Innovative Hybrid Power Plant Design

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Abstract. Currently, humanity is beginning to experience difficulties with unlimited energy consumption since there are fewer and fewer opportunities to increase capacity generation. The use of renewable energy sources is an effective method of solving the problem of shortage of energy sources. One way to do this is to develop a wind-solar power plant, called a "hybrid", which simultaneously uses both wind and solar energy. For such a hybrid power plant, it is suggested to use a new type of medium-speed vertical axial wind power station, with a high utilization coefficient of wind energy and improved strength characteristics. Wind turbine models proposed for vertical axial wind power stations were tested in a wind tunnel. A comparison of the capacity of the specific vertical axial wind power station and the proposed wind turbine confirms the value of the wind utilization coefficient at the level of world samples with an average speed coefficient. The simultaneous working wind power station analysis and solar cells and energy utilization are performed. It is indicated that the feasibility and cost-effectiveness of solar cells should be analyzed in each specific case. Formulas for determining the amount of energy produced by a hybrid power station over a certain period are proposed.

Keywords: Energy efficiency · Industrial growth · Wind-solar power plant · Wind turbine · Solar cells

1 Introduction

Only sustainable development of humanity can ensure the further progress of life on Earth with the satisfaction of the needs of society while not threatening the ability to meet the needs of future generations [1]. Currently, humanity is limited in energy consumption because available generation capacity is insufficient. New energy technologies are not used globally, and their development leaves much to be desired. It should be noted that the existing energy transfer methods inhibit its uniform distribution. In addition to the high cost of equipment, the processes of long-range energy transmission lead to significant energy losses – according to some data, up to 20% of the amount of power generated [2]. Traditional energy (which uses fossil fuel and energy resources) threatens a stable climate and planet ecology. The main hazard is an increase in the atmosphere temperature and its pollution. Developed countries are elaborating new doctrines on fuel

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and energy complexes, which provide for the global introduction of alternative energy sources, such as wind and solar [3].

The purpose of this study is to study the prospects of using vertical-axial wind turbines of medium speed with a new type of blades in a wind-solar power plant based on the results of studies of wind turbines models of proposed wind power plants and analysis of the features of the joint operation of the proposed wind power plant and solar cells with further use of energy.

2 Literature Review

It is known that now, one-third of the world's electricity is already generated by renewable energy sources, but the growing population of the planet and the need for energy until 2050 may cause an increase in the share of renewable energy sources to maintain climate stability [3]. Thus, researchers believe that we should completely abandon fossil fuels. Therefore, the priority direction for the electric power industry globally is renewable energy. Now the global market offers enough options for designing wind and solar power plants. However, both of them are obviously justified in certain climatic conditions. Both wind and solar energy have a significant drawback, namely time instability caused by both the time of the day and the time of the year. The peaks of electric power generation at solar and wind power plants occur at different times of the year and the day. In addition, factors such as the location latitude of solar radiation receivers, the time of year, and the daily irradiation play a determining role for the amount of solar energy produced [4]. The feasibility of solar cells should be analyzed in each specific case, depending on the location latitude, the range of changes in the angle of incidence of the directed radiation flow, the presence or absence of atmospheric pollution, and other climatic conditions. Currently, the maximum efficiency of solar energy conversion does not exceed 25% [5].

As for the wind as a renewable energy, many countries of the world are currently successfully developing this source of alternative energy. It is known that wind power station capacity is determined by the formula:

$$P = C_p \frac{\rho_a}{2} U_\infty^3 S. \quad (1)$$

where Cp is the wind energy utilization coefficient; U∞ a is the air density; U∞ is the wind speed; S is the area of the axial section of the figure swept by the wind power station blades.

The wind speed U_∞ is unstable, its magnitude and direction change stochastically over time, which complicates the direct utilization of wind energy. Therefore, the problem of instability in time of both solar and wind energy needs to be solved in terms of reducing the ripples of the received energy at the output.

One of the ways to do so is to develop a wind-solar power plant, called "hybrid", which simultaneously uses both wind and solar energy. Hybrid wind-solar power plants may be preferable to independent solar and wind power plants, especially as the autonomous power supply for cottages, small farms, mini-enterprises of food industries, etc. The uninterruptible power supply from a centralized source is not fully guaranteed for various reasons. To ensure an uninterruptible power supply and a centralized power system, it is advisable to use local low-powered autonomous power plants close to energy consumers. There are various methods and ways to choose a suitable location for installing wind turbines. One of the most common, using a Multifactorial method of analyzing the possibilities of wind power in the municipality of Knyazhevac (Eastern Serbia), is the unification of the process of analytical structuring and geo-information systems [6]. Geodata acquisition and processing included meteorological data from available sources, an electronic terrain model for analyzing terrain orography, and Landsat 8 satellite data for analyzing land cover. Finding optimal locations for wind turbines (wind farms) through multifactorial analysis using decision theory methods helped figure out how to choose the best places to invest and minimize the impact on the environment. The document [7] shows that such a source will be sufficient to meet the global needs for electricity and energy in its other forms. Special attention is paid to China and the United States of America – the world's largest producers of greenhouse gases. Possible volumes of energy extraction from wind are discussed. Information on hybrid power plants offered on the market is sufficient. The report on the developed hybrid (wind-solar) electric system ECOSPECTR (ECOSPECTR Co. USA-Ukraine) is worth noticing. This system is designed to convert wind and solar energy into high-quality electricity for residential and small industrial facilities and sell surplus electricity to the central electrical grid at a "green tariff". Analysis of information sources shows that in the combination of "wind turbine + solar cell", traditional schemes of wind power stations with wind turbines having a horizontal axis position prevail. However, vertical axial wind power stations are also used, which is due to certain advantages in comparison with horizontal ones: vertical axial wind turbines do not require a change in positioning when the wind direction changes, energy conversion, and storage devices can be located on the ground, it is possible to connect the shaft of a wind power station directly to the shaft of any mechanical power device. In work [8], designs of modern small wind power stations offered on the global market are analyzed. The wind energy utilization coefficient C_p of most wind power stations does not exceed 0.3, along with their high cost. C_p of most wind power stations does not exceed 0.3, along with their high cost. Traditional blade systems are used for vertical axial wind turbines: Savona's, with wing blades. The density of flows of both solar and wind energy is low. The energy supply is unstable, so ensuring a large and stable energy potential over time is associated with certain difficulties [9]. In the study [10], K. Eureka et al. offers the methodologies and assumptions used in developing robust estimates of global terrestrial and offshore wind technical potential. The global trends in the use of wind energy discussed in this document show that renewable energy technologies in common assessment models contribute to demonstrating growth and improvement. These studies help to more accurately determine the impact of renewable energy technologies on the global electricity sector. The methods of stimulating and attracting investors, the procedure for obtaining permits, social and scientific issues, the provision of data on green energy sources and regional production capacities, and support policies are discussed [11]. Possible obstacles to the placement of wind farms and possible ways to increase the received power are considered. The analysis and forecasting of economic development are evaluated, considering the prospects for the introduction of wind power facilities. In favorable developments, the amount of power received from wind could reach 10 GW by 2030. The hybrid wind-solar power plants, to a certain extent, solve the problem of achieving the maximum possible stability. An analysis of simultaneous working wind power stations, solar cells, storage devices, and conversion devices shows that existing power generators often cannot provide the quality of output energy required by the consumer. Therefore, to increase the efficiency of wind and solar energy and meet the requirements of consumers regarding energy quality, it is necessary to improve existing power generators and create fundamentally new ones [12, 13]. Also, in [14], offshore wind turbines are described, which have a special type of structures that have not been tested by long-term tests or industrial operation. In this part, issues related to the development and adaptation of such turbines for use in the maritime territories of China are considered. The natural loads on the turbine typical for this region in conditions of the predominance of typhoons and earthquakes are considered. Attention is paid to loose and layered marine soil from the point of view of the successful installation of the turbine. The problems associated with the combined impact of the above factors are also indicated [15].

There are many designs of vertical-axial wind turbines in the world [16, 17]. A new type of vertical-axial wind turbines with original blades having an open aerofoil has been developed [12]. Power characteristic of wind turbines with such blades have shown that their speed ratio coefficient θ is in the range from 1 to 3 (the so-called average speed ratio). Studies shows the presence of self-starting wind turbines, a fairly high utilization coefficient of wind energy and operation at both high and low wind speeds [18].

3 Research Methodology

3.1 Key Research Results of the Wind Wheel Model with Original Blades of Medium Speed

The research was carried out at the aerodynamic stand of Sumy state university and the wind tunnel of National Aerospace University "Kharkiv Aviation Institute". In the experiments the following parameters were measured: wind velocity, the torque on the propeller axis, the number of revolutions of the axis of the model propeller. Using obtained parameters, the wind energy utilization coefficient C_p and the power-speed coefficient θ were determined using these formulas:

$$C_p = \frac{P}{P_f}. \tag{2}$$

where P is the shaft power of the wind wheel, P_f is the energy of the flow:

$$P_f = \frac{\rho_a}{2} U_\infty^3 S. \tag{3}$$

where ρ_a is the air density; U_∞ is the flow speed; S is the axial section area, swept by the blades of the wind power installation.

The average speed coefficient is according to the formula:

$$\theta = \frac{U_r}{U_\infty}. \tag{4}$$

where U_r is the blade speed, U_∞ is the flow speed.

As a result of the physical experiments carried out in the wind tunnel, the power characteristic of the wind turbine model with KN-M (KN-6) blades in the coordinates $\theta - C_p$ is obtained, shown in Fig. 1. It should be noted that full-scale wind turbines may have a higher wind energy utilization coefficient C_p, compared to the model due to the scale effect [18].

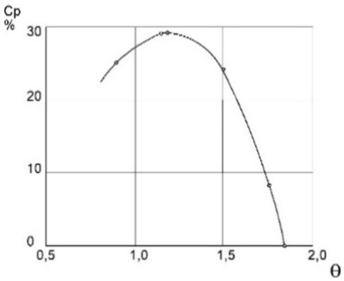

Fig. 1. Characteristics of $C_p = f(\theta)$ wind wheel with KN-M (KN-6) blades, i = 3.

Analysis of the power characteristic of vertical axial wind power installations shows that in general, the dependence curves $C_p = f(\theta)$ maybe approximated by cubic (left branch) and quadratic (right branch of the characteristic) parabolas that have a common vertex at the point with the ordinate $C_{p_{max}}$ (for θ_{opt}). As a result of this approximation, equations were obtained for calculating the left and right branches of the power characteristics of vertical axial wind power plants [14]:

– the left part of the power characteristic (power-speed coefficient area $\theta < \theta_{opt}$):

$$C_p = C\left(\frac{\theta}{\theta_{pt}}\right)^2\left[3 - 2\left(\frac{\theta}{\theta_{opt}}\right)\right]_{p_{max}}; \tag{5}$$

– the right part of the power characteristic (power-speed coefficient area $\theta_{opt} < \theta$):

$$C_p = C_{p_{max}} - \frac{C_{p_{max}}}{\left(\theta_{max} - \theta_{opt}\right)^2}\left(\theta - \theta_{opt}\right)^2 = C_{p_{max}}\left[1 - \frac{\left(\theta - \theta_{opt}\right)^2}{\left(\theta_{max} - \theta_{opt}\right)^2}\right]. \tag{6}$$

The results obtained in physical experiments on models of specific vertical axial wind turbines of average speed with KN-M (KN-6) blades showed that these equations are also valid for vertical axial wind power plants with original KN-M (KN-6) blades. Thus, based on the research of the wind wheel with KN-M blades (i = 3), $C_{p\,max} = 29\%$; $\theta_{opt} = 1.2$; $\theta_{max} = 1.85$ [14], we obtain the following approximation formulas [6]:

– left part of power characteristic $C_p = 20,14\theta^2(3 - 1,66\theta)$;
– right part of power characteristic $C_p = 29\left[1 - \frac{(\theta - 1,2)^2}{0,4225}\right]$.

Obtained C_p values correspond to experimental findings. Tests of the wind turbine with the original KN-M blades showed the presence of self-starting.

The obtained experimental power characteristics of a vertical-axial wind turbine with original KN-M (KN-6) blades are compared with the Betz, Glauert criteria and the characteristics of known vertical-axial wind turbines [5], Fig. 2.

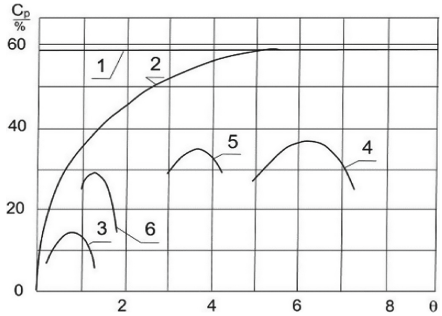

Fig. 2. Comparison of the power characteristics of vertical-axial wind power plants in accordance with the Betz (1) and Gluers (2) criteria [19]; 3 – Savona's rotor [19]; 4 – Darrius wind power installation [19]; 5 − rotor with straight wing blades NACA0018 [16]; 6 − rotor with KN-M (KN-6) blades [18].

The comparison of characteristics shows that the C_p of a new type of wind turbine is high at average θ. Since the value of the power speed coefficient θ of a specific wind unit with KN-M blades is within 1…1.85, the circumferential speed of the blade and the number of revolutions of the shaft of the wind unit are small.

Thus, the operation of a medium-speed wind turbine is accompanied by a significant decrease in the centrifugal force on the blades compared to high-speed ones. The magnitude of the decrease depends on the ratio of the circumferential speeds of the blade with the same mass of the blades and the radius of rotation. This is certainly a positive effect since the requirements for structural strength are reduced. In addition, the low value of the circumferential speed of the blades causes low noise characteristics. Thus, a new type of vertical-axial wind turbines with a sufficiently high wind energy utilization coefficient has improved strength, reliability, environmental friendliness, and maintenance characteristics.

Thus, considering the above, the use of a vertical-axial wind power plant with KN-M blades in a wind-solar power plant is highly advisable.

3.2 Analysis of Simultaneous Working Wind Power Stations and Solar Cells with Energy Utilization

As for solar energy, factors such as the location latitude of solar radiation receivers, the time of the year, and the daily irradiation play a determining role. Daily irradiation is generally determined by the formula [19]:

$$H = \int G dt. \tag{7}$$

where H is the daily irradiation, G is the intensity of solar radiation per unit of time, and dt is the time period under consideration.

The intensity of solar radiation G includes the components of directed and scattered radiation:

$$\mathrm{G} = G_b + G_d. \tag{8}$$

where G is the total irradiance of a random site, G_b is the intensity of directed radiation flow, G_d is the intensity of scattered radiation.

Thus, the feasibility of solar cells should be analyzed in each specific case, depending on the location latitude, the range of changes in the incidence angle of the directed radiation flow, the presence or absence of atmospheric pollution, and other climatic conditions. Electric energy from solar cells can be obtained in two ways [19]: using a heat engine and photovoltaic generation.

At a hybrid power plant, of course, as a source of electromotive force, solar cells are functioning in the presence of a radiation flux. Thus, the amount of energy that can be obtained from a solar cell can be determined by the formula:

$$P_c = C_{\mathrm{pc}} \int G dt. \tag{9}$$

where G is the intensity of solar radiation at a given period, t is the period under consideration, C_{pc} is the efficiency coefficient of a solar cell. The amount of solar insolation in a specific area can be found in the relevant sources.

The efficiency coefficient of a solar cell (C_{pc}) is the ratio of the battery energy to the energy of the solar flow at a specific area on the receiving surface of a solar cell.

The capacity characteristic of a wind-solar power plant is the sum of two energy sources capacities, which ensures greater stability of its supply to the consumer. In general, the amount of energy received over a certain period can be determined by the formula:

$$\mathrm{P} = C_{\mathrm{pc}} \int_{t_1}^{t_2} G dt + C_p \eta \mathrm{S} \frac{\rho}{2} \int_{t_1}^{t_2} U_\infty dt. \tag{10}$$

where C_{pc} is the efficiency coefficient of a solar cell, G is the intensity of solar radiation per unit of time (the t function); C_p is the utilization coefficient of wind power, η is the coefficient of efficiency of mechanical components of wind power installations, U_∞ is the wind velocity (the τ function), ρ is the air density, S is the wind wheel area, t is the time.

The annual amount of energy can be determined using the formula:

$$R_{\mathrm{year}} = C_{pc} \sum C_{tcp} R_{year} = C_{pc} \sum C_{tcp} \tau_Y + \frac{\rho}{2} S \sum U_\infty^3 \tau_n C_p \eta. \tag{11}$$

where G_{tcp} is the average insolation value per hour, τ^{γ} is the annual working time, hour; τ_n is the sum of the time (number of hours) when each type of wind speed repeats, η is the efficiency of the mechanical components of the wind power installation.

4 Results

The results of the study of the prospects for using a vertical-axial wind turbine of medium speed with a new type of blades as part of a wind-solar power plant and the analysis of the features of the joint operation of the proposed wind power plant and solar cells with further use of energy are as follows.

The expediency of using a vertical-axial wind power plant is justified, since:

1. The wind energy utilization factor of the proposed wind unit has a high value for the speed coefficient range ($1 \leq \theta \leq 3$) and is at the world level of wind energy utilization values for both low- and high-speed wind turbines [20, 21].
2. The circumferential speed of the blades in the proposed wind turbine is low. This causes a small amount of centrifugal force, which is important from the point of view of the strength and reliability of operation requirements. In addition, the low circumferential speed of the wind turbine blades ensures a low noise level, which allows you to place a power plant near housing.
3. The presence of self-starting of the wind wheel and the absence of wind orientation requirements greatly simplifies the maintenance of the power plant.

The performed analysis showed that changes in solar insolation to one degree or another have a certain pattern and can be predicted. Speed changes and, consequently, wind energy, are unpredictable. In the second case, the amount of energy received changes and the circumferential speed of the blades, and the number of revolutions of the axis (shaft) of the wind turbine.

Formulas are proposed for determining the amount of energy that a wind-solar power plant will generate over a certain period of time (see above).

Since the speed of the shaft (axis) of the wind turbine of the proposed wind unit ($1 < \theta < 3$) is small, it requires the use of multipliers to increase the number of revolutions, which reduces the overall efficiency and increases the cost of the wind unit. Thus, it is logical to use low-speed generators with soft characteristics for a wind plant [21].

It is concluded that since the amount of energy generated at the wind and solar power plants is unstable, it is necessary to use energy storage and storage systems to organize an uninterrupted supply of high-quality energy to the consumer. They allow storing excess generated electricity and using it in windless and cloudy weather [22]. The choice of accumulating and converting devices, as a rule, is determined by the required amount of energy given over a certain period, the requirements for its quality and consumption schedule, on the one hand, and on the other hand, the time required for energy storage [23]. For an autonomous power plant, an uninterrupted power supply to the consumer is obviously possible due to a storage device accumulating the necessary amount of energy, which can be distributed over time according to the consumer's schedule [24].

5 Conclusions

Analysis of information sources has shown the feasibility of wind-solar power plants, especially autonomous ones.

The prospects of using vertical-axial wind turbines of medium speed with a new type of blades in a wind-solar power plant have been studied.

A new type of medium-speed ($1 < \theta < 3$) vertical-axial wind power plants is promising for use in wind and solar power plants ($1 < \theta < 3$) since it has such qualities of a wind wheel as a sufficiently high wind energy utilization factor, self-starting of the wind turbine, no need for wind orientation, low centrifugal force on the blades, low noise, i.e., it shows improved characteristics in strength, reliability, ecology, and maintenance.

The features of the joint operation of the proposed wind power plant and solar cells with the further use of energy are analyzed. Recommendations are given for determining the capacity of a wind-solar power plant in terms of climatic conditions and its compliance with energy consumption requirements.

Recommendations on the choice of an electric generator and converting devices are offered, taking into account the peculiarities of the proposed wind power station.

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