operational planning, mainly for unexpected grid configuration - For this situation, in the base case, there was deactivating the 138kV Cascadura 1 / Jacarepaguá circuit. This action configures the operation in the altered grid, that is, a situation not foreseen by the operation planning, which is the focus of this study.

Fig.7 presents the safety region around this operating point: altered grid, average load and BLTP off.

Assuming that no immediate action was taken by the control center operators to re-dispatch thermal generation based on this nomogram, in the dynamic simulation of the occurrence of double loss in the Grajaú substation, there are the following immediate consequences:

(1) SPS Grajaú was not sensitized and therefore did not act even with the occurrence of double loss;
(2) There were automatics shutdowns of several 138kV (cascade) circuits due to overload protection (Fig.8)
(3) Voltage instability and occurrence of voltage sinking in the Rio area (Fig. 9)
(4) Transient instability in generating units. Example: Nilo Peçanha HPP (Fig. 10)
(5) Interruption of approximately 2,000 MW in the city of Rio de Janeiro

These results proved the criticality of the unavailability of this 138kV circuit for sensitization and performance of said Special Protection System, as well as maintaining the integrity of the Rio region when the double shutting down occurs Grajaú's substation. Also, these results prove the reliability of the safety region result. Thus, based on this result of the safety region, the application of the algorithm for thermoelectric generation re-dispatch gains relevance and urgency in this case study.

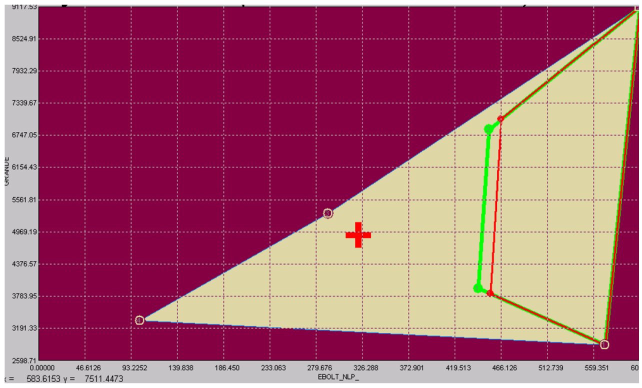

Figure 7. Nomogram:altered grid, average load, BLTP off

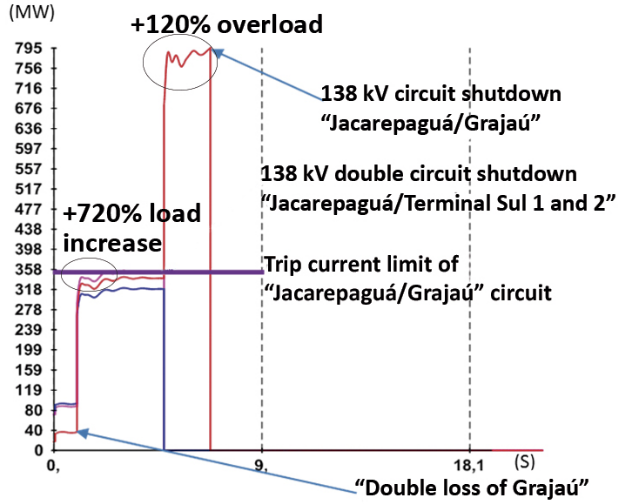

Figure 8. Overloads on 138kV Circuits

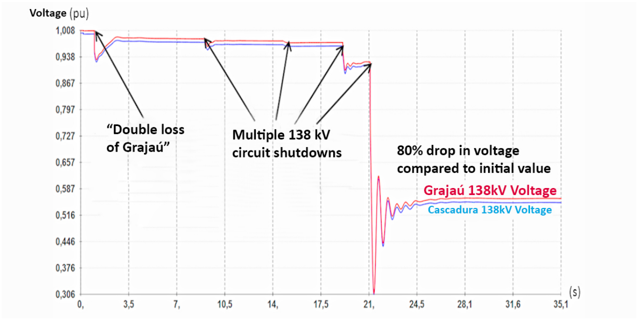

Figure 9. Voltage oscillation in the critical bars: sinking in 21s

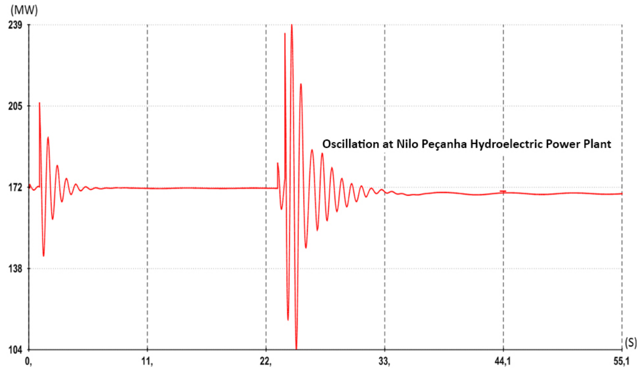

Figure 10. Active power oscillation at Nilo Peçanha Hydropower

The first line of Fig. 11 illustrates the results obtained with the application of the algorithm, which resulted in the re-dispatch indication of the maximum generation value of the plant, considering a safety margin in case of an imminent transition from average to heavy load. In order to validate this result, regarding the time-domain simulation when that double shutting down occurs, among loading of the various 138kV circuits, the Grajaú / Jacarepaguá circuit, which suffers the most substantial instantaneous elevation, stands out. However, as can be seen in Fig.12, it stabilizes and remains within the emergency limit for this equipment. Thus, undoubtedly the algorithm application is also satisfactory in the altered grid configuration.

Then, for the case study to be complete, it is possible considerating performing a re-dispatch on the other load levels. Thus, it is possible to evaluate how the safety margin is exhausted or not, assuming that the moment of occurrence of the grid change is close to the moment of transition from average load to the other levels.

By the sensitivity of the accomplishment of thermoelectric re-dispatch became possible to verify the possibility of reducing the operating cost without losing operational safety. Thereby, for improving the macro visualization of the results, they are in the second and third lines of Fig. Ref TherRed. About the transitions to other levels of load, it was found that:

- *Average to heavy load:* thermal generation re-dispatch is not possible in the direction of BLTP generation reduction, staying at 350 MW level is recommended. At this level, the operating point is on alert because of a thermal limit violation, but permissible, and there is no voltage limit violation.
- *Average load to light load:* thermal generation re-dispatch is possible in the direction of BLTP generation reduction.

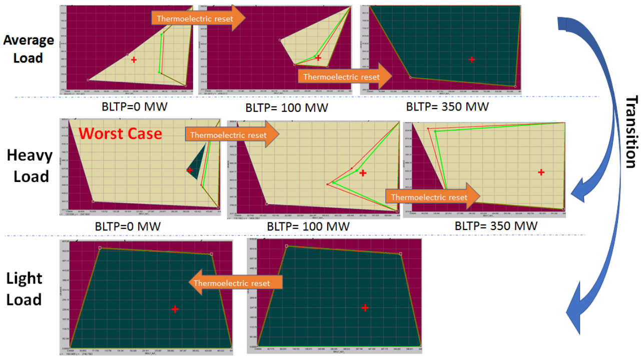

Figure 11. Normograms obtained by aplication of Thermoeletric Re-dispatch

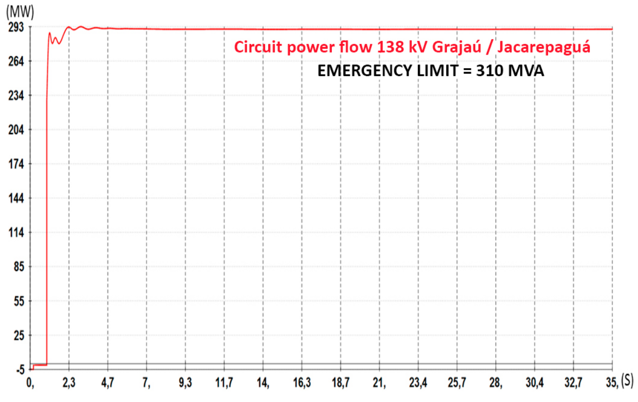

Figure 12. Elevation of 138 kV Grajau/Jacarepagua circuit loading

The worst case is the heavy load condition with the BLTP turned off. It means that if the altered configuration occurs during the heavy load period, the algorithm should be applied immediately until getting the appropriate value of 350 MW. Otherwise, if the double shutting down of Grajaú occurs, there is a serious risk of voltage instability that results in a characteristic of a sinking (abrupt 50% drop in Grajaú 138 kV bus voltage, which stabilizes at 0.451 p.u.). Thus, it would occur a loss of system integrity with severe load cut in the Rio area during the period when the system is most in demand. Fig. 13 illustrates this situation.

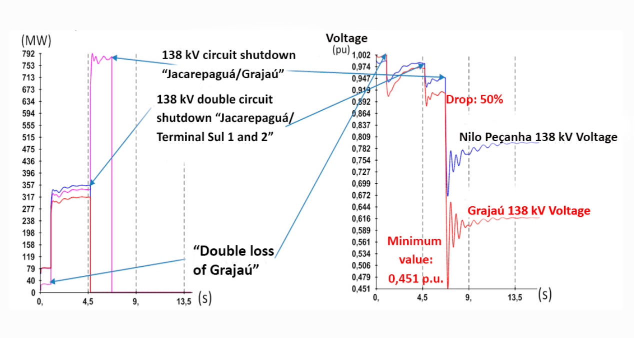

Figure 13. Time-domain simulation for worst-case studied.

5. CONCLUSION

The exposed empirical method has the facility of being applied for the complete grid, for example, to mitigate operating costs when there is desiring of SPS inhibition. However, it is even more relevant to quantify and mitigate the risk of blackout when the system is out of planned conditions, as the altered grid configuration. Thus, by simulating the variation of RED thermoelectric generation over the three load levels of the system, it is possible to quantitatively and qualitatively influence the sensitization of the SPS and, mainly, to maintain the safety of the electrical area, since the disconnection of a distribution circuit (outside the ONS operating grid) compromised the performance of the implemented SPS by ONS.

Since the DSA tool is robust enough to provide the current state accurately and safety margin of the system, the empirical method used subsidizes learning and familiarity in the tool simulation environment by real-time teams, providing greater confidence in deciding to perform resets of RED thermoelectric generation.

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