Planning Expansion of Transmission System Focused on Minimization of Contingency and Power Losses: a Case Study

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***Abstract*—This paper presents a case study of power losses and contingency analysis of a part of the south Brazilian transmission system. The system transfers 5848.3 MW through 27 transmission lines with 147.8 MW of losses. A contingency study shows that the system cannot support the disconnection of any line from a set of six, because of instability in the power flow. This work shows some of the possible solutions to solve or mitigate the contingency problems and reduce the system losses, with a cost analysis of implementing these alternatives.**

***Index Terms* — Costs, Expansion, Planning, Transmission Line**

I. Introduction

The transmission network is the backbone of the electric power system, it is critical to expand it at minimum cost while keeping a high level of reliability [1], [2]. One way to evaluate the reliability is through a contingency analysis, simulating the effects of a failure in different system components.

The existing tools for evaluating contingencies uses, dominantly, the deterministic 'n-1' criteria, which means that the system can be reliably operated following the failure of any one of the 'n' elements in the given some part of the system [3].

Recent studies and global experience in the electrical power systems (EPS) control show that the adequate and rational solution which ensure the reliability of the EPS consider at least n-2 or even n-3 criterion [4], which means the system being able to reliably operate following the failure of any 2 or 3 of the 'n' elements at the same time.

In the 'n-k' criteria, the bigger the value of k, more vulnerabilities can be detected, however, the computational burden also increases exponentially [5]. A computer simulating a 30 bus system under a 'n-1' contingency analysis needs to simulate 30 scenarios, considering that each bus has only one connection. For 'n-2' the number of scenarios jumps to 870 and for n-3 to 24,360. However, a bus can have multiple connections, so the number of scenarios can be much higher than the cited values.

There are several ways to reduce the computational effort of the 'n-k' contingency analysis, like the direct-current power flow and based contingency screening (CS). The CS method consists in removing some contingencies from the simulation list, as not all contingencies may indeed threaten system security [6].

Other important thing about transmission lines is the amount of energy lost during transmission. Active power losses are due to the resistive component and the conductance of the transmission lines and it amounts to about 5% of the total active power load [7].

The ways to reduce the transmission losses are increasing the cable gauge or number of parallel cables per phase and reducing the line length. Sometimes, due to geographical positioning of generators or loads, it is not possible to keep the lines short. So, the only viable solution to reduce the losses is increasing the gauge or number of cables. This solution, however, implies in an increase in the transmission line cost. This way, a cost/benefit study need to be performed to analyze if the increased cost of the transmission lines is compensated by the energy saving.

In this paper a case study was carried out on a part of the south Brazilian transmission system analyzing its reliability through a reduced n-1 contingency analysis. The power losses on the system are also analyzed and some expansion alternatives are proposed to help mitigate the set of problems found.

The model used is representative of the south Brazilian transmission system, connecting the states of Paraná, Santa Catarina and Rio Grande do Sul. Since the complete system is large and complex, for study purpose, it has been considered only the most relevant part, comprising some of the main transmission lines between the 3 states. The system used is shown in Fig. 1. It is composed of three voltage levels, 230 kV, represented by the green lines, and 500 kV, represented by the red lines. There is also a 13.8 kV (black lines) used only in the interface with the generators.

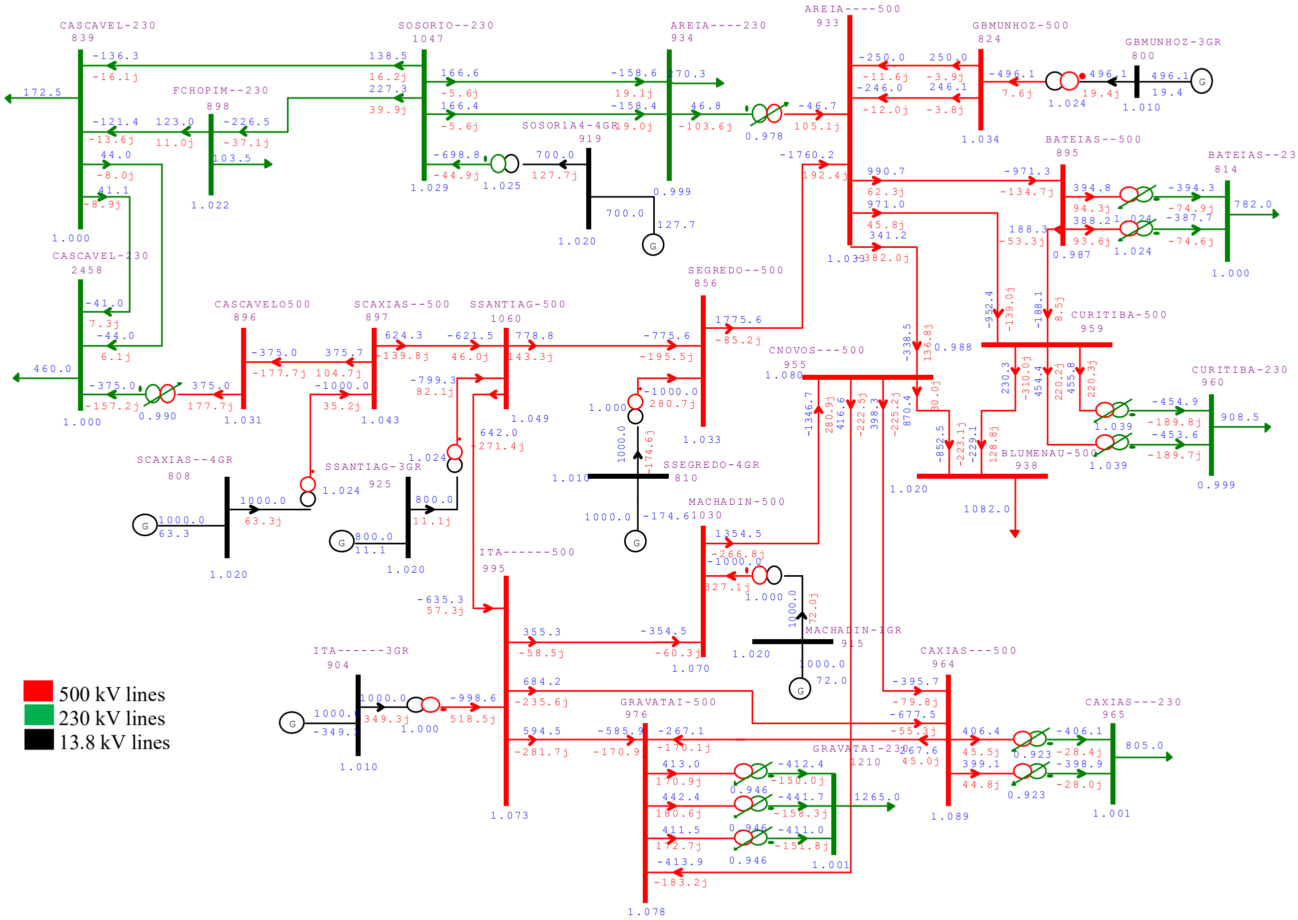

Figure 1. South Brazilian transmission system analyzed

II. Power Losses and Contingency Analysis

A system power losses and a contingency analysis was carried out using the software ANAREDE. The simulation shows a total of 147.8 MW of losses in the entire system.

A common 'n-1' analysis for this system has 45 conditions to be simulated. To reduce the computational burden some of the conditions were disregarded and a reduced 'n-1' contingency analysis has been carried out with 24 scenarios. A list of all simulated scenarios is shown in Table VIII in the appendix.

From the 24 cases, 6 of them resulted in voltage infringements in the system, 4 resulted in power flow infringements and 6 cases do not converged. A summary of the contingency analysis is also shown in Table I to better illustrate the number of infringements in each condition and the severity index calculated by the ANAREDE. Which corresponds to the mean square deviation from the determined limits.

The cases with voltage and power flow infringements, especially the ones with low severity index, can be solved by a system reorganization such as changing the power dispatch. On the other hand, the 6 not convergent cases were treated individually. Three of them occurred in connections among AREIA-500 and other buses, demonstrating that this is a critical bus to the system. A contingency between SEGREDO-500 and AREIA-500, for instance, results in a power overflow through the 230 kV lines, destabilizing the system.

TABLE I. Results of Contingency and System Power Losses

Case #	Total infringements	Severity Index	Contingency identification
Voltage infringements			
19	9	256.4	GRAVATAI-500 / ITA-500
20	5	62.0	ITA-500 / CAXIAS-500
23	3	31.1	MACHADIN-500 / CNOVOS-500
15	2	25.7	BLUMENAU-500 / CURITIBA-500
16	2	1.0	CNOVOS-500 / CAXIAS-500
22	2	0.3	ITA-500 / SSANTIAG-500
Power flow infringements			
Case #	Total infringements	Severity Index	Contingency identification
9	1	2.1	FCHOPIM-230 / SOSORIO-230
3	1	1.3	CASCAVEL-230 / FCHOPIM-230
4	1	1.2	CASCAVEL-230 / SOSORIO-230
22	1	1.1	ITA-500 / SSANTIAG-500
Not convergent cases			
Case #	Total infringements	Severity Index	Contingency identification
24	-	-	SSANTIAG-500 / SCAXIAS-500
14	-	-	BLUMENAU-500 / CNOVOS-500
12	-	-	AREIA-500 / CURITIBA-500
10	-	-	AREIA-500 / BATEIAS-500
8	-	-	CASCAVEL-500 / SCAXIAS-500
6	-	-	SEGREDO-500 / AREIA-500

III. Possible Solutions and Implementation Cost Analysis

To solve the problems pointed out, it is necessary to build new transmission lines to increase the system capacity, reduce system losses and serve as backup routes to power flow in case of contingencies. Several options were analyzed, and the trivial solution to solve all the not convergent cases is to build a total of 3 new transmission lines. However, the cost of 3 new transmission lines may be impeditive so, a solution employing less new transmission lines is proposed by the authors.

Between the possible solutions, the construction of two transmission lines, from AREIA-500 to CASCAVEL-500 (line 1) and from AREIA-500 to BLUMENAU-500 (line 2) had the best cost/benefit ratio, considering the lowest system present value and number of not convergent cases solved. The length of line 1 is 220 km and of line 2 is 266 km.

Those lines have been chosen to solve the two main problems of the analyzed system. The substation AREIA-500 can be considered the backbone of the system and connects to all other regions with lines of high capacity so, AREIA-500 is a key point to distribute the power among the system.

Building a line between AREIA-500 and CASCAVEL-500 creates a new path for power flow to reach AREIA-500, avoiding the 230 kV lines. Blumenau is one of the biggest cities from Santa Catarina and one of the main industrial poles, consuming a high amount of energy, and has no direct connection to AREIA-500. A new line between AREIA-500 and BLUMENAU-500 will alleviate the power flow from surrounding lines through a direct path.

The building cost of a transmission line depends on its configuration and length. In this paper, three configurations have been considered. Table II show their respective costs and electrical characteristics while Table III and Table IV show the total cost of each line in each configuration, calculated based on the reference price bank given by Brazilian Electricity Regulatory Agency (ANEEL) [8]. Reference prices had been adjusted considering the inflation from 2010 to 2018 [9] and are representative of the south Brazilian region, as the values are different in each region of Brazil [7].

Considering that the objective is to find the lowest total cost for the system, which include power losses on operation, the losses costs needs to be calculated considering a horizon of 30 years of operation [10]. The methodology used comprised in transforming all costs to present value C_L, using (1).

$$C_L = 8760.L_C.L_F.EMC.\frac{1-(1+i)^{-N}}{i} \quad (1)$$

where:

L_C: Power losses in MW

L_F: Losses factor = 0.38512

EMC: Expansion Marginal Cost in R$/MWh = 234

N: Time horizon in years = 30

i: Yearly interest rate = 8%

The expansion marginal cost (*EMC*) considered in this paper is the same used in the 10-year power expansion plan from Energy Research Office (EPE) [11].

Table V shows the results of power flow simulations considering all alternatives, to build or not, the proposed lines. The total losses of the system without any additional transmission line are 147.8 MW and can be reduced to 121.1 MW, building the two transmission lines using 4 paralleled ACSR Rail cables per phase, a reduction of 18.1% in the power losses. However, considering the given economic situation (interest rate and EMC), the solution with the lowest present value, and consequently the lowest system total value, is to not build neither of the proposed lines, as shown in Table V.

TABLE II. Basic Transmission Line Parameters

Configuration	Cost (R$/km)	Z (mΩ/km)	C (nF/km)	Capacity (MVA)
LT 500 kV 3 Rail	1,146,475	22.62 + 348.2i	12.42	2000
LT 500 kV 4 Grosbeak	1,197,525	24.80 + 321.5i	13.41	2100
LT 500 kV 4 Rail	1,334,421	16.97 + 318.8i	13.55	2700

TABLE III. Possible Line 1 Configurations

Configuration	Cost (R$)	Z (Ω)	C (μF)	Capacity (MVA)
LT 500 kV 3 Rail	252,224,613	4.98 + 76.60i	2.73	2000
LT 500 kV 4 Grosbeak	263,455,667	5.46 + 70.73i	2.95	2100
LT 500 kV 4 Rail	239,572,788	3.73 + 70.14i	2.98	2700

TABLE IV. Possible Line 2 Configurations

Configuration	Cost (R$)	Z (Ω)	C (μF)	Capacity (MVA)
LT 500 kV 3 Rail	304,870,769	6.01 + 92.59i	3.30	2000
LT 500 kV 4 Grosbeak	318,446,051	6.59 + 85.49i	3.56	2100
LT 500 kV 4 Rail	354,849,436	4.51 + 84.77i	3.60	2700

TABLE V. Losses cost and present value of all alternatives

Configuration Line 1	Configuration Line 2	Losses (MW)	Losses Cost (R$)	Present Value (R$)
DNB	DNB	147.8	1,313,540,165	1,313,540,165
DNB	3 Rail	136.6	1,214,002,615	1,518,873,384
3 Rail	DNB	143.3	1,273,547,399	1,525,772,012
DNB	4 Grosbeak	136.9	1,216,668,799	1,535,114,850
4 Grosbeak	DNB	143.2	1,272,658,671	1,536,114,339
DNB	4 Rail	133.8	1,189,118,228	1,543,967,664
4 Rail	DNB	141.9	1,261,105,205	1,554,677,994
3 Rail	3 Rail	125	1,110,910,153	1,668,005,534
4 Grosbeak	3 Rail	125.1	1,111,798,881	1,680,125,317
3 Rail	4 Grosbeak	125.3	1,113,576,337	1,684,247,001
3 Rail	4 Rail	122.3	1,086,914,494	1,693,988,543
4 Grosbeak	4 Grosbeak	125.5	1,115,353,793	1,697,255,512
4 Rail	3 Rail	123.7	1,099,356,687	1,697,800,245
4 Grosbeak	4 Rail	122.4	1,087,803,222	1,706,108,326
4 Rail	4 Grosbeak	124.1	1,102,911,600	1,714,930,439
4 Rail	4 Rail	121.1	1,076,249,756	1,724,671,981

[a] DNB: Do Not Build

IV. IMPACT ON CONTINGENCY ANALYSIS

Despite the proposed lines do not being economically attractive in terms of energy saving, a new contingency analysis was carried out to evaluate the effectiveness of the proposed solution in reducing the system vulnerabilities. As shown in Section II, the actual system has 6 not convergent cases, 6 voltage infringements and 4 power flow infringements.

The system with the proposed solutions now has 4 voltage infringements, 5 power flow infringements, and 1 not convergent case, as shown in Table VI. Two of the voltage infringements (cases 12 and 14) have a high severity index (450.4 and 54.4, respectively). These cases are not convergent cases in the actual configuration and, with the two new transmission lines, both cases can be solved with generation redispatch and voltage reference adjustment. Considering the power flow infringements, the severity index of all infringements increased by about 1. But all cases can be solved with generation redispatch.

Considering the present value of not building the lines and the lowest present value of building the two lines, the difference is R$ 354.5 million. It represents an increase of 29.99 % in the present value of the system so, building the two lines may be attractive considering the reliability improvement.

Even with the proposed solutions there is one not convergent case, 10 (AREIA-500 / BATEIAS-500). To solve this case two alternatives are also proposed in this paper. To build a new line between AREIA-500 and BATEIAS-500, which may become expensive due to the distance of 256 km between the two substations. Or to build a new line between BATEIAS-500 and CURITIBA-500, with 35 km, plus a 100 Mvar capacitor in BATEIAS-500 to be activated only in the occurrence of a contingency. Both the solutions were simulated in ANAREDE and solved all contingencies, as shown in Table VII.

TABLE VI. RESULTS OF THE CONTINGENCY ANALYSIS WITH THE TWO NEW TRANSMISSION LINES

Case #	Total infringements	Severity Index	Contingency identification
Voltage infringements			
12	5	450.4	AREIA-500 / CURITIBA-500
14	3	54.4	BLUMENAU-500 / CNOVOS-500
15	2	11.1	BLUMENAU-500 / CURITIBA-500
19	1	7.3	GRAVATAI-500 / ITA-500
Flux infringements			
4	2	3.1	CASCAVEL-230 / SOSORIO-230
9	1	3.0	FCHOPIM-230 / SOSORIO-230
8	2	2.7	CASCAVEL-500 / SCAXIAS-500
13	2	2.4	AREIA-500 / CURITIBA-500
3	1	2.0	CASCAVEL-230 / FCHOPIM-230
Not convergent			
10	-	-	AREIA-500 / BATEIAS-500

TABLE VII. RESULTS OF THE CONTINGENCY ANALYSIS WITH THE THREE NEW TRANSMISSION LINES

Case #	Total infringements	Severity Index	Contingency identification
Voltage infringements			
19	1	2.1	GRAVATAI-500 / ITA-500
12	1	0.1	AREIA-500 / CURITIBA-500
Flux infringements			
4	2	3.1	CASCAVEL-230 / SOSORIO-230
9	1	3.0	FCHOPIM-230 / SOSORIO-230
8	2	2.7	CASCAVEL-500 / SCAXIAS-500
13	2	2.4	AREIA-230 / SOSORIO-230
3	1	2.0	CASCAVEL-230 / FCHOPIM-230

V. CONCLUSION

The paper first presented a power losses and contingency analysis of a 30 bus system that represents a part of the South Brazilian transmission system using the software ANAREDE. Results have demonstrated that 25 % of all contingency situations tested resulted in not convergent cases and the system has 147.8 MW of power losses.

From this analysis was proposed a solution of building two new transmission lines, from AREIA-500 to CASCAVEL-500 and from AREIA-500 to BLUMENAU-500. Simulation results demonstrated that this solution could reduce system power losses to 121.1 MW, which represent a reduction of 18.1 %. However, the cost analysis showed that the energy savings do not surpasses the investment cost. On the other hand, a contingency analysis of proposed solution demonstrate that it can reduce the number of not convergent cases from 6 to 1. The construction of the two new lines represents an increase in the present value of the system of 29.99 % so, the proposed solution may be worth to be implemented.

To solve the remain not convergent case the authors proposes two new alternatives. To build a new transmission line between AREIA-500 and BATEIAS-500 (256 km). Or to build a new transmission line between BATEIAS-500 and CURITIBA-500 (35 km) instead of AREIA-500 / BATEIAS-500 and installing a 100 Mvar capacitor in BATEIAS-500 to be used only in case of contingency. The second alternative is more cost efficient due to the distance between BATEIAS-500 and CURITIBA-500 being a fraction of the distance from BATEIAS-500 to AREIA-500.

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APPENDIX

TABLE VIII. LIST OF ANALYZED CONTINGENCY CASES

Case	Line Number	Line Name
1	824-933	GBMUNHOZ-500 / AREIA-500
2	824-933	GBMUNHOZ-500 / AREIA-501
3	839-898	CASCAVEL-230 / FCHOPIM-230
4	839-1047	CASCAVEL-230 / SOSORIO-230
5	839-2458	CASCAVEL-230 / CASCAVEL-230
6	856-933	SEGREDO-500 / AREIA-500
7	856-1060	SEGREDO-500 / SSANTIAG-500
8	896-897	CASCAVEL-500 / SCAXIAS-500
9	898-1047	FCHOPIM-230 / SOSORIO-230
10	933-895	AREIA-500 / BATEIAS-500
11	933-955	AREIA-500 / CNOVOS-500
12	933-959	AREIA-500 / CURITIBA-500
13	934-1047	AREIA-230 / SOSORIO-230
14	938-955	BLUMENAU-500 / CNOVOS-500
15	938-959	BLUMENAU-500 / CURITIBA-500
16	955-964	CNOVOS-500 / CAXIAS-500
17	959-895	CURITIBA-500 / BATEIAS-500
18	964-976	CAXIAS-500 / GRAVATAI-500
19	976-995	GRAVATAI-500 / ITA-500
20	995-964	ITA-500 / CAXIAS-500
21	995-1030	ITA-500 / MACHADIN-500
22	995-1060	ITA-500 / SSANTIAG-500
23	1030-955	MACHADIN-500 / CNOVOS-500
24	1060-897	SSANTIAG-500 / SCAXIAS-500

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