

MODELING OF A HORIZONTAL AXIS WIND TURBINE IN MATLAB

Z. Toirov¹, Q. Sayfiddinov¹

¹*Bukhara Engineering-Technological Institute, Bukhara, Uzbekistan*

Abstract: This paper discusses the current state and development prospects of wind energy utilization, presenting a methodology for determining the optimal power coefficient $C_p = 0.42$ of a horizontal axis wind turbine. The wind turbine modeling was conducted using MATLAB. It was determined that the optimal power coefficient of the wind turbine is achieved at a specific tip-speed ratio $\lambda = 8$ of the blades and a blade pitch angle/tilt angle relative to the horizontal plane.

Keywords: wind speed, power coefficient (wind energy utilization factor), horizontal axis wind turbine (HAWT), tip-speed ratio.

Global development demonstrates that the improvement of living standards is intrinsically linked to rising energy consumption and the growing recognition of the imperative for efficient energy utilization. Consequently, a nation's fuel and energy complex not only serves as a primary engine for leading economic sectors but also exerts a profound influence on societal and social development.

Globally, the utilization of renewable energy sources—particularly wind energy—is assuming a prominent role in conserving fuel and energy resources while enhancing the continuity and reliability of power supplies. Considering global targets for the 2021–2030 period aimed at reducing greenhouse gas emissions by at least 40%, increasing the share of renewable energy to 32%, and improving energy efficiency by 32.5%, there is an urgent need to model, optimize, and deploy wind power installations capable of delivering dependable and uninterrupted energy [1].

The circulation of air masses in the Earth's atmosphere is evaluated differently by various experts. The annual theoretical potential of wind energy exceeds all existing terrestrial energy reserves by a factor of 100, reaching orders of magnitude in kWh. However, only 10–12% of this potential is practically exploitable [2].

Wind energy conversion systems convert aerodynamic wind energy first into mechanical energy, and subsequently into electrical energy. The electricity generated by wind power installations is either fed into the electrical grid to meet residential and industrial demand or utilized in off-grid (autonomous) configurations, either independently or coupled with other decentralized energy sources. Grid-connected horizontal axis wind turbines (HAWTs) account for approximately 98% of all operational wind energy installations worldwide.

Figure 1 illustrates the external layout of a horizontal axis wind turbine. Due to their high efficiency (power coefficient), turbines of this design are widely deployed for commercial power generation.



1 – rotor; 2 – braking system; 3 – yaw drive (yaw ring); 4 – mechanical transmission system (gearbox); 5 – electric generator; 6 – wind speed and direction measurement device (anemometer and wind vane).

The kinetic energy of the air flow is determined by the following formula:

$$E = \frac{m \cdot v^2}{2} \quad (1)$$

where: m – is the mass of the airflow, kg; v – is the wind flow velocity, m/s.

Assuming a constant velocity, the power extracted from a moving wind wheel is equal to the time derivative of the kinetic energy:

$$P = \frac{dE}{dt} \quad (2)$$

The power generated by a wind turbine rotor with a cross-sectional swept area S is defined by the following equation [3]:

$$P = \frac{\rho \cdot S \cdot v^3}{2} \quad (3)$$

where: ρ – is the air density, kg/m³; S is the cross-sectional area (swept area) of the wind rotor, m.

The density of the airflow varies with altitude, temperature, and atmospheric pressure. The empirical relationship describing the dependence of air density on altitude is expressed as follows [4]:



$$\rho = \rho_0 - 1.194 \cdot 10^{-4} \cdot H \quad (4)$$

where: $\rho_0 = 1,225 \text{ kg/m}^3$, $T = 298 \text{ K}$ is the air density at sea level at a temperature. The mechanical power extracted from the wind flow is determined by the following formula [5]:

$$P_M = P \cdot C_p(\lambda, \beta) = \frac{\rho \cdot S \cdot v^3}{2} \cdot C_p(\lambda, \beta) \quad (5)$$

where: $C_p(\lambda, \beta)$ – is the power coefficient (wind energy utilization factor); λ – is the tip-speed ratio of the rotor blades; β – is the pitch angle of the rotor blades (or tilt angle relative to the horizontal plane).

The tip-speed ratio of the wind turbine blades is calculated using the following formula:

$$\lambda = \frac{\omega_M \cdot R}{v} \quad (6)$$

where: ω_M – is the angular velocity of the wind rotor, rad/s; R – is the rotor radius, m; $\omega_M \cdot R$ – is the linear velocity of the rotor (or incoming wind speed), m/s.

The aerodynamic (mechanical) torque of the wind rotor is determined by the following expression:

$$M_M = \frac{P_M}{\omega_M} = \frac{\rho \cdot S \cdot v^3 \cdot C_p(\lambda, \beta)}{2 \cdot \omega_M} \quad (7)$$

The power coefficient of the wind turbine is determined using the following simplified semi-empirical formulation [6]:

$$C_p(\lambda, \beta) = 0.5 \cdot \left(\frac{116}{\lambda + 0.08 \cdot \beta} - \frac{4.06}{\beta^3 + 1} - 0.4 \cdot \beta - 5 \right) \cdot \exp\left(-\frac{21}{\lambda + 0.08 \cdot \beta} + \frac{0.735}{\beta^3 + 1}\right) \quad (8)$$

Equation (8) allows for determining the optimal power coefficient of a horizontal-axis wind turbine. In this context, simulations are conducted in MATLAB across various values of the blade pitch angle β and the tip-speed ratio λ .

Figure 2 illustrates the characteristic performance curves showing the dependence of the power coefficient (C_p) on the tip-speed ratio λ and the blade pitch/tilt angle.

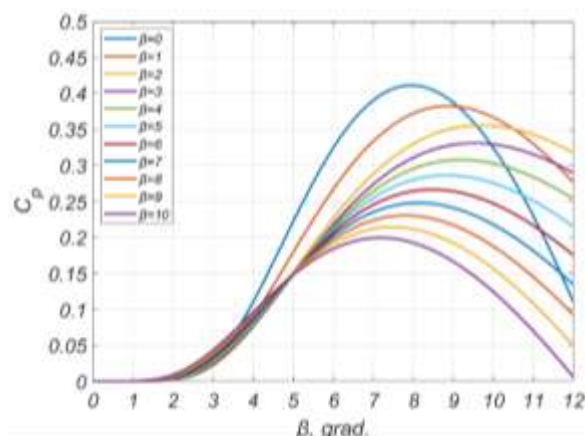


Fig. 2. Performance curves of the power coefficient (C_p).

It was established that the optimal value of the power coefficient for the horizontal-axis wind turbine is attained at a blade tip-speed ratio of $\lambda = 8$ and a rotor installation (pitch) angle of $\beta = 0$ degrees.

REFERENCES

1. European Commission, "2030 Climate & Energy Framework," Available: https://ec.europa.eu/clima/policies/strategies/2030_en
2. T. Y. Yunusov, Current State and Future of Energy Generation (Energiya ishlab chiqarishning bugungi kuni va kelajagi), Tashkent: Fan va texnologiya, 2012, 140 p.
3. N. Sadullayev, A. Safarov, Sh. Nematov, and R. Mamedov, "Statistical Analysis of Wind Energy Potential in Uzbekistan's Bukhara Region Using Weibull Distribution," Applied Solar Energy, vol. 55, no. 2, pp. 126–132, 2019.
4. G. Modukpe and D. Dei, "Modeling and Simulation of a 10 kW Wind Energy in the Coastal Area of Southern Nigeria: Case of Ogoja," IntechOpen, 2019, doi: 10.5772/intechopen.85064.
5. M. Muller, "Realistic loss modelling and minimisation in an air-cored permanent magnet generator for wind energy applications," IET Conference Publications, 2012, doi: 10.1049/cp.2012.0324.
6. T. Micha Premkumar, "Modeling and simulation of pitch controlled FRP material based horizontal axis wind turbine system to extract maximum power," Materials Today: Proceedings, vol. 33, part 7, pp. 3708–3714, 2020, doi: 10.1016/j.matpr.2020.06.096.