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Impact Analysis of a Battery Energy Storage System Connected in Parallel to a Wind Farm

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Abstract: Increasing wind generation insertion levels on electrical grids through power converters may cause instabilities in the AC grid due to the intermittent wind nature. Integrating a Battery Electric Energy Storage System (BESS) in wind generation can smooth the power injection at the Common Coupling Point (PCC), contributing to the power system voltage and frequency stability. In this article, it is proposed to analyze the operation of a lithium-ion battery technology based 1 MW/1.29 MWh BESS connected in parallel with wind generation with a capacity of 50.4 MW. The main characteristics investigated are power smoothing and power factor correction. Experimental results show that BESS contributes to smoothing the active power and correcting the power factor of wind generation, improving the quality of electrical energy at the PCC.

Keywords: storage system; batteries; power smoothing; power factor correction; wind generation; power converter; stability; electrical power quality

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1. Introduction

The growing concern about the environment and the depletion of fossil fuels has given rise to a new scenario to meet the energy needs of society: renewable sources [1,2]. Among the various renewable sources of electricity, wind generation has been presented as the most interesting and the fastest growing in the world [2,3]. According to the Global Wind Energy Council (GWEC) 2022 report, the wind industry had its second-best year in 2021, with nearly 94 GW of capacity added globally. Total global wind power capacity is now up to 837 GW, helping the world avoid more than 1.2 billion tons of CO_2 annually—the equivalent of South America's annual carbon emissions.

The growth of wind energy in the world energy matrix is due to its advantages, such as: it does not emit greenhouse gases; it takes little time to build wind farms; it diversifies the electricity matrix; it is independent of the variation in fuel prices; it is easy to expand the capacity of wind farms; it provides new markets etc. [2]. However, due to the highly uncertain and variable nature of the wind, wind energy can present undesirable characteristics in its generation and impact the Electric Power Systems (EPSs). With an increasing share of EPSs, the uncertainty of wind energy and its power fluctuation will affect the ability of grid operators to balance generation and demand. Furthermore, the significant penetration of wind generation in the grid can harm the Power Quality, the dynamics, and the system reliability [2,4].

According to [2,5], the main concerns regarding the connection of wind generation in electrical systems are related to the impact on the stability and Power Quality of the grid, the ability to compensate for active power fluctuations, and the impact on grid voltage, both short-term and long-term. To minimize some of these problems, additional flexible resources must be used to manage the variability and uncertainty of wind generation. Battery Energy Storage Systems (BESS) can be used to reduce power fluctuations, as well as provide ancillary services (voltage and frequency regulation), manage energy during disturbances (short circuits), and increase network reliability.

There is a wide range of possible BESS applications in the electrical sector, such as power generation, transmission, and distribution, and direct applications to the final consumer. However, it can be said that the attractiveness of each specific solution depends on the characteristics and needs of the applications. For example, BESS can be used for short-term power smoothing in wind farms in a generation. Using BESS, it is possible to mitigate the adverse effects of the power fluctuation in wind generation and, consequently, improve the Electrical Power Quality (EPQ) and the power grid operation. As for the final consumer, BESS can be used to perform arbitrage, charging the batteries during lower-priced hours, and discharging during higher-priced hours (i.e., during peak hours).

The BESS can be idle for a significant fraction of time, depending on the application. Thus, to make this solution more viable, it is possible to merge different applications. For example, BESS systems installed in more robust systems, such as the Brazilian National Interconnected System (SIN), can implement other services such as arbitrage, operating reserve, frequency control, voltage control, and black start. Thus, the merging of applications increases the use of BESS over time.

Energy storage systems have been widely simulated to reduce power fluctuations from wind generation with different control strategies [6–9], and [10] proposed using a storage system integrated into a wind system to reduce high-frequency fluctuations in the generated power, using filters to separate the operation of the inverter controllers and the storage system in the frequency domain. In [11], it is seen that to provide constant supply from a 39.6 MW wind farm, a 2 MWh capacity energy storage system was used to maintain consistent production for one hour and up to 103 MWh to provide consistent output for one day.

In [12], it is seen that the intermittent operation of renewable energy sources, faults occurrences, or PCC disturbances can cause voltage or frequency deviations, resulting in instability problems, which can become severe in weak power networks. In [12], a storage system was used to regulate voltage and frequency in microgrids.

There are many different papers which evaluate the power smoothing of wind generation through BESS. Among the recent papers, there are relevant talks about the problem of the power fluctuation in many different contexts and settings, such as the power smoothing in the context of transmission or distribution, different technologies of BESS, different types of power control for BESS, complementary applications for power smoothing, different settings of connection of BESS, and different ways to evaluate and present the results [2]. However, considering these different contexts and settings there are still topics to be explored and improved. Several papers do not verify the effects of power smoothing in wind generation, as well as do not use numerical indicators to evaluate the performance of the power smoothing techniques. Thus, the main contribution of this article is to analyze the effects of power smoothing in wind generation in a case study at the Campo dos Ventos Wind Complex located in João Câmara, Rio Grande do Norte (RN)—Brazil. The numerical indicator of Maximum Variation Power (MVP) is also used to evaluate the performance of the power smoothing techniques. The MVP indicator quantifies the largest power of wind generation within a predefined time interval.

Furthermore, this paper addresses, in a complementary way, the application of power smoothing, the analysis of the storage system operating in the power factor correction mode, and its impact on Power Quality for the Campo dos Ventos Wind Complex. Experimental results are performed to validate the performance of BESS.

2. Project Description

The purpose of the Research and Development R&D Project PA3026, entitled "Impact Analysis of a Battery Energy Storage System Connected in Parallel to a Wind Farm", is to study energy storage applications from different qualitative and quantitative perspectives. This project is formed by the group of institutions CPFL Energy (Light and Power Company of Sao Paulo State), Institute of Technology Edson Mororó Moura (ITEMM), Federal University of Pernambuco (UFPE), and PSR—Energy Consulting and Analytics.

Brazil still presents a relatively immature environment for the development of energy storage technologies. Faced with regulatory and even non-regulatory gaps, the R&D Project PA3026 seeks to resolve existing uncertainties about the applicability and effectiveness of services and assist recognition through adequate remuneration for these storage systems.

From this perspective, the project proposes to investigate the operationalization of several actions applied to a real wind farm. Among the main functions destined for the storage system identified in the project are produced power smoothing and power factor correction. These two proposals are tested with the operation of a BESS composed, among other components, by a set of Lithium Iron Phosphate (LFP) batteries, which is a lithium-ion battery technology with a capacity of 1 MW/1.29 MWh integrated into an electric power substation of a wind farm. The choice of this technology was due to the benefits that the LFP battery presents, such as: (1) high energy density (about 1932 W/L) [13], (2) high conversion efficiency (90~95%) [14], (3) low self-discharge rate, and (4) fast response time [13]. It should be noted that the service life (>2000 cycles) still needs to be improved and there are potential fire hazards [13,14].

According to [13], flow batteries are safe as they are non-flammable and have a long cycle life (2000 to 20,000 cycles) and do not depend on the depth of discharge. However, the energy density is low, occupies a large amount of land, and the conversion efficiency is low (65–85%) [15]. Hydrogen batteries have the highest specific energy (500–3000 Wh/L) compared to other storage systems and have a high cycle life (about 20,000 cycles). Although hydrogen batteries have a long-life cycle, they have a high initial cost [13]. The lead-acid battery is safe and reliable, but its energy density is low and its cycle times (300–3000 cycles) are limited [16].

The wind farm choice considered the capacity and arrangement of machines with different technologies. The Campo dos Ventos Wind Complex, located at João Câmara—Rio Grande do Norte (RN)—Brazil, a synchronous generator with a full converter and Double Powered Induction Generators (DFIG), was chosen. This farm has twenty-four turbines, each with 2.1 MW rated power, totaling 50.4 MW. Therefore, the 1 MW/1.29 MWh capacity BESS can be analyzed in terms of its real impact on the proposed objectives. The turbines and BESS are connected through a SCADA system. The simplified single-line diagram for the Campo dos Ventos Wind Complex is shown in Figure 1. The installation of BESS at the Campo dos Ventos Electric Substation (ES) is illustrated in Figure 2.

The main objectives of using the storage system are to smooth the wind production through instantaneous power injection and instantaneous power consumption, counterbalancing its instantaneous output and, consequently, removing variations introduced by the wind intermittence acting on each other the wind turbine.

Considering other storage system application options, it is expected to use the remaining storage capacity for reactive power compensation, firstly, to improve the power factor and, secondly, to improve the voltage with the consequent reactive power control.

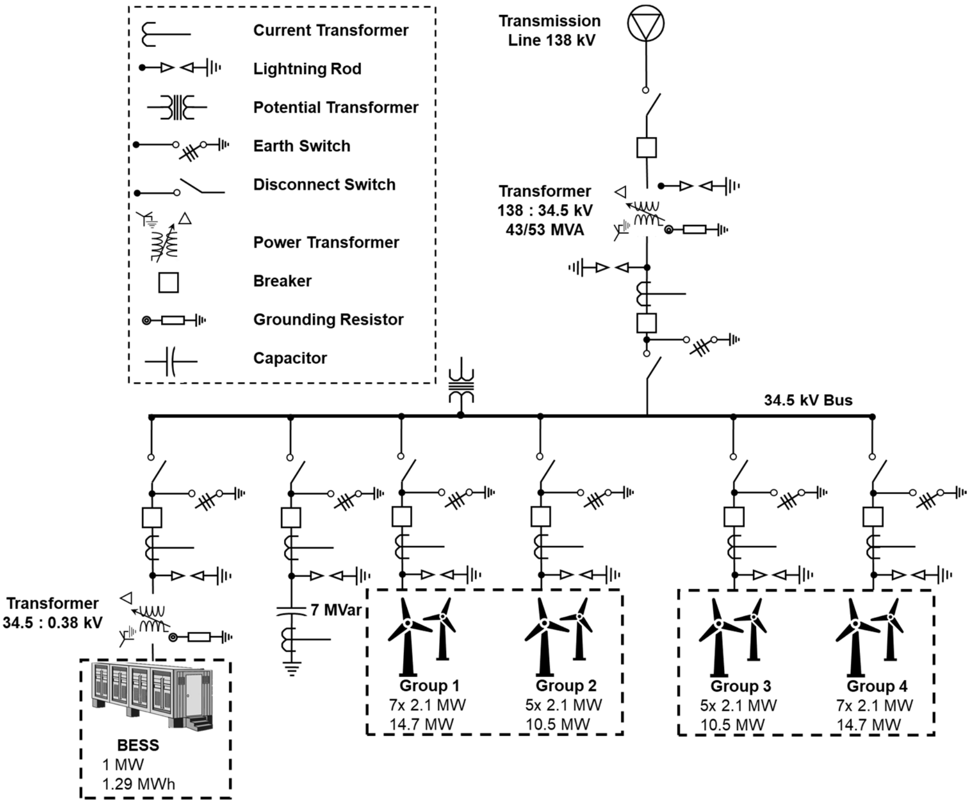

Figure 1. Single-line diagram of the Campo dos Ventos Wind Complex.

Figure 2. Installation of BESS in the Campo dos Ventos Substation.

3. Battery Energy Storage System (BESS)

3.1. General View

In general, the main components of BESS are batteries, battery management system (BMS), energy management system (EMS), power conversion system (PCS), fire detection and suppression system, heating system, ventilation, air conditioning (HVAC), Uninterruptible Power Supply (UPS), container, transformer (if voltage increase is required), cables (primary and secondary) and other auxiliary systems. Figure 3 shows the BESS and some of these components. The system installed at the Campo dos Ventos Wind Complex has two 500 kW PCSs that convert DC energy into AC or vice versa and is connected to the DC side batteries and connected in parallel to the AC side wind generation bus. EMS controls PCSs and communicates with BMS and SCADA and contains all system applications.

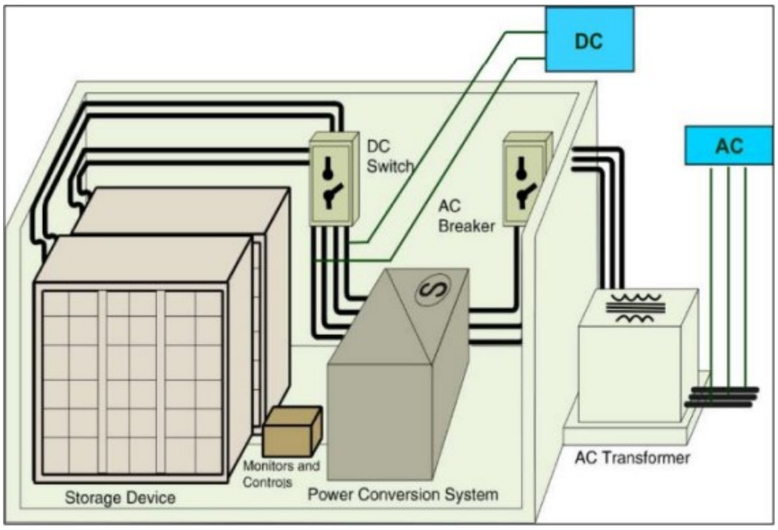

Figure 3. Schematic of BESS and its components [17]. Reprinted from [17] with permission (License 1431469) from U.S. Department of Energy Office of Scientific and Technical Information [17,18].

3.2. Batteries

The battery is one of the main components of the BESS. It is in the battery that energy is stored. There are various battery types integrated into generation, transmission, distribution, and end-consumer worldwide. Each type may use the system differently. Battery selection is mainly focused on the BESS application (e.g., applications that demand more power and energy) and cost-effectiveness ratio due to the high proportion of the battery's monetary value to the total cost of the project (about 50–60%) [19].

LFP batteries were used in the BESS. The LFP battery pack has an output voltage of 51.2 V and a capacity of 180 Ah. Fourteen battery packs are grouped in series in a cluster, totaling an output voltage of 716.8 V and a capacity of 180 Ah. The BESS contains 10 clusters in parallel, leading to an output voltage of 716.8 V and a capacity of 1800 Ah.

3.3. BMS

The BMS plays a vital role in the BESS. The integration of the BESS with the wind generation bus means that multiple batteries are connected in parallel, improving safety and reliability.

The BMS is designed to provide safe operations by monitoring the voltages, currents, and temperature of the cells in the batteries. In addition, the BMS offers the following functions [19–21]:

- Protection for battery cells;
- Evaluation of battery cell recharge and health status;
- Energy balancing between battery cells (including battery charging and discharging patterns).

3.4. EMS

The EMS is responsible for continuously relevant BESS data acquisition and storage, such as voltage, frequency, active and reactive power, power factor, battery cell voltage, etc. This data acquisition and storage can be either in local or remote forms. Additionally, the EMS receives the control setpoints to allow changes in the BESS operating modes and subsystems. The BESS applications of this project are power smoothing, frequency control, voltage control, and power factor correction. Lastly, it contains manual control for active and reactive power injection and absorption.

EMS controls BESS to regulate battery recharges and discharges to achieve optimal efficiency generation requirements. All battery cells are individually monitored to ensure any deviation in performance is detected and corrected before problem occurrences. The EMS can be viewed remotely as needed and communicate with CPFL's local SCADA.

3.5. PCSs

The current project BESS contains two bidirectional PCSs to perform DC/AC and AC/DC conversions. In addition, it controls voltage and frequency, ensuring that the electricity output meets desired connection requirements.

The BESS uses two bidirectional 500 kW PCSs, connected on the DC side to the power bank battery. The PCSs in question contain anti-islanding protection, in which the inverter detects problems in the electrical grid, such as a power outage, and switches off to interrupt the supply. This protection is needed because, after electrical grid problem occurrences, it is assumed that workers will be dispatched to deal with the issue; therefore, it is necessary that the electric power lines are entirely safe and electric current free.

Another functionality of PCSs is stability for under and over voltage/frequency ranges, in which the inverter does not trip if the anomaly duration exceeds a specific period. This function is an essential feature to improve grid stability.

The PCSs' operating modes are:

- P-Q Control mode is when a reference voltage and a constant frequency are supplied by another source (usually the electrical grid). The inverter can change the active and reactive power.
- V-F Control mode (Autonomous Mode): V-F control mode occurs when, regardless of the varying inverter power, the amplitude and frequency of the output voltage are constant. The inverter with V-F control can provide voltage and frequency support to the microgrid during island operation. The inverter acts as a voltage source. The current amplitude and the power factor (PF) will be determined by the sum of the generation (if any) and the consumption load.

The PCSs' operating modes are in four quadrants, as illustrated in Figure 4, both in on-grid and off-grid modes, which means that active power and reactive power can be in four characteristics:

- Consumes active power plus inductive reactive power;
- Consumes active power plus capacitive reactive power;
- Provides active power plus inductive reactive power;
- Provides active power plus capacitive reactive power.

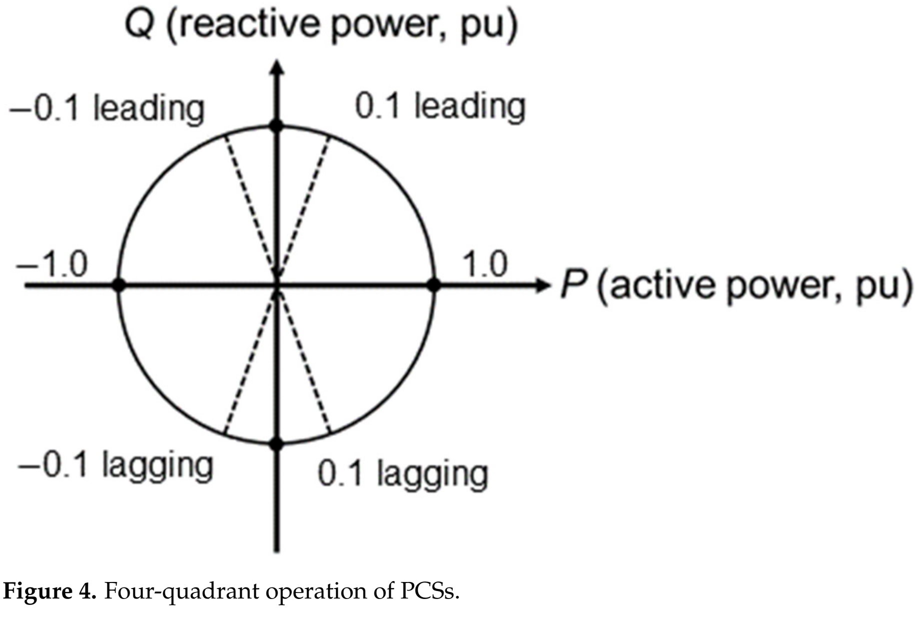

Figure 4. Four-quadrant operation of PCSs.

Control System

The PCS installed on the BESS operates in grid-connected and islanded mode. Active and reactive power control (P-Q Control) is used in grid-connected mode, while constant voltage and frequency control (V-F Control) is employed in islanded mode. These two control strategies are based on [22] and detailed below.

(a) P-Q Control

When the PCS is connected to the electrical grid, it operates in P-Q Control mode. Active and reactive power based on instantaneous active and reactive power theory are shown in Equation (1) [22].

$$\begin{cases} p = 1.5\left(v_d i_d + v_q i_q\right) \\ q = 1.5\left(v_q i_d - v_d i_q\right) \end{cases} \tag{1}$$

When the q component of the voltage is zero and assuming that the voltage vector is in the d-axis direction, Equation (1) can be represented by:

$$\begin{cases} p = 1.5 v_d i_d \\ q = -1.5 v_d i_q \end{cases} \tag{2}$$

The reference current can be calculated by:

$$\begin{cases} i_{dref} = \frac{P_{ref}}{1.5 v_d} \\ i_{qref} = -\frac{Q_{ref}}{1.5 v_d} \end{cases} \tag{3}$$

where P_{ref} represents active power and Q_{ref} represents reactive power, the expected output values. Figure 5 illustrates the simplified P-Q Control block diagram.

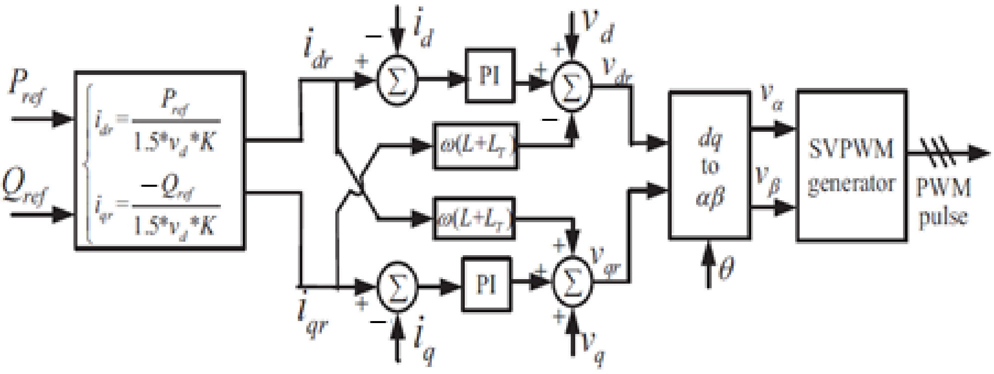

Figure 5. Block diagram of the P-Q Control structure [22]. Reprinted from [22] with permission (License 978-1-4799-7720-8/14) from U.S. Department of Energy Office of Scientific and Technical Information [22].

(b) V-F Control

In the islanded mode operation of PCS, it is controlled as the main power source to supply constant voltage and frequency (V-F Control). To obtain constant V-F Control, a closed loop voltage control structure was adopted. The closed loop voltage control equation using a PI controller is described below [22]:

$$\begin{cases} v_{dr} = k_p\left(1 + \frac{1}{T_i\, s}\right) * \left(v_{dref} - v_d\right) \\ v_{qr} = k_p\left(1 + \frac{1}{T_i\, s}\right) * \left(v_{qref} - v_q\right) \end{cases} \tag{4}$$

where the proportional gain is represented by k_p and the integral time constant of the voltage loop controller is represented by T_i, v_d and v_q are the voltages after the coordinate transform, from *abc* to *dq*, where these are the components of the *d* and *q* axes, respectively.

While v_{dref} and v_{qref} are the voltages after the coordinate transform, also components of the d and q axes, but these represent the component of the reference voltage (v_{aref}, v_{bref} and v_{cref}). Figure 6 illustrates the block diagram of the V-F Control which is equivalent to Equation (4).

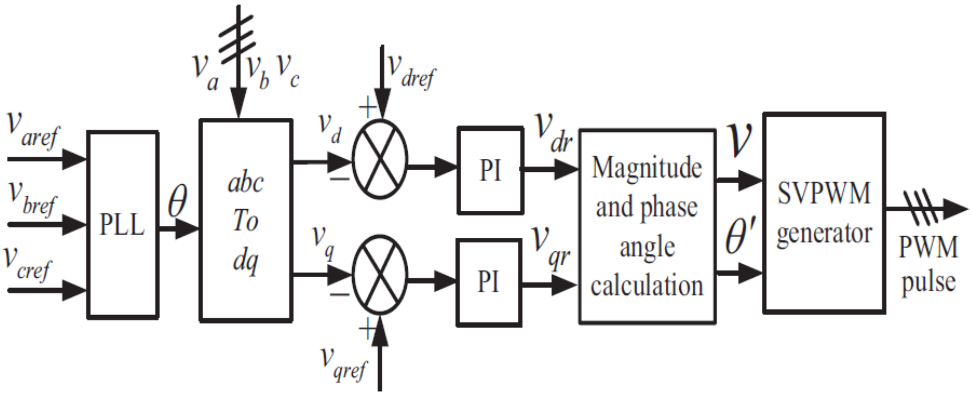

Figure 6. Block diagram of the V-F Control structure [22]. Reprinted from [22] with permission (License 978-1-4799-7720-8/14) from U.S. Department of Energy Office of Scientific and Technical Information [22].

3.6. Fire Detection and Suppression System

The fire detection and suppression system are a set of components used to ensure the safety of the place where it is installed, as well as that of people who transit internally and in the vicinity of the BESS. For this, the system is configured to have quick and efficient responses, ensuring agility to contain/extinguish the fire, as well as ensuring the evacuation of individuals.

The minimum elements that the fire detection and suppression system must include are:

- Control panel or alarm center: equipment responsible for interconnecting all the elements of the system; in other words, it receives and sends warning signals and activation of fire protection devices.
- Sensors/detectors: precision devices that evaluate the conditions of the place where it is installed. The main ones are:
  - Smoke detector;
  - Temperature detector;
  - H2 and H2S detector if the technology is lead.
- Audible alarm: device responsible for emitting audible signals when fire is detected.
- Emergency lights: it is a type of visual alarm, which helps individuals to find the exit from the place.
- Signage: the presence of signs, stickers, and other visual alarms is required, which inform and assist in directing the emergency exit(s).

3.7. HVAC

The HVAC system regards the basic functions of the climatization system, allowing the environment to be in the right conditions for safe and efficient operation. Among the components that make up the HVAC are:

- Heating (H): function of keeping the place at the correct system operating temperature for regions that have low temperature days. Furthermore, it is used to maintain the relative humidity of the air;
- Ventilation (V): used for the renewal of oxygen and air circulation, avoiding the concentration of undesirable gases, as well as removing and/or reducing odors and impurities from the place;

- Air conditioning (AC): used to artificially cool the place, controlling the temperature, and preventing it from becoming high. In addition, this equipment usually has filters, which carry out the removal of impurities and contaminants from the air.

These systems are essential for the proper functioning of the BESS, since by controlling the temperature, leaving it close to the most efficient temperature of the components (25 °C), it increases the productivity of the system. Furthermore, it promotes oxygenation of the place, air filtration, and reduction of air pollutants and the proliferation of fungi/mold.

3.8. UPS

The UPS is a secondary power system, which provides emergency power to the load when the primary supply is interrupted. As opposed to generators, the UPS operates very quickly, avoiding interruptions in the power supply.

In general terms, the UPS is made up of converters and batteries, which may or may not have a bypass switch. With respect to BESS, its load is not all the components of the system, but those that must always be kept in operation, allowing that in case of failure some action can be taken.

4. Results and Discussion

In this topic, the power smoothing and power factor correction functions are analyzed, as well as the approach of results and discussions of the data obtained using the two operating modes.

4.1. Power Smoothing Application

The results related to power smoothing are analyzed mathematically through the Maximum Power Variation (MVP) indicator. The active power smoothing technique performance of wind turbines is numerically evaluated. The MVP indicator corresponds to the maximum power variation in the wind generation rated power within an established time interval. Energy companies and system operators widely use this indicator from different European countries to restrict wind generation fluctuations, limiting the MVP to 10% in 1 min and 10 min intervals [23,24].

In the present article, a 5 min time interval (MVP5) is used, in which the calculation is performed from the difference between the maximum and the minimum power curve values in the specified interval and, according to that, the rated power of the generation to which the BESS that is connected is obtained. For example, considering a 50 MW wind generation rated power and a power curve whose difference between the highest and lowest value is 10 MW during the 5 min interval, the MVP is 20%. Thus, the lower the MVP value, the better the power smoothing quality. In an ideal case (i.e., a constant curve), the MVP would be 0% for any evaluated interval.

The BESS operating principle is performed through the EMS control system for the power smoothing function. The generation active power on the bus where the BESS is connected is verified. When the EMS verifies the 500 kW variation in a 60 s window, the system acts, absorbing or supplying active power, depending on the current generation status, that is, increasing or decreasing. Figure 7 illustrates a BESS operation based on the power wind generation variation.

In Figure 7, when the wind generation (blue curve) decreases in an interval of 60 s, the BESS supplies active power (orange curve). When wind generation increases, the BESS absorbs active power. The negative sign of active power means that the BESS is providing power and the positive sign of power implies that BESS is absorbing power.

The BESS performance operating in power smoothing mode connected in parallel to a group of wind turbines with 50.4 MW rated active power is illustrated in Figures 8 and 9. These figures show the generation curve behavior and its smoothing. Data from different days are shown.

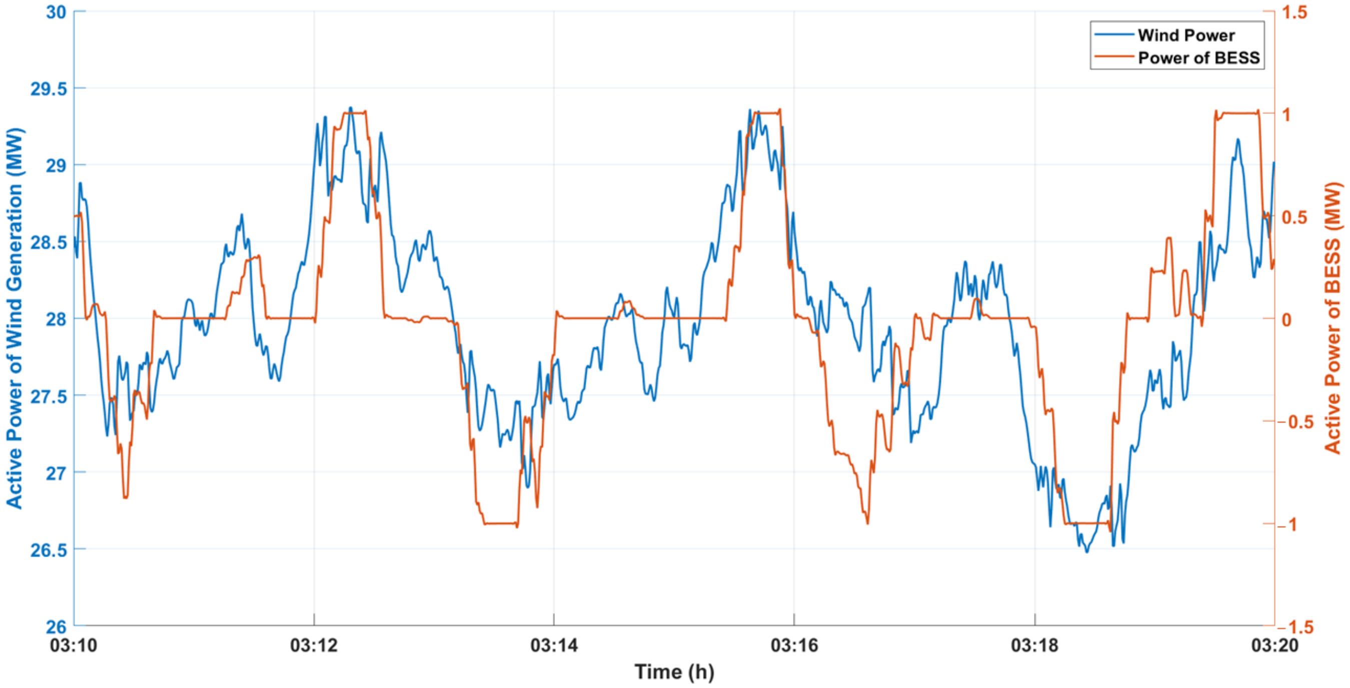

Figure 7. Real-time BESS operation based on power generation variation. The measurement was carried out on 28 July 2021.

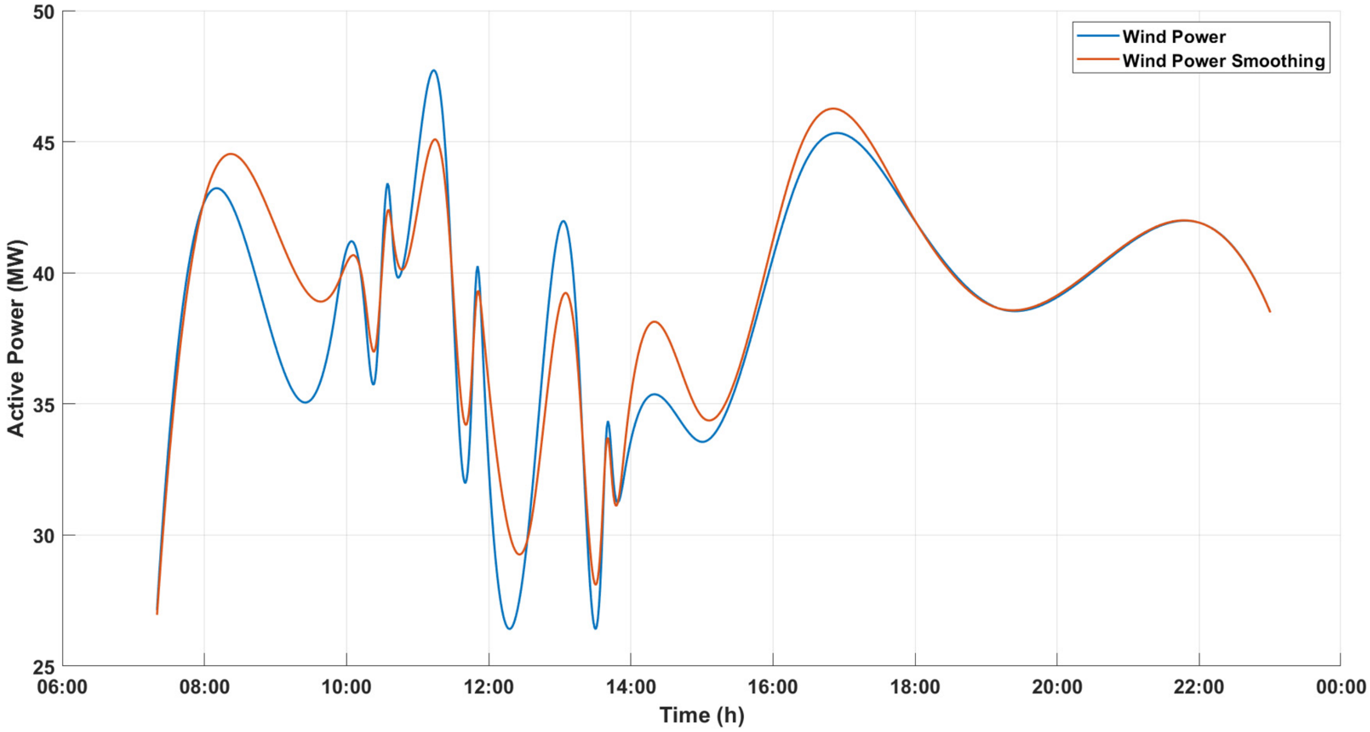

Figure 8. Active power of smoothed wind generation. Real-time measurement performed on 31 August 2021.

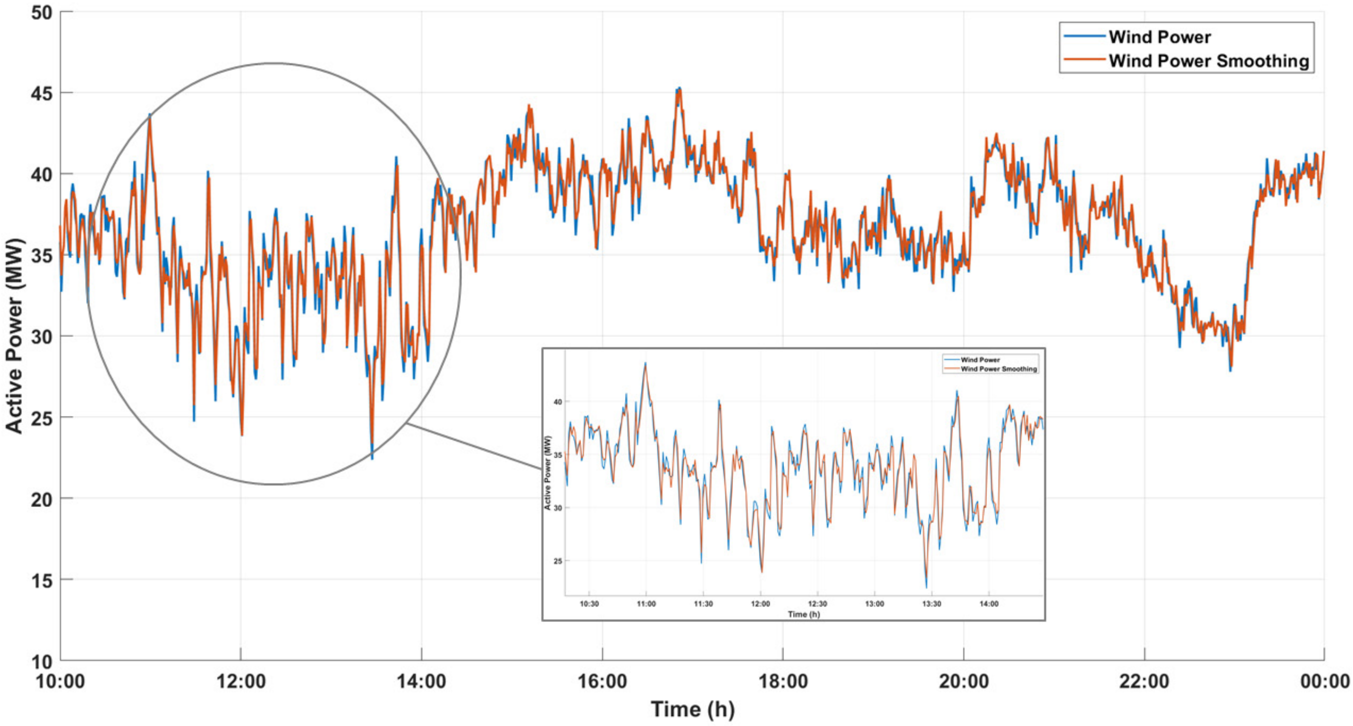

Figure 9. Active Power of Smoothed Wind Generation. Real-time measurement performed on 6 September 2021.

The blue curve indicates the power of the generation without BESS usage, while the smoothed curve is shown in orange. It is observed that the smoothed curves have smaller peaks and valleys and more attenuated curves.

The MVP index is used to evaluate wind generation power smoothing numerically. This analysis has better precision to evaluate power smoothing performed by the BESS in the present wind farm. Thus, in percentage terms, the smoothing effect results with the most significant gains points are presented in Table 1 (measurement in Figure 8) and Table 2 (measurement in Figure 9).

It can be seen from Table 1 that the MVP5 index, with the application of BESS, showed a considerable improvement in different time intervals. The best-obtained result for the 31 August 2021 day was an approximate 3.97% power fluctuation reduction, from 11:20 to 11:25 and 13:10 to 13:15. On the 6 September 2021 day (Table 2), the best result was a 3.97% reduction from 12:25 to 12:30. Different time intervals can be seen in Figures 8 and 9.

Table 1. Main indicators from the 31 August 2021 day.

Case	Time Interval	Maximum Power Value (MW)	Minimum Power Value (MW)	Wind Generation Rated Power (MW)	% Value
Without BESS operation	07:35 to 07:40	39.29	32.00	50.4	14.46%
	09:45 to 09:50	43.71	37.62	50.4	12.08%
	10:20 to 10:25	42.66	35.72	50.4	13.77%
	11:20 to 11:25	43.86	35.99	50.4	15.62%
	11:40 to 11:45	42.35	34.19	50.4	16.19%
	11:45 to 11:50	43.62	34.45	50.4	18.19%
	12:30 to 12:35	33.72	26.67	50.4	13.99%
	13:10 to 13:15	38.37	22.70	50.4	31.09%
	13:30 to 13:35	40.03	28.84	50.4	22.20%
	13:40 to 13:45	34.25	25.39	50.4	17.58%
	17:45 to 17:50	46.05	41.87	50.4	8.29%

Table 1. *Cont.*

Case	Time Interval	Maximum Power Value (MW)	Minimum Power Value (MW)	Wind Generation Rated Power (MW)	% Value
With BESS operation	07:35 to 07:40	38.29	32.83	50.4	10.83%
	09:45 to 09:50	43.52	38.62	50.4	9.72%
	10:20 to 10:25	42.13	36.72	50.4	10.73%
	11:20 to 11:25	42.86	36.99	50.4	11.65%
	11:40 to 11:45	41.53	35.19	50.4	12.58%
	11:45 to 11:50	42.89	35.45	50.4	14.76%
	12:30 to 12:35	32.72	26.76	50.4	11.83%
	13:10 to 13:15	37.37	23.70	50.4	27.12%
	13:30 to 13:35	39.53	29.84	50.4	19.23%
	13:40 to 13:45	33.72	26.39	50.4	14.54%
	17:45 to 17:50	45.69	42.56	50.4	6.21%

Table 2. Main indicators from the 6 September 2021 day.

Case	Time Interval	Maximum Power Value (MW)	Minimum Power Value (MW)	Wind Generation Rated Power (MW)	% Value
Without BESS operation	12:00 to 12:05	34.29	22	50.4	24.38%
	12:05 to 12:10	39.43	26.87	50.4	24.92%
	12:25 to 12:30	38.09	26.73	50.4	22.54%
	13:25 to 13:30	31.22	21.76	50.4	18.77%
	13:30 to 13:35	35.22	25.84	50.4	18.61%
	13:55 to 14:00	36.81	25.64	50.4	22.16%
	14:00 to 14:05	37.23	26.87	50.4	20.56%
	15:30 to 15:35	42.31	36.86	50.4	10.81%
	16:15 to 16:20	44.44	36.84	50.4	15.08%
	19:25 to 19:30	37.72	32.07	50.4	11.21%
	20:40 to 20:45	41.95	35.86	50.4	12.08%
With BESS operation	12:00 to 12:05	33.29	23.00	50.4	20.42%
	12:05 to 12:10	39.43	27.87	50.4	22.94%
	12:25 to 12:30	37.09	27.73	50.4	18.57%
	13:25 to 13:30	30.46	22.76	50.4	15.28%
	13:30 to 13:35	34.22	26.40	50.4	15.52%
	13:55 to 14:00	35.81	26.20	50.4	19.07%
	14:00 to 14:05	36.51	27.87	50.4	17.14%
	15:30 to 15:35	41.64	37.86	50.4	7.50%
	16:15 to 16:20	43.71	37.84	50.4	11.65%
	19:25 to 19:30	36.72	32.72	50.4	7.94%
	20:40 to 20:45	40.95	36.75	50.4	8.33%

4.2. Power Factor Correction Application

The power factor is an energy utilization index whose adequate control in wind generation is significant, not only from an electrical energy point of view but also because it is monitored, in the case of Brazil, by the National Electric System Operator, and the power generator may incur fines. In this case, the BESS compensates for the excess reactive power, bringing the power factor within the regulatory limit (currently, in Brazil, the limit power factor is 0.95 in the PCC between wind generation and the transmission grid).

The EMS checks the power factor information generated by the wind turbines in the bus connected to the storage system. A power factor reduction (less than 1.00) activates BESS to operate with capacitive or inductive characteristics, depending on the wind generation power factor behavior (inductive or capacitive).

Figure 10 illustrates the BESS operation behaving with capacitive characteristics when the power factor measured at the bus is less than one (1.00). Therefore, according to the EMS programming, the system acts by injecting reactive power, trying to correct the power factor to the unit value (1.00). In Figure 10, the left scale refers to the system's reactive power (blue legend), and the right scale refers to the power factor value (orange legend) measured on the bus that connects the BESS to the group of wind turbines. It should be noted that the negative sign for reactive power means that the BESS is operating in capacitive mode and the positive sign in inductive mode.

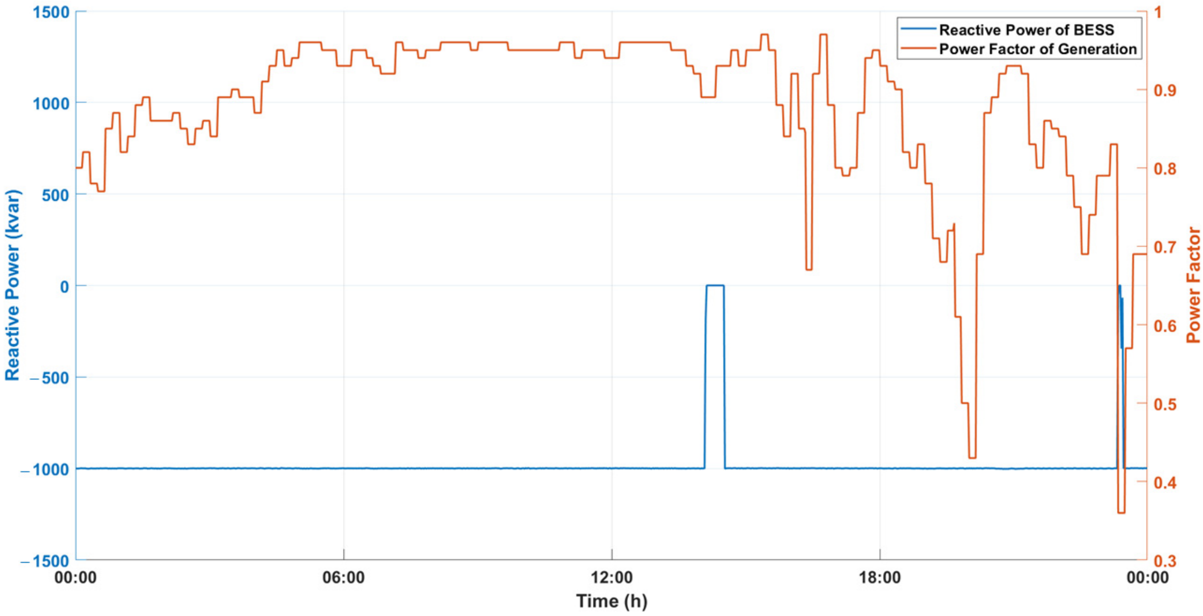

Figure 10. Real-time BESS operation in the power factor correction function. The measurement was carried out on 25 March 2021.

Figure 11 illustrates the BESS operation on 23 March 2021, where it is seen that the system remains without acting while the power factor is unity (1.00). The BESS works by compensating reactive power when there is a drop in the power factor, aiming to establish the unit value. Figure 12 illustrates the operation of BESS on 19 April 2021, where it is seen that the system operates in both capacitive and inductive modes.

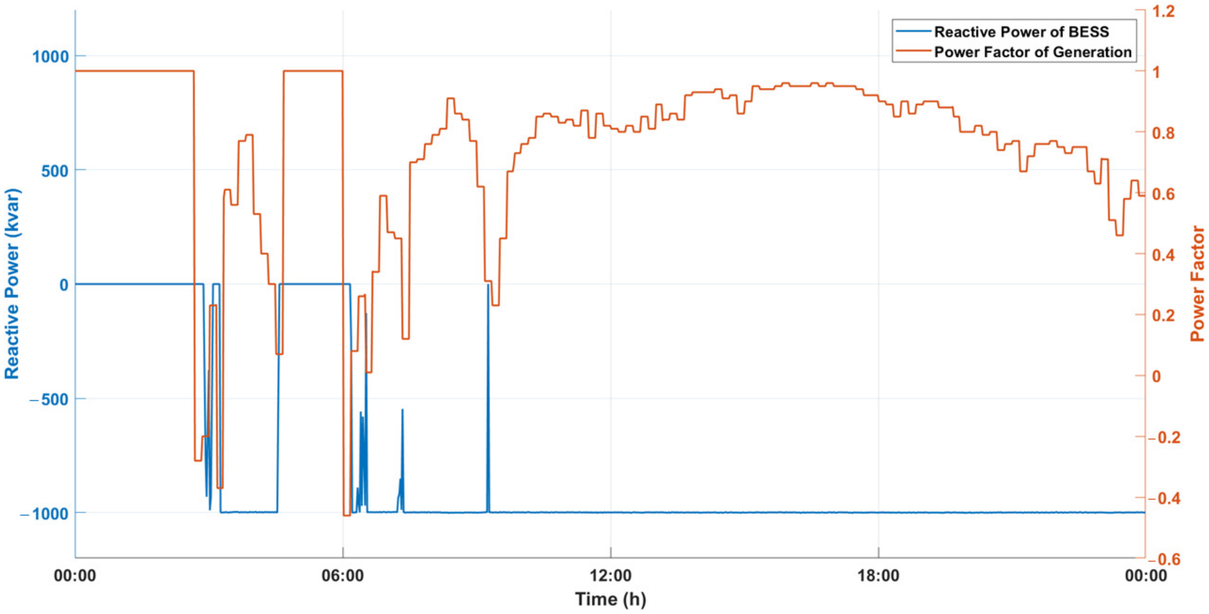

Figure 11. Real-time BESS operation in the power factor correction function. The measurement was carried out on 23 March 2021.

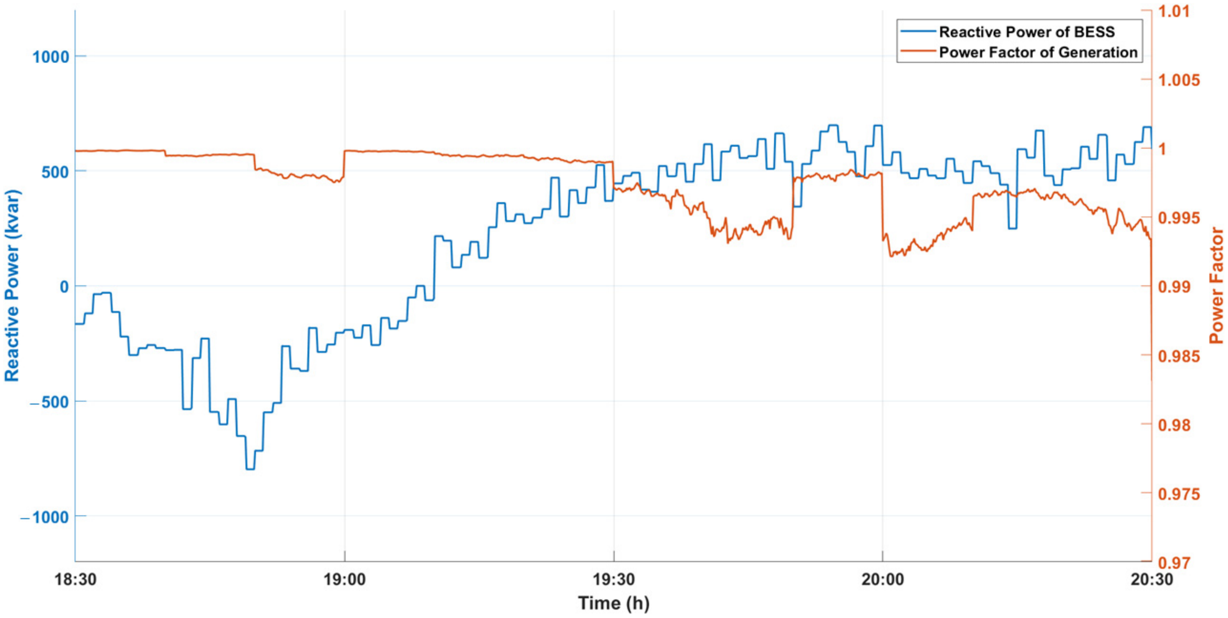

Figure 12. Real-time BESS operation in the power factor correction function. The measurement was carried out on 19 April 2021.

From the 19 April 2021 measurement data (Figure 12), it is possible to graphically characterize the resulting power factor behavior, considering the BESS performance, as illustrated in Figure 13. It can be seen from Figure 13 that the BESS corrects the power factor at different instances of time, aiming at the unit value (1.00), and thus helps to prevent the power factor from falling below 0.95.

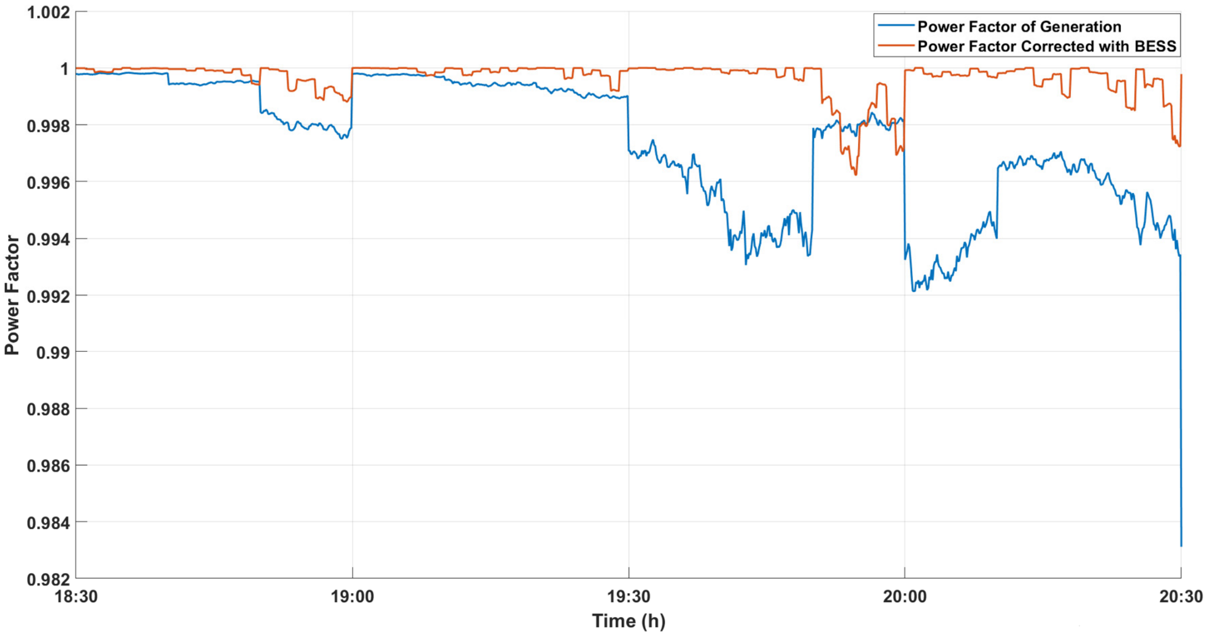

Figure 13. Power factor resulting from the application of BESS. The measurement was carried out on 19 April 2021.

5. Conclusions

From the measurement analysis, it is observed that the power smoothing function implemented in the EMS does not present problems regarding the operating logic and operating time and shows satisfactory results. It was seen that the BESS manages to smooth the wind generation power with gains of up to 3.97% (measurements recorded in Tables 1 and 2) according to the MPV5 indicator. It is noteworthy that this result is considered satisfactory since the BESS rated power is 1 MW, and it is connected to a 50.4 MW wind generation.

From the measurements, it is observed that the BESS usage in power smoothing mode contributes to reducing power fluctuations at the point that connects the power output of the wind farm and the transmission line, generating improvements in the wind farm energy quality.

The power factor correction function performance analysis implemented in the BESS EMS shows that this function does not present problems regarding its operating logic and operating time. It was seen that BESS acted by correcting the power factor whenever necessary, reducing losses to the wind farm.

It should be noted that the constant growth of wind generation should amplify the effect of power fluctuation in transmission, distribution, and microgrid systems. Thus, wind generation should increasingly impact the operation and energy quality of electrical systems. The use of a BESS operating in active power smoothing mode represents a way to circumvent this problem and enable the use of intermittent renewable energy sources.

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