

Methodology For Improving The Efficiency Of A Vertical-Axis Wind Energy Device Under Low-Wind Conditions

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Abstract. The article presents information on the current state and prospects for the development of small-scale wind energy systems in countries with climatic conditions similar to those of our region. It also discusses scientific research conducted on the development and improvement of vertical-axis wind energy systems, as well as the results of research aimed at increasing their efficiency by improving the design of vertical-axis wind energy systems adapted to low-speed wind flows. A methodology is proposed for increasing the efficiency of the device by up to 3–5% under low-wind conditions through the modification of wind turbine blades with a NACA0015 aerodynamic profile and by installing the wind blades at an optimal angle of 5° relative to the tangent to the circumference of the wind rotor.

Keywords: wind speed, vertical-axis wind energy system, efficiency, modification, NACA0015 aerodynamic profile, electric generator.

1. Introduction

Globally, considerable attention is being paid to the use of renewable energy sources to provide continuous and reliable electricity to small-scale autonomous consumers located far from centralized power supply systems. The use of renewable energy sources, particularly small-scale wind energy systems, is developing rapidly. In regions with significant wind potential, electricity generated by wind energy systems is becoming increasingly cost-effective, while causing almost no harm to the environment. As a result, such projects are being increasingly implemented in practice, substantial investments are being directed toward them, and promising developments and research activities are being supported.

We analyze the current status and development prospects of the use of small-scale wind energy systems in countries around the world whose climatic conditions are similar to those of our region. Egypt is located in the northern part of the African continent, and its territory mainly consists of low-lying plains. Its climatic conditions are characterized by high air temperatures, a high level of atmospheric dust, low humidity, and an average wind speed of 4–5 m/s. As of today, the total installed capacity of renewable energy sources in the region amounts to 3.7 GW, of which 2.8 GW is attributable to hydropower and approximately 0.9 GW to solar and wind energy [1]. The installed capacity of small-scale wind energy systems is 1 MW. In the coming years, this figure is planned to be increased to 10 MW.

Kazakhstan is located predominantly in low-lying plains, which account for approximately 80–90% of its territory, and its climatic conditions are similar to those of our region. The average wind speed in the region is (4–6) m/s. More than 1% of the electricity consumed in Kazakhstan is generated from wind energy [2]. Small-scale wind energy systems are being manufactured in the country, and a program has been developed to promote economic and social development by installing these wind energy systems in households and farms located in areas remote from the centralized electricity supply system.

Nigeria is located on the African continent, and its wind-speed characteristics are similar to those of our region. In the southern parts of the country, the average wind speed measured at a height of 10 m ranges from (1.4–3) m/s, while in the northern regions it ranges from (4–5.12) m/s. Currently, approximately 3 GW·h of

electricity is generated annually from wind energy in these regions [3]. More than approximately 10% of the generated wind energy is consumed mainly by farms and small-scale enterprises located in remote areas. Scientific research is currently being conducted both worldwide and in our region on the development of renewable energy technologies, particularly vertical-axis wind energy systems, and on improving their efficiency under low-wind conditions.

In his Candidate of Technical Sciences dissertation [4], Y. V. Solomin presented research on the development of a new type of vertical-axis wind energy system designed to provide full or partial electricity supply to small settlements, residential buildings, farms, and small workshops in remote areas with unstable energy supply, thereby contributing to infrastructure development. The rotor of this wind energy system is directly connected to the generator. The wind blades begin to rotate at a starting wind speed of 3 m/s, while the system operates at its rated power at a wind speed of 12 m/s. The main disadvantages of the system are the complexity of manufacturing the aerodynamic blade design and its low operating efficiency under low-wind conditions.

S. Sh. Tatikyan [5] presented a vertical-axis wind energy system equipped with external guide surfaces for small-scale electricity consumers located in remote areas and urban centers characterized by low wind speeds. The proposed wind energy system consists of two main components: external guide surfaces and internal rotating blades. The use of external guide surfaces significantly increases the operating efficiency of the system. However, the main disadvantages of this system are the large amount of material required for its construction and the use of rails to adjust the external guide surfaces toward the wind when the wind-flow direction changes. This increases the overall cost of the system.

In his Candidate of Technical Sciences dissertation [6], U. G'. Dehqonov developed a vertical-axis wind energy system operating with a direct-current electric generator for dispersed agricultural electricity consumers. His research proposed a rational design of a vertical-axis wind energy system that is independent of the direction of the wind velocity vector and is intended to generate electricity from variable wind flows. The use of a gearbox and direct-current generators in the developed wind energy system resulted in a decrease in its overall operating efficiency.

Based on the analysis of the studies presented above, the main disadvantages of existing wind energy systems are their low operating efficiency and insufficient reliability under low-wind conditions. Therefore, particular attention is being given to the development of vertically oriented wind energy systems with simple designs that can operate efficiently under variable and low-speed wind flows.

2. Material and methods

The objective of the research is to increase the efficiency of a vertical-axis wind energy system by improving its design and adapting it to variable climatic conditions, including wind speeds of 2–9 m/s and temperatures ranging from –20 to +45 °C.

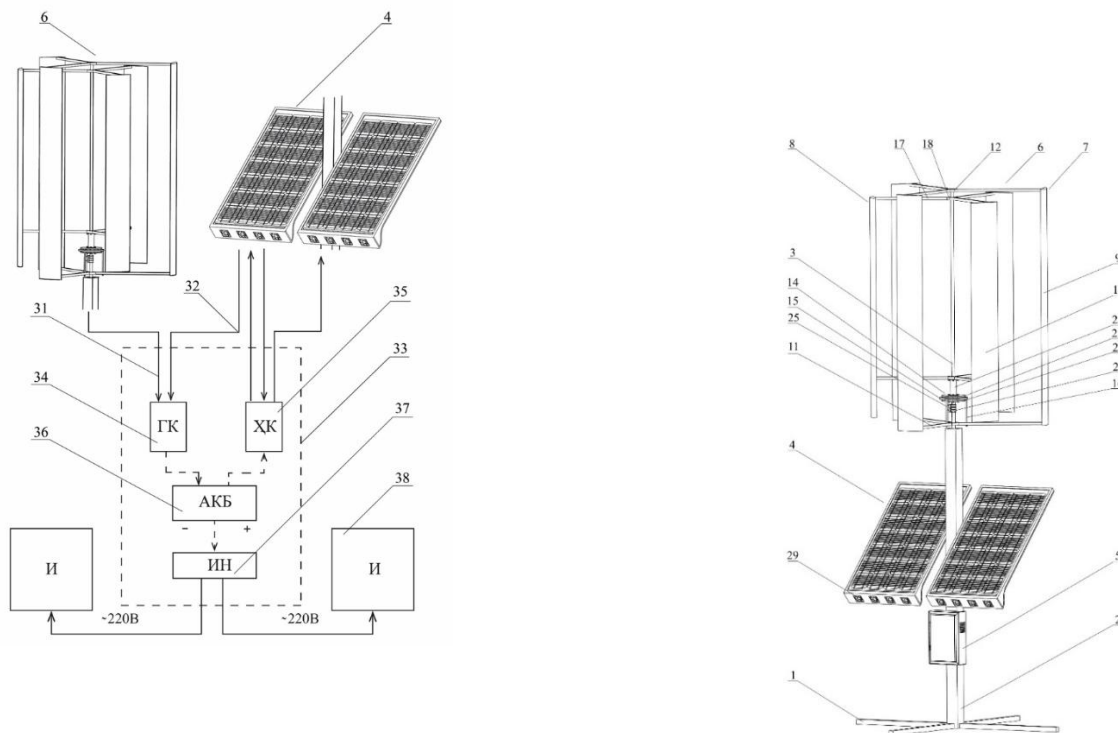
The vertical-axis wind energy system operates as follows. The wind blades (9), installed at an optimal angle β relative to the tangent to the circumference of the outer wind rotor (8), are rigidly connected through metal profiles (10) to the rotating tube (11). The rotating tube (11) is mounted on the stationary shaft (3) by means of tapered bearings (12). The metal profiles (10) are connected to the armature (14) of the electric generator (13) by means of a metal sleeve (15). Under the action of the wind flow, this system begins to rotate in the clockwise direction.

The blades (17) of the inner wind rotor (16) are rigidly connected to the rotating tube (19) through metal profiles (18). The rotating tube (19) is mounted on the stationary shaft (3) by means of tapered bearings (20). The inductors (21, 22) of the electric generator (13) are connected by a flange joint (23). Under the action of the wind flow, this system begins to rotate in the counterclockwise direction.

As a result, the wind energy system (28) converts the kinetic energy of the wind flow into electrical energy. The armature (14) and inductors (21, 22) of the electric generator (13) begin to rotate in opposite directions relative to each other. In this process, the brush (26), connected to the armature (14) through the metal sleeve (15), transmits the three-phase alternating voltage to the collector (27) mounted on the stationary shaft (3).

Thus, electrical energy is generated depending on variations in the wind flow and is transmitted through the cable (29) to the hybrid charge and discharge controller (32) of the control system (31). The hybrid charge and discharge controller (32) converts and supplies the generated electrical energy as direct current, which is

stored in the battery bank (34). The electrical energy stored in the batteries (34) is then converted by the inverter (35) into single-phase alternating voltage, thereby providing autonomous consumers (56) with a continuous electricity supply (Figure 1).

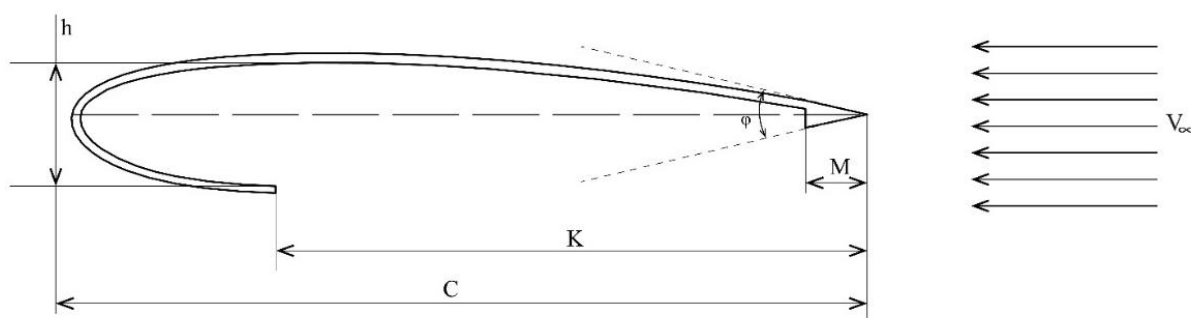


To provide autonomous consumers with a continuous supply of electricity, the wind energy system can be used in combination with solar panels (4) (Figure 1).

Figure 1. General view of the combined solar–wind energy system (a) and schematic diagram of the control system of the combined solar–wind energy system (b).

The proposed two-rotor wind energy system, consisting of external and internal rotors rotating in opposite directions relative to each other, has been found to provide an 8% increase in efficiency compared with conventional wind energy systems. It has also been determined that higher voltage can be generated at low rotational speeds when the armature and inductors of the electric generator are rotated in opposite directions relative to each other [7].

Figure 2 shows the modified aerodynamic surface of the NACA0015 wind blades. In this design, the blades of Savonius- and Darrieus-type wind turbines are used in combination. The purpose of this modification is to improve the utilization of wind energy under low-wind conditions and to increase the tip-speed ratio of the blades.



Modified aerodynamic surface of the wind turbine blades.

Figure 2.

Figure 3 presents the geometry of the wind flow velocities and forces acting on the wind turbine blades. This geometry is used to derive the mathematical equations for the wind energy utilization coefficient and mechanical power of the wind energy system. Based on these relationships, the wind blades are installed at an optimal angle β relative to the tangent to the circumference of the wind rotor.

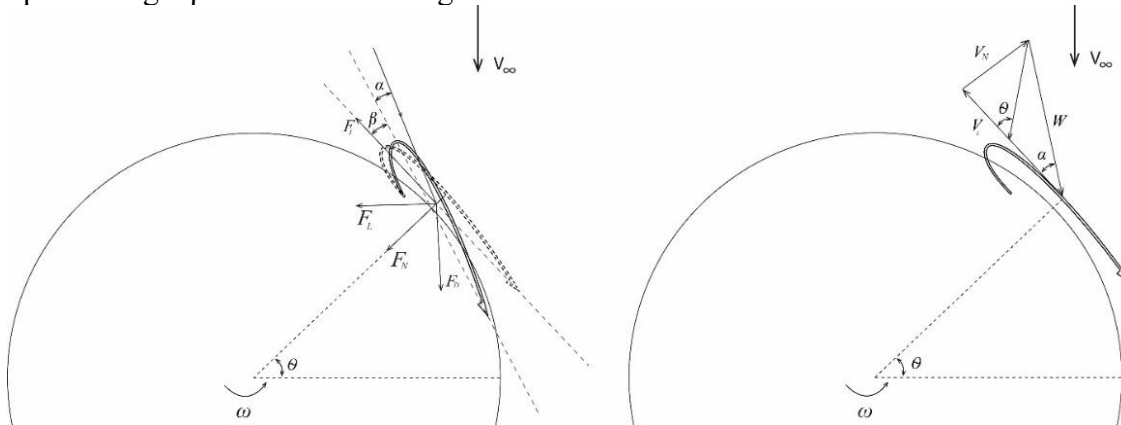


Figure 3. Forces acting on the wind turbine blades (a) and wind flow velocities (b).

The modification of the blades in a wind energy system is of great importance for obtaining a stable supply of electricity under low-wind conditions. In this regard, the results of improving wind turbine blades with a NACA0015 aerodynamic profile to achieve a higher rotational torque under low-wind conditions and to reduce the forces acting in the opposite direction to the rotation of the wind rotor blades are as follows:

$$K = 0,3 \cdot C \quad (1)$$

$$M = 0,075 \cdot C \quad (2)$$

$$\varphi = 24^0 \quad (3)$$

where:

C — the chord length of the wind rotor blade, $[m^2]$.

The method for determining the optimal installation angle of the wind blades relative to the tangent to the circumference of the wind rotor, as well as the amount of electrical energy generated, is described below with reference to Figure 3.

The wind velocity acting on the rotor plane (induced wind velocity) can be expressed as follows:

$$V_a = V_\infty \cdot (1 - a) \quad (4)$$

Wind Speed and Tip-Speed Ratio

where:

V_∞ — wind speed, $[m/s]$;

a — induction factor (the fractional reduction in wind velocity between the free-stream flow and the rotor plane).

The tip-speed ratio of the wind rotor blades is determined using the following equation:

$$\lambda = \frac{R \cdot \omega}{V_\infty} \quad (5)$$

Induction Factor Relationship

The relationship between the induction factor, wind speed, and the geometric parameters of the wind energy system is expressed by the following equation [8]:

$$a = \frac{N \cdot C}{2\pi R} \cdot \frac{R \cdot \omega}{V_\infty} \cdot \sin\theta \quad (6)$$

Wind Rotor Parameters and Normal Wind Velocity

where:

N — number of blades;

R — radius of the wind rotor, [m];

ω — angular rotational speed of the wind rotor, [rad/s];

θ — blade installation angle relative to the azimuth.

The normal wind velocity acting on the wind turbine blades is determined by the following mathematical relationship:

$$V_n = V_a \cdot \sin\theta \quad (7)$$

The tangential wind velocity acting on the blades is determined by the following mathematical relationship:

$$V_t = R \cdot \omega + V_a \cdot \cos\theta \quad (8)$$

The relative velocity acting on the blades is determined by the following mathematical expression:

$$W = \sqrt{V_n^2 + V_t^2} \quad (9)$$

The angle of attack of the wind velocity acting on the blades is determined using the following equation [9]:

$$\alpha = \arctan\left(\frac{V_a \cdot \sin\theta}{R \cdot \omega + V_a \cdot \cos\theta}\right) - \beta \quad (10)$$

where:

β — the installation angle of the wind turbine blades relative to the tangent to the circumference of the wind rotor.

The tangential force coefficient is determined by the following mathematical expression:

$$C_t = C_L \cdot \sin\alpha - C_d \cdot \cos\alpha \quad (11)$$

where:

C_L — lift coefficient of the blades;

C_d — drag coefficient of the blades.

The normal force coefficient is determined by the following mathematical expression:

$$C_n = C_L \cdot \cos\alpha + C_d \cdot \sin\alpha \quad (12)$$

The tangential force acting on the blade is determined using the following expression:

$$F_t = C_t \cdot \left(\frac{1}{2} \cdot \rho \cdot A \cdot W^2\right) \quad (13)$$

where:

ρ — air-flow density, [kg/m³];

A — blade area, [m²].

The normal force acting on the blades is determined using the following expression:

$$F_n = C_n \cdot \left(\frac{1}{2} \cdot \rho \cdot A \cdot W^2\right) \quad (14)$$

The mechanical torque of the wind energy system is determined by the following mathematical expression:

$$M = \frac{N \cdot C \cdot H \cdot R}{2 \cdot \pi} \int_{\theta=0}^{2\pi} \frac{\rho \cdot W^2 \cdot C_t}{2} \cdot d(\theta) \quad (15)$$

where:

H — height of the wind turbine blades, [m];

R — radius of the wind rotor, [m].

The wind energy utilization coefficient of the wind energy system is determined using the following equation [10]:

$$C_P = \left(\frac{N \cdot C}{2 \cdot \pi \cdot R \cdot \rho \cdot V_\infty^2} \int_{\theta=0}^{2\pi} \frac{\rho \cdot W^2 \cdot C_t}{2} \cdot d(\theta) \right) \cdot \lambda \quad (16)$$

The rated mechanical power of the wind turbine is determined using the following equation:

$$P_n = M \cdot \omega \quad (17)$$

The electrical energy generated by the wind energy system is determined using the following mathematical expression:

$$E_{sh} = P_n \cdot \eta_g \cdot t \quad (18)$$

where:

η_g — efficiency of the electric generator;

t — annual operating time of the wind energy system.

3. Result and Discussion

Figure 4 presents the dependence curves of the lift coefficient C_L (a) and drag coefficient C_D (b) of the NACA0015 aerodynamic profile on the Reynolds number and the variation in the angle of attack (α) acting on the blades.

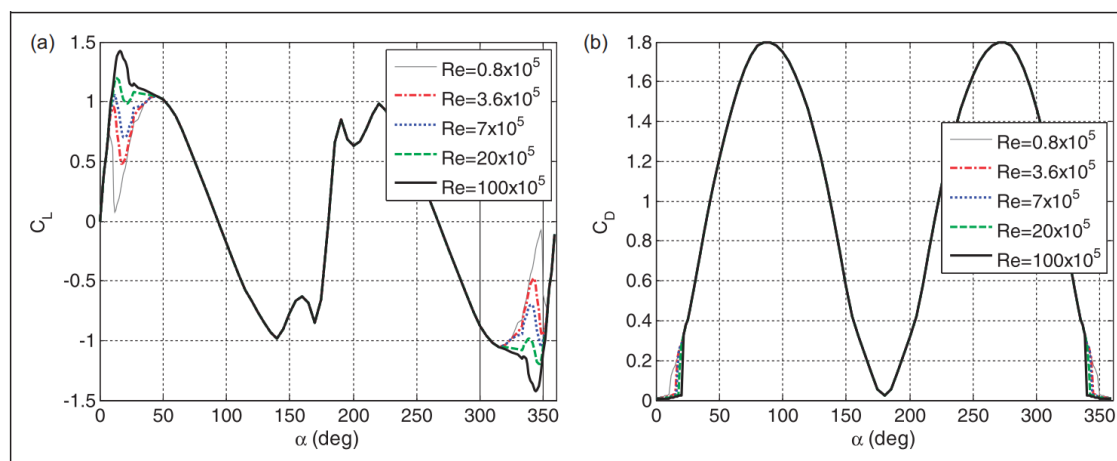


Figure 4. Dependence curves of the lift coefficient C_L (a) and drag coefficient C_D (b) of the NACA0015 aerodynamic profile on the Reynolds number and the angle of attack (α) acting on the blades.

Figure 5 presents the dependence curves of the optimal blade inclination angle (β) on the efficiency parameters of the wind energy system. It was determined that when the inclination angle relative to the tangent drawn to the circumference of the wind rotor is set to 5° , the wind energy utilization coefficient reaches a maximum value of 0.28, while the tip-speed ratio of the wind turbine blades reaches 2.4.

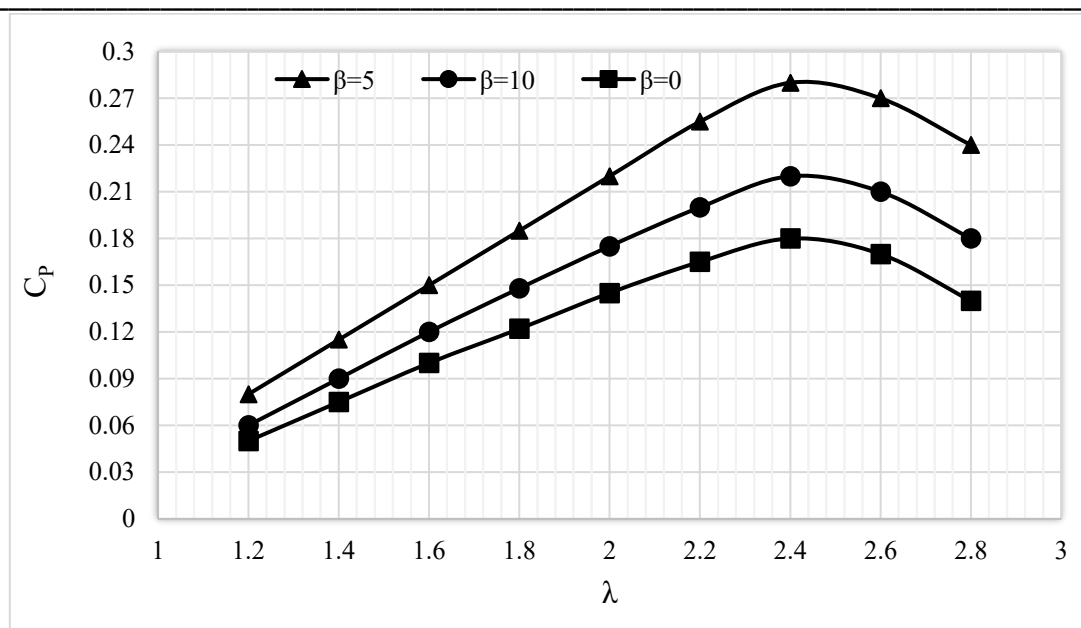


Figure 5. Dependence curves of the wind blade inclination angle on the efficiency parameters of the wind energy system.

The implementation of this wind energy system by small-scale autonomous consumers located far from centralized electricity supply systems can contribute to the development of social and economic sectors.

Conclusion: A methodology has been developed to increase the efficiency of a vertical-axis wind energy system adapted to variable climatic conditions, including wind speeds of 2–9 m/s and temperatures ranging from –20 to +45 °C, through the improvement of its design.

A scheme has been developed for using the wind energy system in combination with solar panels to provide small-scale autonomous consumers with a continuous supply of electricity.

To improve the efficiency of the system under low-wind conditions, the wind turbine blades were modified, and the optimal inclination angle was determined based on geometric relationships. As a result, it was established that when the inclination angle relative to the tangent drawn to the circumference of the wind rotor is set to 5°, the wind energy utilization coefficient reaches a maximum value of 0.28, while the tip-speed ratio of the wind turbine blades reaches 2.4.

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