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Power Smoothing Strategy for Wind Generation Based on Fuzzy Control Strategy with Battery Energy Storage System

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Abstract: This work discusses the use of a battery energy storage system applied to the smoothing of power generated at the output of wind turbines based on a fuzzy logic power control. The fuzzy control logic proposed can perform the aforementioned activity while the state of charge of the energy storage system is maintained within operational limits. In order to assess the fuzzy logic power control's effectiveness at maintaining the state of charge levels within the allowed range, two operating situations are explored: one in which the state of charge is above the upper limit allowed, and another in which the state of charge is in the minimum value allowed. The numerical results show that, when using the battery energy storage system in conjunction with the control logic proposed, the active power provided as the point of common coupling by the wind turbines can be smoothed, thus contributing to the Electric Power System reliability and stability. The main results of this paper are based on measurements of wind and active power associated with a wind generation plant installed in the northeast region of Brazil and equipped with 2.1 MW wind turbines.

Keywords: power smoothing; fuzzy inference; wind turbines; energy storage systems

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1. Introduction

Renewable energy sources have been increasing in recent years, with emphasis on wind power. According to the Global Wind Report [1], there is currently a total installed wind capacity of 837 GW worldwide (onshore and offshore), and global wind power could reach 2000 GW by 2030 and provide from 17 to 19 percent of global electricity.

Despite the promise of growth, due to the intermittent nature of the wind, the massive insertion of wind farms in the electrical power system (EPS) is still difficult. The unpredictability and uncertainties in power production have led planners and power operators to control the amount of wind power penetration to the detriment of other, more traditional dispatchable sources.

One of the problems associated with wind intermittency is power fluctuations that can, in specific situations, also cause frequency and voltage variations, which may then compromise the stability and reliability of the electrical system. Additionally, due to the cubic relationship between electrical power and wind speed, even rapid, small reductions in wind speed, such as during calm moments, can cause, in minutes, significant variations in the instantaneous production of generation.

In order to mitigate the issues generated by the intermittency of the wind source, the following solutions can be applied: (1) use of flexible generating centers with fast response; (2) increase interconnections with neighboring regions; (3) application of Demand Side Management; (4) use of Energy Storage Systems (ESS). Among the solutions presented, the easiest, and therefore most promising, is the use of ESS due to the wide range of options and high flexibility of applications to the electrical system.

Paper Structure

In the context of proposing a power smoothing strategy, this article proposes a management strategy embedded in the energy management system (EMS) that controls the active power dispatched by the battery with the objective of mitigating the power fluctuations of the wind farm by making use of fuzzy logic. Such control logic here is called Power Smoothing Fuzzy Control Strategy: PSFCS.

This work is organized as follows: Section 2 presents a brief review of active power smoothing techniques; Section 3 offers an overview of battery modeling in applications considering the presence of wind powerplants. Section 4 describes the methodologies used to build the fuzzy model. In Section 5, the numerical results and the assessment of the performance of the control logic (PSFCS method) are presented. Section 6 presents the conclusions.

2. Active Power Smoothing Strategies for Wind Power Generation

Wind power generation has rapidly emerged as a viable alternative to conventional energy sources due to its environmental and economic advantages. However, wind energy is inherently intermittent and fluctuating, which can negatively affect the stability and dispatch of energy to the grid. Active power smoothing strategies play a crucial role in mitigating these issues and optimizing the performance of wind power systems.

Despite its potential, the intermittent nature of wind presents challenges in ensuring grid stability and power quality. Active power smoothing strategies help to address these challenges by regulating and stabilizing the power output from wind power generation systems.

A brief overview of wind power generation systems, including horizontal-axis wind turbines (HAWTs), vertical-axis wind turbines (VAWTs), and wind farms is provided in [2].

Active Power Smoothing Strategies are broadly classified into three categories: (i) generator-side control strategies, (ii) grid-side control strategies, and (iii) energy storage-based strategies. Generator-side Control Strategies include techniques such as pitch angle control, torque control [3], and maximum power point tracking (MPPT) [4]. Each strategy is suitable for specific types of wind turbines and has different impacts on the overall system performance.

Grid-side control strategies include reactive power control [5–7], voltage control [8], and current control [9,10]. The role of power electronic converters, such as inverters and rectifiers, in implementing these strategies is discussed in [11]. An overview of grid side control strategies is presented in [12].

Energy Storage-based Strategies, including batteries, supercapacitors, and flywheels, are presented to actively smooth the power output from power systems [13]. Analyses of a battery energy storage system (BESS) connected to a wind farm is presented in [14] and [15].

Each power smoothing strategy has advantages and limitations, considering factors such as cost, reliability, efficiency, and environmental impact. Power smoothing control strategies using energy storage are presented in [16]. Reference [17] proposed a fuzzy logic controller for solar power smoothing based on controlled battery energy storage and varying low pass filter. A fuzzy-logic-based control strategy for power smoothing in high-wind penetrated power systems, and its validation in a microgrid lab is descried in [18]. In this paper, a fuzzy logic controller is proposed considering power measurements from an actual wind farm for active power smoothing using a Li-ion Battery Energy Storage System (BESS).

Since battery storage technologies are versatile, one main advantage of Energy Storage System (ESS) techniques for power smoothing is their compatibility with different wind power systems. The following section presents the general idea of using a battery system for power smoothing.

3. Battery Energy Storage System for Wind Generation Power Smoothing

Considering the available ESS technologies, the BESS (Battery Energy Storage System) type storage systems based on lithium-ion cells have gained prominence in recent years, showing significant growth applied in electrical power systems. This is essentially due to their high versatility in power applications and constant reductions in production costs (associated with an increase in the use of electric cars) [19,20]. Among the storage technologies that use electrochemical cells, Li-ion batteries have been the dominant choice in numerous applications that demand high energy density, higher capacity, better safety, improved performance, and lower costs [21]. In this article, the term BESS refers to a storage system using lithium-ion battery cells.

In order to reduce the power fluctuations of a wind power plant, with the objective of obtaining a more stable power output (with less variability) at the Point of Common Coupling (or at the Point of Interconnection—PoI), a BESS can be applied for power smoothing by providing or draining supplemental power, as illustrated in Figure 1.

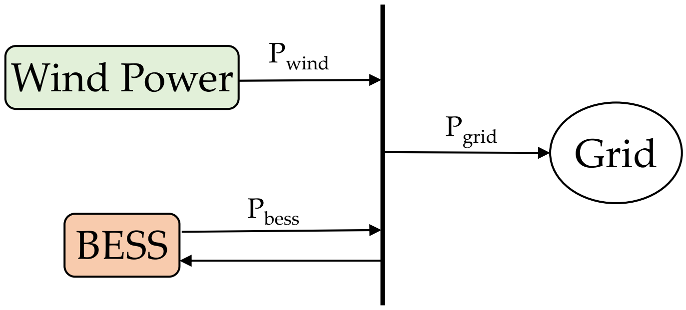

Figure 1. Wind-generated power smoothing scheme.

In the configuration illustrated in Figure 1, the total power delivered to the grid in each interval is equivalent to the sum of the active powers of the wind source and the BESS (Equation (1)). The strategy to mitigate power variations through the BESS is to use the energy storage system to compensate for the fluctuations by injecting active power into the bus at times of reduced wind speed and absorbing active power during peak wind production. BESS also operates during quick ramp ups of instantaneous wind power variations, or when the plant is producing excess generation.

$$P_{grid}(t) = P_{wind}(t) + P_{Bess}(t) \tag{1}$$

The battery energy storage system is responsible for injection and absorption of power, thereby determining the output power. Generally, it can be stated that the controllers in the BESS are divided into four main parts (as illustrated in Figure 2): (i) Battery Monitoring Unity (BMU), which is composed of sensors that measure magnitudes inherent to the battery, such as voltage, current, and temperature; (ii) Energy Management System (EMS), which focuses on the overall energy management and optimization of the battery; (iii) Power Conversion System (PCS), which consists of a bidirectional power converter responsible for DC/AC and AC/DC conversion and connection to the main grid; and (iv) Battery Management System (BMS), which is responsible for a range of applications grouped into four main areas: monitoring, management, estimation, and communication.

Regarding the BMS main roles, a brief description of each can be made. Monitoring is where the BMS observes parameters like cell voltage, current, temperature to ensure safe and efficient battery operation. In management, the BMS is able to manage energy, cell balancing and temperature in order to keep them at acceptable operational levels. It also performs overcharge/over discharge protection and fault detection. With estimation, the BMS estimates State of Charge (*SOC*), State of Health (SOH), internal resistance and current capacity. During communication, the BMS manages communication with other equipment.

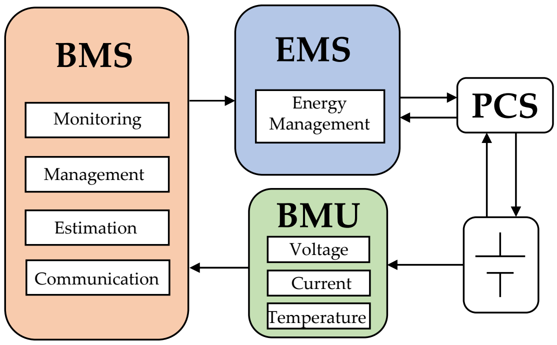

Figure 2. BESS control system.

4. Power Smoothing Fuzzy Control Strategy

In order to understand the Power Smoothing Fuzzy Control Strategy, this section presents the methodology used. Figure 3 presents a major view of the structure of the strategy applied.

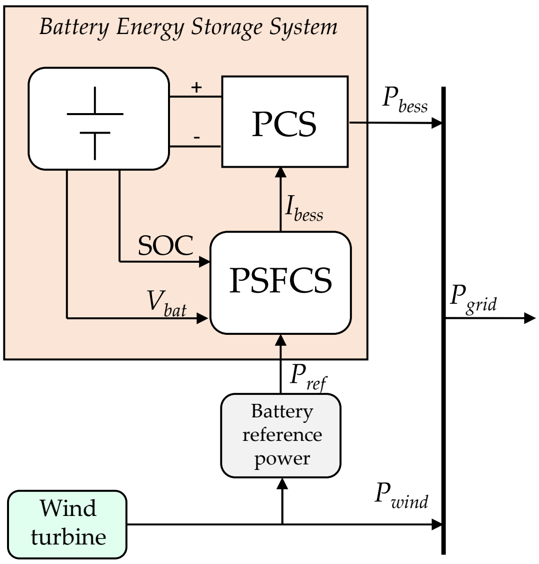

Figure 3. Structure of the Proposed Dispatch Control Strategy based on fuzzy logic.

It is important to denote that the battery and the PCS in Figure 3, for the purpose of the simulation and validations of the proposed strategy, are considered ideal, i.e., there is no time delay and no loss. At this moment, this can be considered a reasonable argument when compared to the time constants from the wind variations in the seconds range [22], and the losses of power converters compared to the MW-sized wind farms are neglectable [23].

In order to investigate the Control Strategy, the application is implemented in Matlab/Simulink® (The MathWorks Inc., Natick, MA, USA), where the wind farm and the BESS were modelled as well as the control strategy acting in the EMS.

The main components of the test model are as follows: Wind Farm Block, a block that simulates the power fluctuation from a wind farm measured or simulated based on actual data; Battery block, which contains a general battery model for lithium-ion chemistry; Battery Power Reference Block, which sets the power output from the battery; and finally, the Power Smoothing Fuzzy Control. Each one of the components is explained as follows.

4.1. Wind Farm Power Block

The wind farm power block is modelled by time series collected from five wind turbines of 2.1 MW double feed type installed in the Rio Grande do Norte, Brazil. The time series were collected from the SCADA system in the wind farm during 2 years with a sampling rate of 5 min. For the sake of simplicity, this paper uses measurements in the increment of 1 month.

The wind farm is located in one of the windiest area in Brazil. It has average annual wind speed of 8.6 m/s with Weibull scale factor of 4.3 [24] (representing a consistent wind speed). A wind speed atlas illustrating the state of Rio Grande do Norte is shown in Figure 4, with the highlighted wind farm and associated power substation.

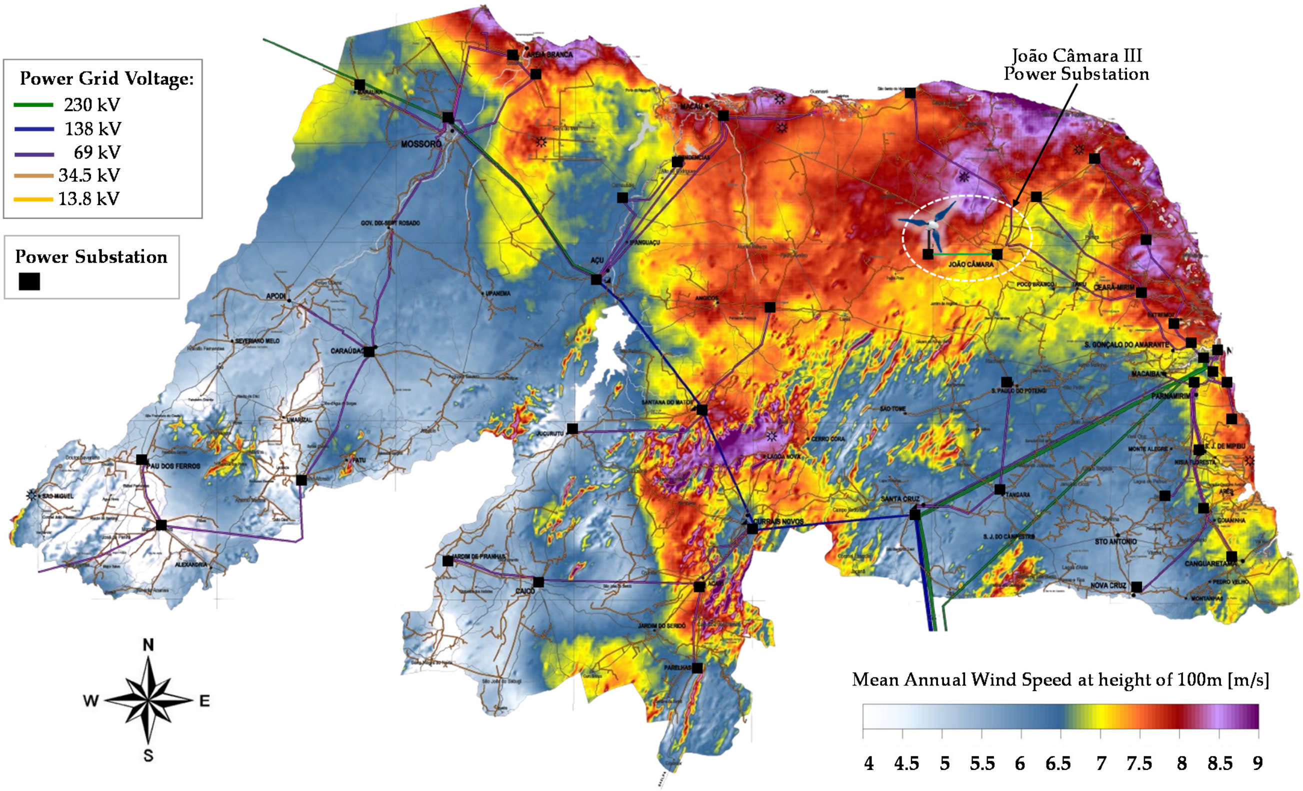

Figure 4. Wind speed atlas—Rio Grande do Norte (Brazil).

Although the local area has a consistent wind speed, the measurements showed the impacts of the sun, which created some turbulence during the solar hours, leading to more unstable power production from 6 to 18 h, as illustrated in Figure 5.

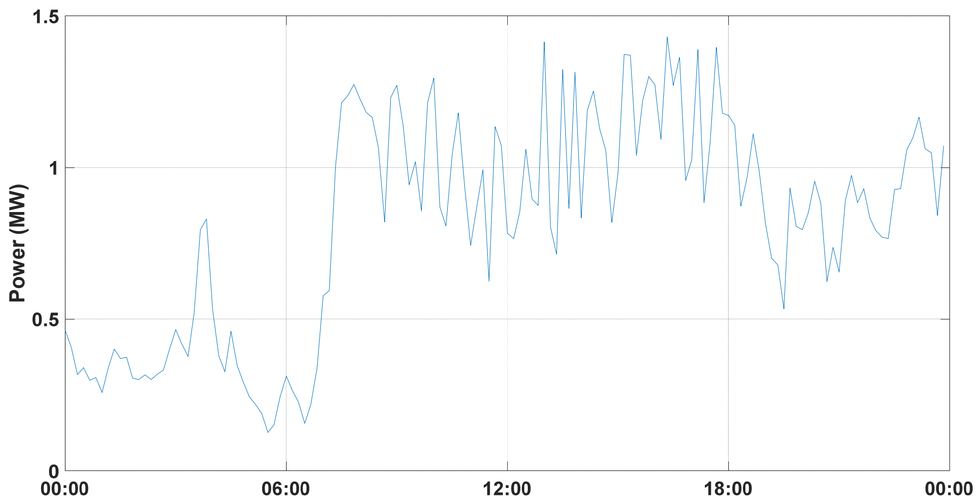

Figure 5. Wind active power time series—24-h operation.

4.2. Battery Model

The model presented in this article, also known as the generic battery model, was proposed by Trambley in [25,26]. Such a model is capable of dynamically representing a battery, making it possible to reproduce non-linear behaviors, such as typical charge and discharge curve and recovery effect. In addition, the model can be parameterized with only information about the discharge curve which is normally provided by manufacturers. The model was originally conceived to simulate batteries with Li-ion, NiMH, NiCD, and lead acid chemistries. The model is implemented in Simulink, and its schematic diagram can be seen in Figure 6.

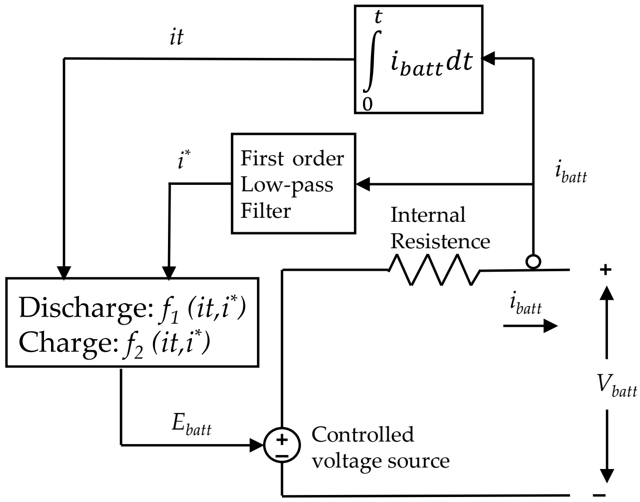

Figure 6. Li-ion battery model simplified schematic diagram.

The model has a constant internal resistance and a controlled voltage source controlled by an equation that describes the dynamic behavior of the battery and takes into account the OCV-*SOC* ratio (open circuit voltage and state of charge) and the polarization voltage. The strategy proposed in this paper is applied to a lithium-ion battery energy storage system. The dynamic behavior of the batteries is described by Equations (2)–(4) [25]:

$$Discharge : f_1(it, i^*) = E_{batt} = E_0 - K\frac{Q}{Q - it}(it + i^*) + Ae^{(-Bit)} \tag{2}$$

$$Charge : f_2(it, i^*) = E_{batt} = E_0 - K\frac{Q}{it + 0.1Q}i^* - K\frac{Q}{Q - it}it + Ae^{(-Bit)} \tag{3}$$

$$V_{batt} = E_{batt} - I_{batt}R \tag{4}$$

where E_0 is the constant voltage in volts (V); I_{batt} is battery current in ampere (A); it is the current charge of the battery in ampere-hours (Ah); i^* is the filtered current (through a low-pass filter) passing through the polarization resistance and is given in amperes (A); R is the internal resistance of the battery in ohms (Ω). Q is the nominal capacity of the battery in ampere-hours (Ah); A is the exponential zone amplitude in volts (V); B is the exponential zone time constant inverse (Ah-1); K is the polarization constant given in volts per amper-hour (V/Ah) or polarization resistance (Ω).

During the charge and discharge, the term $K\left(\frac{Q}{Q-it}\right)it$ refers to the polarization voltage of the accumulator, while the polarization resistance is represented as $K\left(\frac{Q}{Q-it}\right)$ during the charge and as $K\left(\frac{Q}{it+0.1Q}\right)$ during the discharge.

The function $\frac{Exp(s)}{Sel(s)}$ refers to the hysteresis phenomenon that occurs between charging and discharging batteries with lead acid, NiMH, or NiCD chemistry, and there is no need to use it in a model and lithium-ions [25].

The A, B, and K parameters can be determined according to [26] and require only information that can be located on the manufacturer's datasheet.

Another important parameter to define is the State of Charge from the battery (*SOC*). This parameter is relevant because it expresses the amount of energy available in the battery as well as the amount that is possible to absorb from the power system in the power smoothing concept. The *SOC* is measured in % of the total energy available in the battery, ranging from 0%, i.e., absolutely depleted, to 100% when fully charged.

The fuzzy controller needs this parameter to define the operation for charging or discharging in the power smooth control respecting the safe operational limits for the battery to avoid running on overcharge or excessive wearing under a low charge state.

In this paper, the Coulomb counting method is used to estimate the *SOC*, which is defined as follows.

$$SOC(t) = SOC(t-1) - \frac{1}{Q}\int_0^t i_{batt}dt, \quad (5)$$

As previously stated, there are *SOC* limits applied to the storage device in order protect it. The upper and lower limits prevent overloading or complete discharge operations that lead to high wear on lithium batteries that compromise their lifespan. Although the Li-ion battery cells can operate from 0 to 100% of their *SOC*, using the total capacity will rapidly reduce the elements' lifetime as well as the battery's State of Health (SOH) [13]. Thus, the battery *SOC* is maintained from 20% ($SOC_{\min}$—lower limit) to 80% ($SOC_{\max}$—upper limit).

4.3. Reference Power (Setpoint)

The reference power (P_{ref}) is the set point for the control system for the active power behavior for the BESS in order to compensate for the wind power fluctuations in PoI, which can be defined as:

$$P_{ref}(t) = P_{windpred}(t) - P_{wind}(t), \quad (6)$$

where P_{wind} is the instantaneous active power and $P_{windpred}$ is the short term predicted wind power for the next time interval. When P_{ref} is positive, it means that the battery is in the discharging mode (suppling power to the local network), and when negative, it means the battery is charging (draining power from the local network).

The reference power relies on short-term predicted wind power. The short term here applies to a time from 1 to 10 min, where the wind power fluctuations have great impacts on local power network (voltage quality), according to [27,28].

The short-term prediction tool used in this research was the moving average applied with the persistence model for the wind power time series. The persistence model assumes that the future values of a time series will be the same as the most recent observed value and is defined in Equation (7):

$$\hat{y}_i = y_{i-1} \quad (7)$$

The moving average method uses a simple arithmetic average of wind power over a timespan. This is commonly used in the financial market to remove some random and short fluctuations. The key aspect is to define a window that can be used for averaging which does not compromise some important fluctuation. The moving average applied for $P_{windpred}$ is shown in Equation (8):

$$P_{windpred_i} = \frac{1}{n}\sum_{i=m}^{n}\hat{y}_i, \quad (8)$$

where n is the window size (i.e., the number of elements used to average), while i is the element position in the vectorized time series. The time series of the active power produced by the wind farm were composed of a time sample of 5 min, and for the analyses, the moving average was used for hourly averages.

4.4. Dispatch Fuzzy Controller

The dispatch fuzzy controller is based on a rule-based controller [29]. The control is used for power smoothing and only needs information about the *SOC* level and reference power. The flowchart in Figure 7 illustrates how this control logic works.

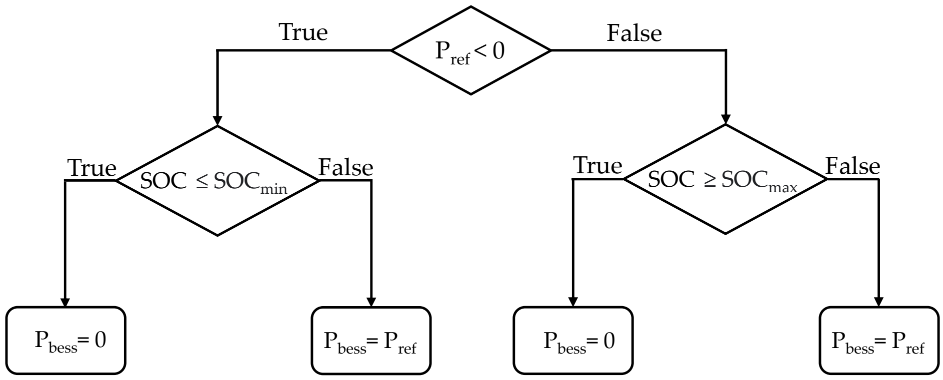

Figure 7. Flowchart for Power Smoothing control.

The rules ensure that the wind power is smoothed by the BESS operation by following the reference power while respecting the upper and lower limits for the *SOC*. Without this, no power will be delivered by the BESS, and in this case, the power at the PoI is exclusively produced by the wind farm.

The rules also guarantee that BESS only charges or discharges, and only if, for some reason, the *SOC* is not within the imposed limits. The BESS is only charged by the wind energy when the *SOC* is equal to or below its inferior limit and is only discharged when the *SOC* is equal to or above its upper limit. This situation remains until the *SOC* is between the operational limits.

Since the *SOC* is kept within the operational limits while following the reference power, the charge or discharge current can be defined through Equation (9). In this case, I_{bess} is limited by the maximum and minimum discharge current of the BESS, which can be calculated by considering the rated voltage and rated power of the BESS.

$$I_{bess} = \frac{P_{bess}}{V_{batt}} \tag{9}$$

In this study, a Mamdani type 1 fuzzy dispatch controller with centroid defuzzification was utilized. The inputs to the controller are the "*SOC*" and "reference power", while "BESS output power" is the controller output. The choice of membership function type was based on empirical analysis, where different functions were assessed to determine which one yielded the lowest error. Triangular shapes were found to provide the best result for both the reference power and BESS output power, while the *SOC* exhibited the best performance with trapezoidal function shapes. The fuzzy inference rules follow the rules established in Figure 7. These rules are applied to the membership function governing the BESS active power dispatch controller and are presented in Table 1. The membership functions are illustrated in Figure 8.

The membership functions for the reference power and the BESS output power are divided into three subgroups: N, zero, and P. N stands for "negative", representing the negative power, which in this work corresponds to the charging of the BESS; zero represents values equal to or close to zero; and P stands for "positive", representing the positive power, which is responsible for discharging the BESS. The suffix "in" is used to indicate the reference power, which serves as an input to the controller, while the suffix "out" refers to the BESS output power, i.e., the power controlled and applied by the controller.

The pertinence functions for the *SOC* are grouped into three sets: S, M, and B. S stands for "small" and represents values that are equal to or less than the *SOC* lower limit; M stands for "medium" and represents the operational range for the *SOC*, encompassing values between the upper and lower *SOC* limits; and B stands for "big" and represents values equal to or greater than the *SOC* upper limit.

Table 1. Fuzzy Inference Rules applied to the power dispatch controller.

		State of Charge			
		S	**M**	**Not M**	**B**
P_{ref}	**Nin4**	Nout4	Nout4	-	-
	Nin3	Nout3	Nout3	-	-
	Nin2	Nout2	Nout2	-	-
	Nin1	Nout1	Nout1	-	-
	Zero	-	Zero	Zero	-
	Pin1	-	Pout1	-	Pout1
	Pin2	-	Pout2	-	Pout2
	Pin3	-	Pout3	-	Pout3
	Pin4	-	Pout4	-	Pout4

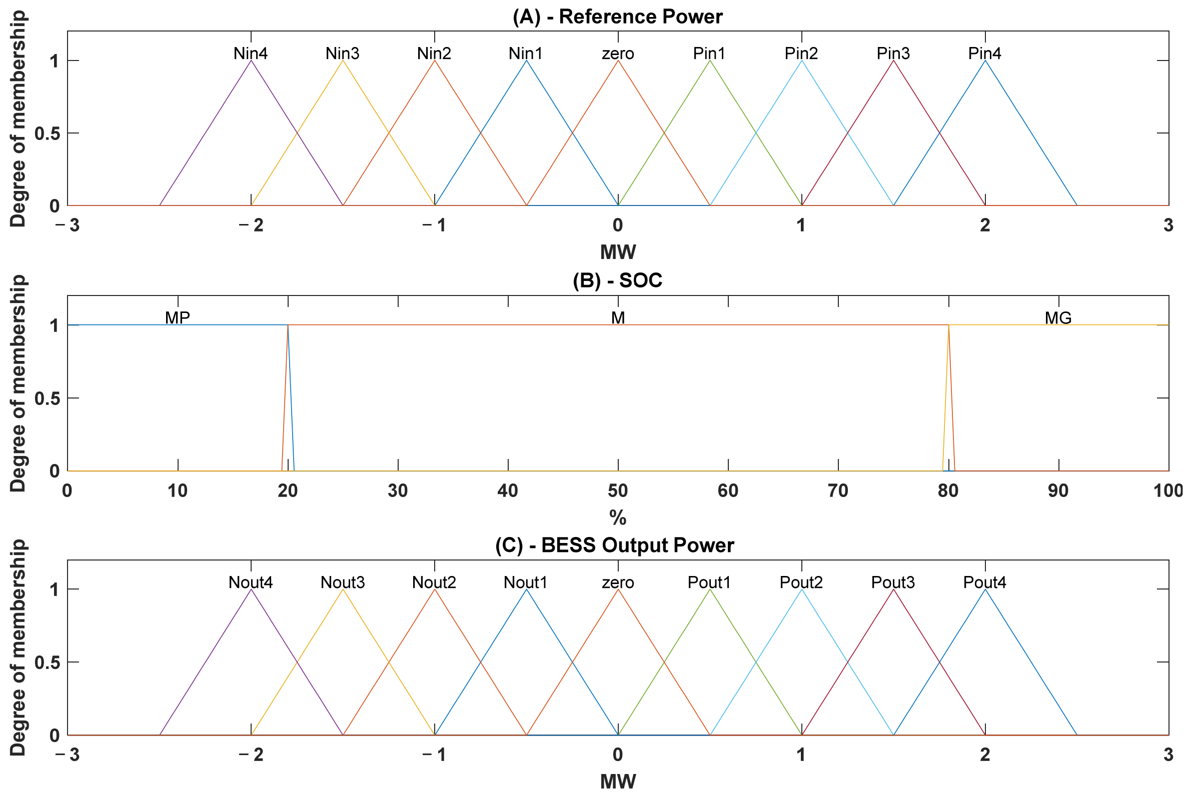

Figure 8. Membership functions: (**A**) reference power; (**B**) *SOC*; (**C**) BESS output power.

5. Smoothing Active Power—Numerical Results

This section presents the results of the fuzzy logic control strategy for wind power output smoothing using the definitions from Section 4. The simulation setups are as indicated on Table 2. The control system was simulated under two initial conditions. In the first condition, the initial *SOC* is 100%, while in the second condition, the initial *SOC* is 10%. The main objective of these two simulation sets was to analyze the charging and discharging operation coordinated by the controller in the event that the *SOC* is outside of its boundaries.

Table 2. Simulation parameters.

Parameter	Value
Type of Battery	Lithium-ion
Rated Voltage	716.8 V
Rated Capacity	2880 Ah
Rated power	2 MW
Rated Energy	2.06 MWh
Max Discharge Current	2790.17 A
Min Charge Current	−2790.17 A
SOC Upper Limit	80%
SOC Lower Limit	20%

5.1. Simulation with Initial SOC at 100%

Considering the first 24 h of the one-month simulation to have an initial *SOC* of 100%, the result of battery power, battery current, *SOC*, and smoothed wind power are illustrated in Figure 9.

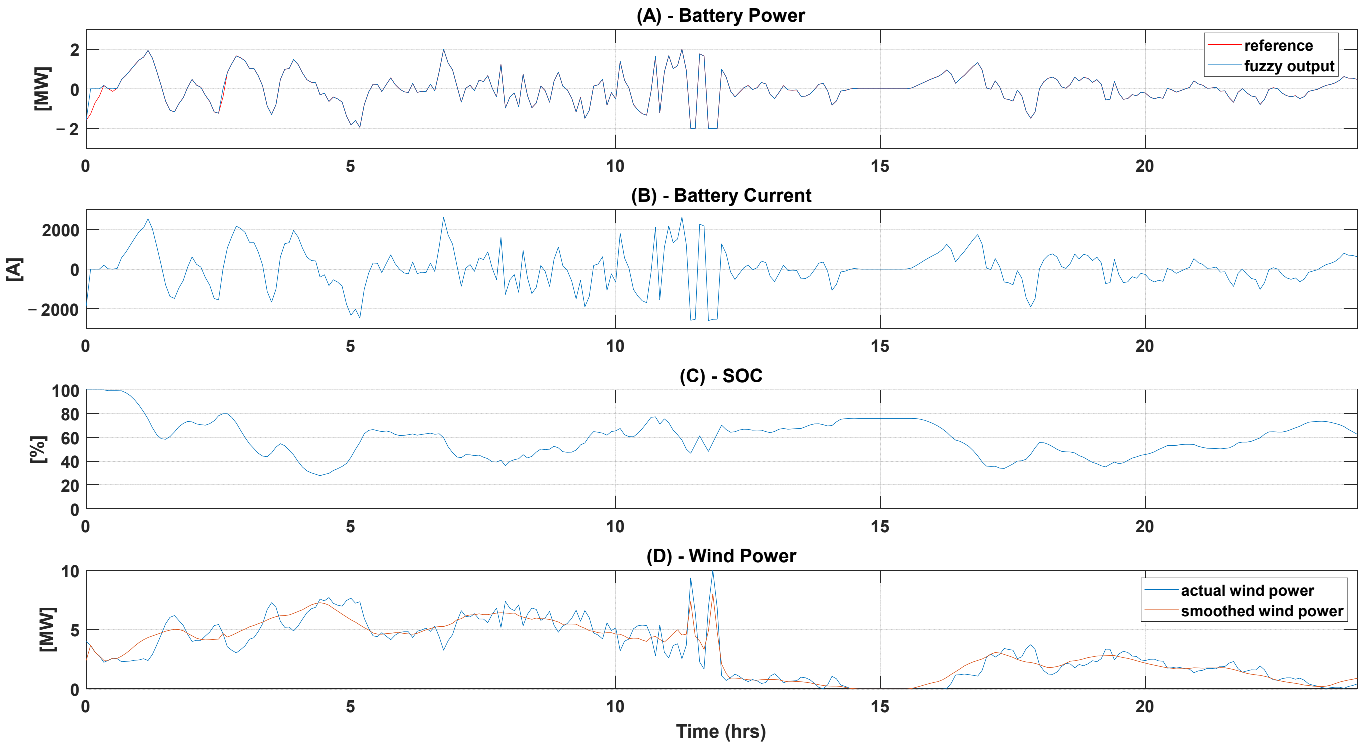

Figure 9. Simulation results for 100% initial *SOC* for the first 24 h. (**A**) Battery Power, (**B**) Battery Current, (**C**) *SOC*, (**D**) Smoothed Wind Power.

Regarding battery power, a comparison between the reference power (red) and the power that is being delivered by the BESS (blue) is illustrated. In the initial moments, the power delivered by the BESS is null, not following the reference. This occurs because the initial *SOC* is 100%, which is inferred from the fuzzy control of only discharging the battery when the reference power indicates a discharge (i.e., positive reference power); therefore the wind power is not smoothed, which can be seen in the wind power graph. This behavior is maintained until the *SOC* levels are within the imposed limits. Once within the *SOC* limits, the controller tries to follow the reference power while limiting the maximum charge/discharge current and observing the *SOC* limits. The result of a month's data can be seen in Figure 10, where it is clearer that the controller does not allow the *SOC*, the battery power, and the battery current to exceed operational limits.

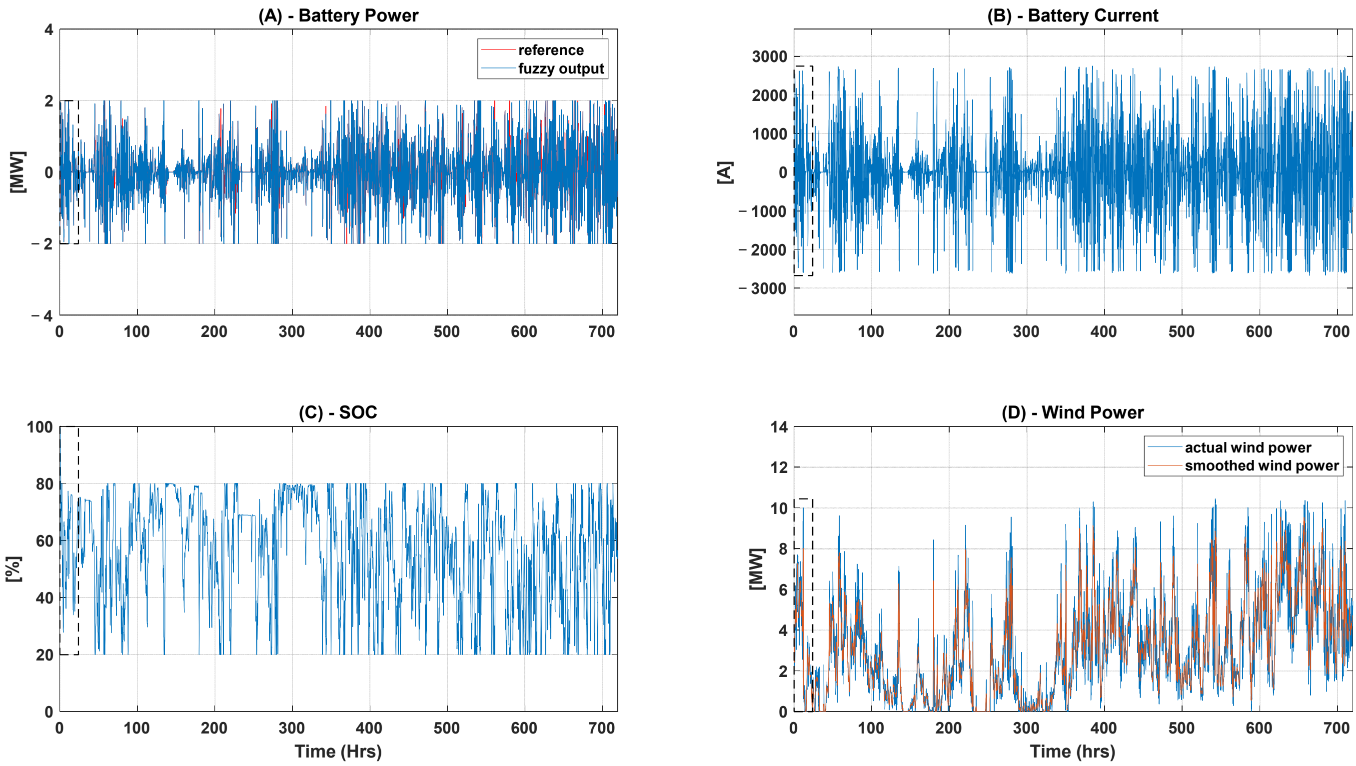

Figure 10. Simulation results for 100% initial *SOC* for one month. (**A**) Battery Power; dashed line highlight refers to Figure 9A, (**B**) Battery Current; dashed line highlight refers to Figure 9B, (**C**) *SOC*; dashed line highlight refers to Figure 9C, (**D**) Smoothed wind power; dashed line highlight refers to Figure 9D.

Due to the capacity and power limit of the battery, in addition to the limit imposed on the *SOC* by the fuzzy controller, the wind power will not always be smoothed according to the reference power, so it is important to determine the error between the ideal case and the one obtained from the controller. This can be completed by using Equation (10). $P_{smoothed\ reference}$ is the smoothed reference wind power obtained from Equation (8), and $P_{smoothed\ fuzzy}$ is the smoothed wind power obtained through the fuzzy controller. The error is shown as a histogram in Figure 11. In most cases, the error is about zero, meaning that, in 93% of one-month simulations, the fuzzy controller was able to smooth the output wind power. Other error values are below 3% of the total and correspond to events such as the controller being unable to smooth the power either because of operational limits or approximation errors by the fuzzy controller itself.

$$Error = P_{smoothed\ fuzzy} - P_{smoothed\ reference}, \tag{10}$$

It is important to highlight that the power reference in this simulation is limited by the nominal battery power, which does not correspond to an ideal smoothing. Figure 12 shows a comparison between ideal and limited reference power. However, with 2 MW nominal rated power, the BESS is capable of proportionally serving around 95.45% of the cases.

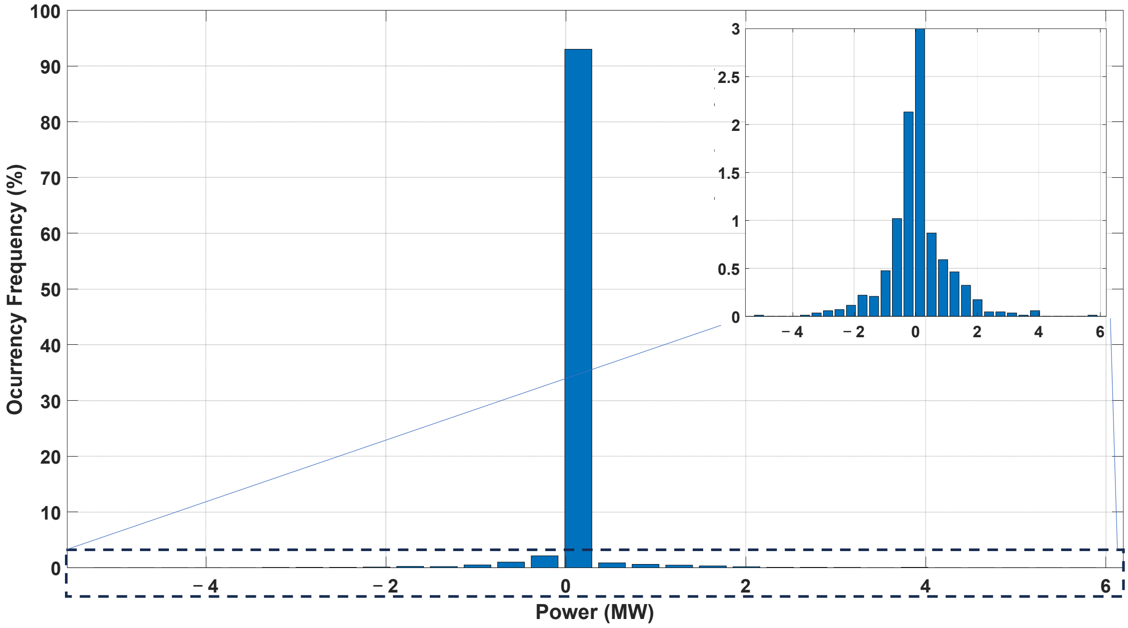

Figure 11. Error between smoothed wind power by fuzzy controller and ideal smoothed wind power.

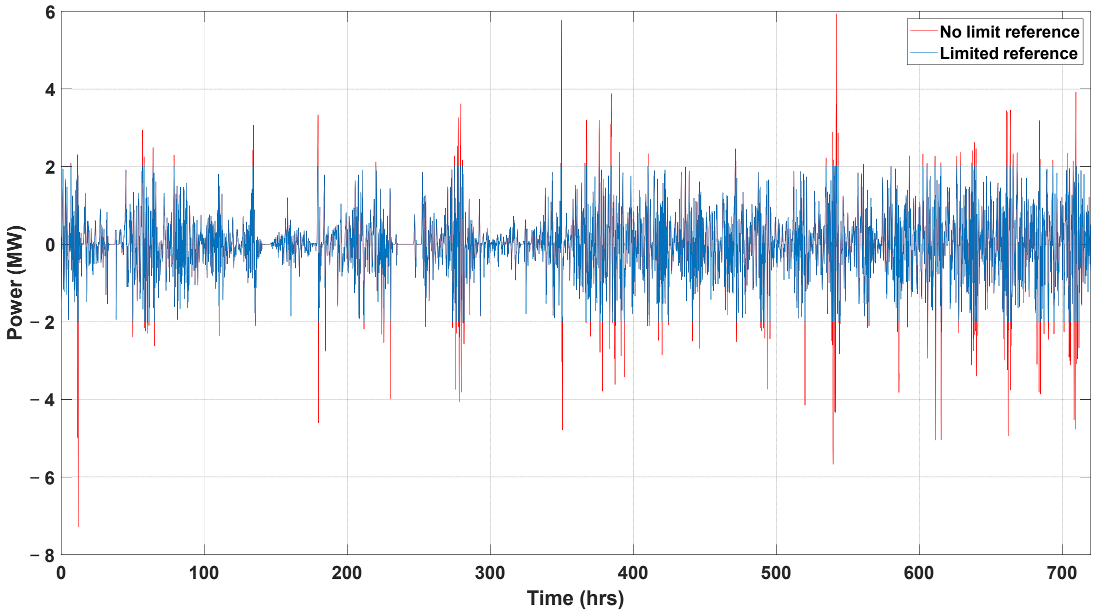

Figure 12. Comparison between ideal reference power and limited reference power.

5.2. Simulation with Initial SOC at 10%

The result of the simulation with an initial *SOC* of 10% for the first 24 h can be seen in Figure 13. Due to the initial *SOC* being 10%, the fuzzy controller can charge the battery only if the reference power is negative. As the reference in the initial moments is negative, the power starts to be smoothed immediately, and the battery is charged until it reaches the *SOC* operational limits.

For this simulation scenario, it is clearer to see the fuzzy logic controller working. At around the first hour, the *SOC* of the energy storage is 20%. At that moment, the output power and the battery current are null, and this state is maintained until the reference power allows the battery to be charged. The same behavior can be seen around the second and third hours. The result for a month of data for this scenario can be seen in Figure 14.

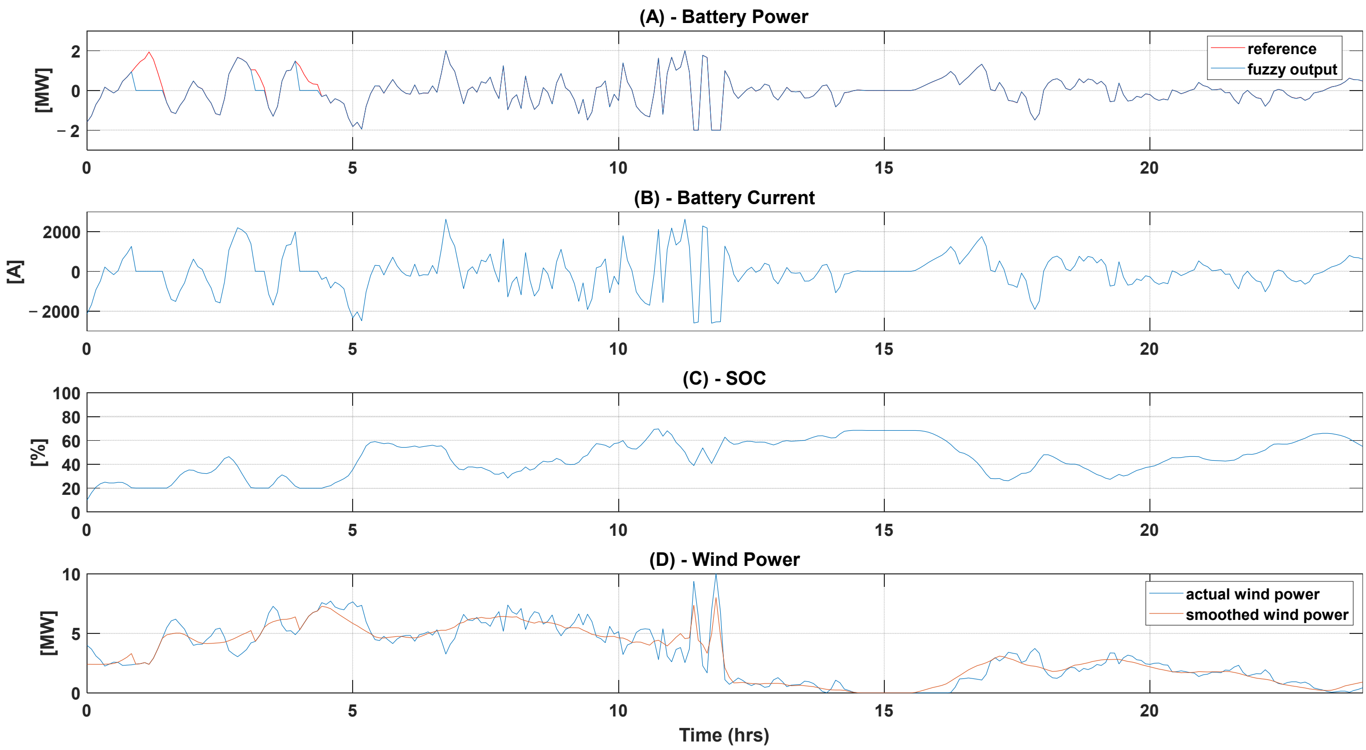

Figure 13. Simulation results for 10% initial *SOC* for the first 24 h. (**A**) Battery Power, (**B**) Battery Current, (**C**) *SOC*, (**D**) Smoothed wind power.

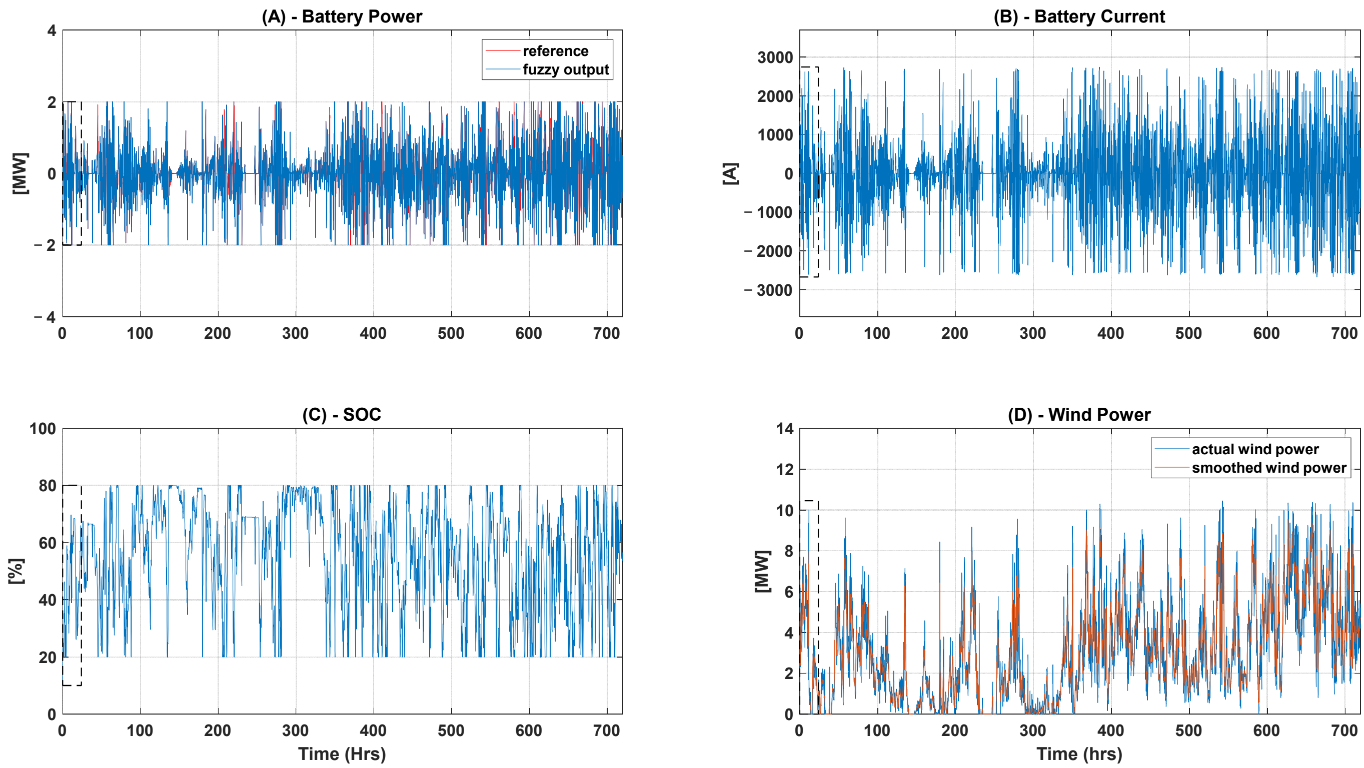

Figure 14. Simulation results for 10% initial *SOC* for one month. (**A**) Battery Power; dashed line highlight refers to Figure 13A, (**B**) Battery Current; dashed line highlight refers to Figure 13B, (**C**) *SOC*; dashed line highlight refers to Figure 13C, (**D**) Smoothed wind power; dashed line highlight refers to Figure 13D.

Equation (10) was used to verify the effectiveness of the fuzzy controller for this case, and the result is illustrated in Figure 15. It is possible to notice that the error around zero is 93%, similar to that seen in the previous scenario.

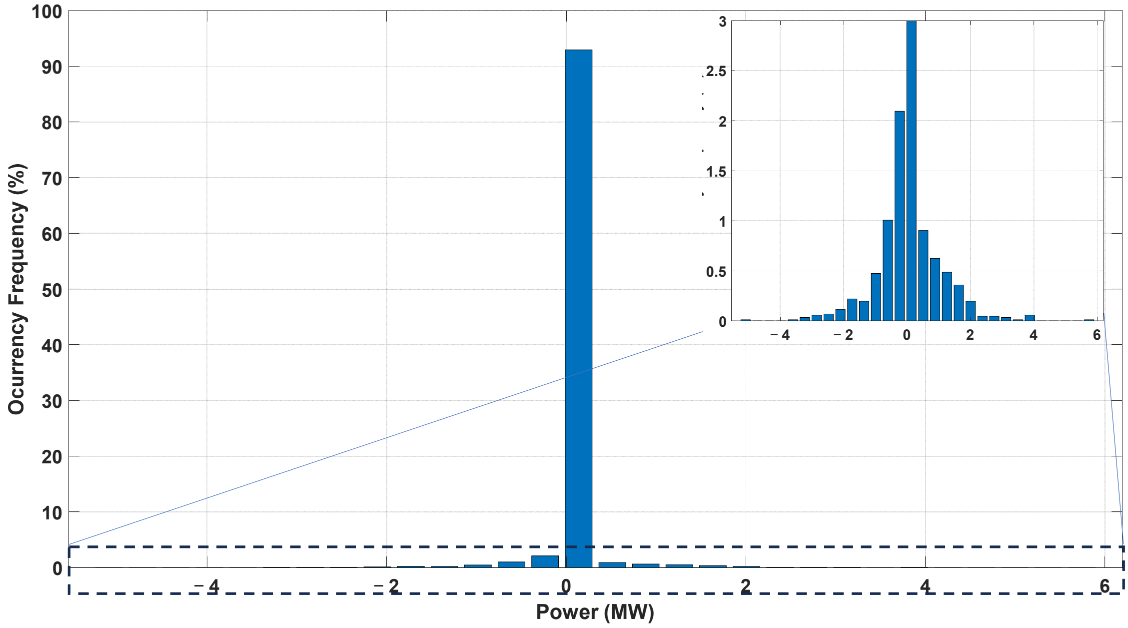

Figure 15. Error between smoothed wind power by fuzzy controller and ideal smoothed wind power for initial *SOC* 10%.

It is possible to conclude that the fuzzy controller proposed in this paper works as it should (i.e., limiting the BESS *SOC*, power, and current) with low error. It is also possible to conclude that a 2 MW/2.06 MWh BESS can appropriately smooth the power fluctuations caused by a wind farm composed of five wind turbines at 2.1 MW each, which is roughly five times the nominal size of the battery.

6. Conclusions

This paper presented a proposal for a controller for smoothing wind power output based on fuzzy logic for a wind farm equipped with a battery energy storage system.

The proposed controller was simulated considering several conditions that used real data collected in a real wind farm. Two conditions were chosen to be used as performance indicators. The first one shows the initial *SOC* condition, from 10% to 100%. The main idea was to verify the correct operation of the fuzzy controller in protecting the battery by conducting the *SOC* to the allowable range, from 20 to 80%.

During the simulations, it was possible to verify that, during the moments of out boundaries for the *SOC*, the controller freezes the smooth operation until the state of charge achieves the minimal or maximal values. During these moments, the fluctuations are not filtered out, but analyzing the results through the error from the controller made it possible to identify that the controller was not running around 3% of the time.

Analyzing the error signal, it is also inferred that the battery needed to smooth the power output from the wind farms does not need to have the same magnitude of the wind farm.

The results showed that the proposed tool was effective in its objective using fuzzy logic. The tool can also be used for the sizing of a battery in order to find the optimal size for each wind farm based on the measurements and in the simulation tool.

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References

1. GWEC. *GWEC Global Wind Report*; Global Wind Energy Council: Brussels, Belgium, 2021; p. 75.
2. Burton, T.; Jenkins, N.; Sharpe, D.; Bossanyi, E. *Wind Energy Handbook*; John Wiley & Sons: Hoboken, NJ, USA, 2011.
3. Munteanu, I.; Bratcu, A.I.; CeangĂ, E.; Cutululis, N.-A. *Optimal Control of Wind Energy Systems: Towards a Global Approach*; Springer: Berlin/Heidelberg, Germany, 2008; Volume 22.
4. Masters, G.M. *Renewable and Efficient Electric Power Systems*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2013.
5. Pena, R.; Clare, J.; Asher, G. Doubly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation. *IEE Proc.-Electr. Power Appl.* **1996**, *143*, 231–241. [CrossRef]
6. Zhai, J.; Liu, H. Reactive power control strategy of DFIG wind farms for regulating voltage of power grid. In Proceedings of the 2014 IEEE PES General Meeting | Conference & Exposition, National Harbor, MD, USA, 27–31 July 2014; pp. 1–5. [CrossRef]
7. Xie, D.; Xu, Z.; Yang, L.; Ostergaard, J.; Xue, Y.; Wong, K.P. A Comprehensive LVRT Control Strategy for DFIG Wind Turbines With Enhanced Reactive Power Support. *IEEE Trans. Power Syst.* **2013**, *28*, 3302–3310. [CrossRef]
8. Kazmi, S.M.R.; Goto, H.; Guo, H.-J.; Ichinokura, O. A Novel Algorithm for Fast and Efficient Speed-Sensorless Maximum Power Point Tracking in Wind Energy Conversion Systems. *IEEE Trans. Ind. Electron.* **2010**, *58*, 29–36. [CrossRef]
9. Rahmani, S.; Hamadi, A.; Mendalek, N.; Al-Haddad, K. A New Control Technique for Three-Phase Shunt Hybrid Power Filter. *IEEE Trans. Ind. Electron.* **2009**, *56*, 2904–2915. [CrossRef]
10. Deng, J.; Qi, Z.; Xia, N.; Gao, T.; Zhang, Y.; Duan, J. Control Strategy and Parameter Optimization Based on Grid Side Current Dynamic Change Rate for Doubly-Fed Wind Turbine High Voltage Ride Through. *Energies* **2022**, *15*, 7977. [CrossRef]
11. Rodriguez, P.; Pou, J.; Bergas, J.; Candela, J.I.; Burgos, R.P.; Boroyevich, D. Decoupled Double Synchronous Reference Frame PLL for Power Converters Control. *IEEE Trans. Power Electron.* **2007**, *22*, 584–592. [CrossRef]
12. Jain, B.; Jain, S.; Nema, R.K. Control strategies of grid interfaced wind energy conversion system: An overview. *Renew. Sustain. Energy Rev.* **2015**, *47*, 983–996. [CrossRef]
13. Luo, X.; Wang, J.; Dooner, M.; Clarke, J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Appl. Energy* **2015**, *137*, 511–536. [CrossRef]
14. Dantas, N.K.L.; Souza, A.C.M.; Vasconcelos, A.S.M.; Junior, W.d.A.S.; Rissi, G.; Dall'orto, C.; Maciel, A.M.A.; Castro, J.F.C.; Liu, Y.; Rosas, P. Impact Analysis of a Battery Energy Storage System Connected in Parallel to a Wind Farm. *Energies* **2022**, *15*, 4586. [CrossRef]
15. Pontes, L.; Costa, T.; Souza, A.; Dantas, N.; Vasconcelos, A.; Rissi, G.; Dias, R.; Mohamed, M.A.; Siano, P.; Marinho, M. Operational Data Analysis of a Battery Energy Storage System to Support Wind Energy Generation. *Energies* **2023**, *16*, 1468. [CrossRef]
16. Teleke, S. *Control Methods for Energy Storage for Dispatching Intermittent Renewable Energy Sources*; North Carolina State University: Raleigh, NC, USA, 2009.
17. Atif, A.; Khalid, M. Fuzzy logic controller for solar power smoothing based on controlled battery energy storage and varying low pass filter. *IET Renew. Power Gener.* **2020**, *14*, 3824–3833. [CrossRef]
18. Ochoa, D.; Martinez, S.; Arévalo, P. A Novel Fuzzy-Logic-Based Control Strategy for Power Smoothing in High-Wind Penetrated Power Systems and Its Validation in a Microgrid Lab. *Electronics* **2023**, *12*, 1721. [CrossRef]
19. IRENA. *Electricity Storage and Renewables: Costs and Markets to 2030*; IRENA: Abu Dhabi, United Arab Emirates, 2017.
20. IRENA. *Battery Storage for Renewables: Market Status and Technology Outlook*; IRENA: Abu Dhabi, United Arab Emirates, 2015.
21. Mitali, J.; Dhinakaran, S.; Mohamad, A. Energy storage systems: A review. *Energy Storage Sav.* **2022**, *1*, 166–216. [CrossRef]
22. Van der Hoven, I. Power spectrum of horizontal wind speed in the frequency range from 0.0007 to 900 cycles per hour. *J. Atmos.Sci.* **1957**, *14*, 160–164. [CrossRef]
23. Leow, Y.Y.; Ooi, C.A.; Hamidi, M.N. Performance evaluation of grid-connected power conversion systems integrated with real-time battery monitoring in a battery energy storage system. *Electr. Eng.* **2019**, *102*, 245–258. [CrossRef]

24. COSERN. Potencial Eólico do Estado do Rio Grande do Norte. 2003. Available online: http://www.cresesb.cepel.br/publicacoes/download/atlas_eolico/atlas_eolico_RN.pdf (accessed on 1 March 2023).
25. Tremblay, O.; Dessaint, L.-A. Experimental Validation of a Battery Dynamic Model for EV Applications. *World Electr. Veh. J.* **2009**, *3*, 289–298. [CrossRef]
26. Tremblay, O.; Dessaint, L.-A.; Dekkiche, A.-I. A Generic Battery Model for the Dynamic Simulation of Hybrid Electric Vehicles. In Proceedings of the IEEE Vehicle Power and Propulsion Conference, Arlington, TX, USA, 9–12 September 2007; pp. 284–289.
27. Würth, I.; Valldecabres, L.; Simon, E.; Möhrlen, C.; Uzunoğlu, B.; Gilbert, C.; Giebel, G.; Schlipf, D.; Kaifel, A. Minute-Scale Forecasting of Wind Power—Results from the Collaborative Workshop of IEA Wind Task 32 and 36. *Energies* **2019**, *12*, 712. [CrossRef]
28. Giebel, G.; Brownsword, R.; Kariniotakis, G.; Denhard, M.; Draxl, C. *The State-of-the-Art in Short-Term Prediction of Wind Power: A Literature Overview*; ANEMOS. Plus: Roskilde, Denmark, 2011.
29. Teleke, S.; Baran, M.E.; Bhattacharya, S.; Huang, A.Q. Rule-Based Control of Battery Energy Storage for Dispatching Intermittent Renewable Sources. *IEEE Trans. Sustain. Energy* **2010**, *1*, 117–124. [CrossRef]