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Case Studies of Battery Energy Storage System Applications in the Brazilian Transmission System

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Abstract: This paper presents the preliminary results of studies aiming to use a battery energy storage system (BESS) in the Brazilian transmission system. The main objective of the BESS is to solve congestion problems caused mainly by the large increase in variable renewable generation in certain system areas. The studies were conducted based on actual forecasted system scenarios using a full representation of the electric grid available from the Brazilian system operator data base. In this work, only the steady-state modeling was considered as this may be the first stage in the assessment of a new technology. A qualitative economic comparison of the BESS application with other possible solutions to the congestion problems is also included.

Keywords: Brazilian transmission systems; battery energy storage systems; variable renewable generation

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1. Introduction

The energy transition presently being implemented in different degrees around the world has added a fundamental role for the electric power system as most of this process relies on the electrification of all economic sectors. One may forecast that demand for electricity will rise two to three times to cope with the transition from an intensive use of fossil fuels to electricity-driven transportation, industry, services, among others. Most of the electricity will come from variable renewable energy (VRE) sources, mainly wind and solar photovoltaic (PV), with its well-known intermittence and difficult predictability [1–3].

An electric power system with a high utilization of VRE presents more complex controllability issues than the ones with conventional power sources [4]. The problems arise from the variable power output of wind and solar photovoltaic plants, including sudden variations caused by weather phenomena, and the reduced synchronized rotational inertia introduced by inverter-based generators (IBGs), which may cause difficulties in following the load curve, in controlling frequency and voltage, and keeping the system stable [5]. To deal with this unpredictable behavior of the variable renewable sources, the power system needs to increase its flexibility to adjust to unexpected situations. New technologies have been proposed to raise the power system flexibility level, like energy storage [6], demand response programs [7], among others [8].

Several energy storage technologies have been proposed for large scale application in power systems [9]. Among those, pumped storage hydropower (PSH) and battery energy storage systems (BESSs) are the ones presently most used [10,11]. PSH has the advantage of using a well-known hydroelectricity generation technology, and it is suitable for long generation periods, but it requires appropriate sites, it is not scalable, and it presents a relatively slow time response [12]. BESS, on the other hand, is a technology not totally mature, mainly related to raw materials, although it has already been well developed and applied, but it has the advantages of fast response and deployment, scalability, mobility, and multiple functions [13]. That last characteristic of BESS introduces the possibility of revenue stacking, which is the possibility to earn revenue simultaneously from multiple sources using the same capacity [14].

The Brazilian interconnected power system (BIPS) has experienced a very large increase in wind and solar photovoltaic generation in the last decade. Presently, wind and photovoltaic energy (both centralized and distributed) account for more than 30% of the total installed capacity. Forecasting for the 2031 horizon indicates that this percentage may rise to even more [15]. The wind generation is located in the northeast (NE) and in the south (S) regions, and the concentrated photovoltaics are also in the NE and in the north of Minas Gerais state (MG) [16] and in the southeast (SE) region. The largest load centers, on the other hand, are located in the SE of the country. This situation has required a great effort to increase the transmission capacity to transfer the renewable energy to the load centers. Despite this effort, the pace of increase in transmission capacity has not been fast enough to cope with the requested connection of new sources [17]. A difficult factor in this question is that the time to obtain the environmental permits and build new transmission lines is longer than to implement photovoltaic power plants.

This paper reports on the partial results of a research and development project, focused on the use of BESS to improve the performance of the BIPS, regarding the capacity to transmit energy from areas of elevated concentration of wind and solar photovoltaic generation to load centers. This technology was first used in Brazil to solve a specific regional transmission situation [18] but has not yet been the objective of exhaustive studies regarding the interconnected system. The main objective of using BESS is to increase the hosting capacity for renewable sources in those regions, reducing energy curtailment due to transmission congestion while deferring transmission investments.

The methodology used in this study is based on the grid steady-state performance, both for normal (N) and contingency (N-1) configurations, with full modeling of the BIPS. The studies were conducted based on actual forecasted system scenarios using a full representation of the electric grid available from the Brazilian system operator data base. The location and capacity of the BESS installation are chosen on an estimate-and-correction methodology, based on the empirical information obtained from planning and operation experience of the BIPS. A simple economic analysis comparing the advantage of the BESS solution with the conventional ones is also presented.

The methodology developed has been tested on actual transmission congestion problems in the MG region. This region, owing to its excellent levels of solar irradiation, affordable land prices, and tax incentives, has been experiencing a fast increase in generation connection requests for photovoltaic energy producers, both in distributed and concentrated forms. This fact has required the expansion of the transmission system that connects the region to the load centers in the SE region. However, the planned transmission expansion has not been able to catch up to the required generation connection requests due to the aforementioned reasons [16].

This article has the following organization: Section 2 presents some principles and benefits of battery energy storage systems applications in power systems; Section 3 describes the Brazilian interconnected power system, the test system to evaluate the benefits of BESS applications; Section 4 presents the case studies carried out and discussions on the results achieved; Section 5 carries out a brief techno-economic analysis; and Section 6 presents the conclusions of the article with the main insights found.

2. Storage as a Transmission Asset

BESSs constitute one of several storage technology options that increase the flexibility of the energy system and allow for increased levels of renewable energy integration. BESSs can be installed in various segments of the electrical system, including (a) in the transmission network close to load centers [19]; (b) in the nearby distribution network or on consumer premises [20]; or (c) integrated with variable renewable sources [21]. The location of the BESS has important implications for the services it can provide, and the most appropriate location for the BESS will depend on its intended use [22–24].

BESSs in the transmission network can provide a wide range of ancillary services related to good transmission performance. These systems can be deployed to replace or postpone peak capacity investments [25], provide operating reserves to help respond to changes in generation and demand [26], or can be used to postpone transmission system expansions in regions facing congestion due to electricity growth load or generation [27]. BESS in the distribution system can offer services similar to those in transmission systems and, in addition, other advantages such as facilitating the hosting of distributed generation [28], reducing voltage fluctuations [29] and enhancing energy quality [30].

Integrated with variable renewable sources, BESSs can reduce the transmission capacity required to integrate these resources by increasing the utilization of the available capacity, using excess generation during periods of high resource availability, and offloading during periods of low resource availability. In this way, BESSs can be used to reduce generation curtailment, whether due to transmission congestion or lack of adequate demand, as well as provide a wide range of ancillary services [31].

BESSs can maximize their value to the electrical system by providing multiple services. As some services are rarely requested, such as black start, or used infrequently at certain times of the day, such as spinning reserve, installing a BESS to provide multiple services allows for greater overall utilization of the BESS. This multi-use approach to the BESS is known as value-stacking. For instance, a BESS project can help postpone the need for a new transmission line by meeting a portion of peak demand with energy stored during a few select hours of the year. When it does not satisfy peak demand, the BESS can obtain revenue by providing operational reserve services to the system operator.

The use of BESSs to postpone investment in the transmission system, or expand the capacity of existing systems, is generically called storage-as-transmission assets (SATA). This concept is also referred to as virtual transmission line (virtual power line) [32] illustrated in Figure 1. The operational procedure is as follows: (a) Charge the BESS 1 with generation above the transmission limit to avoid curtailment; (b) Discharge BESS 1 when transmission capacity allows; (c) Charge BESS 2 in light load and available transmission capacity; (d) Discharge BESS 2 in peak load and insufficient transmission capacity. It is like adding a lane to a highway just for rush hour traffic. Used in this way, storage can increase the capacity of existing transmission lines or even serve as an alternative for the construction of new transmission projects.

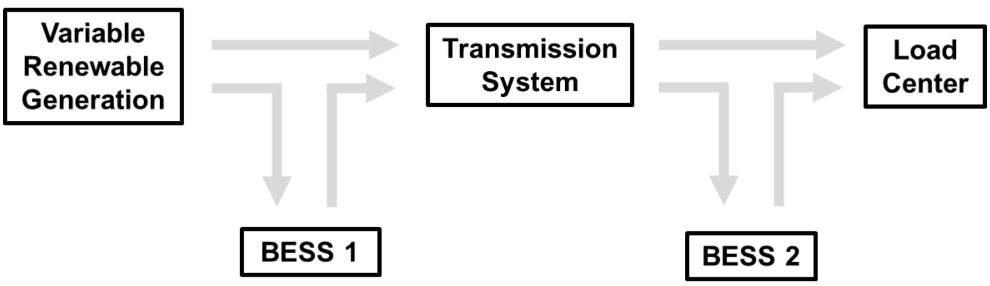

Figure 1. Storage-as-transmission assets.

3. The Brazilian Interconnected Power System

The Brazilian electricity sector is made up almost entirely of private companies, resulting from a process of privatization and restructuring that began in the 1990s. The electricity market operates in two environments: the first one, regulated, negotiates energy in pool-type auctions used by electricity distributors to supply the captive market of their consumers; the second one, free, allows direct negotiation between producers and the so-called free consumers authorized to purchase energy directly from producers.

The system is operated by the National Electric System Operator (ONS) and has the Energy Research Company (EPE) as its planning agency. The Electric Energy Trading Chamber (CCEE) is responsible for managing power purchase agreements, and the National Electric Energy Agency (ANEEL) is the regulatory body.

The BIPS is a continental size power system extending to the whole Brazilian territory with an area of more than 8.5 million km² and distances from its extreme points above 4000 km. It has its demand concentrated in the southeast region of the country, which also used to house most of the power generation units. In the last decades, three major changes in BIPS expansion have been observed: (a) Firstly, the largest new hydro power plants have been allocated to the north (N) region where there are still available sites for this type of installation; (b) Secondly, a large increase in wind and solar generation in the NE region, with some photovoltaic growth also in the SE region; (c) Thirdly, an exponential growth in distributed generation, mostly photovoltaic, spread among several regions of the country. The increase in generation in the N and NE region has been leading the requirements for reinforcements of the transmission system, both as HVDC links and HVAC systems. Figure 2 shows the main subsystems (N, NE, SE/MW, and S) and interconnections in the BIPS. In the Appendix A, some information data from the BIPS are presented.

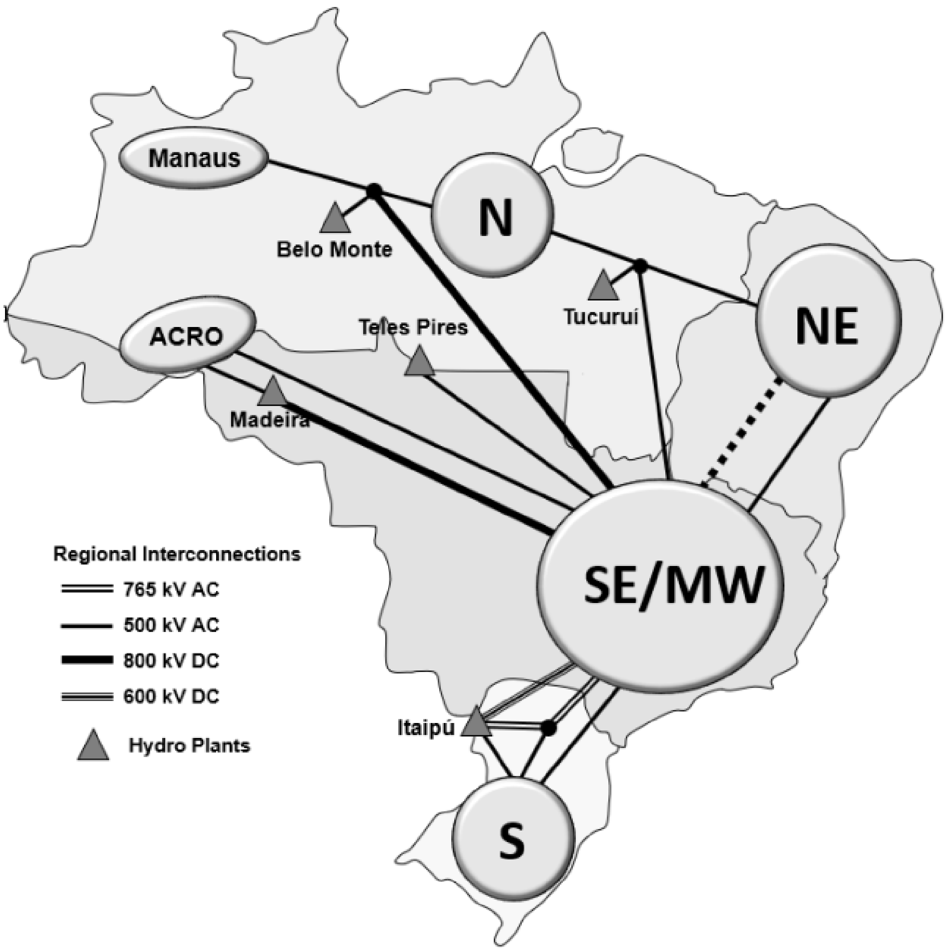

Figure 2. Brazilian electric system main interconnections.

The large increase in variable renewable generation, both in utility scale plants and distributed generation, has been raising concerns regarding the secure operation of the BIPS. The reduced robustness of the system caused by a large amount of generation connected through inverters may produce unforeseen behavior compromising the security of the system. In fact, on 15 August 2023, there was one incident that evolved to a partial blackout of the BIPS that, so far, has been interpreted as a result of wind power plants behaving differently from planning [33]. Furthermore, the large increase in solar photovoltaic and wind generation, particularly for the free market, has forced the expansion of the transmission system. Presently, a legislation is in analysis to regulate the implantation of offshore wind energy in the country. This has caught the attention of several multinational companies, which have already filed licenses for offshore plants. This new technology will add more pressure in the planning and operation of the BIPS.

4. Methodology

The studies addressed in this paper can be approached by different methodologies. These methodologies can be classified into two broad categories:

- Heuristic Techniques—In this type of approach, only a network analysis tool (Power Flow) is used, associated with the analysts' experience, in order to reach satisfactory solutions to each of the problems in a trial-and-error process.
- Optimization Techniques—In this category, the so-called Optimal Power Flow [34] can be used to solve the problem of congestion of the transmission network, assuming the existence of BESS already installed in the system or combinatorial optimization techniques (branch-and-bound, genetic algorithms, etc.) in determining the capacity and location of BESS, aiming to delay the investment in transmission lines or expand the hosting capacity of the network [35,36].

The second approach has the advantage of producing automatic and supposedly optimal methods from a mathematical point of view. However, in most cases, they lead to computational processes that are unfeasible in practice for systems with dimensions such as the BIPS. The first approach, although more laborious and prone to finding suboptimal solutions, has a better chance of producing results applicable in practice, in addition to being the process normally used in the planning and operation studies of actual electrical systems like the BIPS.

The methodology used in the studies reported in this paper follows the heuristic approach and is generically illustrated in Figure 3. The components of the flowchart shown in this figure are as follows:

- Scenarios Data Base: set of base case load flow data corresponding to different operation conditions of the BIPS in the study horizon, including seasonal variations and load levels.
- Power flow Assessment: power flow execution for the base case and selected contingencies for each of the scenarios in the data base with checking of limit variations.
- Scenario Base Case Adjustment: adjustment in the power flow case analyzed based on generation redispatch, HVDC lines power order variation, and voltage control adjustments, in order to relieve limit violations.
- Battery Allocation: definition of battery capacity (MW/MWh) in locations previously chosen based on the analyst's experience.
- Battery Aggregation: final definition of the battery capacity (MW/MWh) in each location able to attend the minimum requirement in each analyzed scenario.

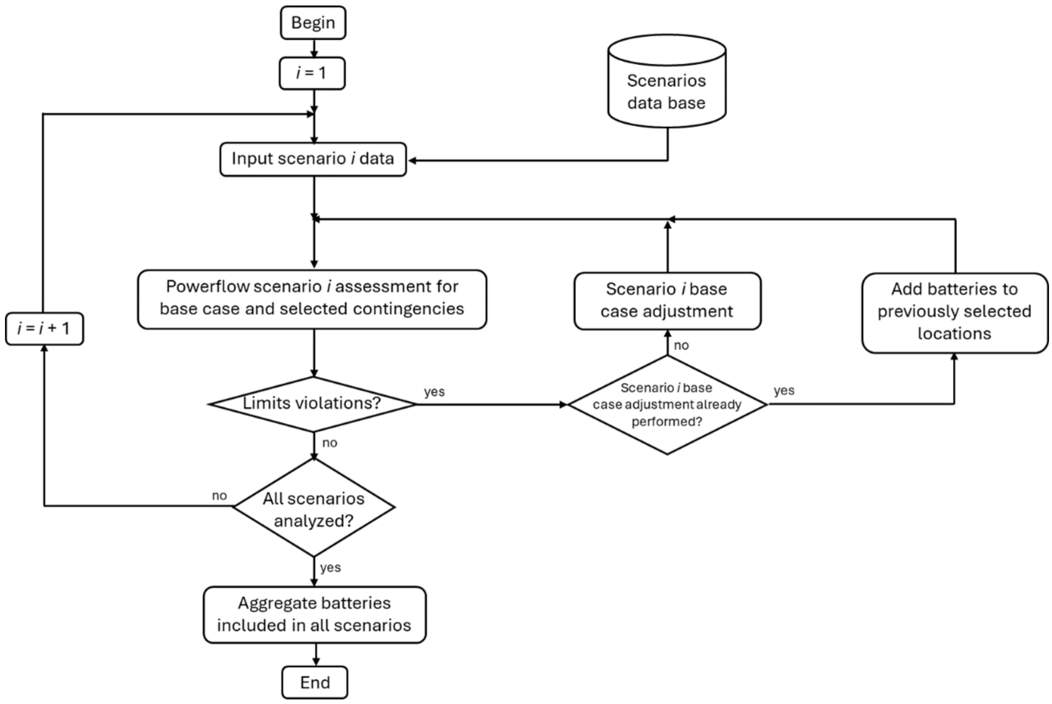

Figure 3. Flowchart of the heuristic methodology used in the studies reported in this paper.

5. Case Studies

The case studies presented here had the objective to assess the performance of BESSs to alleviate the limitation of the Brazilian transmission system to accommodate the fast increase in wind and solar photovoltaic generation. In its first stage, reported in this paper, only steady-state studies were performed. In a next stage, the dynamic performance will be analyzed. The studies are focused on the MG region, as it presents the highest access requests for solar photovoltaic plants in the country but uses a grid model representative of the whole BIPS. The scenarios used are the ones made available by the Brazilian system operator in its Medium-Term Electricity Operation Plan (PAR/PEL 2023) [37] for the 2028 horizon, from which we selected the 2027 winter scenario (low N region hydro generation and high NE region wind generation) and the 2026/2027 summer scenario (high N region hydro generation and low NE region wind generation); both scenarios are at medium load. The grid model has about 12,000 buses, 16,370 transmission lines/transformers, and 14 HVDC links.

5.1. The Minas Gerais Region

The northern region of the state of Minas Gerais has extensive areas of land, with relatively low economic value and excellent levels of solar radiation, which makes this region of the country extremely attractive for the installation of photovoltaic generation, both in its concentrated and distributed forms. These facts produced a rush of entrepreneurs in the energy area to install photovoltaic generation projects in this region, causing an accumulation of requests for connections to the transmission grid, part of which cannot be met due to the limitations of this system. This MG region is also in the way of a robust AC transmission interconnection to transport hydro energy from the N region and wind and solar generation from the NE region to the SE states (Minas Gerais-MG, Sao Paulo-SP, Rio de Janeiro-RJ, and Espirito Santo-ES), and some of the HVDC bipoles available in the Brazilian system (see Figure 4). The increase in photovoltaic generation in the MG region also impacts the capacity of these interconnections, as is demonstrated by the simulation studies in the next sections of this paper. Figure 4 also highlights the location of the substations on which the simulation studies focused.

The performed studies focused in two aspects of the transmission system of the MG region:

- *Local Flow of Photovoltaic Generation:* How the transmission system could cope with and increase demand for the connection of new photovoltaic generation in the area. The obvious solution is to expand the transmission capacity by deploying new transmission lines (TLs) or transformers (TRs). That solution, apart from the cost, has other difficulties like licensing and construction time. In that context, the BESS solution was tested and compared with other alternatives. The study focuses on the Jaíba and Janaúba substation area owing to the high access for new photovoltaic power plant (PVPP) connections.
- *The North-Northeast–Southeast Interconnection:* The study was directed to the analysis of the solution of the interaction of local generation in the MG region with the large flow of energy from the N and NE regions through the AC interconnection and the HVDC bipoles. The study was conducted around the Jaguara, Nova Ponte, and Estreito substations because it is a very sensitive location of the system due to the connection of the Xingu–Estreito bipole (with capacity of 4000 MW) to the AC system.

The scenarios studied were previously adjusted in order to not present violations in normal operational conditions, as it was assumed that the BESS is not recommended to solve this kind of situation. Therefore, the studies were focused for the system performance for contingency cases in which the BESS action is supposed to be required for a relatively small period of time (minutes to a few hours). Therefore, the main objective of the studies was to determine the BESS capacity in MW to deal with the worst situation in each scenario, assuming that the discharge period of the BESS is 2 h.

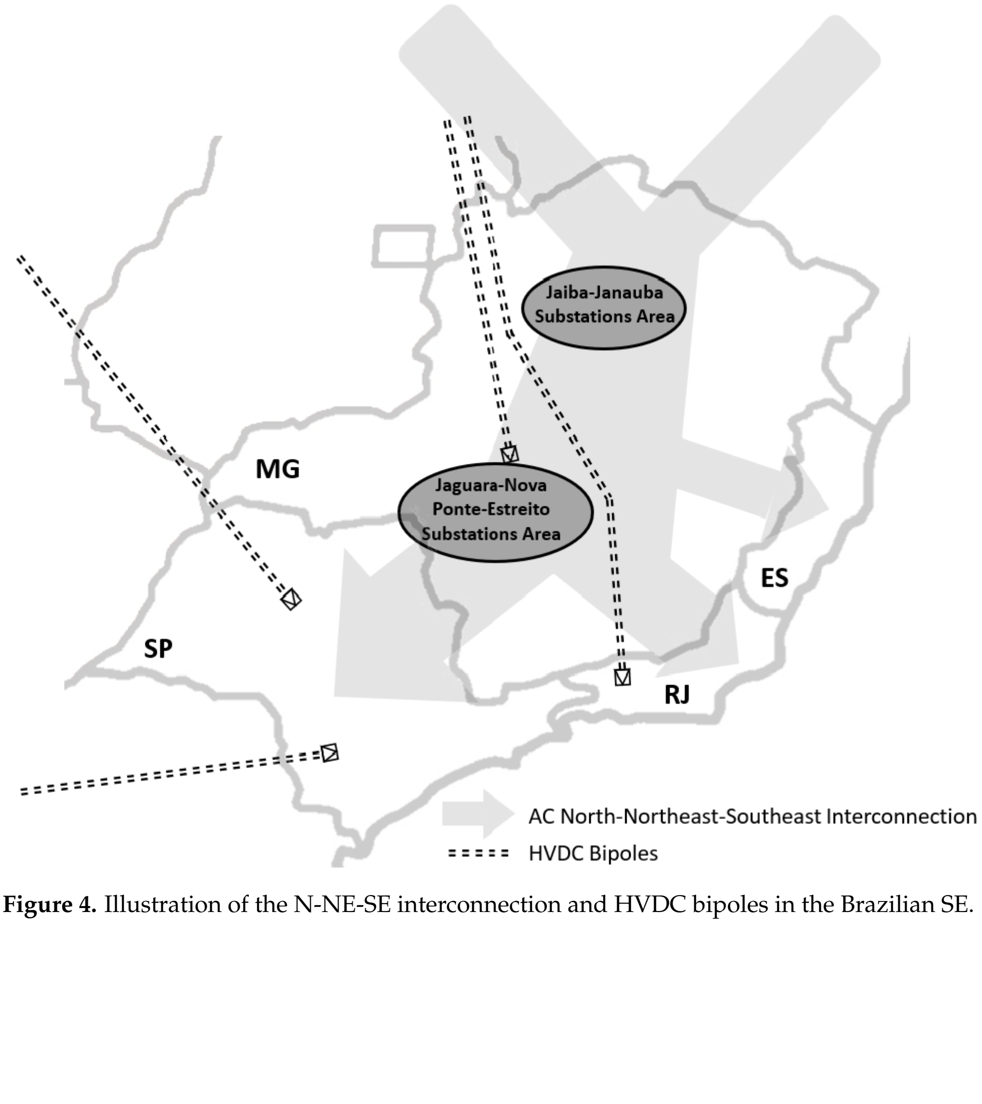

Figure 4. Illustration of the N-NE-SE interconnection and HVDC bipoles in the Brazilian SE.

5.2. Case Study I: Local Flow of Photovoltaic Generation

Figure 5 shows the part of MG electric system, highlighting the Jaiba and Janauba substation connections. These substations absorb most of the photovoltaic generation produced in this area. The analyzed scenario presents the installed capacities and base case dispatch of the local photovoltaic generation presented in Table 1.

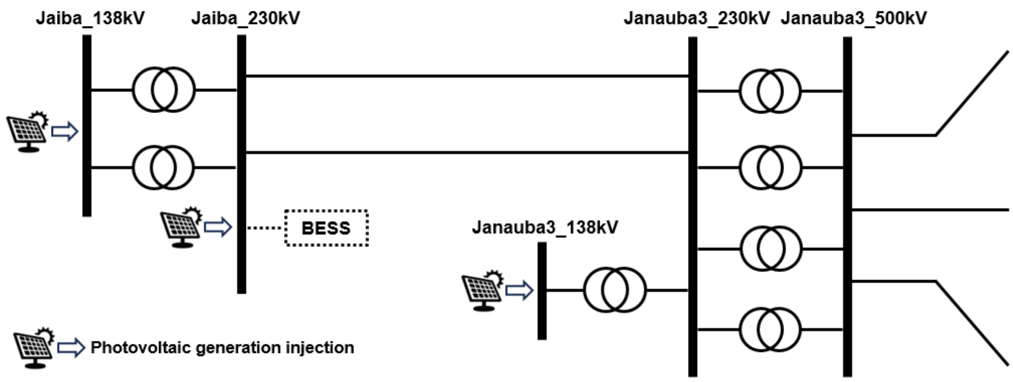

Figure 5. Jaiba and Janauba substations electric connections.

Table 1. Studied scenario photovoltaic generation capacities and base case dispatch.

Voltage Level (kV)	Installed Capacity (MW)	Base Case Dispatch (MW)
138	123.0	100.8
220	1180.0	967.6

Under normal operating conditions, the transmission system of the Jaiba region does not have a voltage or overload problem. However, when considering the disconnection of one of the circuits of the 230 kV transmission line (TL) between the Jaiba and Janauba 3 substations, the remaining circuit presents an overload of around 12%. To solve this overload, the installation of a BESS in the Jaiba SE occurred, as shown in Figure 5. Power flow simulations with increased capacity in the BESS show that a battery with 150 MW capacity is adequate to avoid the overload.

Following the analyses, the dispatch of photovoltaic plants in the Jaiba region was increased to 100% of their installed capacities and, as a result, there was a need to increase the battery capacity to avoid overload problems in the contingency scenarios analyzed. The simulation studies indicate that a 350 MW BESS is adequate to solve this overload problem.

Finally, as a last analysis of the region, the use of a battery with 600 MW of installed capacity was considered, with the objective of verifying how much it would be possible to increase the dispatch of photovoltaics in the region. With this battery capacity, it was possible to increase the dispatch of PV power plants in the Jaiba region by 20%, reaching a level of 1.55 GW of capacity of this type of energy in the region.

Analyzing the results obtained in the study of the Jaiba region, one may say that a 350 MW battery was necessary to enable the dispatch of the existing plants in the region at their total generation capacities. In addition, considering a maximum battery of 600 MW, it was possible to increase the installed capacity of the PVPPs in the region by 20%, which represents an increase of about 400 MW of capacity. This level of increase in flow capacity could allow the operation of new photovoltaic generation in the Jaiba region.

Tables 2 and 3 contain the power flow assessment results for a contingency situation, considering the disconnection of the 230 kV TL Jaiba—Janauba, circuit 2 (C2). In Table 2, the voltage level of the main buses in Jaiba and Janauba are presented. One can notice that the BESS utilization improves the voltage level of the electrical region. When considering a PVPP's dispatch of 120% of the original capacity, the load flow solution did not converge. Using the aforementioned amount of the BESS, this issue can be solved. In Table 3, the equipment loadings are presented for the three different scenarios evaluated: PVPP original dispatch, PVPP dispatch of 100% and PVPP dispatch of 120%. One can notice that the BESS utilization can solve the overloading conditions observed in the simulations without this equipment.

Table 2. Voltage levels with disconnection of the 230 kV transmission line Jaiba–Janauba in Minas Gerais.

Bus	Voltage Level Under Contingency (p.u.)					
	PVPP Original Dispatch		PVPP Dispatch of 100%		PVPP Dispatch of 120%	
	Without BESS	With BESS	Without BESS	With BESS	Without BESS	With BESS
Jaiba 138 kV	1.016	1.025	0.996	1.007	Power flow solution issues	1.013
Jaiba 230 kV	1.029	1.04	1.003	1.012		1.022
Janauba 138 kV	0.966	0.982	0.954	0.972		1.008
Janauba 230 kV	0.975	0.989	0.977	0.981		1.031

Table 3. Equipment loading with disconnection of the 230 kV transmission line Jaiba–Janauba in Minas Gerais.

Equipment	Capacity (N/N-1) (MVA)	Loading Under Contingency (%)					
		PVPP Original Dispatch		PVPP Dispatch of 100%		PVPP Dispatch of 120%	
		Without BESS	With BESS	Without BESS	With BESS	Without BESS	With BESS
TL 230 kV Jaiba - Janauba 3 C1	578/839	112	95.7	142.1	98.8	Power flow solution issues	98
TL 230 kV Jaiba - Janauba 3 C2 [1]	578/839	0.0	0.0	0.0	0.0		0.0
TR 1 230/138 kV of Jaiba	100/120	15.1	12.5	25.4	16.5		24
TR 2 230/138 kV of Jaiba	100/120	15.1	12.5	25.4	16.5		24
TR 230/138 kV of Janauba	225/270	58.3	55.0	65.2	56.5		57
TR 1 500/230 kV of Janauba	300/360	75.1	65.8	92.1	67.6		67
TR 2 500/230 kV of Janauba	300/360	75.1	65.8	92.1	67.6		67
TR 3 500/230 kV of Janauba	300/360	75.6	66.1	92.6	68.0		68
TR 4 500/230 kV of Janauba	300/360	75.6	66.1	92.6	68.0		68

[1] Disconnected for the contingency simulation.

5.3. Case Study II: The North-Northeast–Southeast Interconnection

In this case study, the objective was to analyze the influence of a BESS in the N-NE-SE interconnection in view of a large PV production in the MG state. The following aspects were taken into consideration:

- Power flow in the Xingu–Estreito bipole;
- Total power flow from N-NE to SE;
- Total PV generation in MG state;
- Reinforcement of the transmission system.

It should be pointed out that the power flow in the Xingu–Estreito bipole cannot be raised above a certain limit due to generation capacity available in the N region or interchange capacity between the NE and N regions. On the other hand, reducing the total power flow from N-NE to SE or the total PV generation in MG state means curtailment of the wind or photovoltaic generation with the usual economic and regulatory implications. Furthermore, reinforcement in the transmission system implies high costs and regulatory difficulties.

The combination of the aspects above with a BESS system are studied in the simulations in order to guarantee an adequate performance in all considered contingency cases. Figure 6a presents a part of the BIPS grid showing the Jaguara, Nova Ponte, and Estreito substations, indicating the importance of these substations in the N-NE-SE interconnection, particularly due to the Xingu–Estreito bipole. Figure 6b shows the one-line diagram of the Jaguara, Nova Ponte, and Estreito substation connections, indicating the predominant power flow directions and the location of the BESS system considered in the studies.

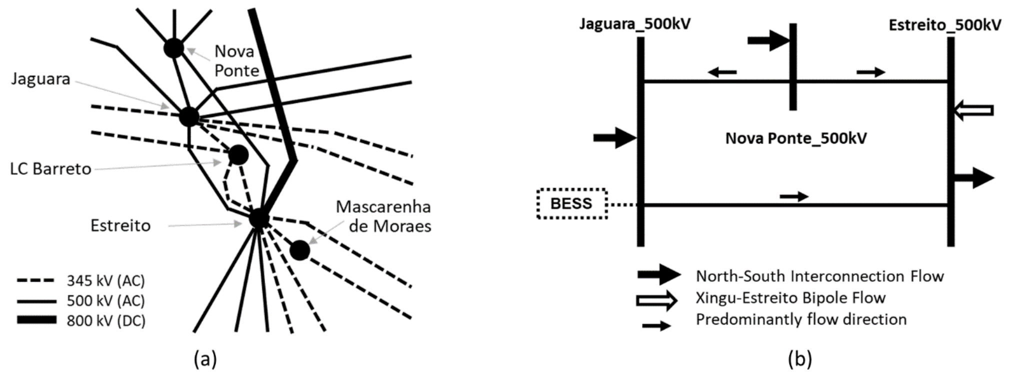

Figure 6. (**a**) Part of the NMG electric grid; (**b**) One-line diagram of the Jaguara, Nova Ponte, and Estreito substation connections.

5.3.1. Winter 2027 Scenario

The original Winter 2027 scenario considered presented the following values for the main simulation parameters:

- Power flow in the Xingu–Estreito bipole: 400 MW;
- Total power flow from N-NE to SE: 5441 MW;
- Total PV generation in MG state: 11,118 MW.

This base case scenario presented an overload of about 10% in the Jaguara_500 to Estreito_500 transmission line in normal operating conditions and an overload of about 30% under the most critical contingency. In order to correct these overloads, the original case was altered by increasing the power flow in the Xingu–Estreito bipole to 1200 MW. This was taken as the new base case for the simulation studies. This base case presented an overload of about 15% for a contingency of the Nova Ponte_550 to Estreito_500.

The results of the simulation studies are summarized in Table 4. Simulation 1 represents the solution with the BESS only, and Simulations 2 to 5 represent alternative solutions.

- Simulation 1: A BESS with a total capacity of 1200 MW, consisting of four units of 300 MW each, is required to overcome the overload;
- Simulation 2: The overload problem is solved by increasing the power flow in the Xingu–Estreito bipole to 2400 MW;
- Simulation 3: In this case, the overload is avoided by reducing the PV generation in the MG state by a little more than 50%;
- Simulation 4: The solution was achieved by reducing the total power flow from the N-NE to SE region to almost zero;
- Simulation 5: In this case, the solution is obtained by the addition of a second transmission line between the Jaguara_500 to Estreito_500 SEs, keeping the other parameters almost constant or with little improvement.

Tables 5 and 6 contain the power flow assessment results for a critical contingency situation in the winter scenario, considering the disconnection of the 500 kV TL Nova Ponte—Estreito, circuit 1 (C1). In Table 5, the voltage levels of Jaguara, Nova Ponte, and Estreito substations are presented, where it can be observed that the bus voltages are adequate inside the limit range from 0.95 to 1.10 p.u. In Table 6, the equipment loadings are presented for Simulations 1 to 5, which represent possible solutions for the overload problem observed in the base case. It is important to notice that the use of BESS enables the operation of the system with an optimized dispatch of photovoltaic power plants in Minas Gerais and the renewable power plants of the NE region for the winter scenario.

Table 4. Results of several operational conditions in the winter scenario.

Parameters	Winter 2027				
	1	2	3	4	5 [2]
Power flow in the Xingu–Estreito bipole (MW)	1200	2400	400	400	400
Total power flow from N-NE to SE [1] (MW)	5382	5222	5590	−474	6127
Total PV generation in MG state (MW)	11,118	11,118	5757	11,118	11,118
BESS installed capacity (MW)	1200	0	0	0	0

[1] Includes the power flow in the Xingu–Estreito bipole. [2] Includes the new transmission line between Jaguara and Estreito substations.

Table 5. Voltage levels with disconnection of the 500 kV transmission line Nova Ponte–Estreito in the winter scenario in Minas Gerais.

Bus	Voltage Level Under Contingency (p.u.)				
	Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 5
Jaguara 500 kV	1.079	1.088	1.081	1.082	1.076
Nova Ponte 500 kV	1.057	1.072	1.094	1.079	1.046
Estreito 500 kV	1.09	1.089	1.085	1.08	1.085

Table 6. Equipment loading with disconnection of the 500 kV transmission line Nova Ponte–Estreito in the winter scenario in Minas Gerais.

Equipment	Capacity (N/N-1) (MVA)	Loading Under Contingency (%)				
		Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 5
TL 500 kV Estreito—Jaguara C1	1992/2390	98.7	99.3	96.9	97.5	76.4
TL 500 kV Nova Ponte—Jaguara C1	2442/2598	85.5	69.5	65.8	64.2	91.5
TL 500 kV Nova Ponte—Estreito C1 [1]	2533/2533	0.0	0.0	0.0	0.0	0.0

[1] Disconnected for the contingency simulation.

5.3.2. Summer 2026/2027 Scenario

For this scenario, the base case presented no overload issues, and the contingency studies indicated an overload of about 10% in the Jaguara_500 to Estreitor_500 transmission line. Therefore, no adjustment was necessary for the base case.

The results of the simulation studies are summarized in Table 7. Simulation 1 shows that a 1000 MW BESS or the four units of 300 MW as indicated above are adequate which is adequate to deal with the overload caused by the contingency. As this value is lower than the lowest one for the winter 2027 scenario, it was not necessary to try other values. Simulations 2 to 4 show the results for the alternative solutions of reducing PV generation in the MG region, reducing the N-NE-SE interconnection flow or adding a second transmission line between Jaguara_500 and Estreito_500 substations. No increase in the Xingu–Estreito bipole power flow was attempted as it is already at its maximum value.

Table 7. Results of several operational conditions in the summer scenario.

Parameters	Summer 2026/2027			
	1	2	3	4 [2]
Power flow in the Xingu–Estreito bipole (MW)	4000	4000	4000	4000
Total power flow from N-NE to SE [1] (MW)	13,165	13,253	10,802	13,164
Total PV generation in MG state (MW)	6723	4293	6723	6723
BESS installed capacity (MW)	1000	0	0	0

[1] Includes the power flow in the Xingu–Estreito bipole. [2] Includes the new transmission line between Jaguara and Estreito substations.

Tables 8 and 9 contain the power flow assessment results for a critical contingency situation in the summer scenario, considering the same disconnection of the 500 kV TL Nova Ponte—Estreito, circuit 1 (C1). In Table 8, the voltage level of Jaguara, Nova Ponte, and Estreito substations are presented, where it can be noticed that the bus voltages are also adequate inside the operation limit range. In Table 9, the equipment loadings are presented for Simulations 1 to 4, which represent the considered solutions for the overload problem observed in the base case. It is important to notice that for the summer scenario, the utilization of BESS also enables the optimized dispatch of photovoltaic power plants in Minas Gerais and the renewable power plants of the NE region.

Table 8. Voltage levels with disconnection of the 500 kV transmission line (Nova Ponte–Estreito) in the summer scenario in Minas Gerais.

Bus	Voltage Level Under Contingency (p.u.)			
	Simulation 1	Simulation 2	Simulation 3	Simulation 4
Jaguara 500 kV	1.066	1.09	1.089	1.057
Nova Ponte 500 kV	1.059	1.083	1.082	1.054
Estreito 500 kV	1.073	1.094	1.091	1.054

Table 9. Equipment loading with disconnection of the 500 kV transmission line (Nova Ponte–Estreito) in the summer scenario in Minas Gerais.

Equipment	Capacity	Loading Under Contingency (%)			
	(N / N-1) (MVA)	Simulation 1	Simulation 2	Simulation 3	Simulation 4
TL 500 kV Estreito—Jaguara C1	1992/2390	99.5	99.7	98.3	66.1
TL 500 kV Nova Ponte—Jaguara C1	2442/2598	94.7	81.2	79.5	64.2
TL 500 kV Nova Ponte—Estreito C1 [1]	2533/2533	0.0	0.0	0.0	0.0

[1] Disconnected for the contingency simulation.

6. Techno-Economic Comparison

A comprehensive techno-economic comparison of the application of the BESS with other possible solutions is beyond the objectives of this paper, as it requires further simulation studies considering 24 h simulations in order to assess accurately curtailed VRE, losses, energy not supplied, and transmission investment, among other important aspects. Moreover, the revenue stack possibility of BESS should also be considered. Despite this limitation, it is possible to draw some conclusions from a qualitative and approximate comparison.

The most important parameters for the economic analysis of a BESS project, the capital and operating costs, are also the more difficult to determine. Different values, and sometimes conflicting ones, can be found in the literature. In this work, the projection for the 2030 horizon in [38] was adopted. The value considered for the capital cost is 400 US$/kWh for a 2 h charging/discharging BESS. The operating costs were not considered in this analysis as they may vary considerably from place to place and are relatively low compared to capital costs.

The Case Study I shows that in order to safely keep the base case dispatch of 1068.4 MW of PV generation, it is required to install a BESS with a capacity of 150 MW/300 MWh. Otherwise, this generation should be reduced by about 10% to avoid overload in contingency conditions. Suppose that these restrictions happen over a period of 2 h daily, that means that there will be a constrained amount of 213.6 MWh daily that, over a period of 5 years, will sum up to 389.82 GWh of not supplied energy. Taking into consideration the price of PV generation in the last Brazilian energy auction (2022) of 32.34 US$/MWh [39], it will reach US$ 12.6 million. That should be compared with the cost of installation of the BESS, which amounts to US$ 120 million. Therefore, from a strictly economic point of view and disregarding the payment for other multiple applications, BESS is not the best solution.

The analysis of Case Study II produces results similar to the previous one. The difference is that in these cases, other alternatives are compared with the BESS solution. The specified BESS (1200 MW/2400 MWh) capital cost is US$ 960 million. The avoided reduction in PV generation in the MG area, using the same criteria as in Case Study I, is 1957 GW with a curtailment cost of US$ 63 million. The option for reducing the total power flow from N-NE to SE by almost 5000 MW implies substituting this variable renewable generation by thermal generation in the SE region, with an average cost of 60 US$/MWh, which is a total extra cost of US$ 219 million, assuming an average capacity factor of 40% over a five-year period. The last comparison is with the installation of the new 500 kV transmission line between the Jaguara and Estreito substations at a cost of approximately US$ 27.4 million [40]. Therefore, as in the previous study, from an economic point of view, the BESS solution is by far the most expensive one.

It should be noted, however, that the main advantages of using BESS at a transmission level in power systems are related to operating flexibility and their multiple functions, such as fast voltage control and frequency control, which should be well valued in order to obtain a more reasonable comparison between this equipment and other similar solutions.

7. General Conclusions

This paper reported the partial results of a research and development project, focused on the use of BESS to improve the performance of the Brazilian interconnected power system, regarding the capacity to transmit energy from areas of elevated concentration of wind and solar photovoltaic generation to load centers. The main contribution of the paper consists of the analysis of battery energy storage systems (BESSs) into a high scale power system, such as the Brazilian interconnected power system (BIPS), whose dimension is presented in this work. The studies were conducted based on actual forecasted system scenarios using a full representation of the electric grid available from the Brazilian system operator data base, through using multiple execution of power flow calculations. Particular attention was paid to the Minas Gerais region owing to a high increase in photovoltaic generation in this area, and also because it is in the route of a robust transmission interconnection from the north and northeast production regions to the large load centers in the southeast. The results obtained indicated that BESSs are technically viable as a way to reinforce the transmission system, particularly to cope with contingency cases, but with a cost that is still superior to other alternatives. This economic disadvantage of BESSs may be overcome if other applications beyond transmission congestion are contemplated through revenue stack.

In terms of future work, several areas remain open for further exploration. One key aspect is the optimal placement of a BESS within the grid, which could significantly enhance system performance while reducing costs. Furthermore, reliability assessments involving BESSs should be conducted to evaluate their long-term impact on system stability and robustness. Finally, dynamic simulations involving BESSs in actual operational scenarios will be critical to understanding their full potential in handling fast transients, voltage regulation, and system resilience during grid disturbances. These studies will contribute to a more comprehensive evaluation of BESSs as a multifunctional asset in modern power systems.

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Abbreviations

The following abbreviations are used in this manuscript:

ANEEL	National Electric Energy Agency
BESS	Battery energy storage system
BIPS	Brazilian interconnected power system
CCEE	Electric Energy Trading Chamber
EPE	Energy Research Company
IGBT	Inverter-based generators
MG	Minas Gerais
MW	Midwest
NE	Northeast
ONS	National Electric System Operator
PVPP	PV power plant
PSH	Pumped storage hydropower
S	South
SATA	Storage-as-transmission assets
SE	Southeast
VRE	Variable renewable energy

Appendix A. The Brazilian Interconnected Power System Data

This appendix complements the information about the BIPS presented in Section 3 of this paper by presenting some data obtained from reports produced by ONS, EPE, and ANEEL. Presently, the BIPS has a total installed generation of 214.8 GW, and the peak consumption reached a maximum of 101.860 MW on 7 February 2024. Table A1 represents the installed capacity and energy generated by different sources. It should be noted that renewable generation accounts for 87.8% of the installed capacity and 89.9% of effective electricity generation.

Table A1. BIPS installed capacity and energy generation.

Generation	Capacity (GW) 2023	Energy (TWh) 2023
Hydroelectric	108.3	437.7
Wind	27.4	102.7
Distributed	26.6	36.3
Thermoelectric	26.3	71.0
Biomass	15.5	28.0
Solar	10.7	27.4
Total	214.8	703.1

Table A2 presents the installed capacity of main hydro plants in the BIPS, which are also depicted in Figure 2.

Table A2. Installed capacity of main hydro plants.

Hydroelectric Plant	Capacity (GW)
Itaipu	14.0
Belo Monte	11.2
Tucurui	8.4
Madeira	7.3
Teles Pires	1.8

Table A3 presents the extension of the BIPS transmission system in its various voltage levels and technologies.

Table A3. Data of the BIPS transmission system.

Voltage Level (kV)	Technology	Extension (km)
800	HVDC	9204
600	HVDC	12,816
765	HVAC	2683
500	HVAC	70,044
440	HVAC	6934
345	HVAC	10,491
230	HVAC	61,137
	Total	179,311

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