UDC [620.9:622.012.2:371.61].001.24:622.012

MAXIMIZING THE EFFICIENCY OF LOW-SPEED HORIZONTAL AXIS WIND TURBINES DESIGNED FOR USE IN COAL MINING INDUSTRY

[1]Khaminich O., [2]Zinchenko A., [3,4]Baiul K.

[1]Oles Honchar Dnipro National University
[2]Institute of Transport Systems and Technologies of National Academy of Sciences of Ukraine
[3]Z.I. Nekrasov Iron and Steel Institute of National Academy of Sciences of Ukraine
[4]Dnipro Metallurgical Institute, Ukrainian State University of Science and Technologies

Abstract. The prospects for using a low-speed wind turbine with a horizontal axis of rotation to improve the efficiency of coal industry enterprises during their diversification are investigated. The necessity of addressing the optimal design of wind turbines with a horizontal axis of rotation for such conditions is emphasized, as this can ensure their use both during the operation of enterprises and after their diversification. The relationship equation from the theory of Sabinin-Yuriev has been adapted to the conditions of rotors of low-speed wind turbines, allowing for its analytical solution to be obtained. As a result, an analytical formula for calculating the value of the skew angle has been derived for the first time. This angle is formed between the directions of the vectors of the total velocity of the undisturbed and disturbed flows, depending on the aerodynamic qualities of the profile and the speed of the rotor blade section. This has led to the formulation of equations to analytically determine the components of the integrand function for calculating the wind energy utilization coefficient by the rotor. An analytical dependence of the coefficient of wind energy utilization, which is created by the blade cross-section under the action of the wind, from the aerodynamic qualities of the profile and the speed of the rotor blade cross-section, which does not require solving the connection equation and allows searching for its extrema and direct integration along the rotor blade. For the intervals of change in values characterizing the dependence of the wind energy utilization coefficient of the blade cross-section on the aerodynamic qualities of the profile and the speed of the rotor blade cross-section, calculations were performed that prove the existence of a single maximum in this function, which is located closer to the outer edge of the blade. The value of this maximum changes with a change in the blade cross-section profile, i.e., it depends on the aerodynamic properties of the profile used. Thus, the developed calculation methods allow determining the geometric characteristics of the rotor blade cross-sections of a low-speed wind turbine with a horizontal axis of rotation, namely the angle of twist of the cross-section and the chord length of the blade in the cross-section, as well as the radius of the rotor, which ensure the maximum coefficient of wind energy utilization, depending on the wind speed, rotor rotation frequency, and type of aerodynamic profile of the blade cross-section. Such a methodological approach to calculating rotor parameters allows for the optimal design of horizontal axis wind turbines for coal industry enterprises during their diversification and during the direct operation of enterprises.

Keywords: wind power plant with a horizontal axis of rotation, wind energy utilization coefficient, Sabinin-Yuriev model, rotor speed

1. Introduction

Leading countries around the world have identified decarbonization of production and green energy as the path for their future development. For Ukraine, this development vector necessitates the inevitable diversification of domestic coal industry enterprises, associated with the reorientation of their core activities. In early 2020, the Ministry of Energy and Environmental Protection presented the Concept of Ukraine's "green" energy transition by 2050. The focus is on the gradual reduction of coal use for energy production. Additionally, challenging geological conditions for extraction, depletion of seams and reserves, and high coal production costs create problems in the coal industry and prompt this shift. Moreover, Ukraine is a signatory to the Paris Agreement. Therefore, the transition to alternative and renewable energy sources is relevant for our country. Wind energy can play a key role in the restructuring of coal enterprises as an alternative energy source and a direction for the economic development of depressed coal regions [1–7]. Electricity generated from such a renewable source can not only meet the needs of the enterprise itself but also

Received: 14.04.2025 Accepted: 16.06.2025 Available online: _________

serve as a source of additional income through the sale of excess electricity to the population and other industrial enterprises. It is believed that organizing energy production from wind does not require stopping the enterprise, meaning it can continue to extract or process coal while installing wind energy systems within its industrial site. Subsequently, if fluctuations in the coal market make its extraction unprofitable, the enterprise can completely switch to the production and sale of electricity from wind power installations.

Unlike other enterprises, whose potential for locating wind power installations is limited to their industrial site [8–11], most enterprises in the coal industry, in addition to the area of the industrial site located on the surface, have the opportunity to additionally place wind power plants in mine workings [12–15]. Such locations may include vertical shafts, chambers near shafts, horizontal and inclined drifts.

Given the specific nature of the underground location of wind power installations and the concentration of coal industry enterprises in Ukraine in predominantly steppe regions, it would be most rational to use rotors with a horizontal axis of rotation for them [1, 7, 9, 13, 16, 17]. The efficiency of such wind power plants is determined by the radius of the rotor, the number of rotor blades, and the patterns of change in the chord length along the blade radius and the change in the twist angle along the blade radius, which are calculated within the design calculation [7, 9, 12, 16]. The purpose of the design calculation is to establish the geometric characteristics of the rotor that provide the desired power on the shaft of the wind power plant for the selected meteorological conditions. When performing design calculations, the following initial data are usually used [4, 6, 9–13]: wind speed; rotor rotation frequency; power at the shaft of the wind turbine; aerodynamic characteristics of the blade profile depending on the angle of attack [7, 8]. The geometric characteristics of the rotor, which must be determined during the design calculation, are [7, 14, 18–21]: rotor radius; number of blades; law of change in blade chord length along the radius; law of change in blade twist angle along the radius. However, a conventional design calculation does not provide for maximum rotor efficiency, i.e., it does not impose the condition that the rotor will be able to extract the maximum amount of energy from the wind flow. This task is multifactorial and, given the large number of parameters, can be solved in various ways.

Thus, the aim of this work is to develop a method for calculating the geometric characteristics of the rotor blade cross-sections of a low-speed wind turbine with a horizontal axis of rotation, namely the twist angle of the cross-section and the chord length of the blade in the cross-section, as well as the rotor radius, which ensure the maximum wind energy utilization coefficient, depending on the wind speed, rotor rotation frequency, and type of aerodynamic profile of the blade cross-section.

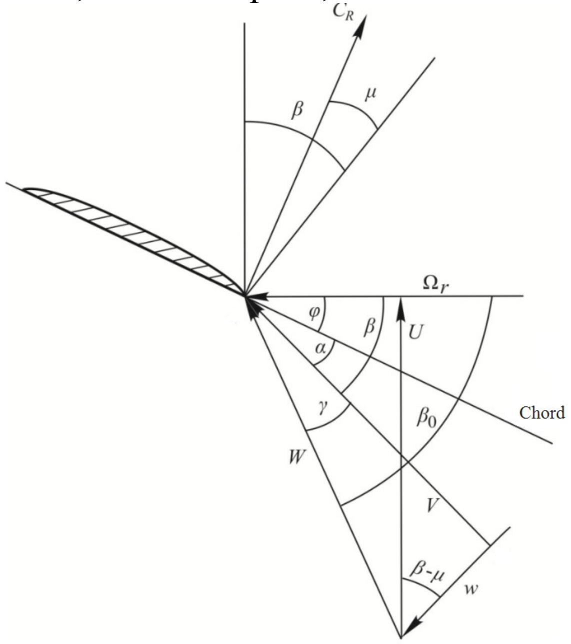
2. Methods

The torque that rotates the rotor around the axis is determined by the characteristics of the flow around the blades, and therefore the design calculation of wind turbine rotors is based on the study of the triangle of velocities and forces acting on the radial cross-section of the blade (Figure 1) [18]. This approach, after integration along the blade length, taking into account the final flow losses, allows determining the torque created by the rotor under the action of air [7, 9, 13, 14, 18–21]:

$$Q = \pi R^3 \rho U^2 \int_{i_0}^{0,9} C_R \sigma \sqrt{1+\lambda^2 i^2} \frac{\cos^2 \chi}{\cos^2 \mu} (\cos \chi - \lambda i \sin \chi) i di ; \qquad (1)$$

$$\chi = \gamma + \mu ; \quad \lambda = \frac{\Omega R}{U} ; \quad i = \frac{r}{R} ; \quad \sigma = \frac{NC}{2\pi R} ; \quad i_0 = \frac{R_1}{R} ,$$

where Q – torque generated by the rotor, N·m; C_R – coefficient of total aerodynamic force; ρ – air density, kg/m^3; R_1 – rotor hub radius, m; i_0 – dimensionless rotor hub radius; N – number of blades in the rotor; C – blade chord length in cross section, m; β – angle formed between the direction of the total velocity vector of the disturbed flow and the plane of rotation of the rotor, degree; μ – angle of deviation of the total aerodynamic force from the normal to the chord of the profile, degree; r – radius of the cross-section, m; γ – angle of skew, i.e. the angle formed between the directions of the total velocity vectors of the undisturbed and disturbed flow, degree; R – rotor radius, m; σ – rotor fill factor; Ω – rotor rotation frequency; i – imensionless radius of the current cross section; λ – rotor speed; χ – effective angle of attack, degree.



W – vector of the total velocity of the undisturbed flow; V – vector of the total velocity of the disturbed flow; w – vector of the total induction velocity due to the presence of a rotor in the flow; α – angle of attack; φ – cross-sectional twist angle; Ω_r – rotor rotation frequency; U – air velocity along the axis; β_0 – flow angle, which is formed between the direction of the full velocity vector of the undisturbed flow and the rotor rotation plane

Figure 1 – Diagram of air velocity distribution and aerodynamic forces in the radial section of the wind turbine rotor blade with a horizontal axis of rotation [18]

Since the general formula for calculating the wind energy utilization coefficient is [7, 9, 13, 14, 18–21]:

$$C_P = \frac{\Omega Q}{\frac{1}{2}\pi R^2 \rho U^3},$$

then, taking into account (1), we obtain:

$$C_P = 8\lambda \int_{i_0}^{0,9} \frac{\sqrt{1+\lambda^2 i^2}}{\cos^2 \mu} \psi i di; \; \psi = G\left(\cos\chi - \lambda^2 i^2 \sin\chi\right)\cos^2\chi; \; G = \frac{C_R \sigma}{4}, \quad (2)$$

where C_P – is the wind energy utilization coefficient; G – is Yuriev's constant.

To determine the integral on the right side of the first equation (2), it is necessary to determine the value of the angle of attack and the aerodynamic characteristics of the blade profile for each cross-section, calculate the value of the angle of skew and the effective angle of skew. For this purpose, according to the recommendations of Sabinin and Yuriev [7, 9, 13, 14, 18–21], the following relationship equation is used

$$\sin(\beta_0 + \mu - \chi)\sin(\chi - \mu) = G\cos\chi; \quad ctg\beta_0 = z; \quad z = \lambda i, \quad (3)$$

where β_0 – the angle of incidence of the flow formed between the direction of the total velocity vector of the undisturbed flow and the plane of rotation of the rotor, degree; z – the speed of the rotor blade cross-section.

As a general rule when performing design calculations, if there are no other restrictions in terms of strength or production, the geometric characteristics that allow for maximum power under the initial conditions should be selected. This principle not only improves the calculation results, but also simplifies the algorithm for selecting and justifying parameters. Accordingly, it follows from the first equation (2) that the rotor's wind energy utilization coefficient will be maximum if the integrand in each blade cross-section reaches its maximum. At the same time, we will require that in each blade section, the twist angle of the section provides such an angle of attack at which the value of the total aerodynamic force coefficient will be maximum:

$$\varphi = \beta_0 - \gamma - \alpha_M,$$

where φ – angle of twist of the cross section, degree; α_M – angle of attack at which the effective coefficient of total aerodynamic force of the selected profile will be maximum, degree.

The maximum of the subintegral function in each blade section is ensured by selecting the value of the rotor fill coefficient, which is part of the Yuriev constant, and by which the chord length of the blade in each section is determined:

$$C = \frac{8\pi}{N}\frac{G_M}{C_R}R,$$

where G_M – the value of the Yuriev constant, which ensures the maximum coefficient of wind energy utilization in a specific section of the blade.

The radius of the wind turbine rotor is selected at the end of the design calculation, taking into account the power of the wind turbine specified in the design assignment

$$R = \sqrt{\frac{P_0}{\rho U^3} \frac{2k_P}{\pi C_P}},$$

where k_P – reserve coefficient; P_0 – power specified in the calculation task, W.

Thus, to implement the method of calculating the optimal parameters of a low-speed wind turbine rotor that ensure the most efficient use of wind energy, it is necessary to obtain an analytical solution to the first of equations (3), determine the analytical form of the subintegral function in the first equation (2) and calculate the corresponding integral in order to calculate the maximum possible value of the wind energy utilization coefficient.

3. Theoretical part

Let us analyze the angles included in the connection equation from the Sabinin-Yuriev theory, the first of equations (3). It includes three angles (Figure 1): the angle of deviation of the total aerodynamic force from the normal to the chord of the profile (μ),which is determined by the type of cross-section profile, the effective angle of skew (χ),which is determined by the angle of skew, i.e., the angle formed between the directions of the total velocity vectors of the undisturbed and disturbed flows, as well as the angle of flow incidence, which is formed between the direction of the total velocity vector of the undisturbed flow and the plane of rotation of the rotor (β_0),which is determined by the speed of the rotor cross-section. Solving the relationship equation consists in determining the value of the effective angle of inclination based on the values of the other two angles. At the same time, as noted by some researchers [7, 9, 13, 14, 18–21], the angles μ and χ are close in value and do not exceed 30° (Tables 1, 2) [18], while the angle β_0 varies between 20 and 90° (Figure 2). Given that for low-speed wind turbines, the speed of the rotors is limited to a value of 3, the following assumption is acceptable:

$$\beta_0 + \mu >> \chi . \tag{4}$$

Taking into account assumption (4), the first equation (3) will take the following form

$$\sin(\beta_0 + \mu)\sin(\chi - \mu) = G\cos\chi . \tag{5}$$

Table 1 – Aerodynamic characteristics of profiles corresponding to the maximum coefficient of total aerodynamic force [18]

Profile	α, °	C_R	μ, °	Profile	α, °	C_R	μ, °
A-9%	16.0	1.090	7.70	NASA-0015	20.0	1.427	5.63
A-12%	16.0	1.051	7.35	NASA-0018	20.0	1.397	5.75

A-15%	16.0	1.046	7.92	NASA-0021	20.0	1.387	5.80
A-18%	18.0	1.241	7.63	NASA-2210	20.0	1.176	10.14
A-21%	20.0	1.353	8.04	NASA-2212	16.0	1.180	5.28
B-8%	16.0	0.813	13.00	NASA-2217	20.0	1.183	9.15
B-12%	16.0	0.957	6.09	NASA-0006	24.0	0.920	25.52
B-16%	18.0	0.972	7.03	NASA-0009	24.0	1.037	19.14
B-20%	16.0	0.965	6.01	NASA-0012	22.0	1.560	6.37
P-II 10%	16.0	1.224	5.46	TsAGI-6-8.2%	12.0	0.926	5.37
P-II 14%	18.0	1.445	6.36	TsAGI-6-12%	18.0	1.200	7.38
P-II 16%	22.0	1.438	9.13	TsAGI-6-13%	14.0	1.055	5.44
P-III 15.5%	24.0	1.780	10.81	TsAGI-6-16%	20.0	1.262	9.20
Mynk-1	18.0	0.829	18.10	TsAGI-6-19%	24.0	1.301	11.35
Mynk-2	15.0	0.911	7.45	TsAGI-6-20%	20.0	1.266	8.45
Mynk-3	15.0	1.072	4.51	TsAGI-719	20.0	1.346	10.48
Mynk-6	18.0	1.228	5.56	TsAGI-731	16.0	1.109	7.39
Mynk-12	18.0	1.299	5.64	TsAGI-732	16.0	1.016	12.60
Mynk-15	18.0	1.261	7.74	TsAGI-734	14.0	1.010	4.91
Clark-YH-8%	14.0	0.985	5.08	TsAGI-831	18.0	1.409	8.08
USA-27	16.0	1.392	5.32	NAVY N60	14.6	1.617	1.75
35A	22.0	1.513	10.33	35B	15.0	1.381	5.68

Table 2 – Intervals of change in the aerodynamic characteristics of profiles, corresponding to the maximum coefficient of total aerodynamic force [18]

Parameter	Change interval limits	
	Minimum	Maximum
α	13.5	24.0
μ	1.75	25.52
C_R	0.81	1.78
G	0.20	0.45
$tg\mu$	0.03	0.48
Λ	0.22	0.46

Equation (5) is a linkage equation from the Sabinin-Yuriev theory, adapted to the conditions of low-speed wind energy installations, where the rotor speed is limited to a value of 3 [7, 9, 13, 14, 18–21]. Obtaining an analytical solution to this equation is a primary task of the article. This equation, after applying the formula for the sine of the difference of two angles and combining like terms, transforms into the equation:

$$\cos(\phi+\chi)=0\,;\ ctg\phi=\frac{\sin\mu\sin(\beta_0+\mu)+G}{\cos\mu\sin(\beta_0+\mu)},$$

the solution of which can be obtained in analytical form:

$$\chi=\frac{\pi}{2}-\phi, \tag{6}$$

where ϕ – characteristic fictitious angle, degree.

It should be noted that formula (6) is a solution to equation (5), that is, the linkage equation from the Sabinin-Yuriev theory, adapted to the conditions of low-speed wind energy installations. The application of formula (6) for design calculations is limited by the condition that the rotor speed does not exceed 3, meaning that assumption (4) must hold. However, using formula (6) as a solution to the first of the equations (3), that is, the linkage equation from the Sabinin-Yuriev theory in its general form, for example, for calculating high-speed wind energy installations, is not permissible.

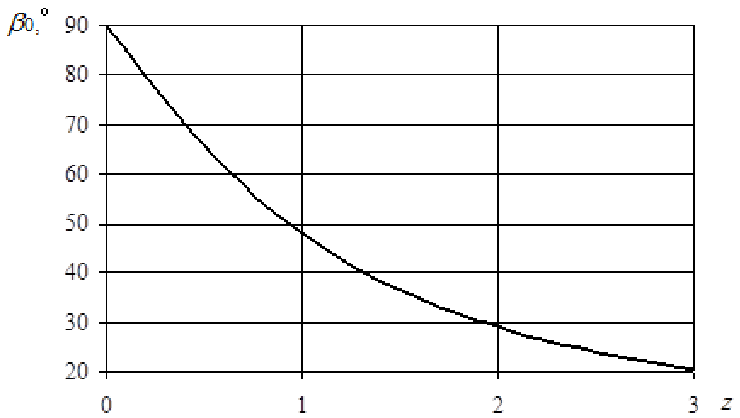


Figure 2 – Dependence of the flow angle on the speed of the rotor blade cross-section

Considering (2), (3) and (6) together, the formula for calculating the coefficient of wind energy utilization by the rotor takes the form

$$C_P = \frac{8}{\lambda}\int_{z_0}^{z_1} F dz;$$

$$F = \frac{z^3\sqrt{1+z^2}\,\Lambda(ba-\Lambda)a^2}{\left(a^2+(atg\mu+\Lambda)^2\right)^{\frac{3}{2}}};\; a = \frac{1+ztg\mu}{\sqrt{1+z^2}};\; b = \frac{1-z^2tg\mu}{z^2};\; \Lambda = \frac{G}{\cos^2\mu}; \quad (7)$$

$$z_0 = \lambda i_0, \qquad z_1 = 0{,}9\lambda, \quad (8)$$

where F – the coefficient of utilization of wind energy generated by the cross-section of the blade under the action of wind; a – Yuriev parameter module; Λ – Yuriev parameter; b – Yuriev parameter coefficient.

4. Results and discussion

The possibility of determining the maximum coefficient of wind energy utilization of the rotor is determined by the existence of maxima in the function F, the first equation (7), at the corresponding interval of values of the rotor blade cross-section speed (8 at characteristic values of the parameters included in it (Figures 3, 4). The results of calculations (Figures 5 and 6) using formulas (7) for the conditions

(Tables 1, 2) show the existence of a maximum of the function F in almost all cases considered (Table 3).

Figures 4 and 5 and Table 3 show that the conditions for the existence of the maximum of the function F, as well as the coordinates of this maximum and the value of the function at it, depend in a complex way on the parameters of the function. That is, there is a need to determine the parameters of this maximum and the conditions for its existence by analytical methods.

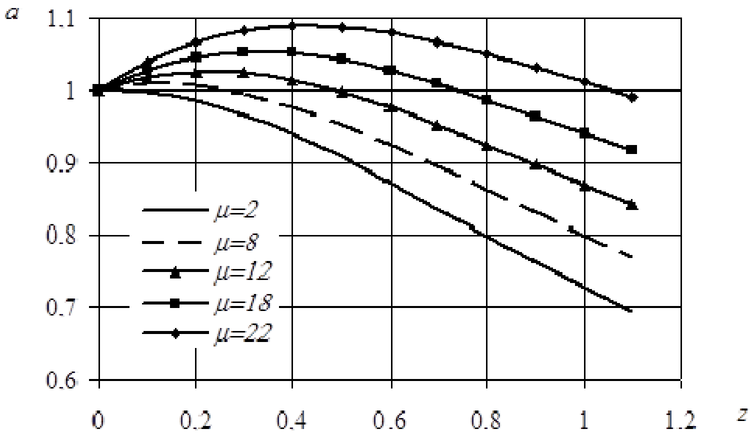


Figure 3 – Dependence of the Yuriev parameter modulus on the rotor blade cross-section speed at different values of the angle of deviation of the total aerodynamic force from the normal to the profile chord

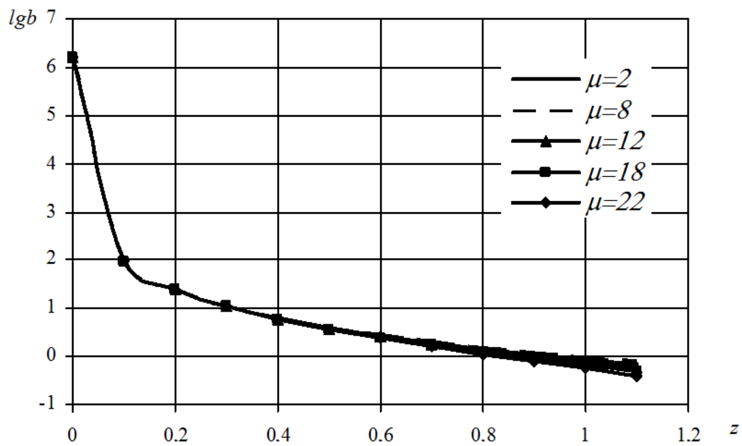
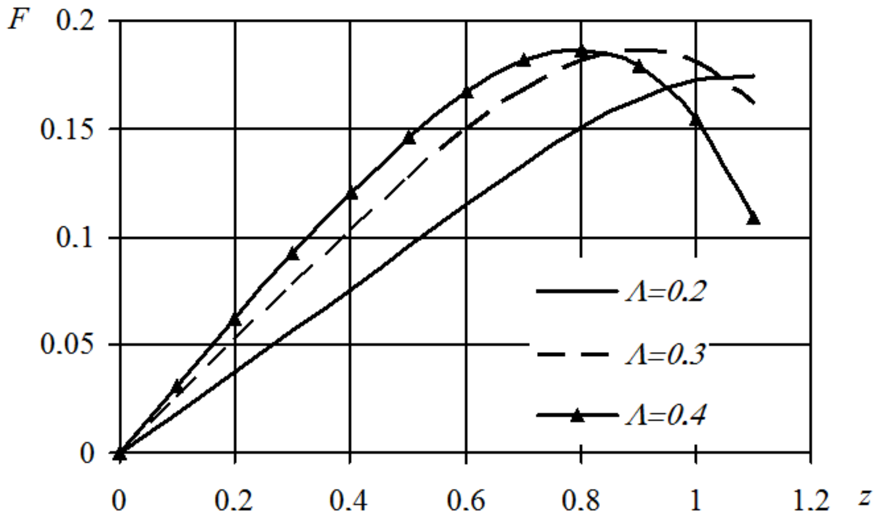
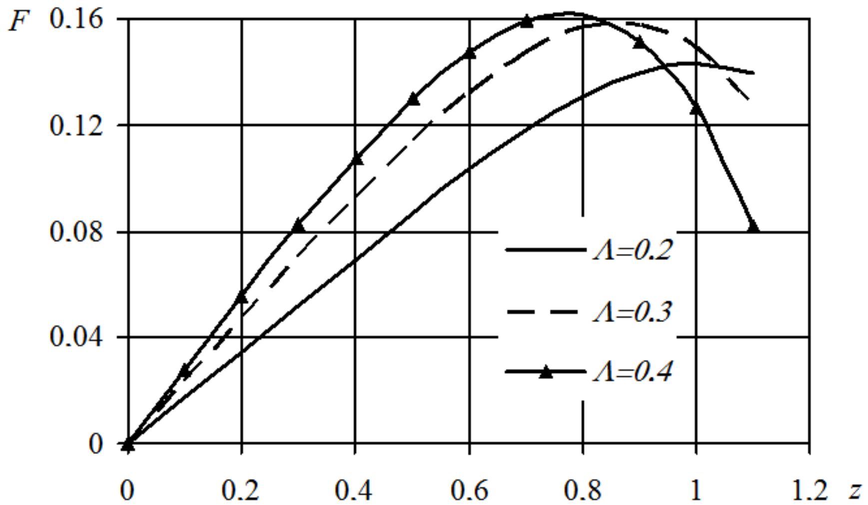


Figure 4 – Dependence of the logarithm on the Yuriev parameter coefficient on the rotor blade cross-section speed at different values of the angle of deviation of the total aerodynamic force from the normal to the profile chord

A)



B)



C)

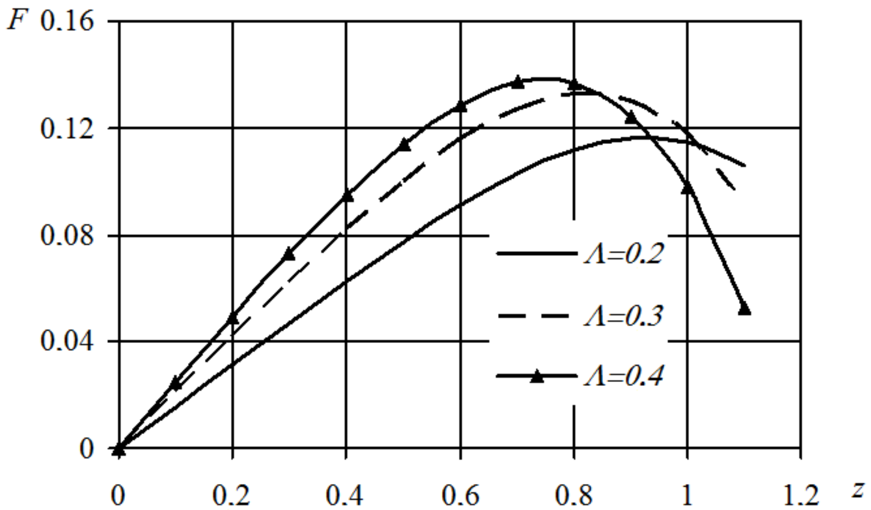
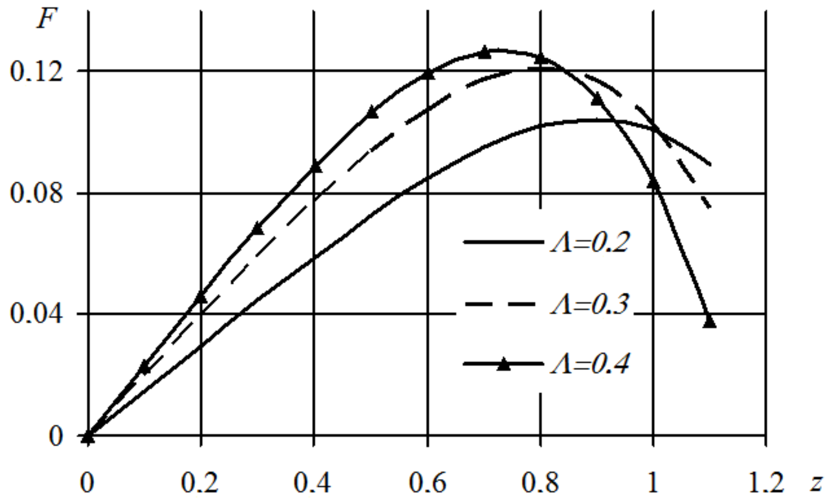
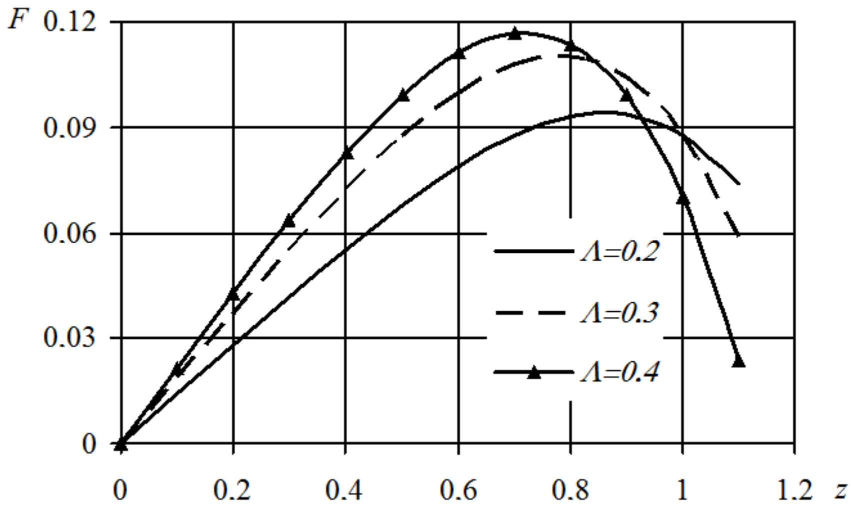


Figure 5 – Dependence of the wind energy utilization coefficient, which is created by the blade cross-section under the action of wind, on the speed of the rotor blade cross-section at different values of the Yuriev parameter coefficient, when the angle of deviation of the total aerodynamic force from the normal to the chord of the profile (μ) is equal to: A) 2°; B) 8°; C) 12°;

A)



B)



C)

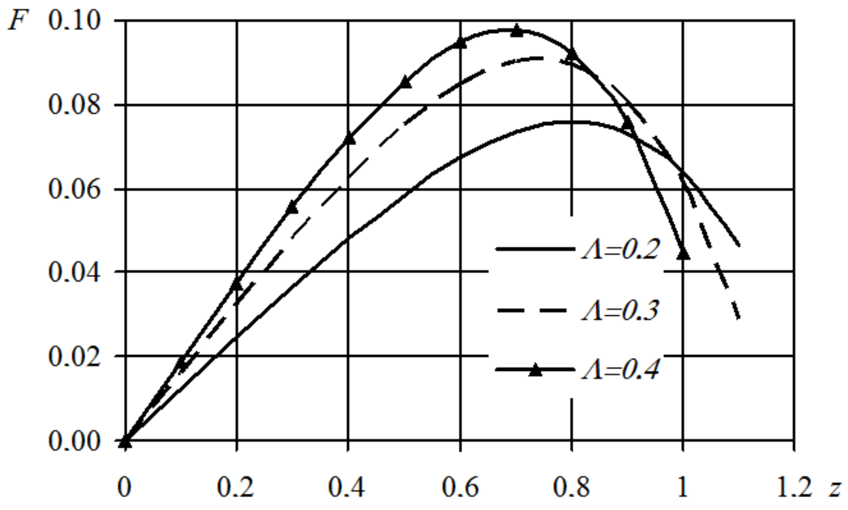


Figure 6 – Dependence of the wind energy utilization coefficient, which is created by the blade cross-section under the action of wind, on the speed of the rotor blade cross-section at different values of the Yuriev parameter coefficient, when the angle of deviation of the total aerodynamic force from the normal to the chord of the profile (μ) is equal to: A) 16°; B) 18°; C) 22°;

Table 3 – Values of rotor blade cross-section speed and wind energy utilization coefficient at which the maximum wind energy utilization coefficient created by the blade cross section is achieved

Λ	z_{max} / F_{max}				
	$tg\mu=0.03$	$tg\mu=0.13$	$tg\mu=0.23$	$tg\mu=0.33$	$tg\mu=0.43$
0.2	0.901/0.1865	1.00/0.1431	0.901/0.1159	0.901/0.0934	0.801/0.0758
0.3	0.801/0.1867	0.901/0.1581	0.801/0.1326	0.801/0.1100	0.701/0.0903
0.4	–/–	0.801/0.1614	0.701/0.1372	0.701/0.1165	0.701/0.0978

The dependencies shown in Figures 5 and 6 have pronounced maxima for the dependence of the wind energy utilization coefficient on the blade cross-section on the blade cross-section speed, which allows determining the ranges of maximum efficiency of the rotor with an aerodynamic profile depending on the wind speed and rotor diameter.

5. Conclusions

The results of the study presented in the article allow us to draw the following conclusions.

It has been shown that the value of the wind energy utilization coefficient created by the blade cross-section under the action of wind is determined by the angle of attack. the effective angle of inclination, and the speed of the rotor blade cross-section. Taking this into account, the linkage equation from the Sabinin-Yuriev theory has been adapted to the conditions of rotors in low-speed wind energy installations, which has allowed for the derivation of its analytical solution. As a result, an analytical dependence has been obtained for determining the angle of skew formed between the directions of the total velocity vectors of the undisturbed and disturbed flows based on the aerodynamic parameters of the profile. Considering this dependence, the components of the integrand function for calculating the wind energy utilization coefficient by the rotor have been determined analytically.

For low-speed wind energy installations, an analytical dependence of the wind energy utilization coefficient created by the blade's cross-section on the aerodynamic qualities of the profile and the rotor blade's cross-section speed has been established, which does not require solving the linkage equation and allows for the search for its extrema and direct integration along the rotor blade.

For the intervals of change in values characterizing the dependence of the wind energy utilization coefficient of the blade cross-section on the aerodynamic qualities of the profile and the speed of the rotor blade cross-section, calculations were performed that prove the existence of a single maximum in this function, which is located closer to the outer edge of the blade. The value of this maximum depends on the aerodynamic properties of the profile used and varies according to the parameters of the blade cross-section.

Thus, the developed calculation methods allow determining the geometric characteristics of the rotor blade cross-sections of a low-speed wind turbine with a horizontal axis of rotation, namely the twist angle of the cross-section and the chord length of the blade in the cross-section, as well as the rotor radius, which ensure the maximum wind energy utilization coefficient, depending on the wind speed, rotor rotation frequency, and type of aerodynamic profile of the blade cross-section. The proposed methodological support for calculating rotor parameters will allow the use of not only the surface areas of coal enterprises, but also underground areas, by placing low-speed wind turbines in horizontal workings. This makes it possible to solve the problem of optimal design of wind turbines with a horizontal axis of rotation for the conditions of coal industry enterprises during their diversification and during the direct operation of enterprises. Thus, wind energy can become an important element of a just transition from coal energy, providing the creation of new jobs, diversifying the economies of regions, and addressing environmental issues, provided that existing barriers to development are overcome.

Conflict of interest

Authors state no conflict of interest.

REFERENCES

1. Tarasov, S.V., Shkrabets, F.P., Zadontsev, V.A. and Otchich, S.V. (2014), *Vetroenergetika. Informatsionno-analiticheskiy obzor po alternativnoy energetike* [Wind Energy. Information and analytical review on alternative energy sector], in Dzenzerskoho, V.A. and Pivnyak, G.G. (ed.), National Mining University, Dnepropetrovsk, Ukraine.

2. European Commission (2020), "Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions. A hydrogen strategy for a climate-neutral Europe", available at: https://op.europa.eu/en/publication-detail/-/publication/5602f358-c136-11ea-b3a4-01aa75ed71a1/language-en (Accessed 25 February 2024).

3. Bulat, A., Voloshyn, O., Potapchuk, I., Yemelianenko, V., Zhovtonoha, M., Zhevzhyk, O., and S. Manigandan. (2019) , "Mathematical Modeling of the Gas Dynamic Parameters of Impinging Heat-Transfer Medium Jet in Borehole Thermal Reaming Process", *Science and Innovation*, no. 15(3), pp. 17–23. https://doi.org/10.15407/scine15.03.017

4. Chemeris, I.F., Oksen, Yu.I. and Bokij, B.V. (2006), "Use of the energy potential of the mine ventilating jet", *Geo-technical mechanics*, vol. 67, pp. 359–370.

5. Dyakun (Slobodiannykova), I.L. (2014), *Povysheniye effektivnosti energeticheskoy pererabotki uglya* [Increasing the efficiency of energy coal processing], Naukova Dumka, Kyiv, Ukraine.

6. Drukovanyi, M.F. and Yanovych, V.P. (2016), *Alternatyvni dzherela enerhii* [Alternative energy sources], Vinnytsia National Agrarian University, Vinnytsia, Ukraine.

7. Abramovskii, Ye.R. and Lychagin, N.N. (2014), *Problemy optimizatsii parametrov venrovykh dvigatelei* [The mathematical modeling and optimal design of wind engine of different capacities and purposes], Science and Education, Dnipropetrovsk, Ukraine.

8. Bardakjian, A., Mandadakis, P. and Tingle, A. (2017), "Efficiency comparison of horizontal axis wind turbines and bladeless turbines", *PAM Review Energy Science & Technology*, vol. 4, pp. 1–16. https://doi.org/10.5130/pamr.v4i0.1461

9. Pivnyak, G.G., Shkrabets, F., Noiberher, N. and Tsyplenkov, D. (2015), *Osnovy vitroenerhetyky* [Basics of wind energy], NMU, Dnepropetrovsk, Ukraine.

10. Pivnyak, G.G. and Shkrabets, F.P. (2013), *Alternatyvna enerhetyka v Ukraini* [Alternative energy in Ukraine], National Mining University, Dnepropetrovsk, Ukraine.

11. Kucheriava, I.M. and Sorokina, N.L. (2015), "Renewable energy in the world and in Ukraine will stagnate in 2019 – early 2020", *Hidroenerhetyka Ukrainy*, vol. 1(2), pp. 38–44.

12. Sinchyk, O.M., Mykhailychenko, D.A., Boyko, S.M., Horodniy, O.M. (2013), "Features of operation of the autonomous wind-power installation in the underground mine iron workings or mines", *Visnyk Of Chernihiv State Technological University. Series. Technical Sciences*, no. 3 (67), pp. 224–232.

13. Dzenzerskyi, V.A., Tarasov, S.V. and Kostyukov, I.Yu. (2011), *Vetroustanovki maloy moschnosti* [Small wind turbines], Scientific Opinion, Kiev, Ukraine.

14. Maiorov, K. (2012), "Wind Energy of Ukraine", *Energosberezhenie,* no. 10, pp. 17–20.

15. Łyskawiński, W., Kowalski, K. and Wojciechowski R.M. (2024), "Experimental Assessment of Suitability of Darrieus and Savonius Turbines for Obtaining Wind Energy from Passing Vehicles", *Energies*, vol. 17, no. 7, 1558; https://doi.org/10.3390/en17071558

16. Begal, V.N. (2011), "Development of wind energy in the Zaporizhzhia region", *Energosberezhenie*, no. 6, pp. 22–23.

17. Carranza Castillo, O., Reyes Andrade, V., Rodríguez Rivas, J.J. and Ortega González, R. (2023), "Comparison of Power Coefficients in Wind Turbines Considering the Tip Speed Ratio and Blade Pitch Angle", *Energies*, vol. 16, no. 6, 2774, https://doi.org/10.3390/en16062774

18. Abramovskii, Ye.R., Gorodko, S.V. and Sviridov M.V. (1987), *Aerodinamika vetrodvigateley: ucheb. posobie* [Aerodynamics of wind engines: tutorial. Benefit], DNU, Dnepropetrovsk, Ukraine.

19. Abramovskii, Ye.R., Avrakhov, F.I., Lychahin M.M. and Leshchenko I.H. (2012), *Zadachi i vpravy z vitroenerhetyky*

[Problems and exercises in wind energy], Science and Education, Dnepropetrovsk, Ukraine.

20. Li, W., Xiong, Y., Su, G., Ye, Z., Wang, G. and Chen Z. (2023), "The Aerodynamic Performance of Horizontal Axis Wind Turbines under Rotation Condition", *Sustainability*, Section Energy Sustainability, vol. 15, no. 16, 12553, https://doi.org/10.3390/su151612553

21. Li, Y., Guo, X., Li, R., Li, D., Dong, Y.and Zhao, L. (2021), "Unsteady characteristics of pressure on wind turbine blade surface in the field", *Modern Physics Letters B*, vol. 35, no. 17, 2150281, https://doi.org/10.1142/S021798492150281X

About the authors

Khaminich Oleksandr*,** Candidate of Technical Sciences (Ph.D.), Associate Professor, Oles Honchar Dnipro National University (DNU) under the Ministry of Education and Science of Ukraine, Dnipro, Ukraine, khaminich_a_v@i.ua ***(Corresponding author), ORCID ***0000-0002-2621-8206***

Zinchenko Andrii, Candidate of Physical and Mathematical Sciences, Senior Researcher, Department of Dynamics and Strength of New Types of Transport, Institute of Transport Systems and Technologies of National Academy of Sciences of Ukraine, Dnipro, Ukraine, zina@dsu.dp.ua, ORCID ***0000-0003-0281-6663***

Baiul Konstantin*,** Doctor of Technical Sciences, Senior Researcher, Department of Technological Equipment and Control Systems, Z.I. Nekrasov Iron and Steel Institute of National Academy of Sciences of Ukraine, Dnipro, Ukraine; Department of Industrial Engineering, Dnipro Metallurgical Institute, Ukrainian State University of Science and Technologies, Dnipro, Ukraine, baiulkonstantin@gmail.com, ORCID ***0000-0003-1426-7956

ЗАБЕЗПЕЧЕННЯ МАКСИМАЛЬНОЇ ЕФЕКТИВНОСТІ ТИХОХІДНИХ ВІТРОЕНЕРГЕТИЧНИХ УСТАНОВОК З ГОРИЗОНТАЛЬНОЮ ВІССЮ ОБЕРТАННЯ, ЩО ПРОЄКТУЮТЬСЯ ДЛЯ ПІДПРИЄМСТВ ВУГІЛЬНОЇ ГАЛУЗІ

Хамініч О., Зінченко А., Баюл К.

Анотація. Досліджуються перспективи використання тихохідної вітроенергетичної установки з горизонтальною віссю обертання для підвищення ефективності функціонування підприємств вугільної галузі в період їх диверсифікації. Обговорюється можливість використання для генерації вітрової енергії не тільки площі промислових ділянок вугільних підприємств, що розташовані на денній поверхні, а, й, підземні площі, які можна використати розташовуючи вітроенергетичні установки в горизонтальних та вертикальних виробках. Вказано на необхідність для таких умов вирішення питання оптимального проектування вітроенергетичних установок з горизонтальною віссю обертання, що може забезпечити їх використання як під час експлуатації підприємств, так, й, після їх диверсифікації. Рівняння зв'язку з теорії Сабініна-Юр'єва було адаптоване до умов роторів тихохідних вітроенергетичних установок, що дозволило отримати його аналітичне розв'язання. За рахунок цього вперше отримана аналітична формула для розрахунку значення куту скосу, тобто куту, який утворюється між напрямками векторів повної швидкості незбуреного та збуреного потоків, від аеродинамічних якостей профілю та швидкохідністю перерізу лопаті ротора. Це дозволило отримати формули для визначення в аналітичному вигляді складових підінтегральної функції для визначення коефіцієнту використання енергії вітру ротором. Встановлена аналітична залежність коефіцієнту використання енергії вітру, який створюється перерізом лопаті під дією вітру, від аеродинамічних якостей профілю та швидкохідністю перерізу лопаті ротора, що не потребує розв'язання рівняння зв'язку, та дозволяє пошук її екстремумів та безпосереднє інтегрування вздовж лопаті ротора. Для інтервалів змінення значень, що характеризують залежність коефіцієнту використання енергії вітру перерізом лопаті від аеродинамічних якостей профілю та швидкохідністю перерізу лопаті ротора, проведені розрахунки, що доказують існування у цієї функції одного максимуму, який розташовується ближче до зовнішнього краю лопаті. Величина цього максимуму змінюється при зміні профілю перерізу лопаті, тобто залежить від аеродинамічних властивостей профілю, що використовується. Таким чином, розроблені методи розрахунку дозволяють визначати геометричні характеристики перерізів лопаті ротора тихохідної вітроенергетичної установки з горизонтальною віссю обертання, а саме кут закрутки перерізу та довжину хорди лопаті в перерізі, а також радіус ротора, які забезпечують максимальний коефіцієнту використання енергії вітру, в залежності від швидкості вітру, частоти обертання ротора та типу аеродинамічного профілю перерізу лопаті. Таке методичне забезпечення розрахунків параметрів роторів дозволяє вирішувати питання оптимального проектування вітроенергетичних установок з горизонтальною віссю обертання для умов підприємств вугільної галузі при їх диверсифікації та під час безпосередньої експлуатації підприємств.

Ключові слова: вітроенергетична установка з горизонтальною віссю обертання, коефіцієнт використання енергії вітру, модель Сабініна-Юр'єва, швидкохідність ротора