

## Article

# Operational Data Analysis of a Battery Energy Storage System to Support Wind Energy Generation

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**Abstract:** The insertion of renewable sources to diversify the energy matrix is one of the alternatives for the energy transition. In this sense, Brazil is one of the largest producers of renewable energy in the world, mainly in wind generation. However, the impact of integrating intermittent sources into the system depends on their penetration level, causing problems in the electrical network. To evaluate this scenario, the present article aims to investigate the power quality problems generated by wind turbines in connection with the electrical system and how battery energy storage systems (BESS) solve or mitigate these disturbances in the network. Knowing the impacts of high generation power variability, the focus of the work is the application of power smoothing. However, results are presented for five applications (factor correction, voltage control, power factor smoothing, frequency control and time shift) that can be carried out at the studied wind farm. This article presents a real BESS, which has a capacity of 1 MW/1.29 MWh, connected in parallel to a group of wind turbines that provides a power of approximately 50.4 MW located in Brazil. In addition to presenting the system simulation in HOMER Pro software, this study validates the effectiveness of this BESS by presenting real operation data for each application.

**Keywords:** renewable resources; energy transition; battery energy storage system; wind power; intermittency; power factor smoothing



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## 1. Introduction

Several countries face a strong and rapid energy transition driven by environmental issues [1], in addition to the need for new energy resources. About 80% of the world's primary energy supply comes from fossil fuels, contributing to an increase in the level of CO<sub>2</sub> released into the atmosphere. The result is an increase in the average temperature of the planet [2,3]. Countless possible alternatives exist from this, including the diversification of the electrical matrix through the incorporation of new renewable resources. According to the latest report released by the Global Wind Energy Council (GWEC), the total capacity of all wind farms in the world is 837 GW [4]. Turning to the Brazilian reality, the National Electric Energy Agency (ANEEL) states that Brazil exceeds the mark of 21.5 GW of installed power, which corresponds to 11.72% of the total power granted in the country [5].

Reducing dependence on fossil fuels is one of the actions agreed upon at COP26 (26th edition of the Conference of the Parties, held annually by the United Nations (UN)) [6,7]. The use of renewable energy sources is essential to promote the de-carbonization of the economy [4]. In February 2022, the conflict between Russia and Ukraine highlighted the serious risks to energy security posed by dependence on imported fossil fuels. These actions reinforce the argument that it is important to diversify energy production through the sustainable use of renewable resources [8]. Among the renewable generation sources,

the use of hydraulic, solar, and wind resources stands out. This research will focus on wind production. The force of the winds has been used by human beings for more than 5000 years to propel the sails of ships [9,10]. Over time, other purposes were met by wind energy until, in July 1887, Professor James Blyth of Anderson's College in Glasgow built the first wind turbine used to produce electricity [10]. In Brazil, electricity from hydroelectric plants is the main source of electric energy. Wind generation is second and is growing quickly because investors are interested in the country's winds, especially in the northeast [11]. However, due to the intermittent nature of wind energy, as well as other renewable sources, integration into power systems causes several problems in the electrical grid. The impact of integrating wind energy into the system, as well as stability and reliability, depends on its penetration level [12].

Brazil achieved the 15th position in the world ranking for total installed capacity in 2012. In 2021, the country moved to 6th place and stood out as the country that installed the most wind power plants. Between 2022 and 2026, an addition of 7.5 GW is expected to the  $\approx 22$  GW currently installed across the national territory [13]. In 2022, the country had more than 880 wind farms, and at least 50 more are expected to be built by 2040 [14].

The greatest Brazilian wind potential is located in the states of the northeast region, where the wind characteristics are more favorable for the installation of wind farms. This region has been given the title of one of the best winds globally [15]. Data from the National Electric Energy Agency (ANEEL) and the Energy Research Company (EPE) indicate that the installed capacity in the northeast region exceeds 20 GW, corresponding to almost 91% of the total installed capacity in Brazil [13].

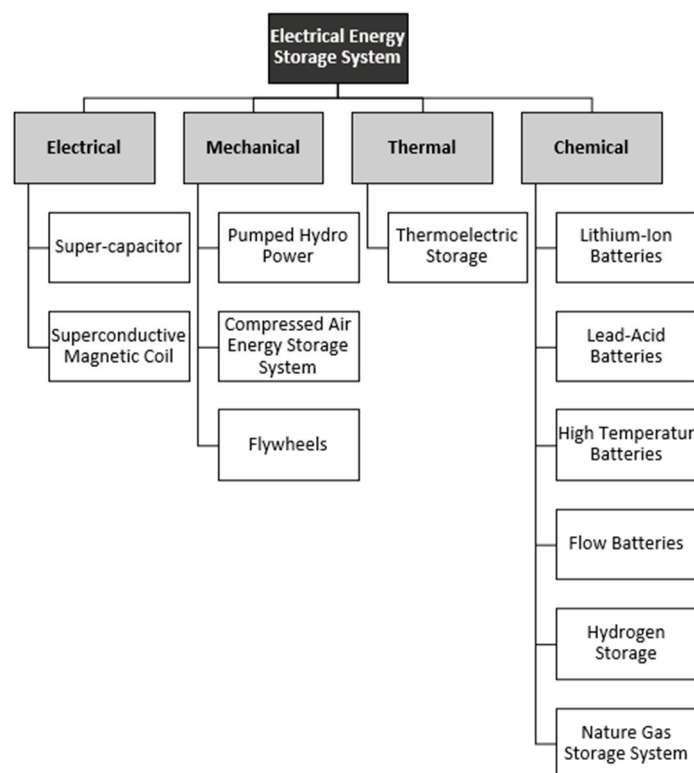
The three largest wind farms installed in Brazil, two of which are in northeastern Brazil, are [14]:

- Lagoa dos Ventos Wind Farm—Located in the state of Piauí, with an installed capacity of 399 MW;
- Osório Wind Farm—Located in the state of Rio Grande do Sul, with 300 MW of installed capacity;
- Alto do Sertão I Wind Complex—Located in the state of Bahia, with an installed capacity of 293.6 MW.

The power plant studied in this work is also located in the northeast region, the wind complex *Campo dos Ventos* (CDV), Campo dos Ventos, is in the city of João Câmara, in Rio Grande do Norte (RN). In the CDV complex, there are twenty-four identical wind turbines, with a total nominal power of 50.4 MW, where each turbine has a nominal power of 2.1 MW.

Although wind farms have a high capacity, they are characterized by the intermittency of energy generation caused by the natural conditions of the source. This intermittence causes power variation in the substation bus of the complex in question, resulting in power quality problems related to voltage, frequency, and power factor. To reduce fluctuations and smooth wind power generation, energy storage systems (ESS) [16] are used. The ESS have been used as a tool to mitigate issues caused by intermittent sources in the electrical system, as well as to assess the viability of wind energy in the grid. Nevertheless, it is important to define criteria that should be considered when selecting the appropriate ESS technology for installation. It is necessary to observe whether the system improves output power factor smoothing and other parameters related to wind generation.

When ESS are integrated with a renewable source, they store energy when production is greater than consumption. However, the form of storage depends on the technology adopted. Thus, electrical energy can be converted into chemical, thermal, and mechanical energy, among other forms, and then stored. One of the most used types of ESS is the battery energy storage system (BESS), which is in Figure 1 among chemical ESS, due to its speed of response and costs compared to other types of storage systems [17]. BESS are associated with renewable energies to store energy at times of high generation. This energy can be used at times of intermittency as well as in other types of applications.



**Figure 1.** Energy storage technologies.

In this context, this article aims to analyze the operational data of a BESS with a capacity of 1MW/1.29 MWh installed in the wind complex of Rio Grande do Norte in the city of João Câmara. This research is part of the research and development (R&D) project “Insertion of Storage System in Multiple Configurations to Support Wind Generation,” which investigates the various impacts that the operation of wind farms can cause on the electrical grid.

Thus, the research carried out involves investigating the energy quality problems generated by wind turbines at the initial point (energy generation) of the electrical system and how the BESS solves or mitigates these disturbances on the network. Due to the high variability of power provided by generation and its predictable consequences on the busbar, the main focus of the article is the application of power smoothing.

The article is divided into four sections. Section 1 of this article contextualizes the need to increase the share of renewable sources in the energy matrix, presenting the BESS as a viable solution to mitigate this problem. Then there is Section 2, which presents the types of energy storage systems, in which it is chosen to discuss the chemical form of storage by batteries, exposing the applications of a BESS incorporated into a wind generation park. Section 3 is composed of a case study of a real system in operation in the northeast region of Brazil. It starts by introducing the place where the BESS is installed, followed by a simulation of the system carried out. Finally, Section 4 presents the conclusions of the study based on all the data collected and all the research carried out for the construction of this article.

## 2. Application of Energy Storage Systems in Wind Generation

In order to understand the analysis of the operational data of the wind turbine/BESS system, this section conceptualizes the possible applications to execute in a generation bus connected to transmission lines. The electrical system is designed to meet the demand for electricity, which varies throughout the day, as well as seasonal fluctuations, which can be hard to predict. Therefore, concessionaires are required to maintain a reserve energy

capacity, which are usually natural gas plants. However, it is worth mentioning that wind energy is not available on demand, as it is only available when there is high wind speed.

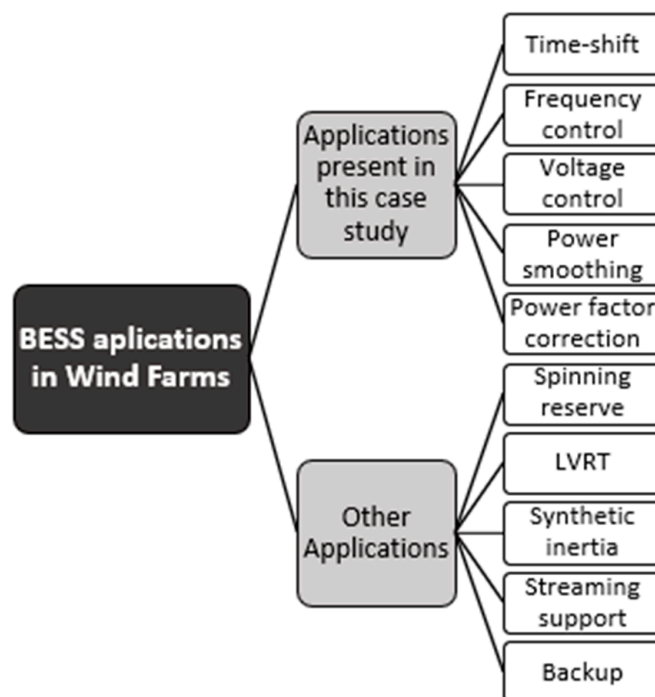
The insertion of wind generation, similar to any uncontrollable source, causes damage to the network, such as operational instability and decreases in frequency control capacity [18]. Therefore, when the percentage of participation of wind energy in the energy matrix increases, the impacts caused by it worsen [19].

An ESS is a solution to mitigate this problem, enabling voltage support resulting from the reduction of voltage level problems in permanent, dynamic, and transient conditions. In addition to smoothing the variability of wind production, it also handles the ramp issue (rate of change in the production of a large block of wind farms) and frequency control, for example.

An ESS can be integrated with a renewable source to store energy when its production is greater than consumption. However, the storage of the ESS depends on the choice of technology. Thus, before being stored, electrical energy can be converted into chemical, mechanical, or thermal energy, among others. Figure 1 illustrates technologies for energy storage. For this work, the storage of chemical energy by a lithium-ion battery is explored.

A BESS is one of the existing types of energy storage systems that stores energy in electrochemical format through batteries. It has several configuration options, including the possibility to define parameters such as battery technology, the location of the installation point, and the number of converters. The power converter system (PCS) must operate in four quadrants, allowing for the bidirectional flow of active and reactive power. Since the accumulator operates only with active power, the PCS must inject or absorb reactive power from the system [20].

The applications for the use of a BESS in wind farms are presented in Figure 2. These applications can be divided into two groups: (i) applications present in this case study and (ii) other applications. Table 1 provides a brief explanation of each of these applications.



**Figure 2.** BESS applications in wind farms.

**Table 1.** Description of BESS applications in wind farms.

| Application            | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
|------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Time-shift             | This application aims to store energy in periods where there is high production and low demand (off-peak hours) and discharge when demand is higher and production is lower-peak hours. The BESS can also be recharged with excess energy production from renewable sources such as wind or photovoltaics and discharged in periods of high grid energy cost.                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          |
| Frequency control      | The frequency is affected or regulated by the system's active power balance, which is subject to faults and disturbances. A reserve amount of active power must be maintained that is dispatched promptly when required. This reserve is composed of dispatchable sources, which may be hydroelectric or natural gas plants, for example [21]. With the diversification of the energy matrix, renewable energies are connected with dispatchable sources. Wind energy, as it depends on weather conditions, is of the non-dispatchable type, and, in this way, the generated energy presents a high variation of active power that is injected directly into the electrical grid, affecting the frequency limits. When the BESS stores the energy produced in excess by renewable generation, it prevents the grid frequency from increasing and allows the energy to be dispatched when the grid needs to meet a demand greater than what is produced, preventing the frequency from decreasing [22]. |
| Voltage control        | The voltage fluctuation resulting from the wind generation variation can be solved through the BESS; however, different from the frequency control, which uses active power, the voltage control is given by the reactive power, which can be injected into the electrical system through the power of the converter of the storage system. When the voltage deviation is less than $\delta V_{limit}$ (voltage limit value, given by the operator of the generation, transmission, or distribution system), it means that the value is within the regular operating range.                                                                                                                                                                                                                                                                                                                                                                                                                            |
| Spinning reserve       | Spinning reserve is the difference between the total power of the synchronized generating stations in the system and the total system demand at a given moment. This application allows the BESS to inject into the system when production is low or when there is a system shutdown, supporting the most critical case of loss of generation and enabling wind energy to be more reliable for the power grid [23].                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| LVRT                   | Low-voltage ride-through is used to prevent the system from collapsing when a voltage dip occurs. Wind turbines need to remain connected to the power grid, providing reactive support and increasing the voltage at the connection point. A BESS can also be used to provide this support to the power grid, as it has bidirectional converters. This characteristic of the converters expands the number of control strategies, as the control system needs to consider whether the BESS is loading or unloading [24].                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| Synthetic inertia      | Traditional energy sources (synchronous generators) often have their own inertia, tending to maintain movement even when power is no longer applied. This property is essential for the stability of the electrical system, but it is not present in renewable sources since the connection to the network occurs through DC/AC converters that do not have this function. Therefore, the growth of renewable sources reduces the inertia of the electrical system, making it more vulnerable to changes in frequency. Using a BESS can provide fast responses, allowing dynamic control of the frequency [25,26]. The storage system, as it contains converters that operate in four quadrants, can inject and absorb power in a time range that can vary from milliseconds to seconds after a disturbance. In this way, the BESS serves as synthetic/virtual inertia, managing to mitigate frequency variation problems during a short period of time [27].                                          |
| Streaming support      | Wind farms that are not located near the load center tend to have problems when a larger wind generation capacity is installed at a point where the transmission lines do not have enough transport capacity, causing it to be unfeasible to transmit the generated energy to the load, wasting part of this energy [25,28]. The use of the BESS with the wind farm allows the available line to have a better use, as the storage system supports the connection of a park with a maximum production higher than that available for the transmission line, in addition to helping to increase the load capacity of the line without increasing the transmission capacity [29].                                                                                                                                                                                                                                                                                                                        |
| Backup                 | A BESS can be used as a backup, that is, to act as emergency support to the wind system when there is a wind generation deficit due to the low production of the park. Furthermore, it can also be used when it is necessary to perform preventive or corrective maintenance on a wind turbine. Thus, when removing a machine, a BESS can momentarily replace it to sustain the park operations without reducing the power delivered to the grid. This continuous operation maintains stable costs arising from the sale of energy, reducing the incidence of fines for the non-delivery of energy purchased by agents of the Brazilian interconnected system [30].                                                                                                                                                                                                                                                                                                                                    |
| Power factor smoothing | Due to the intermittency of generation from a renewable source, the power fluctuation is unpredictable and may vary over seconds, minutes, or even hours. As the share of renewable energy in the electrical network grows, the operation of these sources in the grid becomes more complex. The smoothing of the active power at the source output is one of the ways to allow stability in the network, as well as energy quality. The BESS can act to inject or absorb the power to maintain this variable within the established limits [22,31].                                                                                                                                                                                                                                                                                                                                                                                                                                                   |

Table 1. Cont.

| Application             | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |
|-------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Power factor correction | In Brazil, the power factor must be within the specified range of 0.95 inductive and 0.95 capacitive. In this case study, the BESS energy management system (EMS) verifies the power factor information generated by the wind turbines on the bus where the storage system is connected, and when there is a reduction in the power factor (less than 1), it triggers the two PCS contained in the BESS to operate with inductive or capacitive characteristics, depending on the behavior of the power factor. It should be noted that the programming of the BESS power factor correction function is programmed to act if the power factor is less than 1. |

As an example, we present the case of time-shift in which, generally, at night, the wind speed is higher, but the demand is usually lower; therefore, the cost of energy is cheaper. However, during peak hours, when energy is more expensive, wind generation tends to be lower. The application of energy displacement in time aims to (i) store energy in periods when production is high and demand is low (off-peak hours) and (ii) discharge when demand increases and production decreases (peak hours) [22]. For this function, it is necessary that the BESS be sized to store large amounts of energy lasting for hours or even days [32]. Furthermore, the system must be efficient so that the wind energy generated and stored [25] is not wasted. In Figure 3, a day during the summer is observed, and, as can be seen, wind energy is greater during the night, being stored during this period and consumed during the day when the wind is not favorable for wind generation.

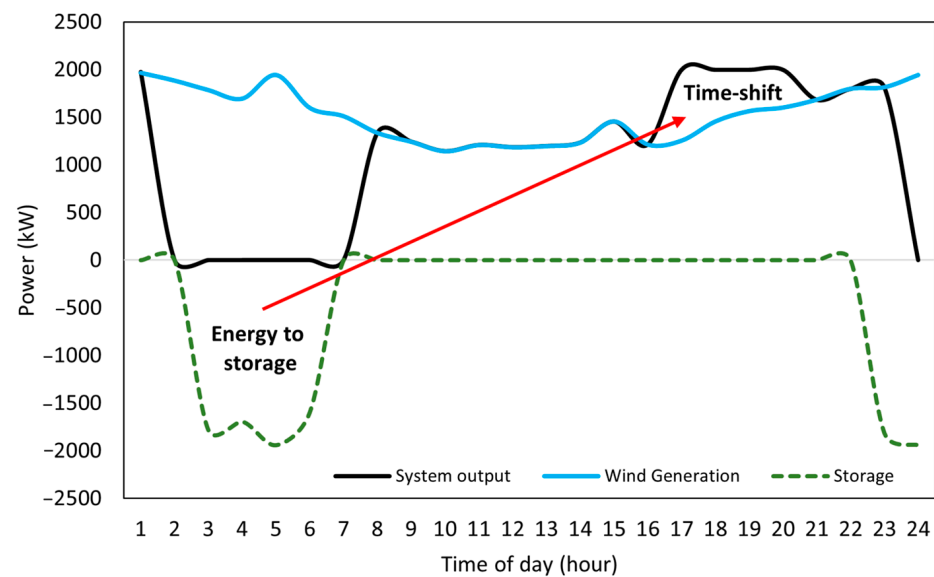


Figure 3. Energy time-shift application example.

The time-shift is defined mathematically by the relation involving the state of charge of the batteries, assuming that the required peak demand ( $D_{req}$ ) is known in advance. The BESS must have sufficient energy to provide peak hours. Thus, the nominal capacity of the BESS for storage is given as  $E_{BESS}$ , the state of charge (SoC) range for the application is  $SoC_{ts}$  and the minimum state of charge of the battery at the end of the application ( $SoC_{min}$ ). The relation is given as:

$$SoC_{ts} = \frac{D_{req}}{E_{BESS}} + SoC_{min} \quad (1)$$

This technique can also be used to meet demand for generation on the transmission line when there is low renewable production. Thus, the time-shift becomes load leveling



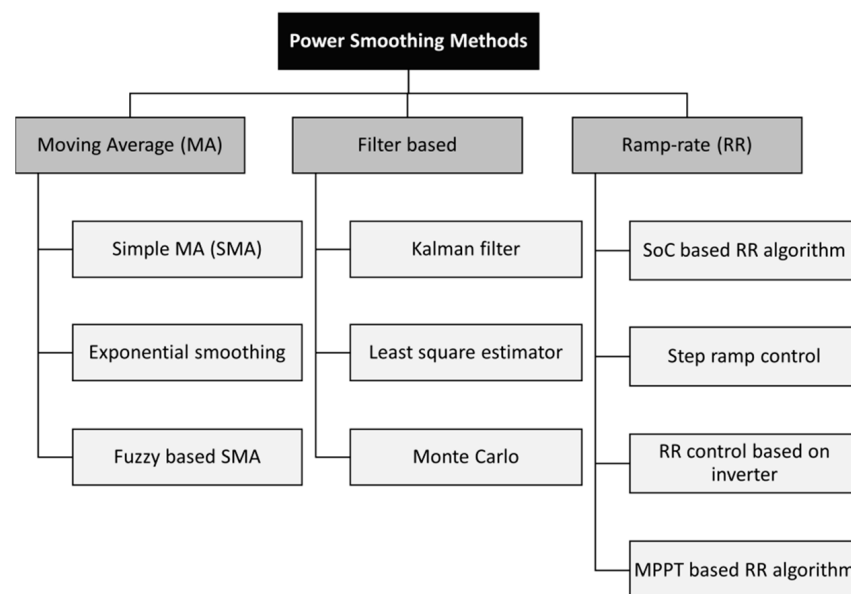
and is defined considering the amount  $N$  of wind turbines that are part of the connection with the BESS. From this, it is possible to find the power balance of the following equation:

$$P_{ons} = \sum_{i=1}^N P_{windi} + P_{BESS} \quad (2)$$

where  $P_{ons}$  is the power required by the transmission line;  $P_{windi}$  is the power generated by each wind turbine on the BESS bus; and  $P_{BESS}$  is the output power of the storage system on the bus. The unloading operation is being performed if  $P_{BESS} > 0$ , and if  $P_{BESS} < 0$ , the BESS is in the process of reloading. Using this same technique, it is assumed that the BESS can operate (discharge) to supply the energy demand required by the transmission line operator, and wind generation is below the required value. The actuation is given by the reference output power  $P_{BESSref}$ , defined as:

$$P_{BESSref} = P_{ons} - P_{tgen} \quad (3)$$

Another widely used application is power factor smoothing, which is employed to stabilize the output power of turbines or wind farms. Many researchers are working on developing methods and techniques that will enable the stability process to be performed more efficiently and quickly. This application is based on control methods for the performance of the BESS by moving average (MA) and exponential methods, filter methods, and methods based on ramp rate control algorithms, as illustrated in Figure 4 [33].



**Figure 4.** Wind power factor smoothing techniques to apply to BESS.

Moving average techniques are widely used due to their simplicity of implementation and the need for less computational effort for the development of algorithms. The objective is to limit wind power from the absorption and injection of energy by the energy storage system. The batteries can control the rapid fluctuations caused by the intermittent generation due to their fast responses [33]. This technique is also found in the literature on energy storage systems such as flywheels and [34] supercapacitors. Its mathematical definition is given by the sum of the power value of the wind turbine ( $P_{wt}$ ), considering the number of elements in relation to the determined time ( $w$ ) and the smoothing represented in the instant  $k$ th, such as [35,36]:

$$P_{batt} = \frac{\sum_{i=0}^{w-1} P_{wt}(k-i)}{w} - P_{wt}(k) \quad (4)$$

On the other hand, filter-based techniques present a high degree of complexity compared to AM. The filter algorithms perform the smoothing based on the frequency selectivity (amplitude, signal phase and current) in a certain range without changing or attenuating the spectral content. In addition to operating in power factor smoothing, this technique makes it possible to extend battery life. The level of complexity of the algorithms and to embark on the system makes some methods of filters not widespread, such as the Kalman and particle filters. The last set of most applied methods are those based on the ramp rate, being the most commonly found in real applications. This technique is based on calculating the derivative of power to determine the operation of the BESS [33,37].

Similar to the MA, the objective is to limit the power output of the turbine or wind farm, emphasizing that the RR acts only when the power variation exceeds a set value, resulting in the maintenance of the useful life of the battery. Ref. [35] presents the calculation of the RR technique considering the difference between two points in an interval of 60 s, in addition to the power of the network ( $P_t$ ) and the time ( $t(t)$ ) at the instant current, the time index ( $t60$ ) representing the time interval 60 s ago. Another important factor is the determination of the nominal power limit of the wind turbine, considered the maximum allowed RR. Accordingly, this technique is defined by Equation (5).

$$RR(t) = \frac{P(t) - P(t - 60)}{t(t) - t(t - 60)} \quad (5)$$

In the literature, several studies have been carried out with the application of these techniques, such as Ref. [38], which addressed in its research the implementation of a control strategy for smoothing the output power for a wind farm. In order to collect data on the maximum available wind power, the proposed control strategy was based on the production of wind speed. This generated the characteristic curve of the system. With this, it was possible to adjust the capacity of the storage system according to the probability distribution of wind speed and the characteristic curve of the power of the wind turbine.

The power tracking control strategy was created using MATLAB with BESS on the DC link of the turbines, while [39] presents a control strategy based on the SoC of the battery. The proposed method considers smoothing through the internal discharge control resistance to reduce the wind/PV hybrid output power fluctuations and regulate the battery SoC under typical conditions. This was also developed in a computational environment with MATLAB/SIMULINK software. In the developed simulations, the following method was considered: (a) this method considers the limit value of the energy fluctuation rate to be 10% for 15 min. However, it is necessary that this variation indicator should be changed according to the real situation of the (b) application strategy based on SoC conditions of excessive overload/discharge.

Ref. [40] proposed a BESS finite-time convergence control algorithm to mitigate wind energy fluctuations. This algorithm is insensitive to uncertainties and disturbances, allowing an adjustable convergence time to accommodate different operating conditions and maintain the SoC in an adequate range for reserve power capacity.

Furthermore, proposals based on power generation and battery conditions have been developed with artificial intelligence techniques. The authors in [41] developed a fuzzy-based discrete Kalman filter approach. This work uses battery health status as feedback to not only achieve smooth output power but also improve battery health by adaptively regulating battery power.

The authors in [42] presented an optimal energy dispatch programming method based on a predictive model control scheme (MPC) for a wind farm with BESS. The proposed method considers continuous information about wind farm production and the state of the battery, carrying out the short-term energy dispatch, considering the forecast of wind speed within the ideal horizon. The optimization problem is solved by a differential evolution (DE) algorithm at each time interval.



Hence, observing all the applications presented that can be incorporated into the generation of wind energy with the use of storage, we proceed to the case study in the next section. Some applications conceptualized here are analyzed in a real context.

### 3. Case Study: BESS Operation in a Wind Complex in Northeastern Brazil

João Câmara city (Countryside) is a town near the City of Natal (capital of Rio Grande do Norte state) in the Northeast region of Brazil. The site is located near the coordinates ( $5^{\circ}19'25.4''$  S  $35^{\circ}56'56.2''$  W). The map in Figure 5 contends the approximated location of the wind farm.



**Figure 5.** João Câmara, RN, site installation with approximate location of the wind farm.

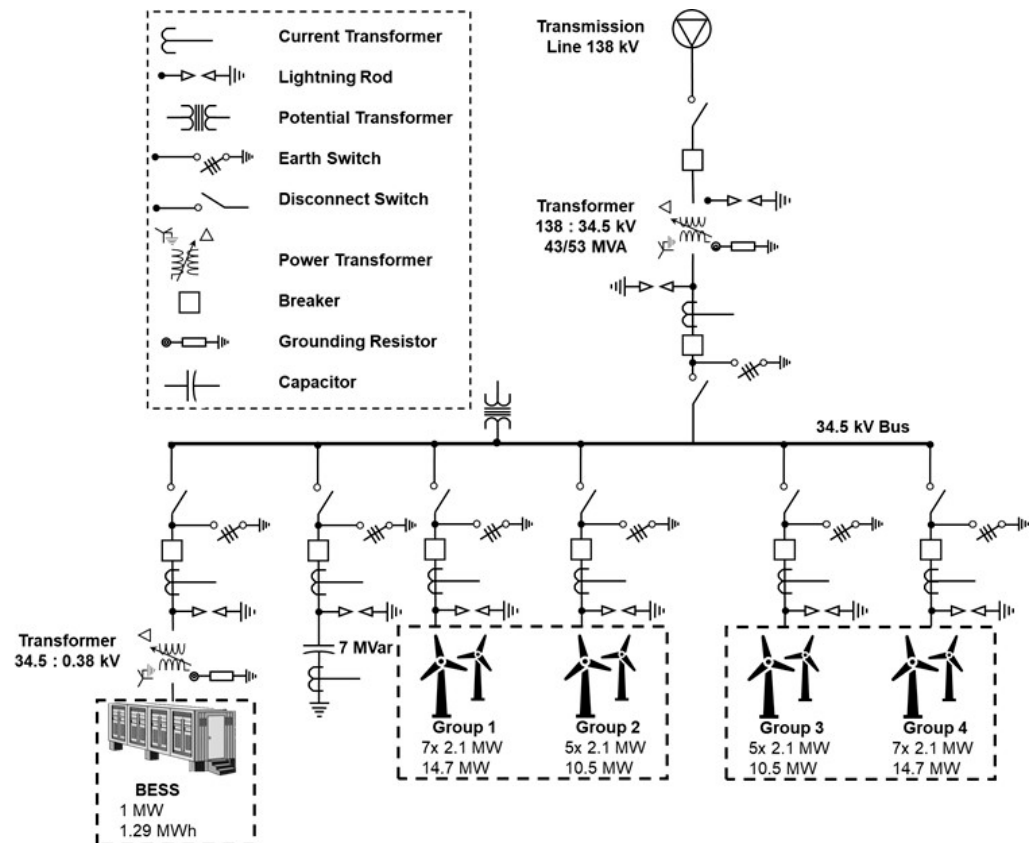
The city of João Câmara has about 35 thousand inhabitants. Despite being a small city, it currently houses 29 wind farms and 327 wind turbines and produces enough wind energy to supply a city almost six times its size [43,44]. One of the wind complexes in the municipality is called *Campo dos Ventos*. The CDV Wind Farm has a total of 105.6 MW and is composed of *Campo dos Ventos I* (25.2 MW), *Campo dos Ventos II* (30 MW), *Campo dos Ventos III* (25.2 MW) and *Campo dos Ventos V* (25.2 MW). The energy produced in CDV is sent to the National Interconnected System (in Portuguese, *Sistema Interligado Nacional–SIN*), which transmits electricity to Brazil.

The BESS installed in CDV is integrated with the wind farm's energy substation and has a nominal capacity of 1 MW and a nominal energy of 1.29 MWh. The BESS connection point is the 34.5 kV bus, which, as shown in Figure 6, represents the CDV single-line diagram. The BESS batteries are lithium-ion batteries of the lithium iron phosphate (LFP) type. Lithium-ion technology is recent but has grown exponentially recently through its application in electric vehicles [45] and in the energy transition. Figure 7 presents the BESS present in the CDV wind complex.

The study of the BESS is necessary to observe the power generated by wind turbines in the transmission bus. In this wind complex, five applications of the energy storage system were inserted, namely: (i) power factor correction, (ii) voltage control, (iii) power factor smoothing, (iv) frequency control and (v) time-shift.

BESS has continuous monitoring assistance in order to collect data on its performance, analyze its performance and implement improvements in applications based on the obtained results. In addition to the analysis of the real data, applications are observed under the computational optics through simulations with HOMER Pro to evaluate the predicted behavior for the BESS and the generation of energy. These results, therefore, serve as a guide for expected behavior. The HOMER Pro tool is included in research due to its consolidation in the scientific and engineering area, bringing speed to daily data manipulation and being widely applied to microgrids in the generation, transmission, and distribution of energy.

The following are the actual data on the operation of the Campos dos Ventos Wind Complex. The results are collected directly from the BESS human-machine interface, which retains system data such as active power from wind generation, the SoC of batteries, reactive power and injected and consumed power from a BESS.



**Figure 6.** CDV single-line diagram. Reprinted from [20] with permission (Licensee MDPI, Basel, Switzerland).



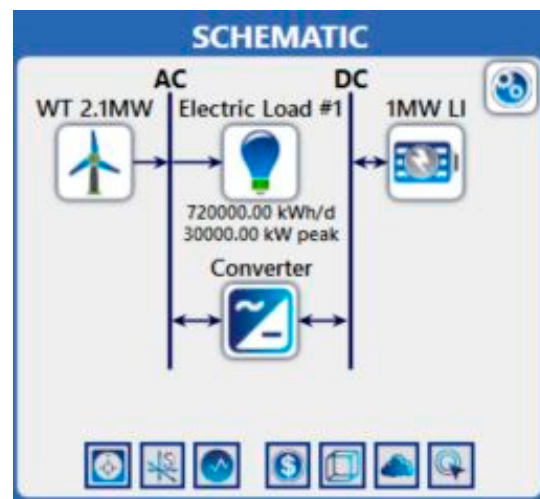
**Figure 7.** BESS installed on CDV.

### 3.1. Simulation Results-HOMER Pro

In order to observe the previous operational behavior, the wind farm was simulated with the BESS/Wind system in the HOMER Pro software. The Hybrid Optimization of Multiple Energy Resources software (HOMER Pro) is a computational model developed by the United States National Renewable Energy Laboratory (NREL) [46].

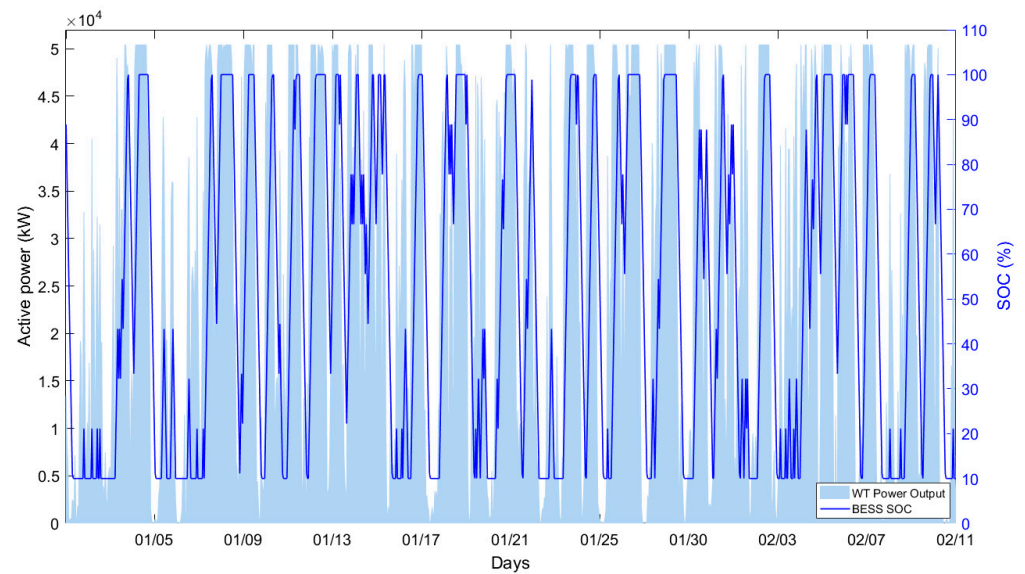
The HOMER software has the ability to evaluate microgrid projects, whether or not they are connected to the grid, taking into account all the equipment involved in the system and calculating all possible combinations of this equipment. In addition, this software evaluates parameters such as stability, economy, size and the number of components, being used to find an optimized configuration of a hybrid energy system. The tool also simulates system operation by analyzing the energy balance over a specified period or one year. The main parameters used for this simulation were 24 wind turbines each of 2.1 MW power; 1264 Li-ion batteries of 1.02 kWh, a 1 MW power conversion system with the HOMER standard model; and a standard electrical network. Costs were not considered in the simulations, and the economic variables were assumed to be zero.

The topology of the system, seen in Figure 8, considered the configuration of a wind farm in an AC connection with 24 turbines with individual powers of 2.1 MW and 50.4 MW of total capacity. Generation calculations were performed using data from the site, which was taken from the NASA database, which is available in the software itself. The BESS connects to the AC bus through its PCS of 1 MW of power and an efficiency of 98.20%, modeled with lithium-ion batteries with a total nominal capacity of 1.29 MWh. Since this system is connected to the Brazilian electricity generation system, its function is only to generate energy for the grid. However, the software presents as a limitation the impossibility of a simulation without load, so the electric load represents the network only absorbing the energy of the wind farm.

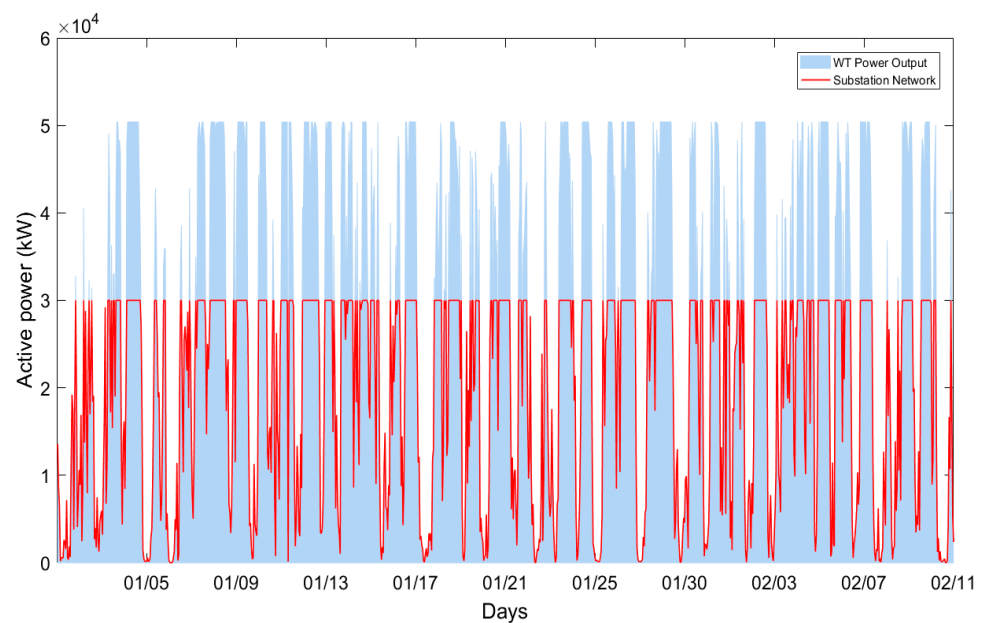


**Figure 8.** Topology of the wind/BESS system of the CDV Wind Complex simulated in HOMER Pro.

As wind generation is associated with the dispatch of reserve energy from the transmission system, it sometimes has its limitations in inserting energy into the substation. However, the production capacity often exceeds the required energy, making the rest of the generation wasted. This operation is observed in Figure 9. It can be seen that the excess energy can be used to increase the efficiency of the wind farm, reducing energy losses. The solution is to insert the BESS to load with the surplus generated and unload when energy is requested from the wind farm by the energy transmission system. By doing this, the BESS may provide energy to complement the power of a turbine with a low generation or maintenance period. The result of this action is an increase in the efficiency of the wind complex and a reduction in the wind farm punishments with fines for providing less energy than required. In the simulated case, the SoC of the battery follows the wind energy production, as seen in Figure 10. During power reduction, the SoC is reduced, as the BESS acts to provide energy to the bus and returns to SoC = 100% when the power increases enough to inject into the grid and recharge the BESS.



**Figure 9.** Result of simulation performed in Homer Pro.



**Figure 10.** BESS state of charge and active output power.

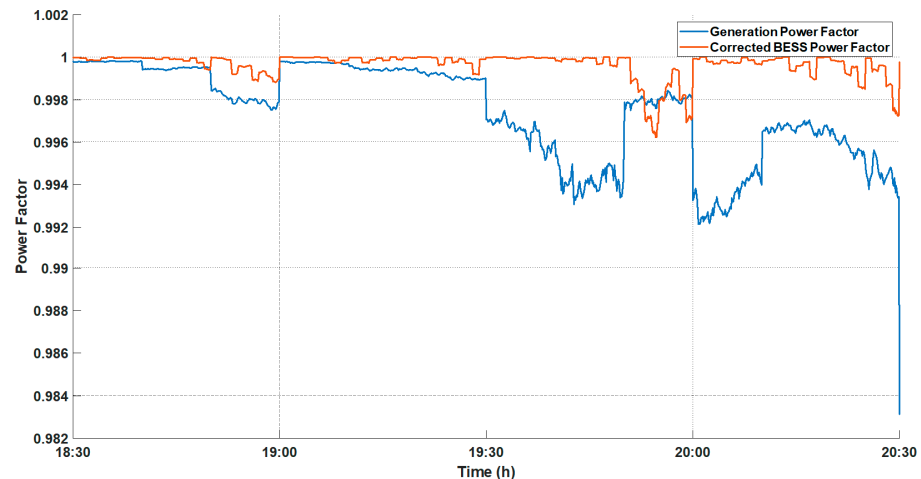
The results obtained from the simulation were based on real analyses for the assisted monitoring of the BESS and its applications, as seen below.

### 3.2. Results of Actual Operation of the Wind/BESS System

In this subsection, real data from the CDV BESS are presented. For this, the following parameters are used: (i) power factor of generation, (ii) power factor corrected by the BESS, (iii) reactive power of the BESS, (iv) line voltage of generation, (v) active power of wind generation, (vi) active power of the BESS and (vii) frequency. Through these parameters, graphs are presented that demonstrate the operation of each BESS application. For example, the parameters (v) and (vi) are needed to observe the performance of power factor smoothing, while only (vi) is needed to evaluate the operation of the time-shift application. The operational data analyzed refer to the period between April and November 2021.

### 3.2.1. Power Factor Correction

The results demonstrated that the system operates with optimal performance, performing the power factor correction using the PCS reactive power. Figure 11 illustrates the power factor curve from wind generation and the corrected curve through the application of BESS at different instants of time to obtain a unity value. Improvements in power factor are seen mainly in the range from 19:30 to 19:50 and from 20:00 to 20:30. It should be noted that the operation of the BESS on 20 April 2021 contributes to reducing energy losses in the CDV wind farm. The performance of the BESS in power factor correction also helps to avoid fines being charged to the wind farm due to a low power factor (below 0.95).



**Figure 11.** Power factor correction performed by BESS. Measurement performed on 20 April 2021.

### 3.2.2. Voltage Control

The purpose of this function is to correct the grid voltage by injecting or absorbing reactive power. The voltage control implemented in the BESS EMS operates in order to maintain the voltage within a range considered ideal by managing the reactive power that the inverter is capable of supplying.

Table 2 presents the voltage values configured in the EMS for the operation of the BESS during measurements. The voltage between  $V_2$  and  $V_3$  is the ideal operating range, and the BESS remains on standby. If the bus voltage is lower than  $V_2$ , the BESS operates in capacitive mode, supplying reactive power to the bus proportionally to the difference between the measured voltage and the  $V_2$  voltage. On the other hand, if the measured voltage is above  $V_3$ , the BESS starts operating in inductive mode, absorbing reactive power from the bus, also proportionally to the difference between the measured voltage and the  $V_3$  voltage, with the aim of reducing it and bringing it back within the ideal operating range ( $V_{ideal}$ ), according to Equation (6).

$$V_{ideal} = V_2 - V_3 \quad (6)$$

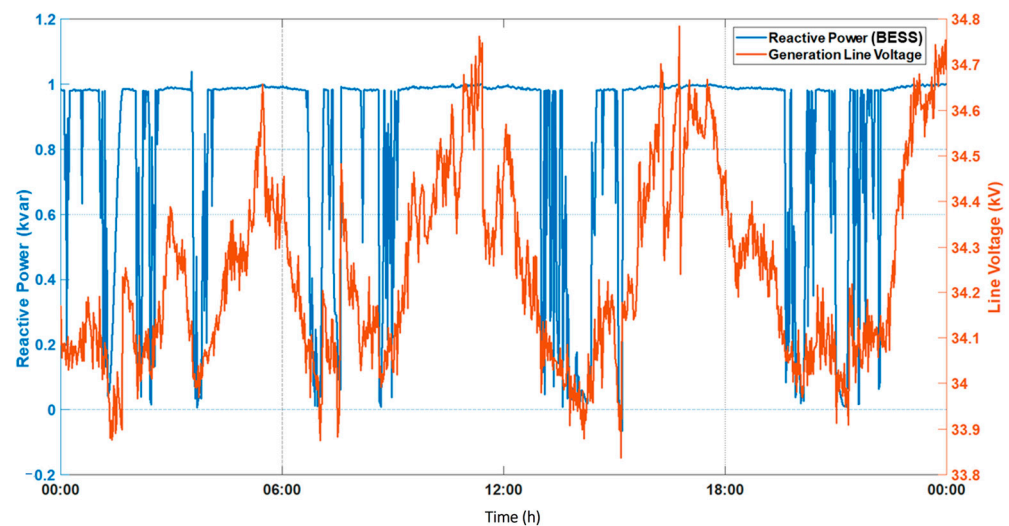
If the voltage is below  $V_1$ , the BESS operates in capacitive mode, providing the maximum reactive power. If the voltage is above  $V_4$ , the BESS operates in inductive mode, absorbing the maximum reactive power.

**Table 2.** EMS configuration for operation in voltage control mode.

| Variable | Value (kV) | Note                |
|----------|------------|---------------------|
| $V_4$    | 38.0       | Upper voltage limit |
| $V_3$    | 34.0       | -                   |
| $V_2$    | 33.8       | -                   |
| $V_1$    | 31.0       | Lower voltage limit |



The operation of the BESS in voltage control mode on 7 April 2021 is illustrated in Figure 12. It can be seen that the BESS started operating at 00:00, absorbing reactive power (blue curve) since the voltage of the bus was above 34 kV (orange curve). When the bus voltage enters the limit of 33.8 kV to 34.0 kV, the BESS stops absorbing reactive power, as it is in the ideal bus voltage operating range.



**Figure 12.** Voltage control performed by BESS. Measurement performed on 7 April 2021.

Then, the BESS returns to absorbing reactive power as the voltage exceeds 34.0 kV, as illustrated in the time interval from 5:00 to 6:00. During this day, a voltage lower than 33.8 kV was not found, so it was not possible to observe the system operating in capacitive mode (providing reactive power). It is concluded that the system operated correctly in the voltage control function, contributing to the control of the voltage on the bus.

### 3.2.3. Power Factor Smoothing

The power factor smoothing function of the present BESS operates in the correction of the active power variations of the wind generation. The BESS of CDV is connected in parallel to a group of wind turbines that provide a power of approximately 50.4 MW. The EMS checks the active power information generated by the wind turbines in the bus where the BESS is connected, and when there is a power variation above 500 kW in a 60 s window, the system acts, absorbing or supplying active power, depending on the current generation state (increasing or decreasing).

Figures 13 and 14 illustrate the action of the injection and consumption of active power by the BESS according to the variations in the active power generated by the wind turbines in CDV. The orange curve represents the active power injected or consumed by the BESS. Meanwhile, the curve in blue represents the active power generated by the wind turbines. As wind generation decreases (over 500 kW), the BESS acts by supplying active power (negative direction of active power) to the busbar. When wind generation increases (over 500 kW), the BESS acts by consuming (positive sense of active power) the excess active power generated. This operation causes the active output power to the grid to be smoothed.

To numerically evaluate the power factor smoothing of wind generation on 19 October 2021 (Figure 14), the maximum power variation (MVP) index is used [20]. The results are presented in Table 3, where it is possible to verify the numbers referring to the power curve of wind generation with and without BESS. It can be seen from Table 3 that the MVP indicator with the application of the BESS showed a significant improvement (the smaller, the better) for different time intervals. The best result obtained was in the interval from 11:26 to 11:31, changing from an indicator of 10.32% to 6.31%, which means a reduction of 4.01%.



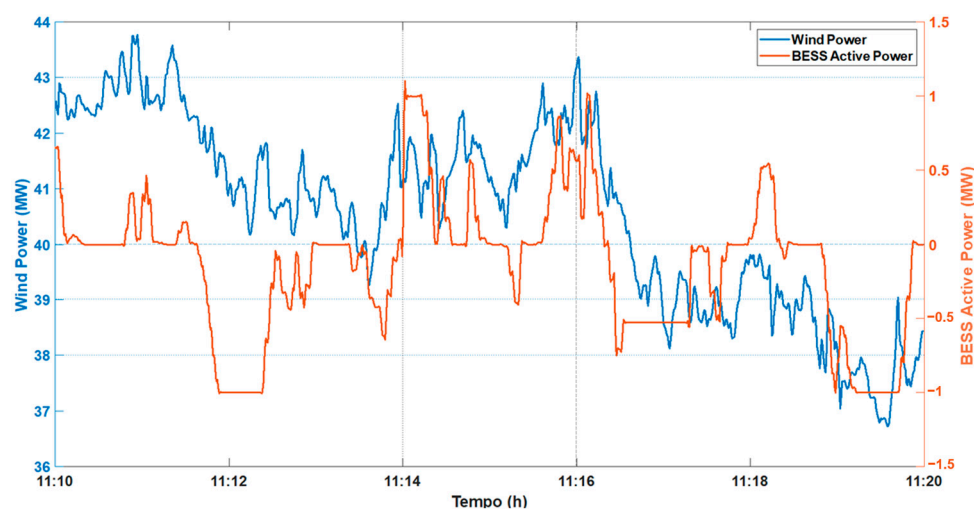


Figure 13. Power factor smoothing performed by BESS. Measurement performed on 13 August 2021.

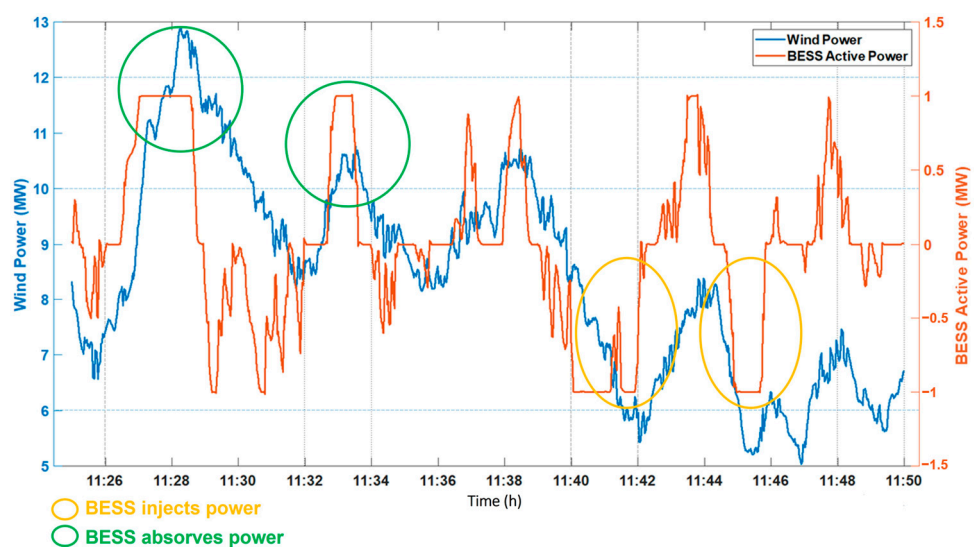
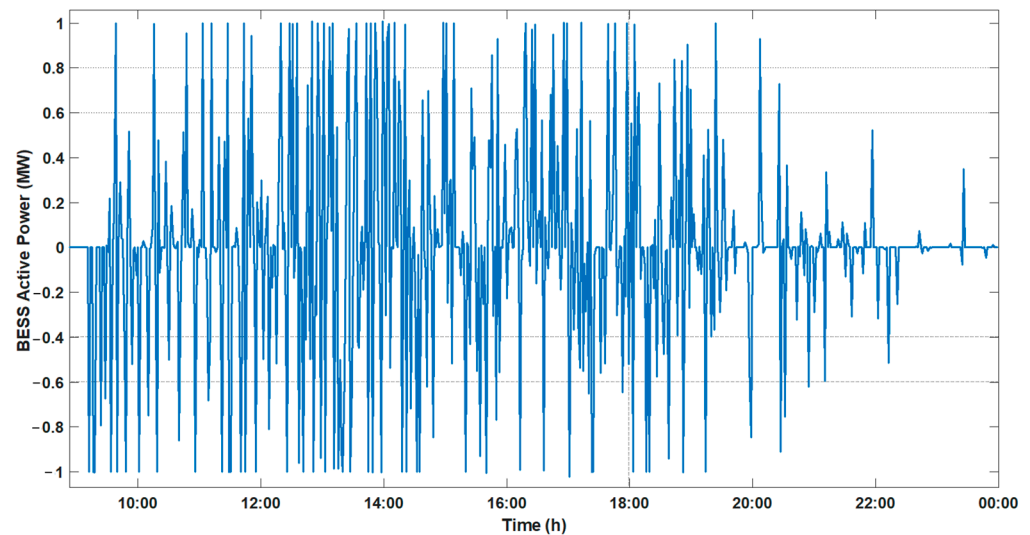


Figure 14. Power factor smoothing performed by BESS. Measurement performed on 19 October 2021.

Table 3. Main indicators of power factor smoothing on 19 October 2021.

| Case                   | Time Interval  | Maximum Power Value (MW) | Minimum Power Value (MW) | Wind Generation Rated Power (MW) | MVP Indicator (%) |
|------------------------|----------------|--------------------------|--------------------------|----------------------------------|-------------------|
| Without BESS operation | 09:30 to 09:35 | 19.21                    | 13.24                    | 50.4                             | 11.85             |
|                        | 11:26 to 11:31 | 12.80                    | 07.60                    | 50.4                             | 10.32             |
|                        | 11:40 to 11:45 | 08.05                    | 05.55                    | 50.4                             | 4.96              |
|                        | 12:30 to 12:35 | 16.00                    | 10.04                    | 50.4                             | 11.83             |
|                        | 13:05 to 13:10 | 20.37                    | 10.19                    | 50.4                             | 20.20             |
|                        | 13:15 to 13:20 | 25.48                    | 15.75                    | 50.4                             | 19.31             |
|                        | 13:45 to 13:50 | 22.02                    | 14.01                    | 50.4                             | 15.89             |
|                        | 14:45 to 14:50 | 38.80                    | 32.69                    | 50.4                             | 12.12             |
| With BESS operation    | 16:25 to 16:30 | 46.28                    | 42.08                    | 50.4                             | 8.33              |
|                        | 09:30 to 09:35 | 18.53                    | 13.92                    | 50.4                             | 9.15              |
|                        | 11:26 to 11:31 | 11.08                    | 07.90                    | 50.4                             | 6.31              |
|                        | 11:40 to 11:45 | 09.05                    | 06.55                    | 50.4                             | 4.96              |
|                        | 12:30 to 12:35 | 15.00                    | 10.36                    | 50.4                             | 9.21              |
|                        | 13:05 to 13:10 | 19.37                    | 10.43                    | 50.4                             | 17.74             |
|                        | 13:15 to 13:20 | 24.48                    | 16.75                    | 50.4                             | 15.34             |
|                        | 13:45 to 13:50 | 21.02                    | 14.94                    | 50.4                             | 12.06             |
|                        | 14:45 to 14:50 | 37.89                    | 33.69                    | 50.4                             | 8.33              |
|                        | 16:25 to 16:30 | 45.63                    | 42.80                    | 50.4                             | 5.62              |

As generation decreases, the BESS supplies active energy to the grid. In contrast, when generation increases, the BESS consumes part of the generated active power. The active power factor smoothing function of the BESS is measured using the BESS meter for the same day, as seen in Figure 15. When the BESS is absorbing power, the graph values are positive. Negative values in the graph indicate that the BESS injected power.



**Figure 15.** Total active power: power factor smoothing. Measurement performed on 19 October 2021.

### 3.2.4. Frequency Control

The frequency control implemented in the EMS of the storage system occurs through the absorption or supply of active power. The EMS analyzes the frequency information so that the BESS takes action the moment a deviation outside the considered range is noticed. Table 4 shows the values configured in the EMS. It should be noted that the electrical frequency determined in Brazil is 60 Hz.

**Table 4.** EMS configuration for operation in frequency control mode.

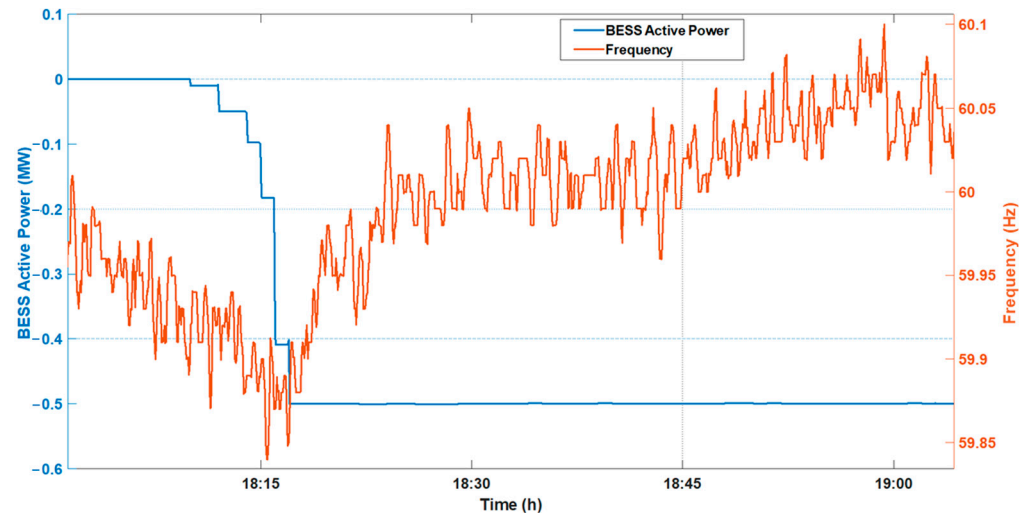
| Variable | Value (Hz) | Note                  |
|----------|------------|-----------------------|
| $F_4$    | 60.5       | Upper frequency limit |
| $F_3$    | 60.2       | -                     |
| $F_2$    | 60.1       | -                     |
| $F_1$    | 59.7       | Lower frequency limit |

The frequency between  $F_2$  and  $F_3$  is the ideal operating range, for which the BESS remains on standby. If the bus frequency is lower than  $F_2$ , the BESS operates by supplying active power to the bus proportionally to the difference between the measured frequency and the  $F_2$  frequency. On the other hand, if the measured frequency is above  $F_3$ , the BESS starts to operate, absorbing active power from the bus, also proportionally to the difference between the measured frequency and the  $F_3$  frequency, with the aim of reducing it and bringing it back within the ideal operating range ( $F_{ideal}$ ), according to Equation (7). If the frequency is below  $F_1$ , the BESS acts, providing the maximum active power. If the frequency is above  $F_4$ , the BESS acts by absorbing the maximum active power.

$$F_{ideal} = F_2 - F_3 \quad (7)$$

The measurement in frequency control mode was performed on 24 April 2021 and can be seen in Figure 16. It can be seen that the operation starts at 18:00 when the BESS is enabled for frequency control mode, and this occurs when active power is supplied (−500 kW) since the BESS recognizes that there is a frequency dip (operation in the zone

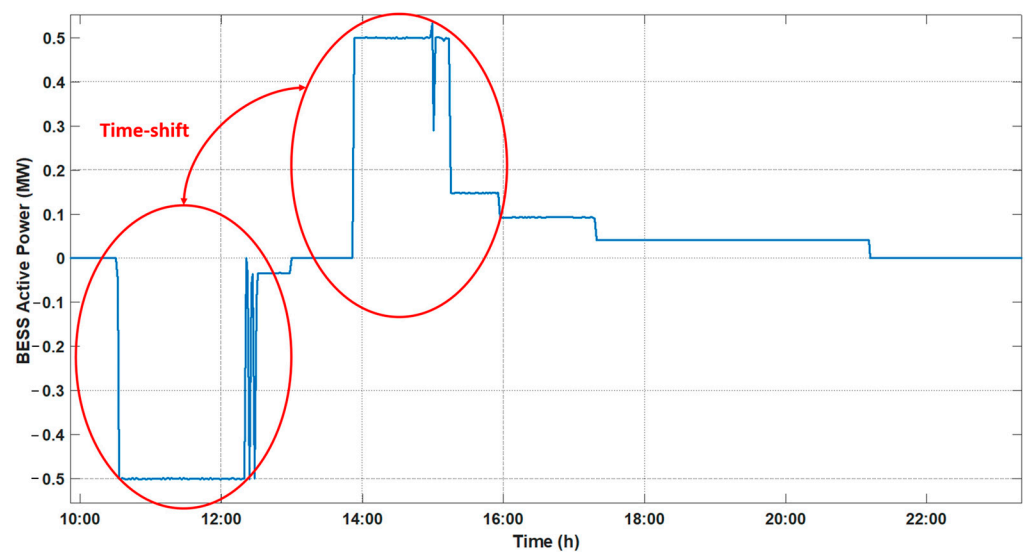
between  $F_1$  and  $F_2$ ), i.e., a frequency lower than 60.1 Hz. Figure 16 shows that the system operated correctly in the frequency control function, contributing to the control of the frequency on the bus.



**Figure 16.** Frequency control performed by BESS. Measurement performed on 24 April 2021.

### 3.2.5. Time-Shift

The use of this function is fundamental to balancing moments of the day with high production (more wind) with moments of low production (less wind), allowing the operator to supply energy when it is needed and, consequently, avoid wasting energy. Through the operating data of the BESS, it is possible to identify the possibility of programming the system to absorb energy at certain times and supply energy at other times. Figure 17 details the performance of the system in the energy time-shift function from the BESS active power curve, supplying or absorbing. When the SoC approaches 100%, the characteristic of the system has a behavior of falling power absorbed in steps. This is because the energy management system controls the amount of power that enters the battery bank. Regardless, this characteristic is less significant in the discharge.



**Figure 17.** Energy time-shift performed by BESS. Measurement performed on 3 November 2021.

#### 4. Conclusions

The objective of this work is to present the applications that the *Campo dos Ventos* storage system has. The information presented is merely a sample of the contribution of BESS to wind generation. Comparing the size of the BESS in terms of nominal power with the wind farm in terms of generation, the storage system has a discrete effect on wind generation and, consequently, on the electricity grid. It is, therefore, possible to identify the participation of the system in the wind farm, even though the BESS is a pilot project.

This research brings together results from real system operation data through applied research in the electric generation segment. These data allow the designer to determine which applications are suitable for the system that will be used for his research, for example. BESS has a way of mitigating the problems of intermittency of renewable sources, increasing its possibility of integration into the electrical system. It is noteworthy that the studied energy storage system was acquired with functions that met the reality of the wind complex in question. Although the BESS may have different applications and capacities, it is still a system that can be tailored to serve the purpose for which it is used.

Nevertheless, it is worth noting that not all applications presented in this article have a great influence on the generation to which they were coupled. Among the applications, power factor smoothing stands out due to the natural behavior of variation in the active power of the winds that impact the electrical grid. However, it should be noted that other applications are not as active as this because the Brazilian electrical matrix is very robust, which means that there is not much oscillation in frequency. The substation has, for example, capacitors that correct the factor power when energy leaves generation for transmission. In addition, the National Electrical System Operator (ONS) grid procedures define the maximum and minimum limits for form voltage. The connection of a wind farm to the transmission system is only carried out in compliance with this and other parameters. However, these applications can be better exploited in weaker networks, that is, those that do not have firm energy as their main characteristic.

The authors suggest that future work should focus on expanding the study of the operational data of the applications to analyze failures in the BESS and identify damage measured during a stoppage in the system for maintenance, in addition to mapping the impacts of the BESS on the electrical system to which it is connected.

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