Journal Renewable Energy & Mechanics (REM)
DOI: 10.25299/rem.2025.vol8(02).21931
Received 2025-04-05; Revised: 2025-09-23; Accepted 2025-09-30

Vol. 08 No.02 2025
E-ISSN: 2614-8315
P-ISSN: 2714-621X

Development of a vertical-axis wind turbine design

Katkov Valerii Vitalevich*
Cherepovets State University, Cherepovets, Russia[1]

*Corresponding author: catcov.valera2016@mail.ru

ABSTRACT

The article presents the development of a modernised vertical-axis wind turbine design aimed at improving energy efficiency by eliminating turbulent losses and optimising aerodynamic characteristics. Key innovations include the implementation of a nozzle grid with a cosine-shaped profile to stabilise airflow, the use of rotor blades with a confused-diffuser geometry, and upgraded guide vanes. Results from computational modelling and wind tunnel tests confirmed a 57% increase in airflow velocity, reduced turbulence, a 5.3% improvement in efficiency, and enhanced structural stability. The system demonstrates potential for application in standalone power supply systems at low wind speeds (3 m/s or lower).

Keywords: Aerodynamic optimisation, nozzle grid, cosine-shaped profile

INTRODUCTION

Wind turbines, also known as wind power plants, are devices that convert the kinetic energy of atmospheric flow into mechanical work, causing the rotation of the turbine rotor and subsequently generating electricity through an electromechanical converter. According to the type of turbine, Bezrukikh et al. (2014) and Howell et al. (2010) categorise wind turbines into two main types: those with horizontal and those with vertical axes of rotation.

Known designs of vertical-axis wind turbines include a housing with plates, a rotor with working blades, and a generator housing. The plates in the housing are located at an angle (Bhutta et al., 2020; Tutaev et al., 2024; Saburova et al., 2019) to direct and accelerate the flow. Also, the working blades can be curved or have a streamlined shape.

Disadvantages of existing models, Smirnov and Kozlov (2019):

1. Turbulence in the housing and above the generator;
2. High aerodynamic drag due to non-optimal blades;
3. Low efficiency of the guide elements.

Research at KSU Kvitko and Azaryan. (2022), SUSU, and KSAU Solomin et al. (2018) are aimed at improving wind power plants, but the problem of minimising energy losses remains relevant.

Objective: Optimisation of the characteristics of a vertical-axis turbine wind power plant by upgrading the geometry to reduce turbulence, aerodynamic losses, and increase efficiency.

Tasks:

1. Analysis of prototype defects that limit efficiency.

2. Design of an improved design using CFD modelling.
3. Wind tunnel tests with flow visualisation.
4. Comparison of the modernised wind power plant with analogues in terms of power factor (Kp), noise, and durability.

This set of tasks will provide a systematic approach to modernising the plant, combining engineering analysis, calculation methods, and experimental verification of the results.

Structural description of the vertical-axis wind turbine (VAWT) model

The wind generator is designed based on a turbine rotor (Fig. 1) integrated into a casing with two plate fairings and vertical guide plates (Faradanesh & Schuff, 2003; Solomin, 2011; Frimpong, 2021), which direct the flow to the working blades. Despite a partial increase in flow velocity due to the casing geometry, the analysis revealed critical shortcomings:

The absence of a nozzle grid due to the non-optimal Afrouzi et al. (2021) shape of the blades and plates, which causes:

1. Turbulent losses;
2. Uneven distribution of flow energy;
3. Uneven loads on structural elements.
4. Reduced efficiency due to uncontrolled vortex formation and kinetic energy losses.

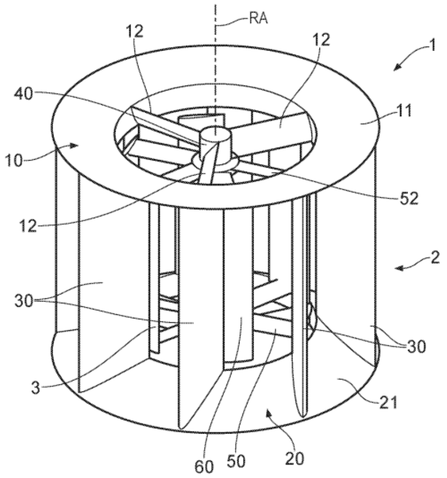

Figure 1. General view of the prototype WTU

Structural and functional description of the modernised vertical-axis wind turbine (VAWT)

The modernised VAWT is a complex system designed to minimise aerodynamic losses and optimise energy conversion.

The main elements of the turbine Katkov (2024) are the vertical-axis rotor 4, located in the cylindrical casing 2. This consists of horizontally located guide plates 3, which form one period of a cosine wave between themselves, and also form nozzle channels of variable cross-section. Such geometry allows for increasing the speed of the incident flow due to the Venturi effect and stabilising the laminar flow regime by eliminating the separation zones of the boundary layer.

Vertical-axis rotor (4): Consists of four working blades (5) with spatially variable geometry:

Vertical bending according to the law, where H is the height of the blade, and z is the vertical coordinate.

The blade profile forms a narrowing-expanding channel (confuser-diffuser), which leads to flow acceleration in the maximum torque zone and pressure gradient reduction due to controlled expansion. Rotor 4 is mounted on support bearings and connected to the generator rotor via an elastic coupling, which compensates for the misalignment between the rotor shaft and the generator, thereby reducing the vibration load. The gap between the working blades and the generator housing is up to 5 mm, ensuring the free movement of the blades and minimising air resistance. All elements can be made of various materials, including metal and plastic. These materials are selected based on the turbine's operating conditions and requirements for reliability and durability. Generator housing 6 has four channels, numbered 8, which play an essential role in turbine operation. These channels ensure the passage of air flow through the working blades and the removal of exhaust gases from the turbine. During the operation of turbine 1 of the wind generator, Smirnov and Kozlov (2020) report that air flow passes through the plates of housing 3. Flow, passing through the nozzle channels of plates, increases its speed. Then, the flow enters working blades 5, causing the rotor 4 to rotate. After the flow passes through the working blades 5, the exhaust flow is removed through channels eight into the generator housing 6. This prevents the occurrence of turbulent flow in the lower part of working blades five and increases the reliability of the turbine. Additionally, the flow passing through the channels cools the rotor winding, which helps improve the turbine's service life and increase its efficiency.

Brief description of drawings

Drawings, which explain the developed model:

Fig. 2 shows a general view of a vertical-axis wind generator.

Fig. 3 shows a general view of the generator and turbine.

Fig. 4 shows a horizontal section of a vertical-axis wind turbine.

Elements of design and other objects are designated in drawings by following the positions:

1 – turbine;
2 – wind generator housing;
3 – housing plates;
4 – rotor;
5 – working blades;
6 – generator housing;
7 – generator;
8 – channels;
9 – reinforcing beams.

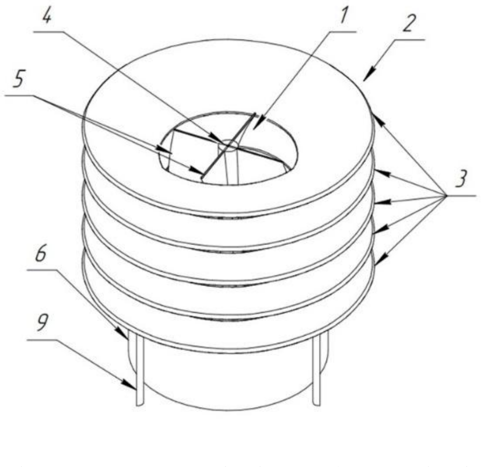

Figure 2. General view of a vertical-axis wind turbine

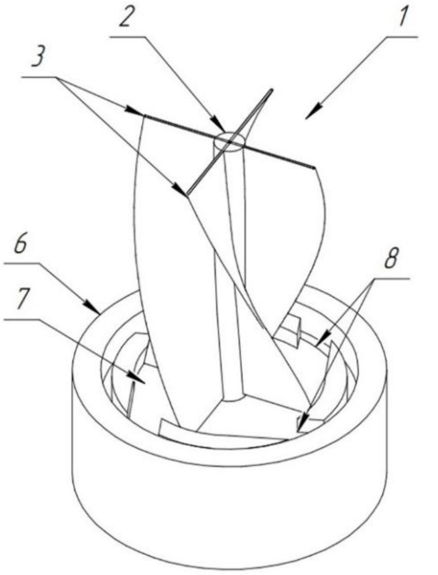

Figure 3. General view of the generator and turbine

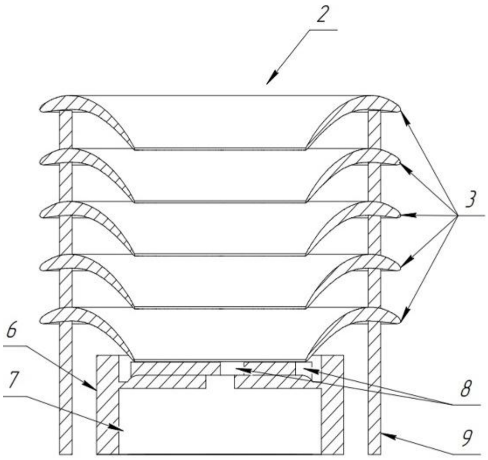

Figure 4. Horizontal section of a vertical-axis wind turbine

Wind tunnel tests

As part of the study, the setup was loaded into the SolidWorks program (Babatunde et al., 2019; Sharma et al., 2021; Saryyey et al., 2022), where it was tested in a wind tunnel.
Air flow parameters:

- Inlet velocity: Vin=3.5 m/s.
- Temperature: T=20∘CT=20ºC.
- Relative humidity: ϕ=35%ϕ=35%.
- Pressure: P=10500 kPa

Figure 5 illustrates the increase in flow velocity after passing through the nozzle grid, which is formed by curved annular plates inclined relative to the rotor axis. This geometry ensures focusing and acceleration of the flow in the area of the working blades due to the Venturi effect.

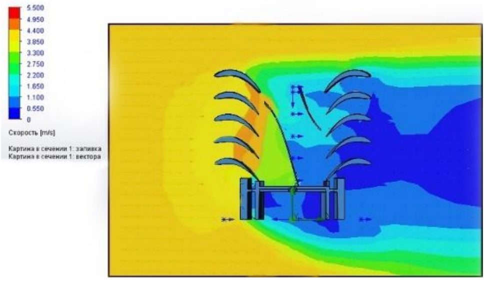

Figure 5. Change in flow velocity in the cross-section

In Figure 6, we see how the flow passes through the blades. The blades form a channel between themselves, which narrows toward the centre of the installation and widens toward the generator, resulting in an increase in flow velocity in this area. This allows for the flow energy expenditure to be minimised for the rotor to rotate.

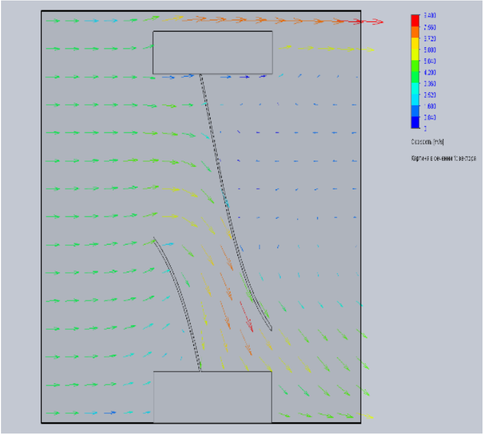

Figure 6. Velocity vectors in the cross-section of the installation

In Figure 7, we see the flow trajectory and the complete absence of turbulence. In the area of the generator, we observe how the flow exits through the channels, thereby eliminating the occurrence of turbulent flow between the blades and the housing.

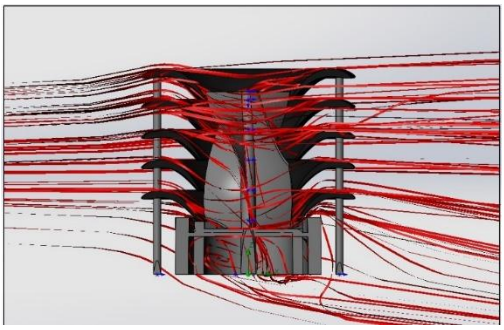

Figure 7. Flow trajectory through the VTU

The resulting simulation model allows us to evaluate the efficiency of the VTU blade design. The mathematical model of Luis et al. (2021) enables the analysis of the main operating parameters of the installation.

Study of the efficiency of the improved wind turbine unit (WTU) during experimental tests

During the experiments conducted in the wind tunnel, the main operating characteristics of the system were recorded (see Table 1). Processing of the experimental data allowed us to evaluate the correctness of the modernised computer model and identify the main patterns:

1) Air flow dynamics:

- Inlet section: 3.6 m/s;
- Average value inside the WTU: 5.6 m/s (intensity increase by 57%).
- Peak speed: 6.7 m/s.

2) Pressure: A decrease to 101,032 Pa (by 0.3% of atmospheric pressure) indicates low friction losses but requires monitoring of local vacuum zones.

3) Torque: 1.2 N confirms a stable interaction of the flow with the blades

A mathematical model of the WTU has been calculated. During the calculations of the installation's efficiency, an assessment was made of the influence of general parameters on the operational indicators of the VTU Min (2025); Anupam et al. (2023); Kumar et al. 2018). During the study, it was established that increasing the area of the mast base from 1 m² to 36 m² results in a 2215 W increase in generated power, accompanied by a simultaneous decrease in rotation frequency from 245 to 40 rpm. Such dynamics indicate the optimisation of the design: a decrease in the rotation frequency increases the system's resistance to mechanical loads, reducing the risk of deformation of the elements. To check the adequacy of the mathematical model, historical data of the YASHEL SV - 680 system (Orenburg) were used, covering operating modes at wind loads of 3-6 m/s and an ambient air temperature of +23°C (table

Comparison of the modelling results with real operating indicators allowed us to draw the following conclusions:

1. Generating capacity: The discrepancy between the model

and archived values reaches a twofold level.

2. Energy efficiency: Exceeding the efficiency of the experimental setup by 4.8%.
3. Rotor kinematics: Minimum deviation in rotation speed (≈ 25 rpm).
4. Aerodynamics: The difference in air flow speed through the VTU is, on average, 17%.

Development of a Mathematical Model

When developing a mathematical model, Smirnov and Kozlov (2020) use a previously developed VTU model that has undergone wind tunnel testing as a basis. The model incorporates both the calculated characteristics and the data obtained during the tests. Among the equations used to implement the GTU modelling, the following can be distinguished: Bezrukikh et al. (2014), Howell et al. (2010), Bhutta et al (2020), and Tutaev and Bezborodov (2024).

1. Calculation of the area occupied by the wind turbine:

$$S = D \cdot H,$$

Where D – is the diameter of the wind wheel, and H – is the rotor height.

2. Calculation of the aerodynamic power:

$$P_A = \frac{m \cdot v^2}{2} = \frac{p \cdot V \cdot v^2}{2} = \frac{p \cdot S \cdot v \cdot v^2}{2} = \frac{p \cdot S \cdot v^3}{2},$$

Where P_A – is the aerodynamic power, W; ρ – is the density of the air passing through the rotor (taken as 1.2041 kg/m^3 in dry air at a temperature of 20 °C and a pressure of 101.325 kPa), kg/m3; v is the speed of the wind flow before hitting the rotor, m/s; m is the mass of air passing through the rotor in 1 s, kg; V – is the volume of air passing through the rotor in 1 s, m^3; S is the swept (streamlined?) area of the rotor.

3. Calculation of the electric power:

$$P_э = \xi \cdot P_A,$$

Where – is the wind energy utilisation factor.

4. Calculation of the rotor speed: were

$$\omega_{RPM} = \frac{60 \cdot Z \cdot v}{\pi \cdot D},$$

Z – is the speed factor.

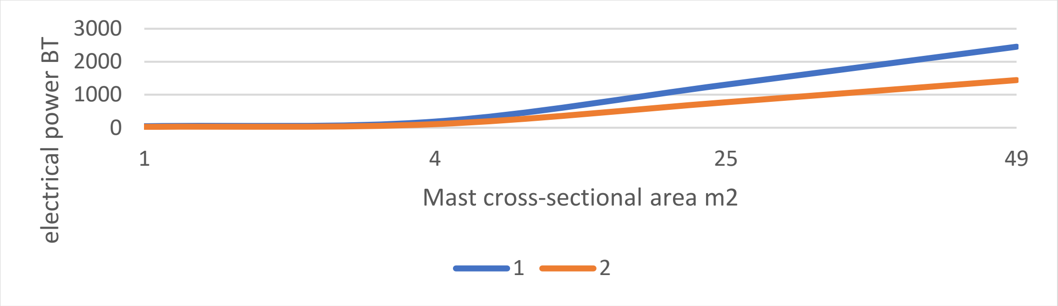

Fig. 6. Dependence of electric load on the cross-sectional area of the mast 1 - developed model; 2 - archive data of the automated process control system

Table 1. Data obtained during aerodynamic tests

D	H	S	ξ	υ	ρ	P_a	$P_{\text{э}}$	n	ω
1	1	1	0,44	5,6	1,2	106	43	3	245
2	2	4	0,46	5,6	1,2	412	190	4	125
4	4	16	0,52	5,6	1,2	2187	1234	5	56
6	6	36	0,49	5,6	1,2	4669	2215	6	40

Table 2. Data from the archive of the ROSVETRO FX-800 automated process control system

D	H	S	ξ	υ	ρ	P_a	$P_{\text{э}}$	n	ω
1	1	1	0,37	4,7	1,2	76	32	3	223
2	2	4	0,40	4,7	1,2	412	135	4	113
4	4	16	0,45	4,7	1,2	1594	738	5	36
6	6	36	0,43	4,7	1,2	3019	1370	6	32

CONCLUSION

The developed vertical-axis wind turbine (VAT) is a technologically advanced solution that overcomes the key limitations of traditional analogues. The conducted research, aerodynamic tests and verification of the mathematical model confirmed the following achievements:

Complete suppression of turbulent flows inside the housing and in the generator zone is achieved by introducing a nozzle cascade with a cosine profile and optimising the geometry of the working blades that form confuser-diffuser channels.

Increasing the efficiency of the guide plates due to their spatially periodic configuration, providing laminar acceleration of the flow.

Aerodynamic cooling of the generator module.

This model has practical significance. The installation is capable of providing basic energy consumption (3-5 kWh / day) even at a minimum wind speed (3 m / s). The modular architecture allows the system to scale up and supply energy to residential complexes, remote villages, and infrastructure facilities.

REFERENCES

Afrouzi, H. N., Hassan, A., Wimalaratna, Y. P., et al. (2021). Sizing and economic analysis of stand-alone hybrid photovoltaic-wind system for rural electrification: A case study Lundu, Sarawak. Cleaner Engineering and Technology, 4, 100191. https://doi.org/10.1016/j.clet.2021.100191

Babatunde, O. M., Munda, J. L., & Hamam, Y. (2019). Selection of a hybrid renewable energy system for a low-income household. Sustainability, 11(16), 4282. https://doi.org/10.3390/su11164282

Bezrukikh, P. P., Bezrukikh, P. P. Jr., & Gribkov, S. V. (2014). Wind energy: Reference-methodological publication (P. P. Bezrukikh, Ed.). Intekhenergo-Izdat: Teploenergetik.

Bhutta, M. M. A., Hayat, N., Farooq, A. U., Ali, Z., Jamil, S. R., & Hussain, Z. (2020). Vertical axis wind turbine – A review of various configurations and design techniques. Renewable and Sustainable Energy Reviews, 116, 109404. https://doi.org/10.1016/j.rser.2011.12.004

Faradanesh, B., & Schuff, A. (2003). Dynamic studies of the NYS transmission system with the Marcy CSC in the UPFC and IPFC configurations. IEEE Conference on Transmission and Distribution, 3, 1175–1179.

Frimpong, S. O., Millham, R. C., & Agbehadji, I. E. (2021). A comprehensive review of nature-inspired search techniques used in estimating optimal configuration size, cost, and reliability of a mini-grid HRES: A systemic review. Lecture Notes in Computer Science, 12957, 492–507.

Howell, R., Qin, N., Edwards, J., & Durrani, N. (2010). Wind tunnel and numerical study of a small vertical axis wind turbine. Renewable Energy, 35(2), 412–422. https://doi.org/10.1016/j.renene.2009.07.025

Katkov, V. V. (2024). Vertical-axis wind turbine (Patent RU 230843). Russian Federation Patent Office.

Krishnan, A., Al-Obaidi, A. S. M., & Hao, L. C. (2023). A comprehensive review of innovative wind turbine airfoil and blade designs: Toward enhanced efficiency and sustainability. Sustainable Energy Technologies and Assessments, 60, 103511. https://doi.org/10.1016/j.seta.2023.103511

Kumar, R., Raahemifar, K., & Fung, A. S. (2018). A critical review of vertical axis wind turbines for urban applications. Renewable and Sustainable Energy Reviews, 89, 281–291. https://doi.org/10.1016/j.rser.2018.03.033

Kvitko, A. V., & Azaryan, A. A. (2022). Design features of wind power plants. Kuban State Agrarian University named after I. T. Trubilin.

Luis Silva-Llanca, & Inostroza-Lagos, S. (2021). Optimum power generation assessment in an H-Darrieus vertical axis wind turbine via exergy destruction minimization. Energy Conversion and Management, 243, 114312. https://doi.org/10.1016/j.enconman.2021.114312

Saryyev, K. A., Nazarov, S. B., & Matyakubov, A. A. (2022). Scientific and technical basis for the implementation of combined technologies using renewable energy sources. Syktyvkar University Bulletin. Series 2: Biology. Geology. Chemistry. Ecology, 1(21), 78–86. https://doi.org/10.34130/2233-1277-2021-4-78

Sharma, K. K., Gupta, A., Kumar, R., et al. (2021). Economic evaluation of a hybrid renewable energy system (HRES) using hybrid optimization model for electric renewable (HOMER) software: A case study of rural India. International Journal of Low Carbon Technologies, 16(3), 814–821. https://doi.org/10.1093/ijlct/ctab012

Smirnov, A. V., & Kozlov, D. I. (2020). Advantages and disadvantages of vertical-axis wind turbines. Renewable Energy, 3(45), 34–41.

Solomin, E. V. (2011). Iterative optimization of parameters and operation modes of vertical-axis wind turbines. Bulletin of South Ural State University. Series "Power Engineering", 15(232), 73.

Solomin, E. V., Kirpichnikova, I. M., Amerkhanov, R. A., Korbatov, D. V., Lutavac, M., & Maryanov, A. S. (2018). Application of a wind-hydrogen uninterruptible power supply complex in various climatic conditions. Alternative Energy and Ecology, 30–54.

Saburova, E. A., & Tsytzelskaya, V. A. (2019). Wind energy, working principles of wind turbines, and development prospects. In Proceedings of the XXI International Scientific-Practical Conference (pp. 460–465). Tyumen Industrial University.

Sun, M., Peng, L., Lei, H., Zhang, J., Zhang, Z., Chen, Q., Zhang, G., & Li, J. (2025). A novel small-scale H-type Darrieus vertical axis wind turbine manufactured of carbon fiber reinforced 2.2. Experimental procedures