



(RESEARCH ARTICLE)



Determination of the Optimal Parameters of a Horizontal-Axis Wind Energy System under Variable Wind Speeds

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International Journal of Science and Research Archive, 2025, 17(03), 627-632

Publication history: Received 06 November 2025; revised on 16 December 2025; accepted on 18 December 2025

Article DOI: <https://doi.org/10.30574/ijrsra.2025.17.3.3275>

Abstract

In the article, a modeling block diagram was developed in the Matlab/Simulink environment for a horizontal-axis wind energy system with a rated power of 20.5 kW. This model makes it possible to analyze the energy performance of the turbine under variable wind flows and different blade pitch angles. According to the research results, when the wind speed varies within the range of 3–12 m/s and the blade installation angles are between 0° and 10°, the rotor rotational speed is 7–25 rad/s, the turbine mechanical torque is 45.71–821 Nm, and the turbine mechanical power is 0.32–20.6 kW. It has been substantiated that when the wind turbine blades are installed at a pitch angle of 0°, the optimal tip-speed ratio is equal to 8.1.

Keywords: Horizontal-Axis Wind Turbine; Wind Speed; Wind Energy Utilization Coefficient; Mechanical Power and Torque; Matlab/Simulink; Modeling.

1. Introduction

In the world, renewable energy sources, including wind energy, occupy a leading position in saving fuel and energy resources, reducing greenhouse gas emissions into the environment, and ensuring continuous and reliable electricity supply to the population and industrial enterprises.

In Europe, 16.4 GW of new wind energy capacity was installed in 2024. At present, the total installed wind energy capacity amounts to 285 GW, including 248 GW onshore and 37 GW offshore. According to Europe's prospective plans for wind energy development, 187 GW of new wind energy capacity is expected to be installed during 2025–2030. Capital raised for new wind projects in Europe amounted to 33 billion euros in 2024 [1]. As of 2024, China has installed 521 GW of wind energy capacity. Since 2014, when 90 GW of wind energy was connected to the national grid, the country has achieved more than a threefold increase [2].

In Uzbekistan, studies have been conducted on the potential use of wind energy, and a map of the region's wind energy resources has been developed. According to the research results, the gross (theoretical) potential of wind energy in an area of 17,000 km² at a height of 80 m amounts to 520 GW, while the technical potential is 10 GW [3,4]. On January 28, 2022, the President of the Republic of Uzbekistan adopted the decree "On the Development Strategy of New Uzbekistan for 2022–2026." According to this decree, eight wind power plants with a total capacity of 4000 MW will be built. In particular, during 2023–2024, four wind power plants with a total capacity of 1600 MW will be commissioned in the Republic of Karakalpakstan, Bukhara, and Navoi regions, while in 2025–2026, four more wind power plants with a total capacity of 2400 MW will be launched across the republic [5,6].

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Currently, horizontal-axis wind energy systems account for 98% of the total installed capacity in wind power plants. Studies analyzing the energy parameters of horizontal-axis wind energy systems under different wind flows have been reviewed.

C. Beldjaatit and T. Sebbagh conducted research on modeling and investigating wind turbines in the MATLAB/Simulink environment. This study focused on the field of wind energy, particularly on turbine dynamics and efficiency. It included a detailed examination of wind energy conversion systems, such as the rotor, generator, and mechanical gearbox. The research provided a comprehensive analysis of the mechanical energy produced by wind turbines, identifying key parameters such as the power coefficient, tip-speed ratio, and blade pitch angle [7].

C.H. Chong and other scholars carried out scientific studies on modeling and simulating wind turbines in Matlab. Research was conducted to explore wind energy potential in Sarawak, Malaysia. The article presented modeling and simulation of various wind energy conversion systems operating under identical parameters using different generators, with the aim of testing generator efficiency in Matlab/Simulink. For nominal wind speed, the efficiencies of SCIG, DFIG, and PMSG were found to be 66.25%, 69.38%, and 71.88%, respectively [8].

A group of scientists led by A.A. Teyabeen conducted scientific work on mathematical modeling of wind turbine power curves. In the study, new models were developed to evaluate the power factor using Weibull and Gamma probability density functions, and comparative results of nine mathematical models of WTPC were presented based on manufacturer data from 32 wind turbines ranging from 330 to 7580 kW [9].

Despite the positive results achieved, insufficient research has been conducted on modeling the energy parameters of horizontal-axis wind energy systems in the Matlab/Simulink environment, considering the variability of wind speed, blade pitch angles, and tip-speed ratios.

The aim of the study is to model a 20.5 kW wind energy system in Matlab/Simulink and determine its optimal parameters.

Wind energy systems use various control methods to optimize or limit power depending on changes in wind speed. The turbine can be controlled by adjusting the generator speed, blade pitch angle, and the overall rotation of the wind turbine.

2. Materials and Methods

Wind power systems are characterized by the following wind speeds: cut-in speed in the range of 3–4.5 m/s, at which the rotor of the wind energy system begins to rotate gradually; nominal wind speed, usually between 10 and 13 m/s, at which the wind energy system reaches its rated power; and cut-out wind speed, at which the wind energy system disconnects from the grid and stops, typically in the range of 20–25 m/s. Figure 1 shows the appearance of a horizontal-axis wind energy system (a) and the power curve of the wind turbine (b).

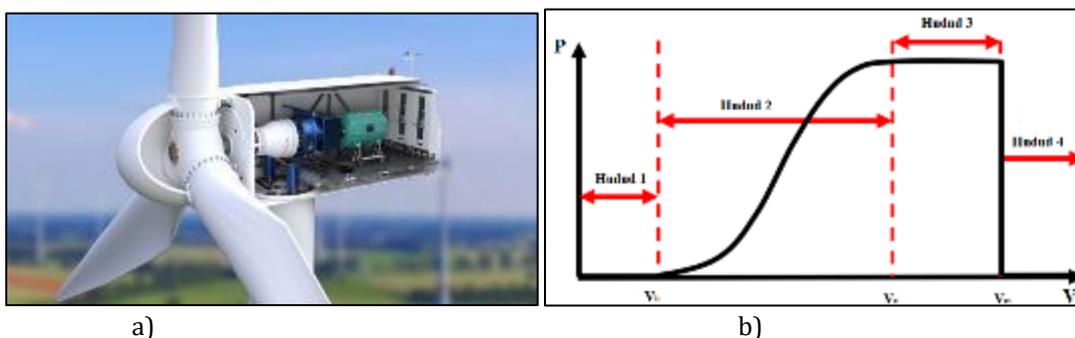


Figure 1 Representation of a horizontal-axis wind energy system (a) and the power curve of the wind turbine (b).

In order to improve the continuity and reliability of the electrical energy obtained from wind energy systems under variable wind speeds, it is necessary to correctly select the control system connected to the wind rotor, mechanical gearbox, and electric generator. Figure 2 presents the schematic diagram of the control system of horizontal-axis wind energy systems.

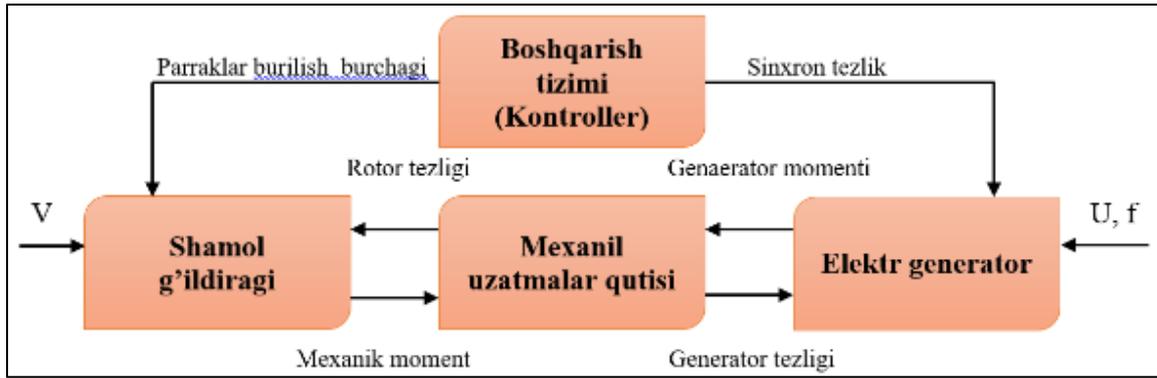


Figure 2 Schematic diagram of the wind energy system control.

Alongside The power that can be obtained from a wind turbine is expressed by the following formula [10]:

$$P_M = \frac{\rho \cdot S \cdot v^3}{2} \cdot C_p(\lambda, \beta) \quad (1)$$

where: $C_p(\lambda, \beta)$ – coefficient of wind energy utilization, λ – tip-speed ratio of the wind blades, β – pitch angle of the wind blades around their axis, v – wind flow velocity, ρ – air density, S – cross-sectional area of the wind rotor. The mechanical torque of the wind rotor is determined by the following formula [11]:

$$M_M = \frac{P_M}{\omega_M} = \frac{\rho \cdot S \cdot v^3 \cdot C_p(\lambda, \beta)}{2 \cdot \omega_M} \quad (2)$$

The mathematical expression of the dependence of the tip-speed ratio on the turbine radius, rotational speed, and wind velocity is given as [12]:

$$\lambda = \frac{\omega_M \cdot R}{v} \quad (3)$$

where: ω_M – mechanical angular velocity of the wind rotor, R – radius of the wind rotor.

The coefficient of wind energy utilization for a horizontal-axis wind turbine can be determined using the following empirical formula [13,14]:

$$C_p(\lambda, \beta) = 0.5 \cdot \left(\frac{116}{\lambda + 0.08 \cdot \beta} - \frac{4.06}{\beta^3 + 1} - 0.4 \cdot \beta - 5 \right) \cdot \exp \left(-\frac{21}{\lambda + 0.08 \cdot \beta} + \frac{0.735}{\beta^3 + 1} \right) \quad (4)$$

To determine the energy parameters of a horizontal-axis wind energy system at different wind speeds and optimal blade pitch angles, modeling was carried out in the Matlab/Simulink environment. The following initial conditions were adopted: wind speed variation range of 3–12 m/s, rotor radius of 3.87 m, blade pitch angle range of 0°–10°, and maximum turbine power of 20.5 kW.

3. Results and Discussion

Figure 3 shows the modeling block diagram of a 20.5 kW wind energy system constructed in Matlab/Simulink. Under the conditions of blade pitch angle of 0°, wind flow velocity of 12 m/s, rotor rotational speed of 25 rev/min, and tip-speed ratio of 8.1, the turbine mechanical torque was found to be 821.7 Nm, the nominal power 20.6 kW, and the wind energy utilization coefficient 0.41.

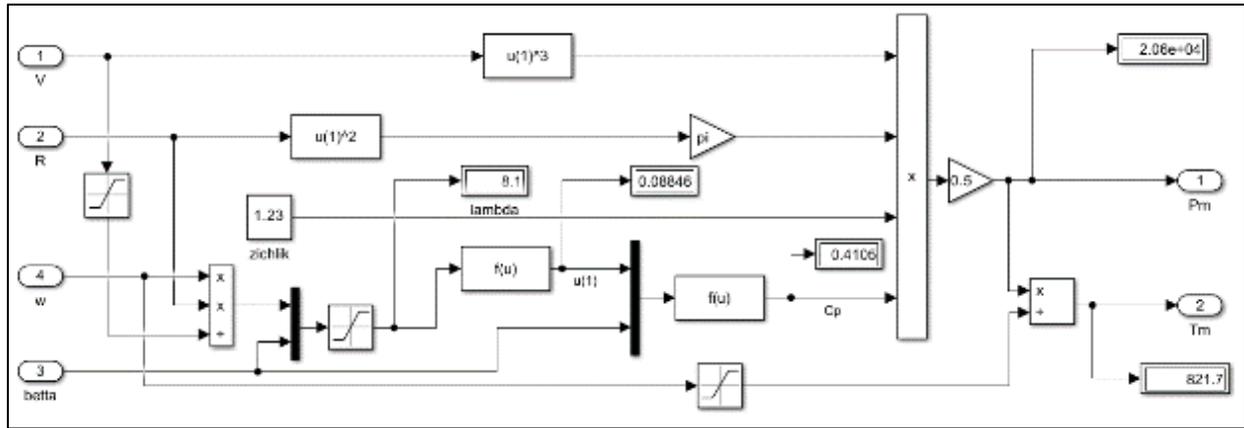


Figure 3 Modeling block diagram built in the MATLAB/Simulink system.

Figure 4 (a) presents the sub-block modeling scheme with the ability to vary parameters. In this case, when the wind flow velocity is within 3–12 m/s, the blade pitch angle is 0° – 10° , and the rotor rotational speed is 7–25 rad/s, the wind energy system was found to generate correspondingly 0.32–20.6 kW of power. Figure 4 (b) shows the graph of the wind energy utilization coefficient. It was determined that when the blade pitch angle is set to 0° , the efficiency indicator reaches its maximum value.

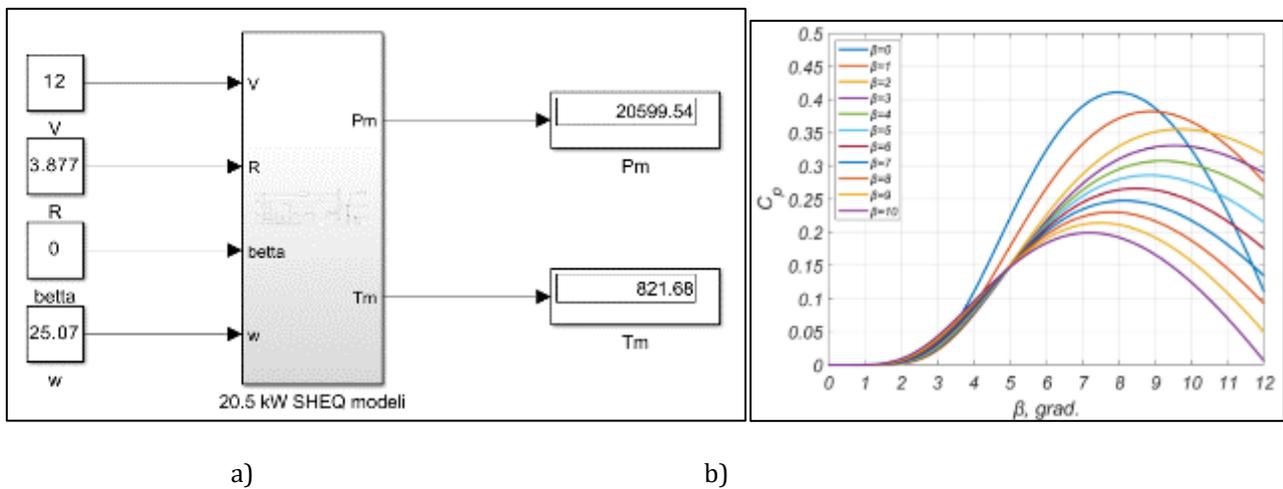


Figure 4 Sub-block modeling diagram (a) and the wind energy utilization coefficient graph (b).

Figure 5 shows the graph of the dependence of wind energy system power on wind speed. It was determined that at the cut-in wind speed of 3 m/s the output power is 0.32 kW, while at the nominal wind speed of 12 m/s the system operates with a power of 20.5 kW.

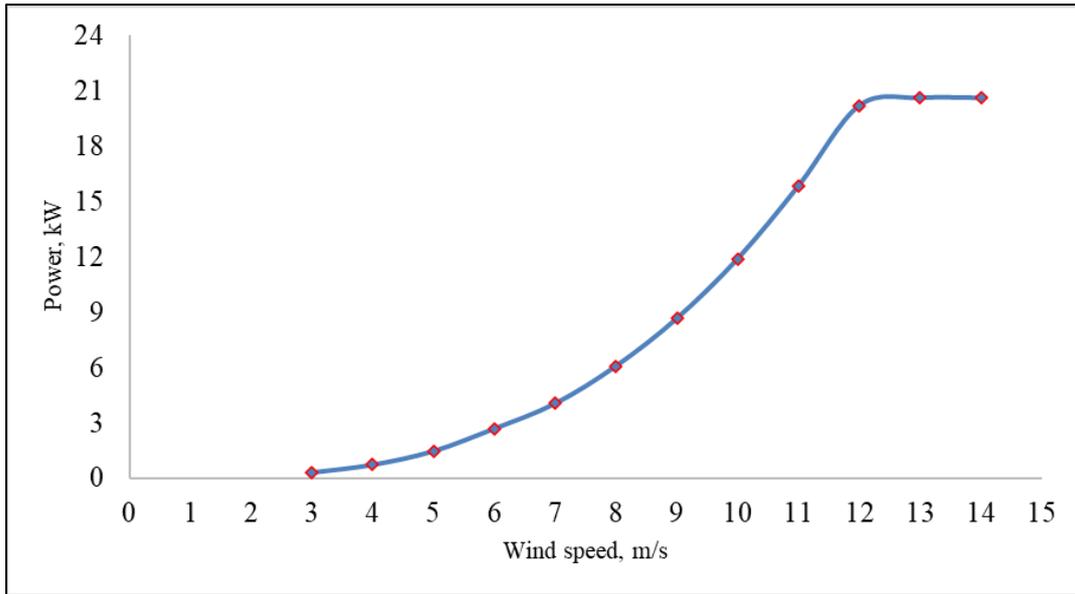


Figure 5 Graph of the dependence of wind energy system power on wind speed.

Table 1 presents the parameters of a 20.5 kW wind turbine depending on variations in wind flow velocity. The calculations were carried out using equations (1) and (2).

Table 1 Parameters of a 20.5 kW Wind Turbine

No	Wind speed, m/s	Rotor rotational speed, rad/s	Mechanical torque, Nm	Mechanical power, kW
1	3	7	45,71	0,32
2	4	9	82,22	0,74
3	5	10	148	1,48
4	6	12	214,16	2,57
5	7	14	290	4,06
6	8	16	380,62	6,09
7	9	18	482,22	8,68
8	10	21	567,14	11,91
9	11	23	689,56	15,86
10	12	25	821	20,6

4. Conclusion

A modeling block diagram of a 20.5 kW horizontal-axis wind energy system was developed in the Matlab/Simulink environment, enabling the analysis of its energy performance under variable wind flows and different blade pitch angles. According to the research results, when the wind speed varies within the range of 3–12 m/s and the blade pitch angle is between 0° and 10°, the rotor rotational speed is 7–25 rad/s, the turbine mechanical torque is 45.71–821 Nm, and the turbine mechanical power is 0.32–20.6 kW. It has been substantiated that when the wind turbine blades are installed at a pitch angle of 0°, the optimal tip-speed ratio is equal to 8.1.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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