BULLETIN OF THE POLISH ACADEMY OF SCIENCES
TECHNICAL SCIENCES, Vol. 72(6), 2024, Article number: e151954
DOI: 10.24425/bpasts.2024.151954

MECHANICAL AND AERONAUTICAL ENGINEERING, THERMODYNAMICS

Study on the efficiency of small-scale wind turbine with rotor adapted for low wind speeds

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Abstract. This article aims to present the results of tunnel tests and field tests of small-scale horizontal-axis wind turbines. The article proposes a new concept of turbine rotor adapted to improve efficiency at low wind speeds. The methodology for calculating the rotor and generator is shown. The turbine construction solution is presented briefly, along with the technology for manufacturing turbine components and assembly. An analysis of the obtained results is also conducted.

Keywords: wind turbine; turbine rotor; wind turbine efficiency; wind tunnel tests of wind turbines; field tests of wind turbines.

1. INTRODUCTION

Wind turbines play a significant role in electricity production, especially in the context of sustainable development and greenhouse gas emissions reduction. However, the efficiency of these energy-producing devices is strongly dependent on wind speed, which poses a challenge, especially for small-scale wind turbines. With the increasing demand for sustainable energy sources, small-scale wind turbines are gaining importance as a key element of energy strategy. Research on the efficiency of these turbines at low wind speeds, which are common in many regions of the world, is particularly interesting. This article focuses on an innovative approach to designing wind turbine rotors adapted to operate under such conditions. This article aims to present the results of research on the efficiency of small-scale wind turbines with rotors adapted for low wind speeds. The presented research includes an analysis of both tunnel test results and field test results, allowing for a comprehensive assessment of the performance of these turbines. The article proposes a new concept of turbine rotor aimed at improving device efficiency at low wind speeds. The methodology for calculating the rotor and generator is also presented, providing the basis for analyzing the solution efficiency. The article reviews the existing scientific literature on the study of the efficiency of small-scale wind turbines. Research on the quality of electrical energy under various load conditions, as presented in reference [1], provided valuable data on the impact of small-scale turbines on the power grid. Issues related to energy quality in the power grid, discussed in reference [2], directly affect the efficiency of wind turbines. Reviewing modern design solutions for wind turbines, as outlined in reference [3], identified potential areas for optimizing rotor design. The study on improving the aerodynamic efficiency and structural integrity of turbines, described in reference [4], was crucial for rotor design work. Reference [5] evaluated different turbine concepts in terms of their potential in low wind quality conditions, directly related to the topic of this article. Research on wind turbine rotor efficiency, integrated with a construction tunnel, as presented in reference [6], provided insight into the influence of tunnel width on turbine efficiency. The paper [7] focused on optimizing the shell rotor configuration, which was significant in designing a rotor adapted for low wind speeds. Research on the impact of design TSR on wind speed parameters, described in reference [8], is essential for understanding the operation of multi-blade wind turbines. The machine learning-based blade design method proposed in reference [9] was applied in the algorithm described in Section 1 (Fig. 1) for rotor parameter optimization. Reviewing the control of small wind turbines in challenging conditions, as presented in reference [10], underscores the importance of turbine adaptation to variable wind conditions, which was useful for active braking system development (Fig. 4b). Experiments in the wind tunnel aimed at

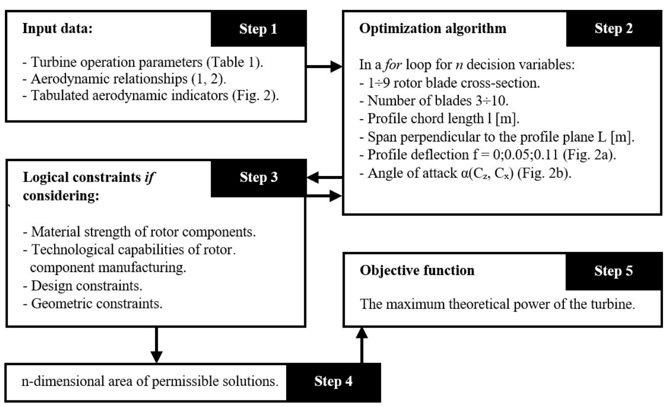

Fig. 1. Schematic diagram of turbine rotor geometry selection. The description of the numerical optimization methodology for geometry is further detailed in reference [27, 29]

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Manuscript submitted 2024-05-21, revised 2024-08-12, initially accepted for publication 2024-08-27, published in November 2024.

investigating the influence of adverse pressure gradients on turbine wake dynamics, as described in reference [11], provided insight into the behaviour of wind turbine wakes. The characterization of wind turbine wake using the FSI method, discussed in reference [12], and the analysis of fluid-structure interaction for wind turbine, presented in reference [13], are essential for understanding the aerodynamic loads and aeroelastic response of turbines. Research on optimal geometric parameters of diffusers for wind turbines, described in reference [14], and evaluation of aerodynamic properties of small wind turbines, presented in reference [15], provide knowledge about airflow optimization around turbines. Studies on the aerodynamic stability of wind turbine blades, discussed in reference [16], are crucial for ensuring turbine safety and efficiency. Research on the aerodynamic stability of wind turbine blades, discussed in reference [17], provided significant information about technological limitations in the development of large-scale wind turbines. In the article [18], experiments in a wind tunnel were presented, allowing for the examination of the influence of adverse pressure gradients on the dynamics of a small horizontal-axis wind turbine wake. The article [19] examined the optimal geometric parameters of diffusers for wind turbines, which is important for increasing the mass flow of air around turbines. The evaluation of the aerodynamic properties of small wind turbines, presented in the article [20], provides knowledge about airflow optimization. Research on the aerodynamic stability of wind turbine blades, discussed in reference [21], is crucial for ensuring turbine safety and efficiency. In [22], the author explores the potential of integrating rooftop-mounted wind turbines into urban buildings. The study develops a seven-step framework to assess the viability of small wind turbines (SWTs) on a 29-metre building, emphasizing the importance of site selection and wind pattern analysis to maximize energy generation, with an estimated annual energy production (AEP) of 1030 kWh and a reduction of 0.64 tCO_2/y. This research provides a comprehensive approach to urban wind energy utilization, potentially applicable to the turbines discussed in this article. In [23], the study investigates whether wind zones in open areas reflect wind conditions in built-up urban areas, focusing on four Polish cities. It highlights that wind zones characterizing an open area do not significantly influence the wind conditions in the built-up areas within those zones, indicating the need for site-specific wind measurements for effective turbine implementation. [24] evaluates the feasibility of wind energy in Surat, Gujarat, India, aiming to select an optimal small commercial turbine for residential use. Using Rayleigh and Weibull probability distribution functions based on yearlong velocity data, the study identifies the most suitable turbine for the location, suggesting an annual energy yield of 8 MW. The insights from these studies are crucial for implementing the described wind turbines in the mentioned areas.

2. CALCULATION OF TURBINE ROTOR GEOMETRY

To design the rotor and generator, boundary conditions for wind turbine operation were assumed according to Table 1. For the selected parameters, generator calculations were performed using dedicated DASYLab software [25]. The rotor geometry was designed in Matlab software [26] using loops and logical conditions [27] according to the scheme presented in Fig. 1. The presented optimization algorithm was based on classical aerodynamic relationships (1, 2) and tabulated values of aerodynamic coefficients (C_z, C_x) for equations (1) and (2) (Fig. 2b) [28] as a function of angle of attack α and variable deflection value f of profile (Fig. 2a). Based on the obtained results in the form of a point cloud (Fig. 3a), rotor geometry was generated using CAD software (Fig. 2b). Considering manufacturing technology and design requirements, a complete rotor was designed (Fig. 3c). Based on data from DASYLab software, a turbine generator was designed (Fig. 4a) with parameters presented in Table 2. In such a designed construction, due to the large surface area of the rotor in the direction parallel to the wind direction and the characteristic shape of the blades, generating high stresses at the rotor axis, a decision was made to apply an active braking system (Fig. 4b), which in critical situations would assist the braking system by setting the turbine rotor parallel to the rear steering flap. This would allow the elimination of the axial force value and reduce rotor speed.

Table 1
Boundary conditions for wind turbine operation

Rotor diameter	1 [m]
Minimum starting wind speed initiating turbine movement	1.5 [m/s]
Optimal wind speed for generator	5 [m/s]
Maximum wind speed activating turbine brake	18 [m/s]

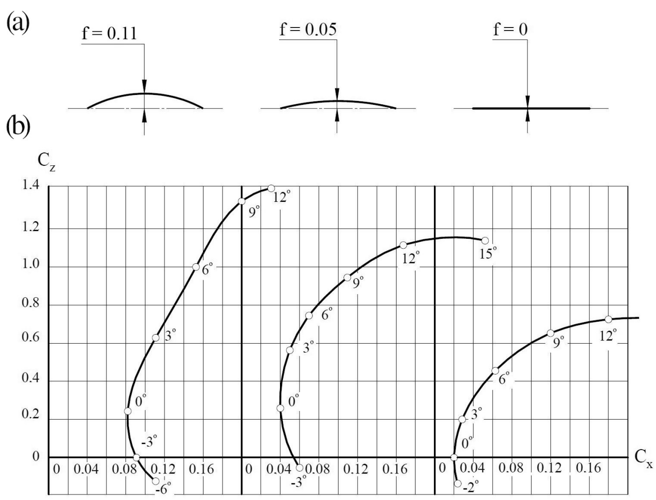

Fig. 2. Characteristics of the bent blade, maximum bending of the profile occurs at half-width [29]

Equations (1) and (2) for selecting rotor geometry [30] implemented in the optimization algorithm (Fig. 1) [27]

$$P_x = C_x \frac{\rho \cdot V_\infty^2}{2} l \cdot L, \tag{1}$$

$$P_z = C_z \frac{\rho \cdot V_\infty^2}{2} l \cdot L, \tag{2}$$

where C_x – drag coefficient; C_z – lift coefficient; ρ – fluid density [kg/m^3]; V_∞ – velocity in the undisturbed area [m/s]; l – chord of the profile [m]; L – span perpendicular to the profile plane [m].

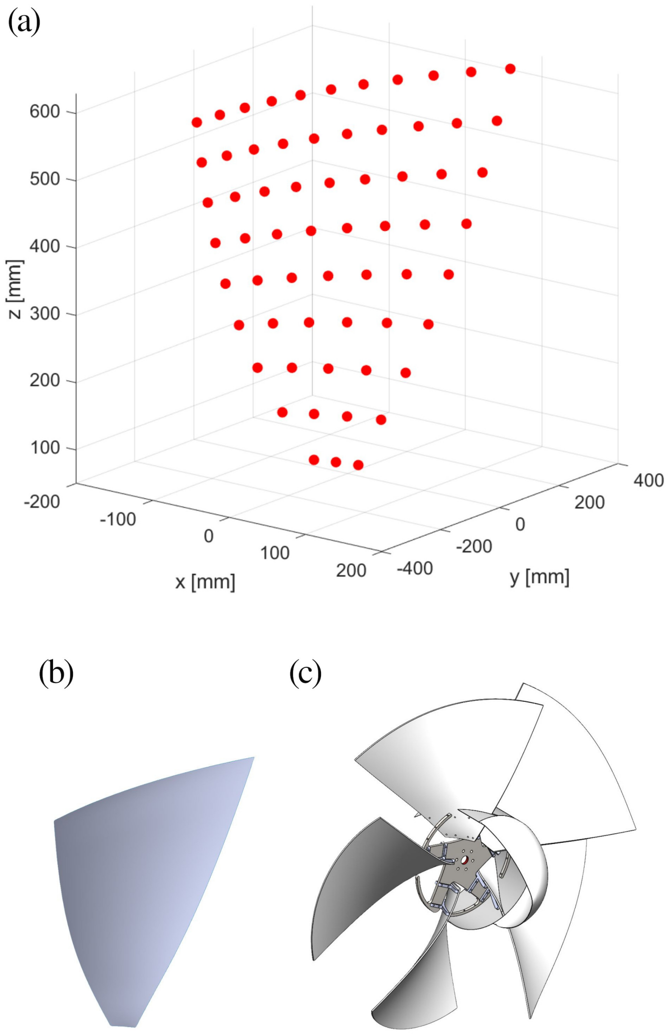

Fig. 3. Stages of rotor design: (a) generation of points defining the blade geometry in Matlab software, (b) modelling of the turbine rotor blade surface based on point cloud in CAD software, (c) turbine rotor design taking into account technological and design requirements

Table 2
Generator turbine parameters

Average magnetic flux diameter	200 [mm]
Number of pole pairs	8 [–]
Number of coils	12 [–]
Number of phases	3 [–]
Number of coils per phase	4 [–]
Neodymium magnets	$40 \times 15 \times 5$ [mm]

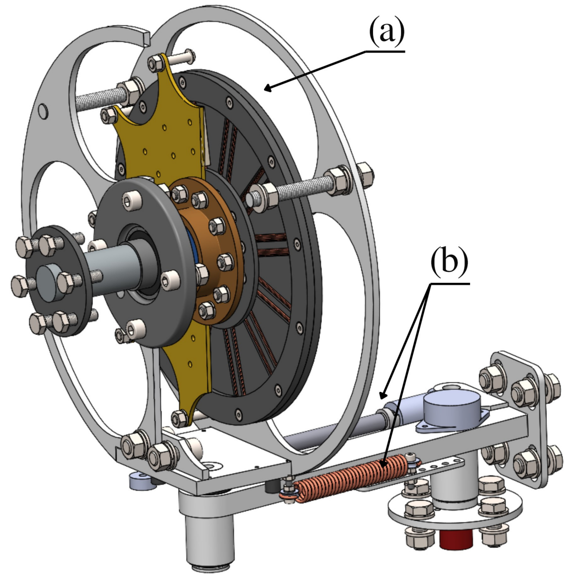

Fig. 4. Spatial model of the turbine generator: (a) turbine generator, (b) active braking system

After the design process, the physical production of all turbine components began. The physical model was created using technologies such as:

- CNC milling on a 3D plotter: blade forms, front hub form, rear blade form, rotor (Fig. 5a).
- Vacuum moulding of composite parts (Fig. 5b) – fiberglass, phenolic resin (LG 285 resin, Hardener HG 286, BX glass fabric 200 g/m^2).
- CNC machining on horizontal and vertical machining centres – generator components (Fig. 5c).
- 2D cutting of flat metal parts on plasma and laser cutters: housings, generator covers, and nacelles (Fig. 5d).

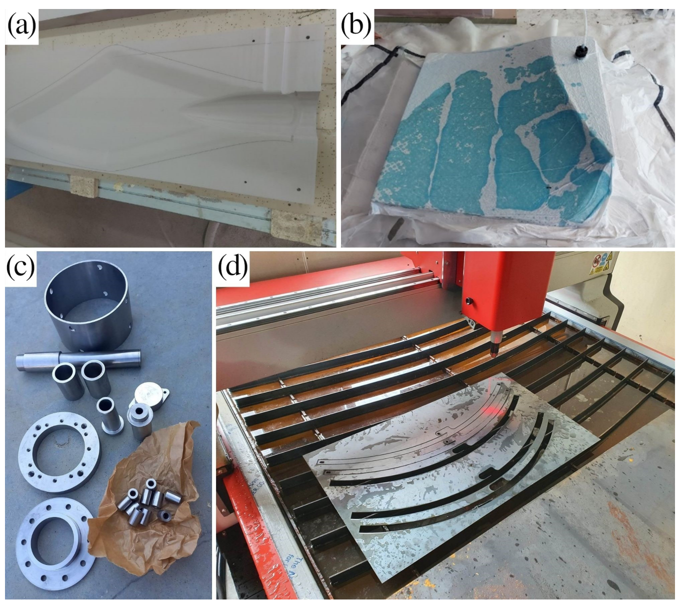

Fig. 5. Wind turbine components: (a) rear blade form, (b) turbine blade, (c) generator components, (d) rotor components

Finally, after validating some of the components and subassemblies, the wind turbine was fully assembled. Figure 6 shows all turbine components in two main views.

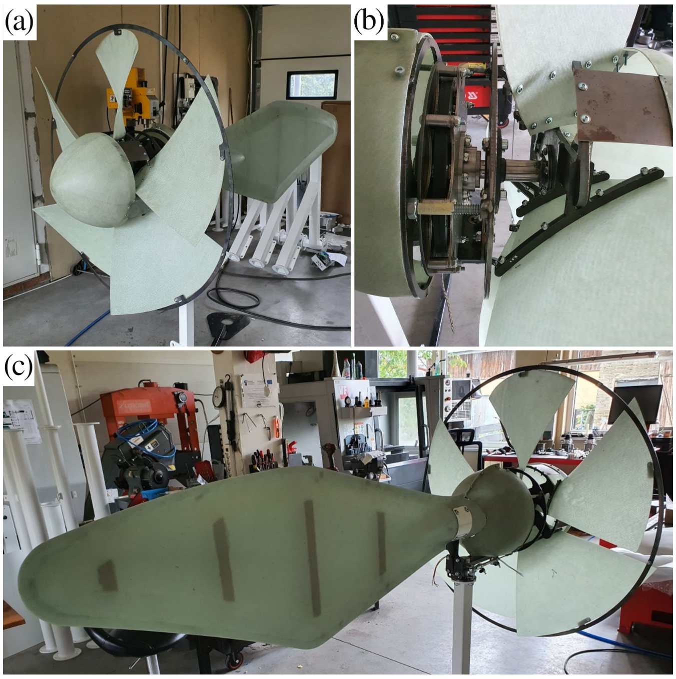

Fig. 6. Wind turbine: (a) isometric front view, (b) generator view, (c) isometric rear view

3. WIND TUNNEL TESTS

After the design, manufacturing, and assembly phases, turbine testing in controlled wind tunnel conditions commenced. The TA 1000 wind tunnel (Fig. 7) along with a dedicated set of sensors was used for the study. Measurement results are presented accordingly in the graphs (Figs. 8– 10).

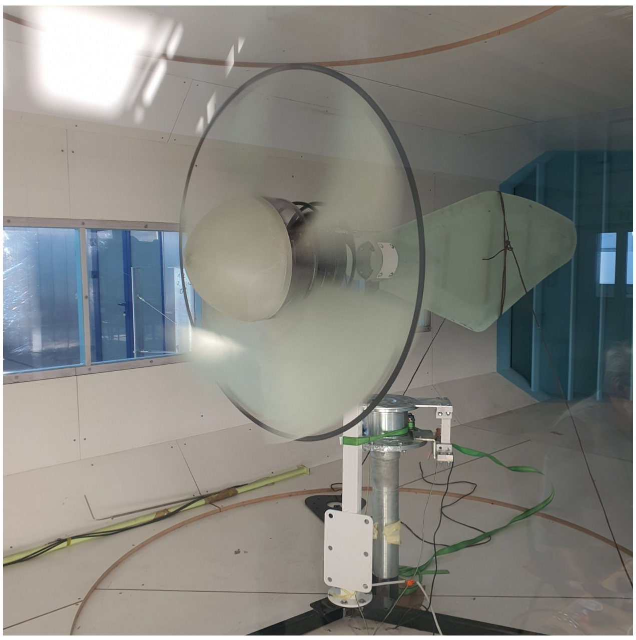

Fig. 7. Testing in the TA 1000 wind tunnel

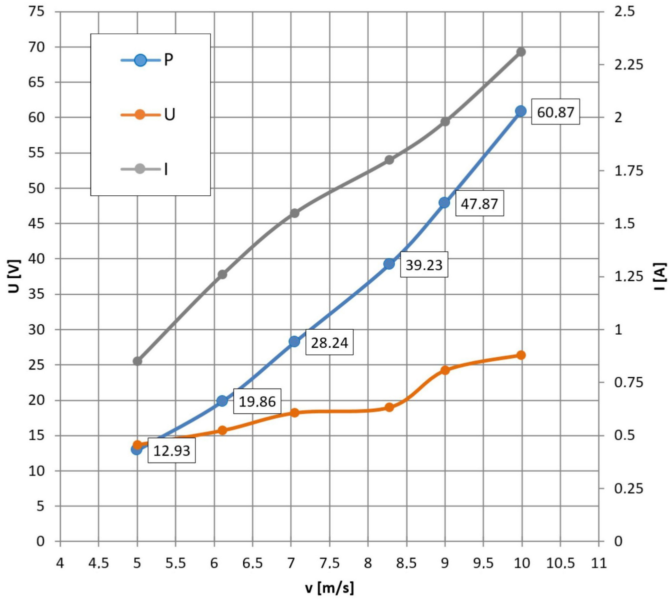

Fig. 8. Wind turbine power as a function of wind speed. P – power [W], U – electrical voltage [V], I – electrical current [A], v – wind speed [m/s]

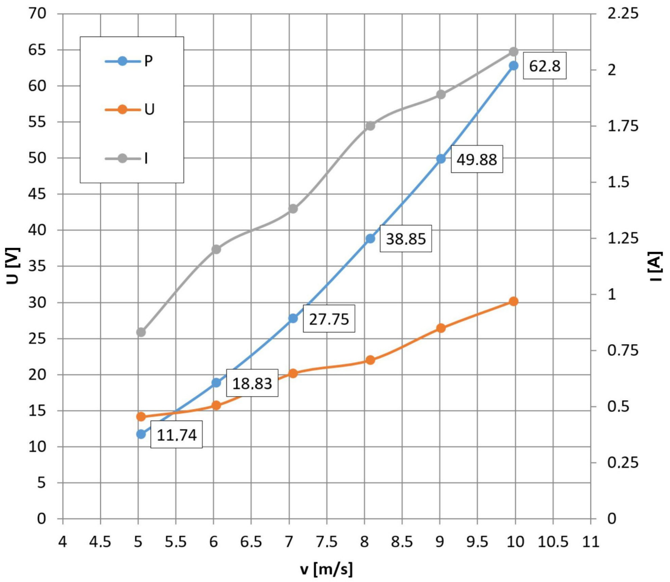

Fig. 9. Wind turbine power as a function of wind speed, without external stiffening clamp. P – power [W], U – electrical voltage [V], I – electrical current [A], v – wind speed [m/s]

After initial tests, it was found that the clamp located on the outer part of the rotor (Fig. 6a) caused a slight imbalance of rotating elements, which could affect the accuracy of the results. Ultimately, it was decided to remove it.

It should be emphasized that the measured power coefficient C_p is for the entire assembly and not just the turbine part. The presented results are discussed in detail in Section 5 (discussion of results).

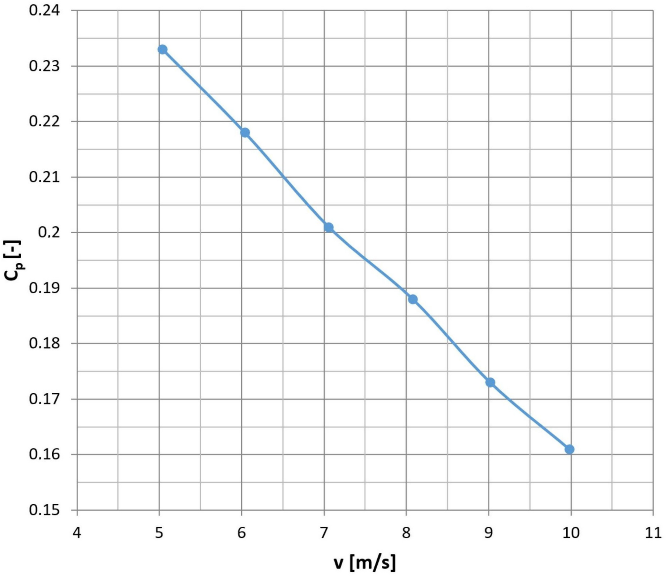

Fig. 10. Dependency of the power coefficient C_p of the entire assembly on wind speed

4. NATURAL ENVIRONMENT TESTING

The final stage of the research was conducting turbine tests in the natural environment to validate the laboratory results. For this purpose, the turbine was placed in a segregated area (Fig. 11a). The measurement area was located in the Podkarpackie Voivodeship in Poland. The turbine was equipped with an electronic system for remote measurement of rotor speed and generated energy (Fig. 11b). Measurements were continuously taken over two months (2023). The obtained results were visualized in the graph (Fig. 12).

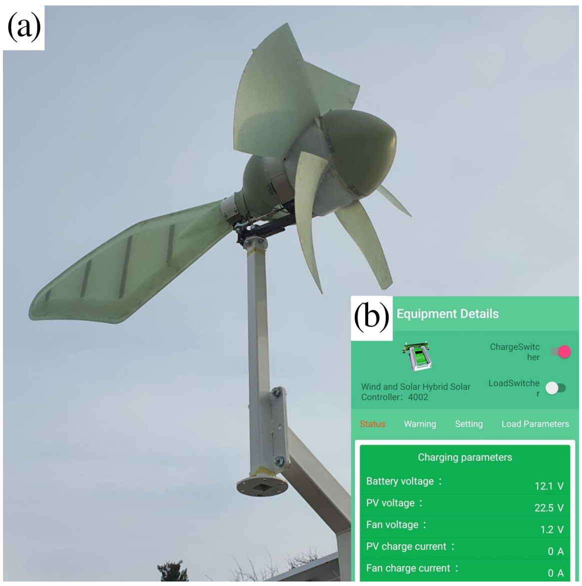

Fig. 11. Testing turbine in the natural environment: (a) view of the tested turbine, (b) remote turbine parameter measurement system

The presented results are discussed in detail in Section 4 (discussion of results).

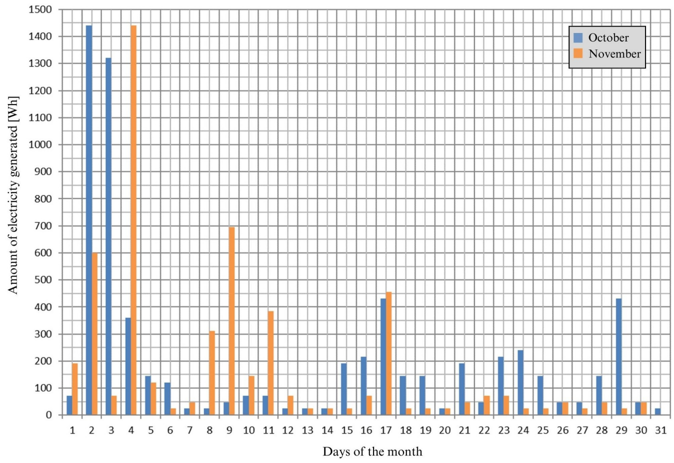

Fig. 12. Results of turbine power measurements in natural conditions

5. DISCUSSION OF RESULTS

The article presents the results of wind tunnel tests and natural environment tests of small-scale horizontal-axis wind turbines adapted for low wind speeds. The laboratory tests presented in Section 3 allowed for estimating the power coefficient C_p of the wind turbine in the wind speed range from 5 m/s to 10 m/s. It should be noted the character of the power curve in Fig. 10 shows that with increasing wind speed, the C_p value decreases. This curve pattern is opposite to the curves of power coefficient in wind speed for analogous V-type wind turbines, as observed, for example, in reference [25]. This suggests that the tested turbine achieves a higher C_p coefficient at low wind speeds but decreases as the wind speed increases. This suggests that turbines of this type could be used wherever, for various reasons, relatively low wind speeds occur.

This curve pattern certainly results from the reactive nature of the rotor operation. At low wind speeds, the axial force directly from the force of the airflow has a much greater impact on rotor movement than the generated aerodynamic force from rotational speed (1, 2). As the rotational speed of the rotor increases, the aerodynamic force becomes more significant, while the axial force decreases in importance. Additionally, considering the characteristic shape of the rotor blades, they increase their surface area from the smallest at the rotor axis to the largest at the outer circumference of the rotor. It can be concluded that with an increase in rotor rotational speed, the circumferential resistance force, which is greatest at the outer part of the rotor, acting on a relatively large surface area, begins to act as a brake. This negatively affects the C_p coefficient value.

The obtained C_p coefficient value of 0.2 for the tested turbine is not satisfactory. According to research [25, Section 3.2], turbines with a similar rotor diameter achieve C_p values around 0.3. However, it should be taken into account that the tested turbine was a prototype. Factors such as manufacturing inaccuracies, assembly inaccuracies, and rotor and generator imbalance could have influenced the C_p value. In the future, further turbine tests are planned in which corrections related mainly to manufacturing techniques and the method of assembly of turbine components will be made.

Tests in the natural environment show that the proposed solution is resistant to atmospheric conditions. The turbine efficiency is at a satisfactory level, indicating that it can be used in the areas described in Section 6.

6. CONCLUSIONS

The proposed solution aims to demonstrate the potential for increasing the efficiency of wind turbines in low-wind speed areas. The described turbines can be applied in locations such as powering road signs, and pedestrian crossings, monitoring systems in areas without access to the grid, supporting the power supply of small residential and commercial buildings, and many others.

Work on the described solution is ongoing. Currently, testing is being conducted to integrate them with photovoltaic systems and independent sources for storing accumulated energy.

To improve the power coefficients, a series of minor changes in the turbine design are planned. The changes will mainly involve blade manufacturing technology to increase repeatability and improve the quality of the obtained surfaces. Minor adjustments will also be made to the turbine generator, focusing on aspects related to the ability to smoothly adjust the alignment between the rotor and stator elements.

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