Enhancing Wind Turbine Performance with Adaptive Maximum Power Point Tracking Controller

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Abstract

The pursuit of sustainable energy solutions has led to increased interest in wind energy systems, which offer a clean and renewable alternative to fossil fuels. This paper presents an advanced approach to efficient energy conversion and management in wind energy systems utilizing controllers. The Maximum Power Point Tracking (MPPT) controllers are pivotal in optimizing the performance and reliability of wind turbines by maintaining optimal operating conditions and ensuring maximum energy extraction from variable wind speeds.The study explores the integration of MPPT controllers in wind energy systems, focusing on their role in managing the dynamic behaviour of wind turbines. Key aspects include the control of generator speed, torque, and power output to align with the ever-changing wind conditions. The implementation of advanced control algorithms within MPPT controllers is discussed, highlighting their effectiveness in mitigating issues such as overspeed, power fluctuations, and mechanical stress on turbine components.A comprehensive simulation model is developed to evaluate the performance of wind turbines equipped with MPPT controllers. The model simulates various wind scenarios, incorporating stochastic wind profiles to assess the robustness and adaptability of the control strategies. The results demonstrate significant improvements in energy conversion efficiency and system stability compared to traditional control methods.Additionally, the paper examines the economic and environmental benefits of employing MPPT controllers in wind energy systems. By enhancing energy efficiency and reducing wear and tear on turbine components, MPPT controllers contribute to lower maintenance costs and extended turbine lifespans. The reduction in mechanical failures and downtime further ensures a more reliable and continuous energy supply, making wind energy a more viable option for meeting global energy demands.

Keywords: wind energy systems, static controllers, energy conversion, wind turbines, control algorithms, renewable energy, system stability, economic benefits, environmental impact.

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1. Introduction

Energy has played a critical role in driving industrial, commercial, and residential development. However, the increasing demand for energy has led to the need to explore additional resources to boost energy production. While fossil fuels are a common energy source, they also have negative environmental consequences such as air pollution and global warming. In contrast, renewable energy sources such as wind power are clean and do not have a greenhouse effect on the atmosphere, making them ideal for generating electricity without any environmental hazards. Wind power is a viable solution due to its abundance and non-depleting nature, making it an attractive option to address the growing concern for clean and green energy resources [1,2].Electrical energy conversion from wind energy is achieved by WEHS, which mainly consists of a wind turbine (rotor hub and blades), a generator, and electric power converters [3]. In WEHS, the wind turbine converts the wind kinetic energy into mechanical energy, and the generator further transforms the mechanical energy into electrical energy [4,5].

The electrical power converter connected to the system converts the generated AC power to DC power which the DC load, such as battery charging, can use. For grid-connected WEHS, other devices such as boost converters, inverters, and transformers are required [6,7]. The boost converter increases the DC output power before passing it to the inverter, which converts the DC power to AC. The step-up transformer boosts the AC power and connects it to the grid. The diagram of a typical grid-connected WEHS is shown in Figure 1.

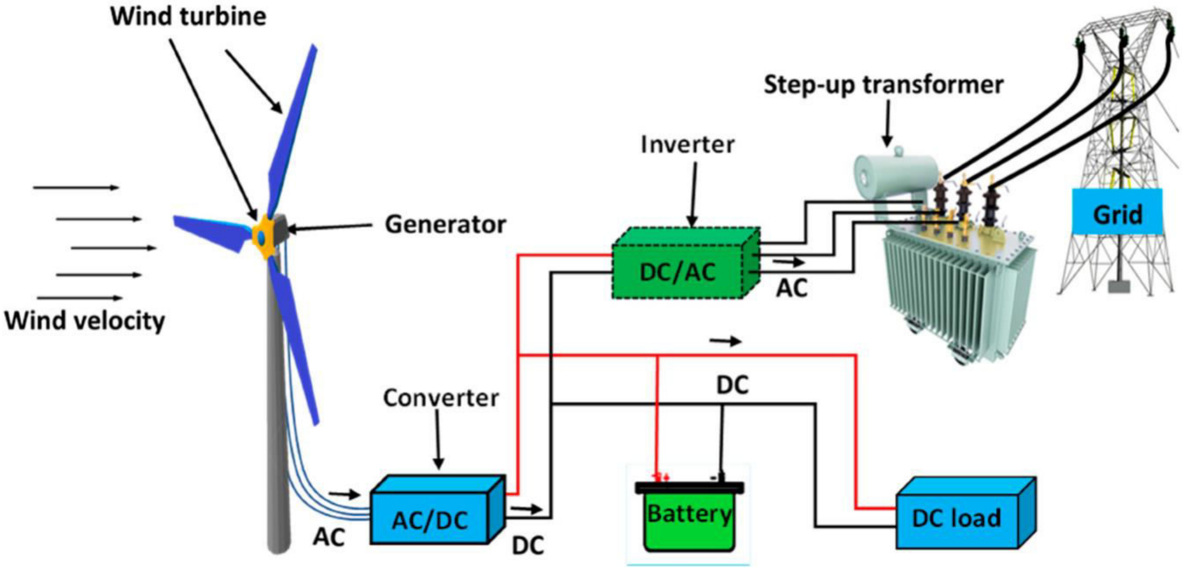


Figure 1. Grid-connected WEHS.

The MPPT controller is an essential component of modern wind energy systems, as it is necessary for optimizing energy conversion and maximizing power generation. Both Photovoltaic Systems (PVS) and WEHS face significant challenges in the implementation of MPPT techniques. These challenges include ensuring the efficiency and accuracy of MPPT, managing environmental factors, maintaining system stability, controlling costs, and overcoming the complexity of implementation.Despite these challenges, MPPT remains a crucial component of modern energy generation systems. By effectively addressing these challenges, MPPT techniques can improve the overall efficiency and performance of renewable energy systems, making them more viable for widespread adoption and use. Therefore, researchers and engineers continue to work towards developing innovative solutions to overcome these challenges and enhance the implementation of MPPT techniques in both PVS and WEHS systems.Hence, it is crucial to explore new MPPT techniques and evaluate their performance based on different factors. Recent studies have shown that the hybridization of MPPT techniques with advanced AI methods, such as deep learning, can significantly improve the efficiency and accuracy of MPPT systems. Thus, reviewing and comparing recent MPPT techniques that hybridize with AI methods in both wind and photovoltaic power generation can aid in the development of more efficient and reliable MPPT systems for renewable energy generation.

2. Literature survey

Active power can be routed in both directions (wind/grid) using voltage source back-to-back power converter technology. Therefore, it is possible to completely control the power (extracted/supplied) through a back-to-back power converter from voltage source to full power [8,9]. With more and more advanced control techniques, static power converters play a very important role, not only to reduce mechanical stress and increase energy efficiency, but also to make the whole generation system a conversion of fully controllable energy [10]. The use of power converters becomes an attractive solution for grid-connected generated energy applications, even if there are losses due to switching [11,12].Mohammed H. Q et al. [13] present in their work the results obtained for the control of the two statics (converter on the machine side/converter on the network side) via eight proportional-integral regulators. The wind system is based on the direct drive permanent magnet synchronous generator in this study. The main objective during this work is the maximization of the power extracted via the MPPT control, and the improvement of the low voltage transmission capacity. The results obtained attest that the control algorithm can offer satisfactory results in terms of monitoring. However, the moderate quality and the ripples in the energy produced present the major disadvantages obtained by using the conventional regulation.

Several control strategies can be applied to the PMSG-based wind energy conversion system. We find, among others, the field-oriented control (FOC), the direct torque-power control (DTC-DPC) and, of course, more robust and reliable controls, such as the nonlinear Adaptive Backstepping control, which is the subject of this article.

Works [14,15,16] exploit fuzzy proportional integral (PI) controllers to control the energy flow through static power converters. In the works of Yang. B et al. [17,18], the authors used the sliding mode algorithm to improve the work promised by the standard regulators. Other authors exploit artificial intelligence technology in the form of fuzzy logic to estimate the energy yield, and to optimize the amount of wind energy extracted, such as the work of Jafarian. M et al. [19]. Siahkali et al. [20], on his side, developed a method based on fuzzy logic to properly plan wind energy production, while Calderaro. V et al. [21] exploited fuzzy logic technology to extract the maximum power coming from the wind, as well as the control of the pitch angle and the intermediate bus voltage, this for different types of wind generators.The important remark drawn between these cited works or other works is that the regime of the wind system is previously well-known, and its parameters are considered as known and controlled. However, the wind system and its uncertain nature make the control applied to extract electrical energy less efficient. It is with this in mind that this present work has just applied a control algorithm applied to nonlinear systems, known as Adaptive Backstepping Control. The application of this control algorithm is important, to overcome the anomalies of the parametric variations of wind system, and to have a control which adapts with the variations of the parameters of the wind system based on the PMSG, and then offers a powerful high-quality electricity to the distribution grid.

3. Proposed control system

The MPPT is a pivotal technique in optimizing the performance of wind energy systems. The primary objective of MPPT is to adjust the operating point of the wind turbine to ensure it extracts the maximum possible power from the wind at any given time. Given the variable nature of wind speed, the operational parameters of the turbine must be continuously adjusted to match the wind conditions, making MPPT essential for efficient energy conversion.MPPT controllers operate by continuously monitoring the wind turbine's performance parameters, such as wind speed, rotor speed, and generated power. The controller uses these inputs to calculate the optimal operating point, typically involving the adjustment of the generator's electrical characteristics and the turbine's mechanical components. The core principle is to maintain the turbine's operation at its maximum power coefficient, *Cp*, which is a function of the tip-speed ratio (TSR) and blade pitch angle. Figure 2 shows the architecture of proposed control system.

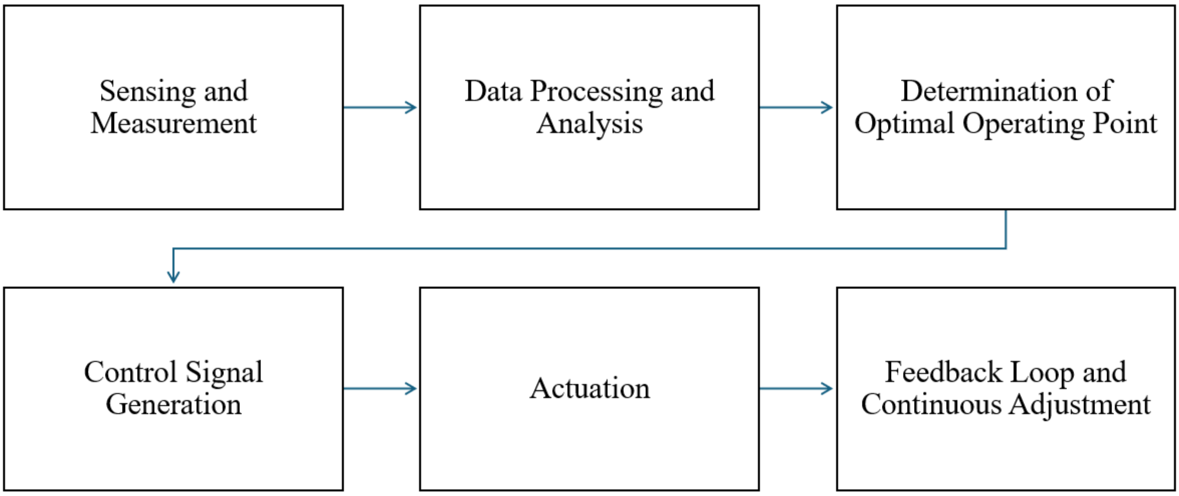


Figure 2. Proposed control system.

Step-by-Step MPPT Controller Operation

Step 1: Sensing and Measurement: The MPPT controller begins by gathering real-time data from various sensors. These include anemometers for wind speed, tachometers for rotor speed, and power meters for electrical output. Accurate and high-resolution sensors are crucial for reliable data acquisition.

Step 2: Data Processing and Analysis: The gathered data is processed by the controller's embedded processor. The processor calculates the current power output and compares it with the expected power output based on the wind speed and rotor speed. This step involves complex algorithms that include perturb and observe (P&O), incremental conductance, or more sophisticated adaptive algorithms.

Step 3: Determination of Optimal Operating Point: Using the processed data, the controller determines the optimal TSR and adjusts the generator's electrical load or the turbine's mechanical settings accordingly. For instance, if the wind speed increases, the controllerneeds to adjust the rotor speed to maintain the optimal TSR.

Step 4: Control Signal Generation: The controller generates control signals to adjust the turbine's operating parameters. These signals can modulate the generator's power electronics to change the load or directly adjust the blade pitch through a pitch actuator mechanism.

Step 5: Actuation: The control signals are sent to actuators or power electronic interfaces. If blade pitch adjustment is required, the pitch actuator modifies the angle of the blades to either capture more wind energy or reduce load during high wind speeds. For electrical adjustments, the controller modifies the settings of the power converter, changing the load on the generator to match the optimal power point.

Step 6: Feedback Loop and Continuous Adjustment: The MPPT controller operates in a continuous feedback loop. After adjusting the operating point, it continuously monitors the system's response to ensure the new settings achieve the desired power output. If deviations are detected, the controller iteratively fine-tunes the settings to re-align with the maximum power point.

The implementation of MPPT controllers in wind energy systems offers several advantages. By continuously optimizing the turbine's operating point, MPPT controllers maximize energy extraction, leading to higher efficiency and more consistent power output. This efficiency gain translates to economic benefits, such as reduced energy costs and lower wear and tear on turbine components, which extends their operational lifespan.However, the deployment of MPPT controllers also presents challenges. The dynamic and unpredictable nature of wind requires robust and adaptive algorithms capable of real-time processing and adjustment. Additionally, the integration of MPPT controllers with existing turbine control systems must be seamless to avoid conflicts and ensure stable operation.

3.1 Introduction to TSR

The tip-speed ratio (TSR) is a fundamental parameter in wind turbine design and operation, defined as the ratio of the speed of the tip of a wind turbine blade to the wind speed. Mathematically, it is expressed as:

$$TSR = \frac{\omega_R}{v_w} \qquad (1)$$

Here, ω is the angular velocity of the rotor (rad/s),R is the radius of the rotor (m),v_w is the wind speed (m/s).Understanding and optimizing TSR is crucial for maximizing the efficiency of wind turbines, as it directly influences the aerodynamic performance and energy conversion efficiency.The TSR is significant because it affects the aerodynamic forces acting on the turbine blades and consequently the power coefficient (*Cp*) of the turbine, which is a measure of the turbine’s ability to convert wind energy into mechanical energy. Each type of wind turbine blade design has an optimal TSR at which it achieves maximum $CpCp$.

- **Optimal TSR**: At the optimal TSR, the blades move at a speed that allows them to capture the maximum possible energy from the wind. This optimal value depends on the blade design, specifically the aerodynamic shape and angle of attack.
- **High TSR**: If the TSR is too high, the blades move too fast relative to the wind speed, causing excessive drag and reducing the efficiency of energy conversion.
- **Low TSR**: If the TSR is too low, the blades move too slowly, causing inefficient energy capture as the wind passes through the rotor without being effectively harnessed.

Calculating and maintaining the optimal TSR involves monitoring both the wind speed and the rotational speed of the turbine. This requires accurate sensors and real-time data processing capabilities. The power coefficient, *Cp*, is a dimensionless number that represents the efficiency with which a turbine converts the kinetic energy in wind into mechanical energy. It is defined as:

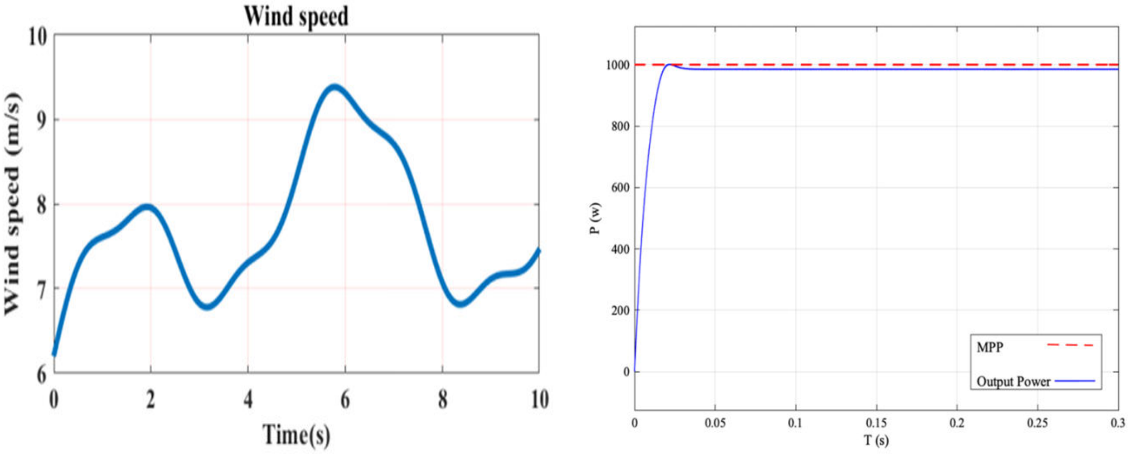
$$Cp = \frac{P_t}{0.5\rho A v_w} \qquad (2)$$

Where, P_t is the power extracted by the turbine,ρ is the air density (kg/m³),A is the swept area of the rotor ($\pi R 2 \pi R 2$),v_w is the wind speed (m/s).The relationship between *Cp* and TSR is typically represented by a *Cp*-TSR curve, which is specific to each turbine design. The peak of this curve indicates the optimal TSR where *Cp* is maximized.

Wind turbine blades are designed to operate efficiently at a specific TSR. Blade length, shape, and angle are optimized to achieve the best performance at the desired TSR.Maintaining the optimal TSR is a primary objective of wind turbine control systems. This involves adjusting the generator load and blade pitch angle dynamically to ensure that the rotor speed aligns with varying wind speeds.Deviation from the optimal TSR results in suboptimal performance. Control systems equipped with MPPT algorithms continuously adjust the turbine operation to maintain the TSR close to its optimal value.Rapid changes in wind speed require quick adjustments in rotor speed, which demands responsive control systems.The mechanical inertia of the rotor and the structural limits of the turbine impose constraints on how quickly adjustments can be made.Accurate measurement of wind speed and rotor speed is critical for calculating TSR, necessitating high-quality sensors and data acquisition systems.

4. Results and Discussion

In Figure 3a, the wind speed response graph illustrates how the wind turbine system reacts to changes in wind speed over time. The x-axis represents time, showing a temporal sequence of wind speed variations, while the y-axis represents wind speed values in units like meters per second (m/s). The graph displays fluctuations in wind speed, showcasing both gradual changes and potentially abrupt gusts or drops.The response of the wind turbine to varying wind speeds is crucial for understanding its performance. Different wind speeds affect the turbine's rotational speed and power generation capacity. When wind speeds increase, the turbine accelerates to capture more energy from the wind, increasing its power output. Conversely, during periods of low wind speed, the turbine's rotational speed decreases, affecting its power generation capability.This graph could show how a wind turbine equipped with effective static controllers responds to changes in wind conditions. Ideally, the turbine should adjust its operating parameters, such as blade pitch or generator load, to optimize power generation across different wind speeds. This adaptive response is crucial for maximizing energy extraction and ensuring stable operation under varying environmental conditions.



(a) (b)

Figure 3. (a) Wind speed response. (b) output power response.

Figure 3b depicts the output power response of the wind turbine system corresponding to the changes in wind speed shown in Figure 3a. The x-axis represents the same time scale as in Figure 3a, while the y-axis displays the power output of the wind turbine, typically measured in kilowatts (kW) or megawatts (MW).The output power response graph demonstrates how the wind turbine's power generation varies in response to fluctuations in wind speed. When wind speeds increase, the turbine's output power should ideally rise to harness the additional energy available from the wind. This relationship between wind speed and power output is nonlinear and is influenced by factors such as the turbine's efficiency, design characteristics, and control strategies.Static controllers play a critical role in optimizing the output power response of wind turbines. By implementing advanced control algorithms like MPPT, static controllers adjust the turbine's operating parameters to ensure it operates at or near its maximum power point across a range of wind speeds. This optimization leads to improved energy conversion efficiency and overall system performance.

Table 1 provides a comparative analysis of different control systems based on two key performance metrics: THD and Power Factor. Each control system listed in the table represents a specific approach or methodology used in the control of power electronic systems, applied in the context of renewable energy systems such as wind turbines or other power generation systems.THD is a measure of the distortion in the waveform of an electrical signal, typically caused by nonlinear loads or power electronic converters. A higher THD indicates greater distortion in the waveform, which can lead to inefficiencies, increased losses, and interference with other electrical equipment. In Table 1, the THD values associated with each control system represent the effectiveness of the respective control strategies in reducing waveform distortion.

- The DTC-DPC (Direct Torque Control with Direct Power Control) system, referenced from source [14], shows a THD value of 29.47%, which is relatively high and indicates significant waveform distortion.
- Other control systems like Fuzzy PI control [15] and Fuzzy logic control [18] demonstrate slightly lower THD values (28.63% and 27.18%, respectively), suggesting some

improvement in waveform quality compared to DTC-DPC.

- The Adaptive Backstepping control system [21] exhibits a further reduction in THD (26.19%), indicating improved waveform quality and reduced distortion.
- The "Proposed Control System" in the table achieves the lowest THD value at 25.482%, signifying superior performance in mitigating waveform distortion compared to the other listed control systems.

Power Factor is a measure of the efficiency with which electrical power is converted and utilized in a system. A higher power factor (close to 1) indicates efficient power usage with minimal reactive power, while a lower power factor (closer to 0) suggests inefficient power utilization with a significant reactive component.

- The power factor values associated with each control system in Table 1 reflect their effectiveness in improving power factor and reducing reactive power consumption.
- Control systems like DTC-DPC and Fuzzy PI exhibit relatively low power factors (0.33 and 0.387, respectively), indicating inefficient power utilization with a significant reactive power component.
- The Adaptive Backstepping control system demonstrates a higher power factor of 0.536, suggesting improved efficiency compared to the earlier systems.
- The "Proposed Control System" achieves the highest power factor among the listed systems at 0.591, indicating superior efficiency in power utilization and reduced reactive power consumption.

Table 1. Comparison of various control systems.

Control System	THD	Power Factor
DTC-DPC [14]	29.47	0.33
Fuzzy PI [15]	28.63	0.387
Fuzzy logic [18]	27.18	0.415
Adaptive Backstepping [21]	26.19	0.536
Proposed Control System	25.482%	0.591

5. Conclusion

The integration of MPPT controllers in wind energy systems marks a significant advancement in the quest for efficient and sustainable energy solutions. This study has demonstrated the critical role that MPPTcontrollers play in optimizing the performance and reliability of wind turbines. By effectively managing the dynamic behavior of wind turbines, MPPTcontrollers ensure maximum energy extraction from variable wind speeds, thereby enhancing overall energy conversion efficiency.Through comprehensive simulation models and the application of advanced control algorithms, the research has shown that MPPT controllers can significantly improve system stability and reduce mechanical stress on turbine components. This leads to fewer mechanical failures, lower maintenance costs, and extended turbine lifespans, making wind energy systems more reliable and economically viable.Furthermore, the adoption of MPPTcontrollers contributes to the environmental benefits of wind energy by reducing the frequency of mechanical interventions and enhancing the continuous supply of clean energy. This positions wind energy as a more attractive option for meeting increasing global energy demands while mitigating the environmental impact associated with conventional energy sources.

References

[1] M. R. Islam, A. M. Mahfuz-Ur-Rahman, K. M. Muttaqi, and D. Sutanto, ‘‘State-of-the-art of the medium-voltage power converter technologies for grid integration of solar photovoltaic power plants,’’ IEEE Trans. Energy

Convers., vol. 34, no. 1, pp. 372–384, Mar. 2019.
[2] Yildirir, V.; Rusu, E.; Onea, F. Wind Energy Assessments in the Northern Romanian Coastal Environment Based on 20 Years of Data Coming from Different Sources. Sustainability 2022, 14, 4249.
[3] Echiheb, F.; Ihedrane, Y.; Bossoufi, B.; Bouderbala, M.; Motahhir, S.; Masud, M.; Aljahdali, S.; ElGhamrasni, M. Robust sliding-Backstepping mode control of a wind system based on the DFIG generator. Sci. Rep. 2022, 12, 11782.
[4] Rad, N.N.; Bekker, A.; Arashi, M. Enhancing wind direction prediction of South Africa wind energy hotspots with Bayesian mixture modeling. Sci. Rep. 2022, 12, 11442.
[5] Annual Global Wind Reports 2022. Available online: https://gwec.net/category/annual-global-wind-reports/ (accessed on 12 October 2022).
[6] Hoxha, B.; Shesho, I.K.; Filkoski, R.V. Analysis of Wind Turbine Distances Using a Novel Techno-Spatial Approach in Complex Wind Farm Terrains. Sustainability 2022, 14, 13688.
[7] El Mourabit, Y.; Derouich, A.; ElGhzizal, A.; El Ouanjli, N.; Zamzoum, O. Nonlinear Backstepping control of variable speed wind turbine based on permanent magnet synchronous generator. In Proceedings of the International Conference on Wireless Technologies, Embedded and Intelligent Systems (WITS), Fez, Morocco, 3–4 April 2019; IEEE: New York, NY, USA, 2019; pp. 1–7.
[8] Bodini, N.; Lundquist, J.K.; Moriarty, P. Wind plants can impact long-term local atmospheric conditions. Sci. Rep. 2021, 11, 22939.
[9] Salime, H.; Bossoufi, B.; Zine Laabidine, N.; Saady, I.; Elalami, H.; Majout, B.; ELMourabit, Y. FOC-DPC Hybrid Structure of a Wind Energy Conversion System Based on PMSG. In Proceedings of the International Conference on Digital Technologies and Applications, Fez, Morocco, 28–30 January 2022; Springer: Cham, Switzerland, 2022; pp. 693–702.
[10] Gunturu, U.B.; Hallgren, W. Asynchrony of wind and hydropower resources in Australia. Sci. Rep. 2017, 7, 8818.
[11] Bossoufi, B.; Karim, M.; Lagrioui, A.; Taoussi, M.; Derouich, A. Observer backstepping control of DFIG-Generators for wind turbines variable-speed: FPGA-based implementation. Renew. Energy 2015, 81, 903–917.
[12] Rodrigues, G.; Valério, D.; Melicio, R. Controller Development and Experimental Validation for a Vertical Axis Wind Turbine. Sustainability 2022, 14, 13498.
[13] Weber, J.; Reyers, M.; Beck, C.; Timme, M.; Pinto, J.G.; Witthaut, D.; Schäfer, B. Wind Power Persistence Characterized by Superstatistics. Sci. Rep. 2019, 9, 19971.
[14] Qais, M.H.; Hasanien, H.M.; Alghuwainem, S. A Grey Wolf Optimizer for Optimum Parameters of Multiple PI Controllers of a Grid-Connected PMSG Driven by Variable Speed Wind Turbine. IEEE Access 2018, 6, 44120–44128.
[15] Wang, Z.; Liu, W. Wind energy potential assessment based on wind speed, its direction and power data. Sci. Rep. 2021, 11, 16879.
[16] El Mourabit, Y.; Derouich, A.; Allouhi, A.; El Ghzizal, A.; El Ouanjli, N.; Zamzoumyes, O. Sustainable production of wind energy in the main Morocco's sites using permanent magnet synchronous generators. Int. Trans. Electr. Energy Syst. 2020, 30, e12390.
[17] Asgharnia, A.; Shahnazi, R.; Jamali, A. Performance and robustness of optimal fractional fuzzy PID controllers for pitch control of a wind turbine using chaotic optimization algorithms. ISA Trans. 2018, 79, 27–44.

[18]Yang, B.; Yu, T.; Shu, H.; Zhang, Y.; Chen, J.; Sang, Y.; Jiang, L. Passivity-based sliding-mode control design for optimal power extrac-tion of a PMSG based variable speed wind turbine. Renew. Energy 2018, 119, 577–589.

[19]Yang, B.; Zhong, L.; Yu, T.; Shu, H.; Cao, P.; An, N.; Sang, Y.; Jiang, L. PCSMC design of permanent magnetic synchronous generator for maximum power point tracking. IET Gener. Transm. Distrib. 2019, 13, 3115–3126.

[20]Jafarian, M.; Ranjbar, A.M. Fuzzy modeling techniques and artificial neural networks to estimate annual energy output of a wind turbine. Renew. Energy 2010, 35, 2008–2014.

[21]Siahkali, H.; Vakilian, M. Fuzzy generation scheduling for a generation company (GenCo) with large scale wind farms. Energy Convers. Manag. 2010, 51, 1947–1957.