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Studying, modeling, and simulation of wind turbine using MATLAB/Simulink

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ABSTRACT

The increasing demand for renewable energy worldwide has positioned wind power as a leading solution of clean energy solutions. This paper dives into the realm of wind energy, specifically focusing on wind turbine dynamics and efficiency. As wind power surpasses other alternative energy resources in growth rate, there is a compelling need to enhance the productivity and efficiency of wind turbines. The study encompasses a detailed exploration of the components comprising wind energy conversion systems, namely the rotor, generator, and gearbox.

The primary contribution of this work lies in the meticulous mathematical modeling and simulation of wind turbine components using MATLAB/Simulink. The study presents a comprehensive analysis of the mechanical energy produced by wind turbines, incorporating key parameters such as power coefficient, tip speed ratio, and blade pitch angle. The simulations offer insights into the complex relationships governing wind turbine performance under varying conditions. The experimental section provides a detailed exploration of wind turbine modeling.

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1. INTRODUCTION

The global energy landscape has changed radically over the last few decades due to the growing recognition of traditional fossil fuel-based energy sources' environmental, economic, and societal challenges. This evolution has been characterized by an increasing interest in renewable energy solutions, with wind power emerging as a critical player in transitioning to a cleaner, more sustainable energy future [1].

Renewable energy sources, including wind, solar, hydro, and geothermal power, have gained prominence as viable alternatives to fossil fuels. Wind energy, in particular, has demonstrated remarkable growth, outpacing other renewable resources in terms of installed capacity and energy production [2].

Wind power is considered a clean energy source and has recently surpassed all other alternative energy resources in the world regarding growth rate [3]. Specialists have been actively seeking alternative energy sources to decrease reliance on fossil fuels. Renewable energy encompasses a range of diverse sources, such as wind, solar, hydrogen, biomass, and hydro [4]. Due to the exponential expansion of the industry, considerable effort has been devoted to improving the productivity and efficiency of wind turbines [5], which serve as the main components of wind energy conversion systems. A wind turbine is a device used to harness the power of the wind and convert it into electricity [6, 7]. The three primary components of an aerodynamic system for energy conversion are the rotor, generator, and gearbox. The blades, as part of the rotor, capture wind energy and convert it into mechanical energy. The generator then absorbs this mechanical power from the rotation and converts it into electricity. The gearbox transmits the mechanical energy from the low-speed shaft to the high-speed shaft, enabling the generator to produce electrical power [8].

According to the orientation of the rotating axis, recent wind turbines fall into two separate classes: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs) [9].

HAWTs consist of rotor blades connected to a horizontal shaft and a generator. These wind turbines must be oriented to face the direction of the wind [10]. In contrast, VAWTs comprise rotor blades connected to a vertical shaft to generate electrical power [11]. HAWTs are commonly used due to their durability and efficiency, and they are commercially available in various sizes, ranging from a few kilowatts to several megawatts [12]. HAWTs can capture a significant portion of wind energy and can adjust the pitch angle of their blades to mitigate the effects of strong gusts [13].

Energy management and speed regulation techniques are additional criteria for categorizing wind turbines. The process of converting wind energy can be defined by variable and fixed velocities [14]. Understanding wind characteristics is crucial for efficiently harnessing wind energy. It is widely acknowledged that wind direction and speed vary significantly across different locations, seasons, and over time [15]. Thus, even slight variations in wind speed or direction can lead to significant and unpredictable differences in wind turbine power output, which

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can impact the quality of voltage and current in the network to which it supplies energy. At a specific wind speed, the system achieves its optimum conversion efficiency; at other wind speeds, efficiency decreases. Fixed-speed wind turbines (FSWT) operate at nearly constant velocity; however, variable-speed wind turbines (VSWT) can utilize a wide range of wind velocities to maximize energy conversion efficiency [16].

Testing and analyzing wind energy power systems, however, pose a challenge in laboratory conditions due to the complex equipment and environmental conditions. Therefore, they are typically assessed through simulations and numerical methods. [17, 18].

Various wind turbine systems have been developed for diverse applications. In [19], a wind turbine model with variable speed was developed and simulated, driven by a doubly fed induction generator (DFIG). A comprehensive review of wind turbine generator models for various stability analyses was presented in [20]. Additionally, the study described in reference [21] utilized MATLAB/Simulink to model and simulate various wind energy conversion systems with distinct generators operating under identical parameters to determine their efficiency. Moreover, researchers in [22] introduced a high-precision wind power curve modelling technique based on wind speed vectors, including wind velocity and wind directions at various levels of wind measuring towers. The study referenced in [18] examined the wind energy absorption and aerodynamics of a wind turbine. It involved simulating the turbine's characteristics using various control methods such as direct control, induction, and permanent magnet synchronous motors controlled by space vector, frequency control, and direct torque control (DTC) methods. Additionally, the aerodynamic characteristics of the turbine system were analyzed through numerical simulations using space vector modulation and induction control techniques in MATLAB. Shamshirband et al. [23] employed adaptive neuro-fuzzy inference system (ANFIS) artificial neural networks for the analysis and prediction of deficit power in wind turbines. Their study investigated the impact of aerodynamic interactions among multiple turbines on the grid's overall power generation capacity using MATLAB Simulink. Narayanan and Ramakrishnan [24] employed an advanced digital pitch control system in their wind turbine study. Their approach involved implementing the proposed digital pitch control system on a hardware-in-loop simulator and utilizing predictive modelling of flow circuits to enable real-time pitching adjustments within the system.

The contributions of this work include presenting a comprehensive mathematical model for each component of the wind turbine's aerodynamic system, facilitating understanding and simulation of wind turbine operation. MATLAB/Simulink simulation of the wind turbine's kinematic chain provides a practical tool for analyzing turbine behaviour under different conditions. The paper also offers a detailed analysis of the power coefficient, including its relationship with the tip speed ratio and blade pitch angle, aiding in determining optimal operating conditions for maximizing energy conversion efficiency.

The rest of the paper is organized as follows: In section two, the experimental aspect is delved into, with a focus on wind turbine modelling. This section discusses the mechanical energy produced by the wind turbine and outlines the mathematical expressions used to characterize its performance. Section three presents the simulation results and subsequent discussions. We showcase characteristics of the power coefficient against tip speed ratio for various blade pitch angles, explore the impact of wind speed and tip speed ratio on mechanical power, and analyze the temporal evolution of mechanical torque and power. The conclusions drawn from the simulation results are discussed in section four. Finally, section five offers a comprehensive conclusion, summarizing the key findings of this study and providing insights into potential future research directions in the field of wind energy.

2. EXPERIMENTAL ASSESSMENT

2.1. Wind Turbine Modeling

The mechanical energy produced by the wind turbine, which is characterized by a speed of rotation and a mechanical torque, is created from the kinetic energy of the wind. The system investigated in this study consists of a wind turbine in Figure 1 with a rated capacity of 1.8 MW. It includes blades with a radius of 23.2 meters that propel a generator via a multiplier with a gain of 23.75. Other characteristics are illustrated in Table 1.

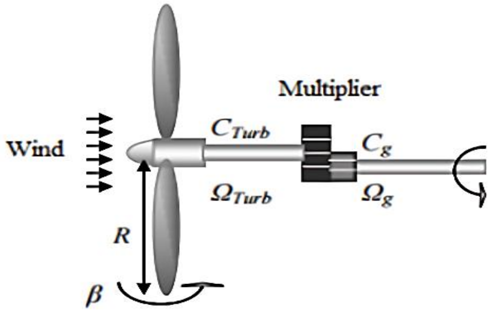


Fig. 1. Wind turbine model [25].

As illustrated in the aerodynamic model, the variation in the force of the airflow before and after encountering the rotor is instrumental in determining the amount of power the rotor can extract from the wind [26]. According to Betz theory, the mechanical power produced by a wind turbine can be described by the Equations (1) and (2) [27].

$$P_{mech} = \frac{1}{2}.C_p(\lambda,\beta).\rho.A.V_w^3 \tag{1}$$

$$A = \pi.R^2 \tag{2}$$

Where $C_p(\lambda,\beta)$ is the wind turbine's power coefficient, ρ is the air density (1.225 kg/m^3), A is the surface area of the blade (m^2), R is the rotor radius (m), and V_w is the wind speed (m/s).

The power coefficient C_p is a function of both the tip speed ratio λ and the blade pitch angle β. The power coefficient has been modelled using a variety of approaches. The analytical expression used to model this coefficient in this work is as Equation (3) [28, 29]:

$$C_p = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \tag{3}$$

With the Equation (3) and using coefficients are obtained characteristic [30].

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \tag{4}$$

The term "tip speed ratio" refers to the ratio of the rotating speed of the wind turbine to the wind velocity.

$$\lambda = \frac{\Omega_t R}{V_w} \tag{5}$$

Where: Ω_t is the rotational speed of a wind turbine (rad/s).

The theoretical upper limit of C_p is equal to 16/27, this signifies that the highest achievable wind power obtained from the kinetic energy of the wind by a wind turbine is less than 59.3%. This is called the Betz limit [27].

To simulate the behaviour of the wind turbine, the mechanical torque is calculated practically from the mechanical power (P_{mech}) by using the wind turbine's rotational speed (Ω_t) using Equation (6) [30].

$$T_{mech} = \frac{P_{mech}}{\Omega_t} \tag{6}$$

For the mechanical part, a mathematical representation of the multiplier is provided by the Equations (7) and (8) [31]:

$$\Omega_{mec} = G\Omega_t \tag{7}$$

$$T_{mech} = GT_g \tag{8}$$

Where: Ω_{mec} represents the angular speed of the generator (rad/s) or (r/min), and G is the speed multiplier gain.

$$J = \frac{J_{turbine}}{G^2} + J_g \tag{9}$$

The basic dynamic equation for determining how the mechanical speed evolves from the overall mechanical torque T_{mec} applied to the rotor is defined as [32]:

$$J\frac{d\Omega_{mec}}{dt} = T_{mec} \tag{10}$$

Where; J denotes the total apparent inertia on the generator rotor.

The numerical values for various parameters of the wind turbine are presented in Table 1.

Table 1. Wind turbine model parameters [33].

Parameters	*Values*
Rotor diameter (D)	23.2 m
Multiplier coefficient (G)	23.75
Number of blades	3
Air density (**ρ**)	1.22Kg/m^3
Moment inertia of the turbine (J$_T$)	102.8 Kg.m^2
Coefficient of viscous friction (f)	0. 0024N.m.s^{-1}

The total mechanical torque depends on the load torque (T_g), the viscous friction torque (T_{vis}), and the electromagnetic torque (T_{em}) generated by the generator.

$$T_{mec} = T_g - T_{em} - T_{vis} \tag{11}$$

The viscous friction torque is modelled by:

$$T_{vis} = f.\Omega_{mec} \tag{12}$$

f: Is the viscous friction coefficient.

In MATLAB/Simulink, the complete kinematic chain of the wind turbine is simulated as shown in Figure 2. The model was developed based on the equations previously presented. The subsystems of aerodynamics and power coefficient are shown in Figure 3 (a) and (b) respectively.

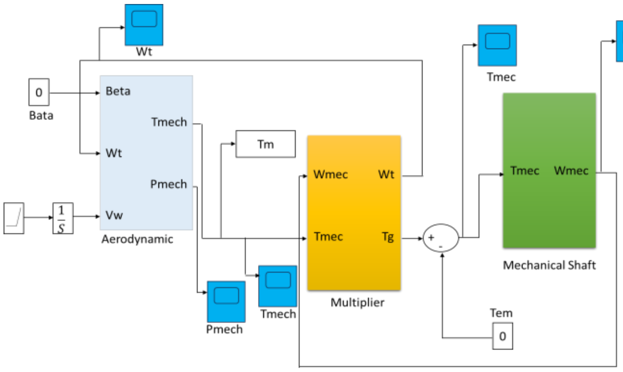
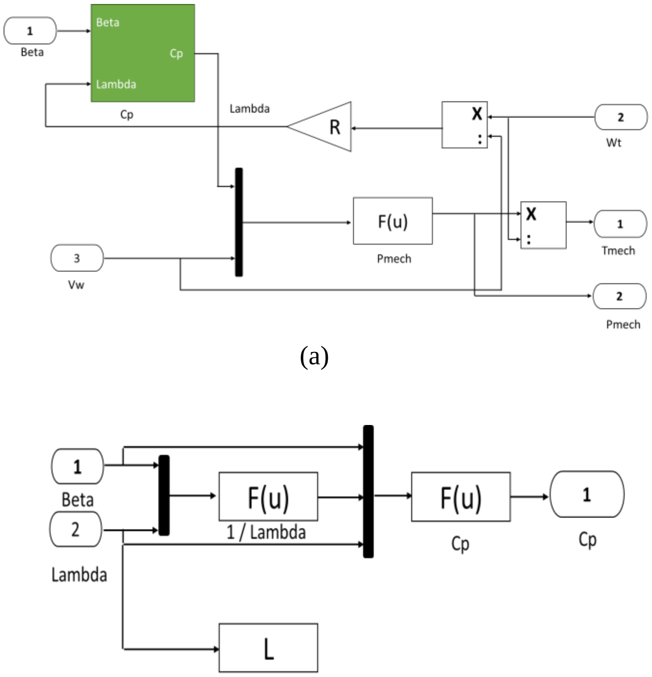


Fig. 2. Wind turbine simulation model.



(a)

(b)

Fig. 3. Aerodynamics and power coefficient models; (a) Aerodynamics simulation model, (b) Power coefficient simulation model.

3. SIMULATION RESULTS AND DISCUSSION

The following section presents the results obtained from the simulation of the wind turbine model and provides a detailed discussion of their implications. By examining these results in detail, we aim to gain a better understanding of the functionality and effectiveness of the wind turbine model. This in-depth examination and discussion aim to provide a solid understanding of the wind turbine system and its behaviour as simulated in this study.

Figure 5 displays the results of simulations of the power coefficient against the tip speed ratio for various blade pitch angles. There is only one ideal maximum speed ratio, $\lambda_{op}=8$ ($\beta = 0$), where the power coefficient can reach its peak value. Therefore, the mechanical power provided by a variable-speed wind turbine reaches its maximum value, as depicted in Figure 8.

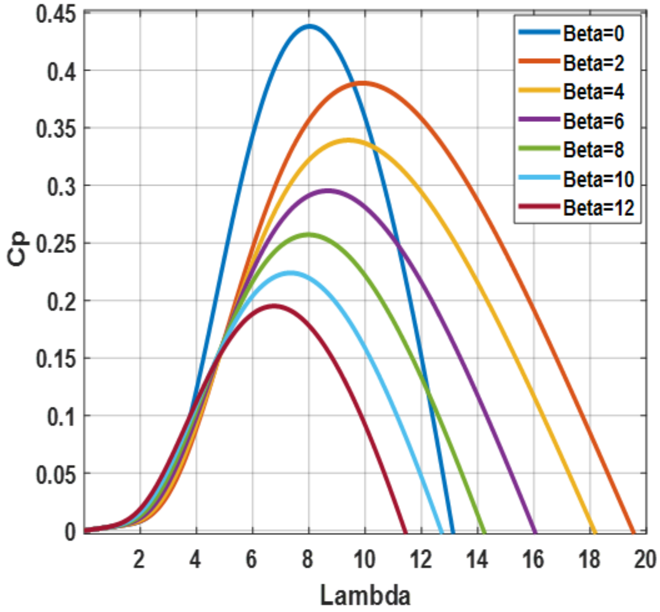


Fig. 5. Characteristics of C_P with Lambda for different blade pitch angles.

Figure 6 and Figure 7 show the simulation results curves at various wind speeds for the mechanical power versus rotor speed. It can be observed that wind speed and tip speed ratio directly impact the mechanical energy generated by a wind turbine. Up to a certain point, the amount of power the turbine can produce increases directly with the wind speed; after that, it decreases, and due to the monitoring system installed in the wind turbine for safety reasons, it will be taken out of service. It is necessary to maintain constant power at the design limit. In addition, the Coriolis forces [34] may also be responsible for the decrease in power. If the frictional and pressure gradient forces are not balanced, the Coriolis force causes the wind to rotate. The Coriolis force turns the wind if the pressure gradient and frictional forces are unbalanced. When the pressure gradient and frictional forces are not balanced, the Coriolis force turns the wind. As a result of the imbalance, the wind direction shifts with height.

The wind turbine angle of attack varies due to changes in the pitch angle. Figure 6 demonstrates that maximum power is achieved when the wind speed is 12 m/s, and the pitch angle is zero. However, adjusting the pitch angle to four for the same wind speed results in reduced power output, indicating the influence of the pitch angle on power output. The pitch angle must be adjusted according to the ideal wind speed to optimize energy production.

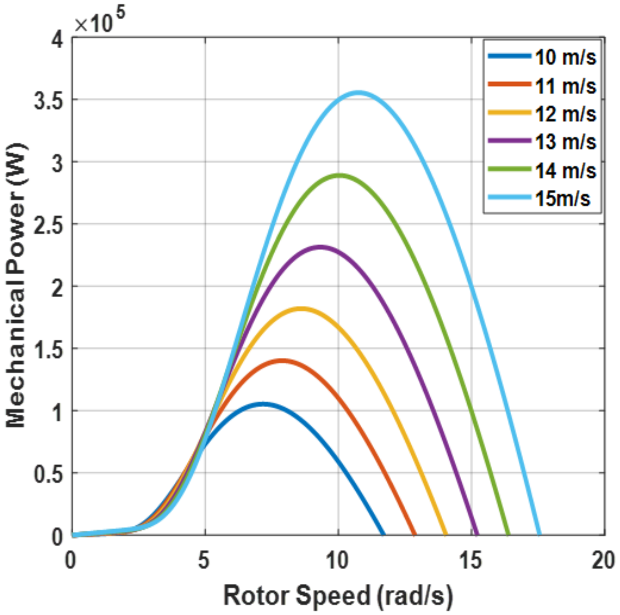


Fig. 6. Curves of mechanical power versus rotor speed at different wind speeds when the pitch angle is zero.

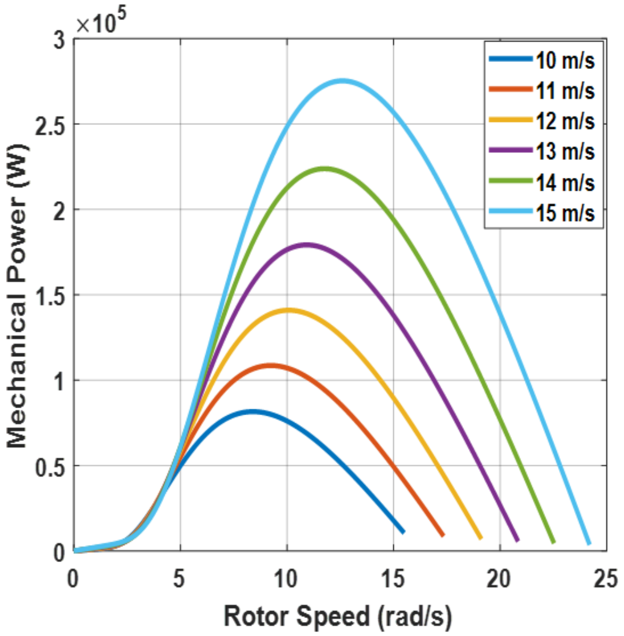


Fig. 7. Curves of mechanical power vs. rotor velocity under various wind speeds when the pitch angle equals 4 rad/s.

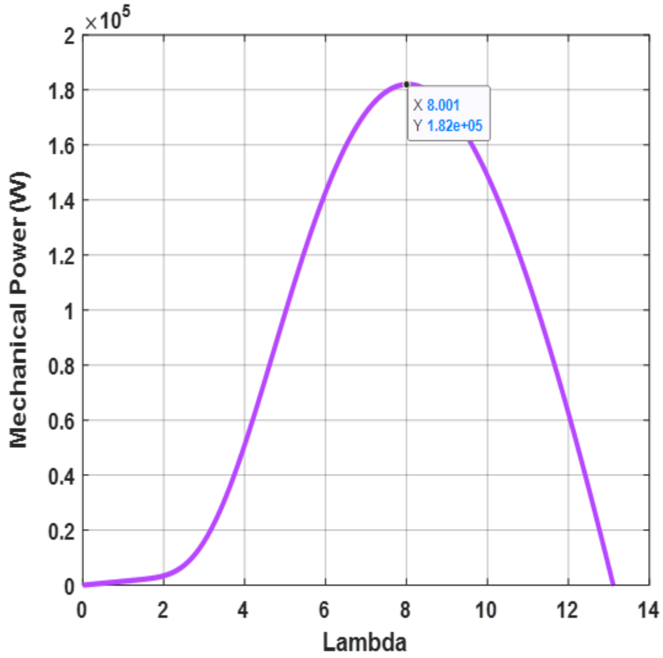


Fig. 8. Mechanical power vs. tip speed ratio.

Figure 9 and Figure 10 depict the temporal evolution of the mechanical torque and mechanical power of the turbine, respectively. For a constant wind speed ($V_w = 12m/s$), these deviations exhibit an increasing trend over time, followed by a decrease and eventual stabilization. This clearly illustrates the impact of constant wind speed on the functionality of the wind turbine.

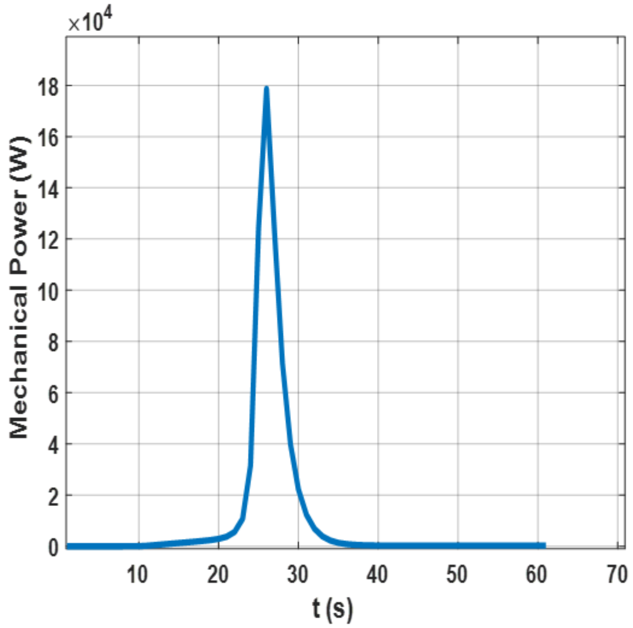


Fig. 9. The mechanical power of the turbine.

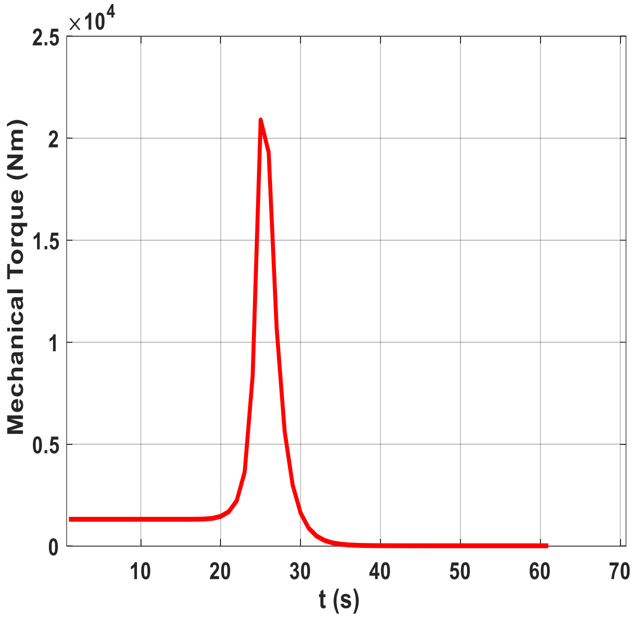


Fig. 10. The mechanical torque of the turbine.

The results presented provide valuable insights into wind turbine performance, elucidating the complex interplay between key parameters and external factors. The identification of an optimal tip speed ratio (λ_{op}=8) and corresponding blade pitch angle (β=0) signifies conditions for maximizing the power coefficient and mechanical power output, essential for efficient turbine design. Additionally, the simulation results underscore the direct influence of wind speed and tip speed ratio on mechanical power, while also recognizing the monitoring system's role in preventing operation beyond design limits. The mention of Coriolis forces adds complexity, underscoring the importance of comprehensively understanding external forces. Furthermore, Figure 8 demonstrates how adjustments in pitch angle directly impact power output, highlighting the significance of optimization. Figures 9 and 10 offer a temporal perspective, illustrating dynamic adaptations of mechanical torque and power under fixed wind speed conditions. These findings significantly contribute to wind turbine dynamics, providing practical insights and paving the way for further research into the complex interactions of parameters and external influences.

The findings of this study demonstrate a high level of accuracy and quality when compared to existing research in the field, such as in [33].

4. CONCLUSION

In this study, wind turbine operation was comprehensively explored using mathematical modeling and simulation techniques. The intricate interplay of the aerodynamic system components rotor, generator, and gearbox was scrutinized to understand their collective contribution to energy conversion. Valuable insights into the dynamics of wind turbines were gained through the development and simulation of a mathematical model using MATLAB/Simulink.

Significant relationships between the power coefficient, tip speed ratio, and blade pitch angle were revealed by the simulations conducted in section three. Insights into the nuanced behaviour of wind turbines were provided by the analysis of mechanical power and torque under varying wind speeds. Particularly, the importance of adjusting the pitch angle for optimal energy production at specific wind speeds was underscored, highlighting a critical consideration for practical wind turbine installations.

The theoretical understanding of wind turbine dynamics is advanced by our work, which also holds practical implications for the design, installation, and operation of wind energy systems. The simulation results serve as a foundation for optimizing wind turbine performance across various conditions, thereby ensuring sustainable and efficient energy conversion.

As this study is concluded, potential avenues for future research in wind energy are highlighted. Further investigations could focus on refining mathematical models by incorporating additional parameters or evaluating the impact of environmental factors on wind turbine performance.

Additionally, experimental validations and field studies could complement simulation-based findings, comprehensively understanding wind turbine behaviour in real-world conditions. Moreover, advancements in control strategies for wind turbines to enhance their adaptability to dynamic environmental conditions need to be explored. Novel opportunities for real-time optimization and improved energy yield may be provided by integrating intelligent technologies and machine learning algorithms.

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References

[1] A. Boztaş, O. Demirbaş, & M. E. Şahin, “Investigation of vertical axis wind turbines and the design of their components,” *Turkish Journal of Electromechanics and Energy*, 6(2), pp. 64-72, 2021.

[2] A. Kumar, D. Pal, S. K. Kar, et al., “An overview of wind energy development and policy initiatives in India,” *Clean Techno. Environ Policy*, vol. 24, pp. 1337–1358, 2022.

[3] T. Bakka, H. R. Karimi, “Bond graph modeling and simulation of wind turbine systems,” *J Mech Sci Technol*, vol. 27, pp.1843–1852, 2013.

[4] D. Gemayel, M. Abdelwahab, T. Ghazal, & H. Aboshosha, “Modelling of vertical axis wind turbine using large Eddy simulations,” *Results in Engineering*, vol. 18, p.101226, 2023.

[5] F. Balduzzi, A. Bianchini, E. A. Carnevale, L. Ferrari, & S. Magnani, “Feasibility analysis of a Darrieus vertical-axis wind turbine installation in the rooftop of a building,” *Applied Energy*, vol. 97, pp. 921-929, 2012.

[6] T. Sebbagh, A. Zaatri, “Optimal sizing of a hybrid renewable energy system to feed a clinic in the region of Tamanrasset,” *Third International Conference on Energy, Materials, Applied Energetics and Pollution (ICEMAEP2016)*, 30-31 October 2016, Constantine, Algeria.

[7] K. Boucenna, T. Sebbagh, and N. E. Benchouia, "Modeling, optimization, and techno-economic assessment of a hybrid system composed of photovoltaic-wind-fuel cell and battery bank," *J. Eur. Syst. Autom.*, 56(1), pp. 29, 2023.

[8] A. Chaudhuri, R. Datta, M.P. Kumar, J.P. Davim, and S. Pramanik, "Energy conversion strategies for wind energy System: Electrical, mechanical and material aspects," *Materials*, vol. 15, pp. 1232, 2022.

[9] A. Christ and C. Abeykoon, "Modelling of a wind power turbine," in *Proc. (Host publication)*, pp. 205-210, 2015.

[10] P. Ghiasi et al., "CFD-Study of the H-Rotor Darrius wind turbine performance in Drag-Lift and Lift Regime: impact of type, thickness and chord length of blades," *Alexandria Eng. J.*, vol. 67, pp. 51-64, 2023.

[11] M. M. M. Saad, "Comparison of horizontal axis wind turbines and vertical axis wind turbines," *IOSR J. Eng.*, 4(8), pp. 27-30, 2014.

[12] S. Rehman et al., "Vertical axis wind turbine types, efficiencies, and structural stability - A review," *Wind Struct.*, 29(1), pp. 15-32, 2019.

[13] M. Vyas, M. Singh, and S. Santoso, *Handbook of Wind Power System*. Springer, 2011.

[14] G. Ofualagba and E. Ubeku, "Wind energy conversion system- wind turbine modeling," in *Proc. IEEE Power Energy Soc. Gen. Meet.: Convers. Deliv. Electr. Energy 21st Century*, 2008.

[15] R. T. Ahmad and M. A. Abdul-Hussain, "Modeling and simulation of wind turbine generator using Matlab-Simulink," *J. Al-Rafidain Univ. College Sci.*, vol. 40, pp. 282-300, 2017.

[16] L. A. Soriano, W. Yu, and J. De J. Rubio, "Modeling and control of wind turbine," *Math. Probl. Eng.*, vol. 2013, pp. 1-13, 2013.

[17] E. Vani and N. Rengarajan, "Improving the power quality of the wind power system using low-cost topology," *Int. J. Model. Simul.*, 37(2), pp. 108-115, 2017.

[18] P. Vijayalakshmi, S. Sivasankar, and G. Karthikeyan, "Simulation of wind turbine system using field oriented control and Levenberg-Marquardt Back Propagation (LMBP) neural network model," *Biomed. Signal Process. Control*, vol. 92, p. 105961, 2024.

[19] I. Idrissi et al., "Modeling and simulation of the variable speed wind turbine based on a doubly fed induction generator," *IntechOpen eBooks*, 2019.

[20] X. He, H. Geng, and G. Mu, "Modeling of wind turbine generators for power system stability studies: A review," *Renew. Sustain. Energy Rev.*, vol. 143, p. 110865, 2021.

[21] C. H. Chong, A. R. H. Rigit, and I. Ali, "Wind turbine modelling and simulation using MATLAB/Simulink," *IOP Conf. Ser.*, 1101(1), p. 012034, 2021.

[22] W. Zha et al., "A wind speed vector-wind power curve modeling method based on data denoising algorithm and the improved transformer," *Elect. Power Syst. Res.*, vol. 214, p. 108838, 2023.

[23] S. Shamshirband et al., "An appraisal of wind turbine wake models by adaptive neuro-fuzzy methodology," *Int. J. Electr. Power Energy Syst.*, vol. 63, pp. 618-624, 2014.

[24] V. L. Narayanan and R. Ramakrishnan, "Design and implementation of an intelligent digital pitch controller for digital hydraulic pitch system hardware-in-the-loop simulator of wind turbine," *Int. J. Green Energy*, 18(1), pp. 17-36, 2021.

[25] B. Benyachou et al., "Modelling with MATLAB/Simulink of a wind turbine connected to a generator asynchronous dual power (GADP)," *J. Mater. Environ. Sci.*, 8(S), pp. 4614-4621, 2017.

[26] P. Jansuya and Y. Kumsuwan, "Design of MATLAB/Simulink modeling of fixed-pitch angle wind turbine simulation," *Energy Procedia*, vol. 34, pp. 362-370, 2013.

[27] T. Sebbagh, R. Kelaiaia, A. Zaatri, T. Bechara, & L. Abdelouahed, "Investigation of the use of a central unique renewable energy system versus distributed units for crop irrigation," *Clean Technologies and Environmental Policy*, *20*(10), pp. 2365-2373, 2018.

[28] T. Sebbagh, "Contribution to the dynamic optimization of hybrid systems combining renewable energies and backup systems," Ph.D. dissertation, Mechanical Engineering Dept., Univ. of Skikda, Skikda, Algeria, 2019.

[29] M. E. Şahin, A. M. Sharaf, & H. İ. Okumuş, "A novel filter compensation scheme for single phase-self-excited induction generator micro wind generation system," *Sci. Res. Essays*, 7(34), pp. 3058-3072, 2012.

[30] H. Siegfried, *Grid integration of wind energy conversion systems: onshore and offshore conversion systems*, UK, John Wiley & Sons Ltd., 2014.

[31] F. Kendouli, K. Nabti, K. Abed, and H. Benalla, "Modélisation, simulation et contrôle d'une turbine éolienne à vitesse variable basée sur la génératrice asynchrone à double alimentation," *Revue des Energies Renouvelable*, 14(1), pp. 109-120, 2011.

[32] H. Hamiani et al., "A wind turbine sensorless automatic control systems, analysis, modelling and development of IDA-PBC method," *Int. J. Power Electron. Drive Syst.*, 11(1), pp. 45-55, 2020.

[33] A. Persson, "How do we understand the Coriolis force?" *Bulletin of the American Meteorological Society*, 79(7), pp. 1373-1386, 1998.

[34] L. Abderrazak, R. Adlene, and M. Mohamed, "Modeling and simulation of a wind turbine driven induction generator using bond graph," *Renew. Energy Sustainable Dev.*, 1(2), pp. 236-242, 2015.

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