Wind Turbine's Aerodynamic Multiplication Parameters for Different Types of Generators

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Abstract. Energy transition is impossible without wind power development. The need for a mechanical multiplier to match the speeds of a wind turbine and generator leads to deterioration of the technical system's indicators. Refusal of a mechanical multiplier is possible with the help of aerodynamic multiplication. Despite the presence of work in this direction, there is still no coverage of the influence of aerodynamic multiplication parameters on the choice of a generator. Main objectives of the study – analyze the requirements that a generator makes to wind turbine's aerodynamic multiplication parameters. How these objectives were achieved: construction of regression models for existing wind turbines describing the dependence of the rotor diameter and the angular velocity of the wind turbine on the power; optimization of secondary wind velocity by the power of the wind turbine; proof of maximum of the secondary wind does not depend on the fixing radius of the secondary wind turbine; obtaining the dependence of the fixing radius of the secondary wind turbine on the angular velocity of the generator. The most important results are the calculation of the upper power limit, at which the use of aerodynamic multiplication is appropriate; obtaining recommendations for the selection of the secondary wind turbine fixing radius for different types of generators. The significance of the obtained results is in the systematization of experience foundations for selection of aerodynamic multiplication parameters; the formation of tasks for the optimization of wind power plant parameters according to strength parameters and the development of special generators.
***Keywords*:** aerodynamic multiplication, regression model, secondary wind flow, fixing radius, wind turbine power, angular velocity.

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Parametrii de multiplicare aerodinamică ai turbinelor eoliene pentru diferite tipuri de generatoare

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***Rezumat*.** Tranziția energetică este imposibilă fără dezvoltarea energiei eoliene. Necesitatea unui multiplicator mecanic care să se potrivească cu vitezele unei turbine eoliene și ale generatorului duce la deteriorarea indicatorilor sistemului tehnic. Refuzul unui multiplicator mecanic este posibil cu ajutorul multiplicării aerodinamice. În ciuda prezenței muncii în această direcție, nu există încă o acoperire a influenței parametrilor de multiplicare aerodinamică asupra alegerii unui generator. Obiectivele principale ale studiului – analiza cerințelor pe care un generator le face față de parametrii de multiplicare aerodinamică ai turbinei eoliene. Cum au fost atinse aceste obiective: construirea unor modele de regresie pentru turbinele eoliene existente care descriu dependența diametrului rotorului și viteza unghiulară a turbinei eoliene de putere; optimizarea vitezei vântului secundar prin puterea turbinei eoliene; dovada maximului vântului secundar nu depinde de raza de fixare a turbinei eoliene secundare; obţinându-se dependenţa razei de fixare a turbinei eoliene secundare de viteza unghiulară a generatorului. Cele mai importante rezultate sunt calculul limitei superioare de putere, la care este adecvată utilizarea înmulțirii aerodinamice; obţinerea de recomandări pentru selecţia razei de fixare a turbinei eoliene secundare pentru diferite tipuri de generatoare. Semnificația rezultatelor obținute este în sistematizarea bazelor experienței pentru selectarea parametrilor de multiplicare aerodinamică; formarea sarcinilor de optimizare a parametrilor centralei eoliene în funcție de parametrii de rezistență și dezvoltarea de generatoare speciale.
***Cuvinte-cheie*:** multiplicarea aerodinamică, modelul de regresie, fluxul secundar al vântului, raza de fixare, puterea turbinei eoliene, viteza unghiulară.

Параметры аэродинамического мультиплицирования ветротурбины для разных типов генераторов

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Аннотация. Энергетический переход невозможен без развития ветроэнергетики. Потребность в наличии механического мультипликатора для согласования скоростей ветротурбины и генератора приводит к ухудшению технико-экономических показателей системы. Отказ от механического мультипликатора возможен с помощью аэродинамического мультиплицирования. Несмотря на наличие робот в этом направлении, до сих пор отсутствует освещение влияния параметров аэродинамического мультиплицирования на выбор генератора. Основные цели исследования – анализ требований, которые предъявляет генератор к параметрам аэродинамического мультиплицирования ветротурбины. Для достижения поставленных целей были решены следующие задачи: построение регрессионных моделей для существующих ветротурбин, описывающих зависимость диаметра ротора и угловую скорость ветротурбины от мощности оборудования; оптимизация скорости вторичного ветрового потока по мощности ветротурбины; доказательство тезиса, что максимум вторичного ветрового потока не зависит от радиуса закрепления вторичной ветротурбины; получение зависимости радиуса закрепления вторичной ветротурбины от угловой скорости генератора. Наиболее важными результатами является расчет верхнего предела мощности, при котором использование аэродинамического мультиплицирования целесообразно; получение рекомендаций по выбору радиуса закрепления вторичной ветротурбины для генераторов разных типов. Значимость полученных результатов заключается в систематизации опыта и теоретических основ для выбора параметров аэродинамического мультиплицирования; формирование задач для оптимизации параметров ветроэнергетических установок по прочностным параметрам и разработки специальных генераторов.

***Keywords*:** аэродинамическое мультиплицирование, регрессионная модель, вторичный ветровой поток, радиус закрепления, мощность ветротурбины, угловая скорость.

INTRODUCTION

Improving the environmental situation is possible only with the active development of alternative energy, which includes wind energy. According to the report [1], from 2021 to 2028 the installed capacity of wind power plants (WPP) will triple. With the development of materials for wind turbine blades, it is possible to increase the unit power of WPP [2]. But on the way to reducing the cost of high-power WPP technology, an insurmountable obstacle is the need for a mechanical multiplier (step-up gearbox) to match the angular velocity of rotation of the wind turbine and the generator axis [3]. With increasing WPP power, there is a tendency to reduce the angular velocity of rotation of its rotor to reduce mechanical loads on the blades, reduce noise emissions and vibrations of the support. For generators, on the contrary, increasing their angular velocity helps to reduce weight and dimensions and improve dynamic characteristics. The presence of a mechanical multiplier leads to:

- reduction in reliability indicators of mechanical equipment of wind turbines (the average time to failure of the multiplier is 2.5-3 times less than for the generator) [4];
- deterioration of environmental characteristics due to oil leakage [5] and increased noise emission (for example, a 15 MW Vestas wind turbine has a noise emission [6] of 115.3 dB, a significant part of which is associated with the operation of the multiplier [7]);
- increased costs for service and replacement of lubricant in the multiplier [8].

Currently, an alternative to using a multiplier can be:

- the use of low-speed generators, which eliminates the advantages of using high-speed generators and significantly worsens the weight and size indicators [9];
- introduction of aerodynamic multiplication (ADM), in which small wind turbines with generators are placed on the blades of a large wind turbine that does not have its own generator, for which the speed of the secondary wind flow is proportional to the fixing radius [10].

Despite the fact that the scheme with ADM was proposed by Ufimtsev A. almost 100 years ago and implemented by Krasovsky N. [11, 12], the lack of strong and at the same time light materials for the construction of large turbine blades did not allow the widespread implementation of their ideas and proposals by

Hutter U. [13] and Madsen H. [14]. Only in the 21st century, the Concord company, headed by Golubenko M., built and patented a wind power plant with aerodynamic multiplication using a primary wind turbine with a horizontal axis of rotation [10, 15]. The theoretical principles of such wind turbines are developed in the works of Aleksievsky D. [16, 17], who developed a mathematical model of a wind turbine with ADM, investigated the manifestations of auto-optimization at a constant speed of the secondary wind turbine and obtained the power characteristics of the secondary wind turbine. The development of practical power control schemes for wind turbines with ADM is the subject of the work of the Andrienko P. team [18, 19], which proved that the use of a converter at full generator power allowed to reduce the minimum operating speed of the primary wind flow. Author in his research focused on the use of schemes with partial energy conversion to reduce the installed power of the converter. Several years ago, the Morgan L. team from the UK introduced the study of wind turbines with ADM based on a primary wind turbine with a vertical axis of rotation (X-rotor) [20-22]. They managed to develop the ideas of Jamieson P. [23] on the study of limitations associated with the operation of a secondary wind turbine and conduct detailed modeling of aerodynamic processes of wind turbines with ADM.

A separate issue is 3D transient Computational Fluid Dynamics (CFD) modeling to study the load on the blades of the primary wind turbine, the issue of air turbulence, etc. In traditional wind turbines, this issue is actively studied [24]. But for CFD modeling of a wind turbine with ADM, input data on the radius of attachment of the secondary wind turbine are required, tied to the generator speed. Currently, this task is not covered in the literature.

It should be noted that all existing works are focused on the use of serial electric machines: Krasovsky N. – synchronous generator 1000 rpm, Golubenko M. – inductor generator 600 rpm, Andrienko P. and Aleksievsky D. – synchronous generator with permanent magnets 600 rpm, author in previous research – asynchronous motor with a phase rotor of the crane series in the generator mode 1200 rpm, Morgan L. – synchronous generator with permanent magnets 400 rpm. Accordingly, based on these conditions, the parameters of the wind turbine were calculated. Unlike the mechanical multiplier, aerodynamic multiplication has a nonlinear dependence on the power of the wind turbine, the speed of the secondary wind flow and the fixing radius [16]. There is currently no study in the literature of the influence of the parameters of aerodynamic multiplication on the choice of the generator. The purpose of this article is to analyze the requirements that the angular velocity of the generator imposes on the aerodynamic multiplication parameters of a wind turbine.

I. METHODS OF RESEARCH

To achieve the goal, the work used methods of regression analysis of the parameters of existing high-power wind turbines. The parameters for the regression model were calculated using MS-EXCEL. Due to the fact that the results for regression modeling were obtained in the form of existing technical solutions, statistical processing of the obtained data was not provided. Optimization methods were used to find the optimal power of the primary wind turbine at the maximum of the secondary wind flow. The study was conducted on the basis of LLC "Pluton IC" (Zaporizhzhya) and the Laboratory of Industrial Electronics of the Engineering Educational and Scientific Institute of Zaporizhzhia National University in accordance with existing plans.

A feature of the ADM wind turbine was the installation of small high-speed secondary wind turbines on the blades of a large primary wind turbine (Fig. 1), which, rotating under the action of the primary wind flow, created a secondary wind flow of significant speed for the secondary wind turbines. This allowed the secondary wind turbine to drive generators without using a multiplier.

In Fig. 1, the following designations are used: 1 – blades of the primary wind turbine; 2 – nacelle with generator and electrical equipment; 3 – secondary wind turbines; 4 – support; Rz – fixing radius of the secondary wind turbine; H – height of the axis of the primary wind turbine; D1 – diameter; w1, w2 - angular velocity of primary and secondary wind turbine; V2 - secondary wind flow. The parameters that determine aerodynamic multiplication are the secondary wind flow and the fixing radius of the secondary wind turbine.

II. RESULTS OF RESEARCH

The theory of analysis and construction of wind power plants with aerodynamic multiplication is currently in its initial state. Only low-power models have been physically built by Krasovsky N. [12] and Aleksievsky D. [16] and a prototype of a 750 kW wind turbine by Golubenko M. TG-750 [10]. Andrienko P. has studied in detail an autonomous wind turbine with an ADM of 1000 kW. Due to the lack of experimental data, it makes sense to turn to a large-power wind turbine of a traditional design and statistically process a large number of options.

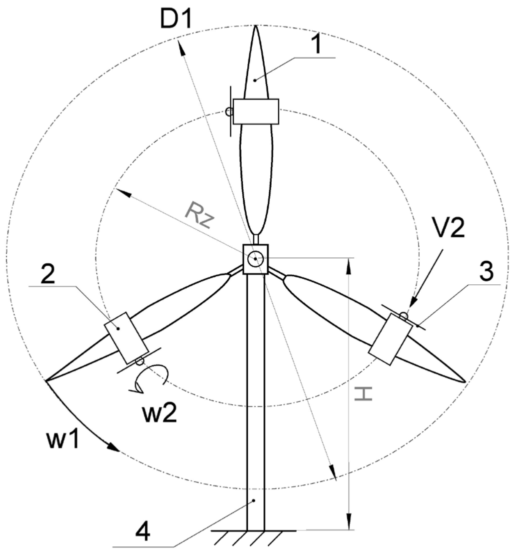


Fig. 1. Scheme of a wind turbine with ADM.

Considering that the primary wind turbine should be designed with the best power and strength characteristics, that is, it is possible to use the experience of powerful wind turbines that currently exist.

Using information from the site [25], markers were used to plot the dependence of the diameter D_1 of existing wind turbine models (points) and the angular velocity ω_1 of rotation (triangles) on the power P of the wind turbine (Fig. 2, a and Fig. 2, b, respectively). Using regression analysis methods [26-28], these dependencies were approximated by linear equations [29], the graphs of which are shown in Fig. 2 by solid lines:

$$D_1 = 0,0133P + 66,355\,. \quad (1)$$

$$\omega_1 = -0,0011P + 19,06\,. \quad (2)$$

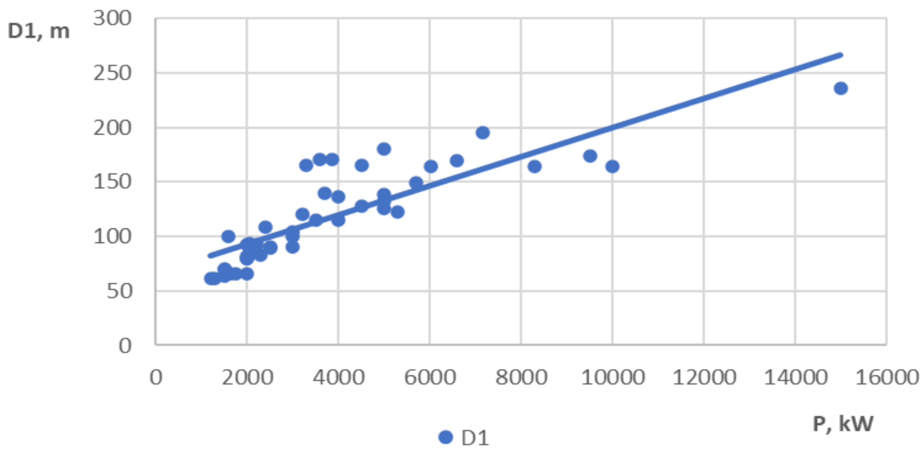
It is known [16, 23] that the speed of the secondary wind flow V_2 proportional to the fixing radius of the secondary wind turbine R_Z and the angular speed of rotation of the primary wind turbine ω_1.

$$V_2 = \omega_1 \cdot R_Z\,. \quad (3)$$

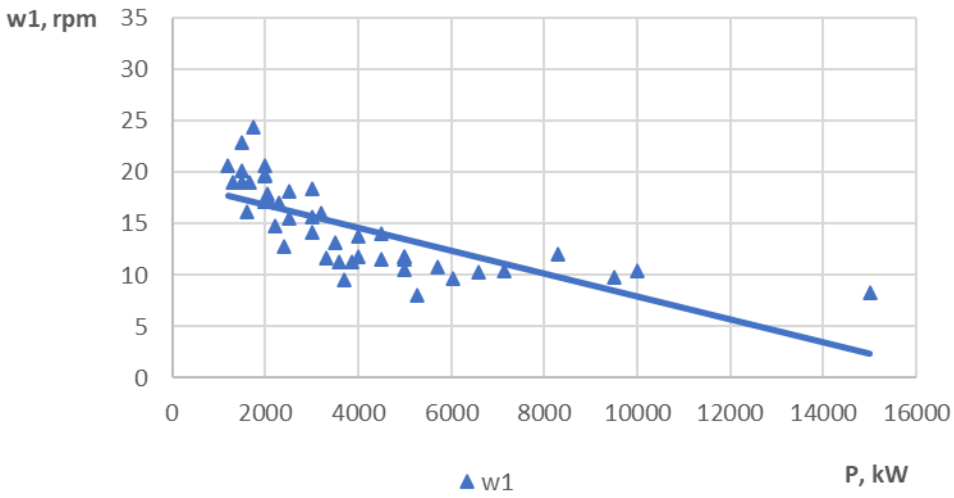
Conveniently enter the relative fixing radius $R_Z^* = \frac{R_Z}{R_1}$, where $R_1 = 0,5D_1$ - radius of the primary wind turbine.

If we find the product of expressions (1) and (2) taking into account (3), the expression for the secondary wind flow after simplification can be written as:

$$V_2 = \left(-7,59 \cdot 10^{-7} P^2 + 0,00937P + 66,17\right) \cdot R_Z^*\,. \quad (4)$$



a



b

Fig. 2. Dependences of the diameter D_1 of existing wind turbines (a) and the angular velocity of rotation ω_1 (b) on the power of the wind turbine P.

The obtained value does not mean that you should focus only on this figure. This power characterizes the current level of technology, which provides the maximum ratio for aerodynamic multiplication. Obviously, other parameters of the primary wind turbine can be used under given conditions, but the question of effective aerodynamic conversion of wind energy by the primary wind turbine becomes open in this case.

But it is clear that the efficiency of the secondary wind turbine decreases due to the decrease in the speed of the secondary wind flow for large-capacity wind turbines.

It should also be noted that the secondary wind flow velocities do not reach the values at which the effects of aerodynamic compressibility and excessive aeroacoustic emission begin to play a role. In the study [30], this threshold wind flow velocity was estimated at 184 m/s.

It is not difficult to show that the resulting equation has a maximum that does not depend on the fixing radius. If we find the derivative of the function V_2 by power P, equating it to zero and solving the resulting expression, we can find that the maximum speed of the secondary wind flow is achieved for a wind turbine with a capacity of 6100 kW. The graph of the dependence of the speed of the secondary wind flow on the power of the wind turbine at a relative fixing radius of $R_Z^* = 0,5$ is shown in Fig. 3.

The required radius of the secondary wind turbine can be calculated from its power:

$$R_2 = \sqrt{\frac{1/i \cdot P}{0,5 \cdot \rho \cdot \pi \cdot C_p \cdot V_2^3}}, \quad (5)$$

where ρ - air density, C_p - power coefficient, i - number of ADM channels (number of secondary wind turbines).

At a given speed ratio of the secondary wind turbine Z_2 and its radius can be found for the speed V_2 possible angular velocity of rotation of the generator ω_2.

$$\omega_2 = \frac{V_2 \cdot Z_2}{R_2} \quad (6)$$

Given a power coefficient $C_p = 0,4$ of and speed ratio $Z = 5$ [23], it is possible to obtain the required fixing radius of the secondary wind turbine for existing generators of various types [25] by the method of successive approximation using formulas (4)-(6).

Currently, such generators are used in wind power in various power ranges (Table 1).

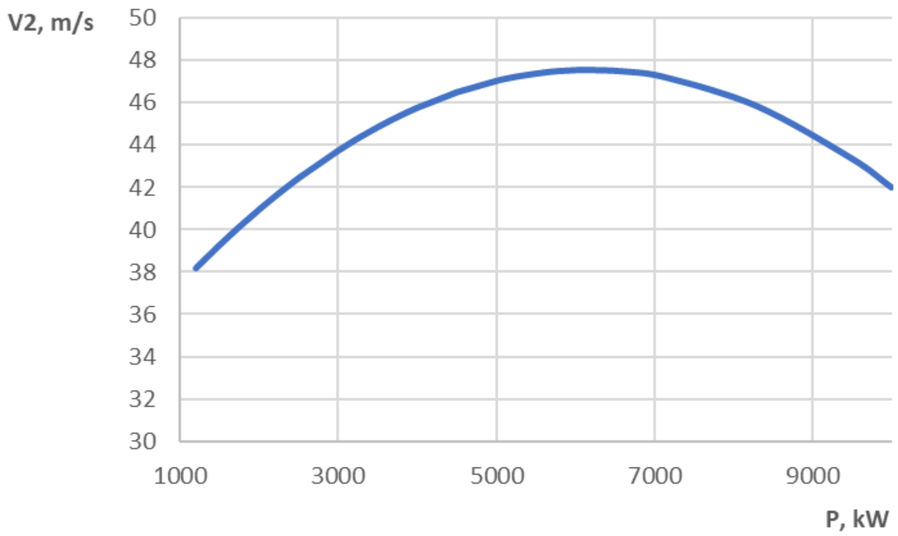


Fig. 3. The graph of the dependence of the speed of the secondary wind flow on the power of the wind turbine.

Table 1

Generator types and their speeds for different wind turbine power ranges

Generator	Angular velocity, rpm		
	250-1000 kW	1000-3000 kW	>3000 kW
Asynchronous with squirrel-cage rotor	1500	1500	-
Asynchronous with phase rotor	1500	1300-2000	1300-2000
Synchronous	600, 1645	1100-1500	400-500

The most typical angular velocity of generators are: synchronous with permanent magnets 400, 600, 1000 rpm, asynchronous with a squirrel-cage rotor at 1500 rpm, and asynchronous with a phase rotor at 1200, 1500 and 2000 rpm [25]. We will perform a calculation for this angular velocity.

The calculation results are presented in Fig. 4.

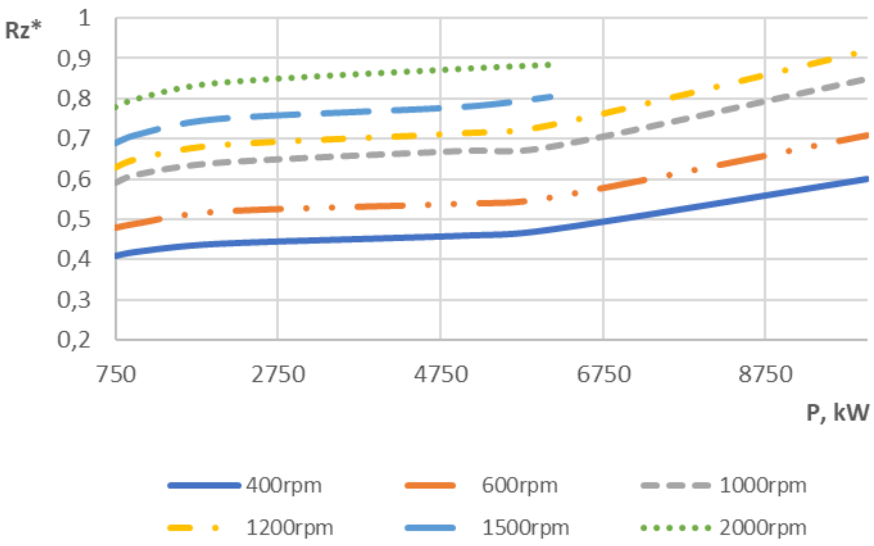


Fig. 4. Fixing radius for different generator speeds depending on wind turbine power.

As can be seen from Fig. 4, at high wind turbine capacities it is not possible to use high-speed generators due to the need to have a relative fixing radius $R_Z > 1$. The problem has a technical solution if you install a nacelle with a secondary wind turbine and a generator on the extension of the primary wind turbine blade, but this worsens its aerodynamic properties. The characteristic is approximately linear in the power range of 2000-6100 kW, which may indirectly indicate that in this area the use of ADM is quite convenient and effective. The relative fixing radius will be 0.4-0.8. In addition, in this power range there are generators of various types with high speeds.

III. DISCUSSION

Reducing the speed of the secondary wind flow after 6100 kW requires an additional increase in the radius of attachment or the use of generators with low speeds. Although it is theoretically possible to use a relative radius of attachment of more than 0.9, the issue of ensuring the strength of the blade in this case becomes crucial. Obviously, the use of a relative fixing radius of about 1 from the point of view of the mass-dimensional indicators of the generator and the secondary wind turbine is attractive (and the first attempts to build a wind turbine of this design were with the final location of the nacelle [11-14]), but increasing the load moment on the blade makes it impossible to build such wind turbines.

It is obvious that with the increase in the power of the wind turbine, they try to make the diameter of the primary wind turbine as small as possible to reduce the mass and mechanical loads. This is possible if you switch to blades with low speed. This circumstance does not allow for a further increase in the speed of the secondary wind flow, as a result of which it turns out to be insufficient to maintain the required angular velocity of the secondary wind turbine and the generator. The disadvantage of the wind turbine with ADM is the increased load on the blades of the primary wind turbine. The larger the fixing radius of the secondary wind turbine, the greater the load moment on the blade of the primary wind turbine.

Although the issue of calculating the strength is well worked out for traditional wind turbines [31…40], there is still a lack of such work for wind turbines with ADM. Optimizing the fixing radius of the secondary wind turbine based on the blade strength of the primary wind turbine goes beyond the scope of this article and is the subject of further research. Additionally, the possibility of further developing a series of non-standard speed generators should be considered to ensure the optimal design of the primary wind turbine. Thus, this study provides an opportunity for further multifactor optimization of the fixing radius of the secondary wind turbine, taking into account the strength of the blade of the primary wind turbine, the required angular velocity of the generator and its mass, and the power of the wind turbine.

In any case, the statement proposed in [10] that the efficiency of wind turbines with ADM continuously increases with the power of the installation is incorrect due to the impossibility of using high-speed generators under such conditions.

The question of the lower limit of application of wind turbines with ADM remains unclear. In publications [10, 14, 23], the value of 500-750 kW appears. Probably, considering that the speed of the secondary wind flow at such power values is far from the maximum possible, it can be stated that the feasibility of building a wind turbine with ADM for such power should take into account the economic component and the cost of the installation in comparison with wind power plants with a mechanical multiplier.

CONCLUSIONS

The constructed characteristics of the secondary wind flow velocity provide estimates of the upper limit of the effective use of wind turbines with ADM of about 6100 kW capacity due to a decrease in the secondary wind flow velocity.

The lower limit for the application of wind turbines with ADM can be cautiously estimated at 2000 kW, taking into account that from this level, the fixing radius of the secondary wind turbine required to ensure the angular velocity of the generator changes linearly and can take values from 0.4 to 0.8 for generators of different types.

It is important that in no case is the secondary flow velocity threshold of 184 m/s exceeded, at which air compressibility and excessive aeroacoustic emissions begin to play a role.

With large capacities of wind power plants, the use of high-speed generators becomes difficult and leads to a significant mechanical load on the primary wind turbine blade due to the need to install $R_Z^* \geq 1$. The task of optimizing the design of the primary wind turbine in terms of strength indicators and the formation of requirements for the development of a series of generators for use in wind turbines with ADM is determined. This is the subject of further research using CFD-modeling.

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