Development of wind power installations with the accelerator of an air stream for areas with a low speed of wind

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Abstract. The most part of the territory used for accommodation of the population and agriculture belongs to areas with the low speed of wind insufficient for effective work of wind power installations. In this regard, the aim of article is development of the methods providing and effective use of wind power that lower than the minimum speed of wind at which rated power develops, that is in the wind turbine capacity shortage mode. We have developed the wind-receiving device with the axial aerodynamic accelerator of an air stream. As a result of pilot studies and modeling it has been shown that use of wind power installation (WPI) with vortex accelerators of a wind stream leads to increase in power production in the annual mode up to 400% depending on the average annual speed of wind in comparison with traditional WPI. Also use of the offered wind-receiving device with the axial aerodynamic accelerator of an air stream allows to increase the installed capacity utilization factor (ICUF) up to 52%.

1. Introduction

The most part of the territory used for accommodation of the population and agriculture belongs to areas with the speed of wind insufficient for effective work for wind power installations (WPI). One of the most important ranges of application of WPI is provision of energy of remote settlements, livestock farms, pumps for watering of crops and providing with water livestock pastures [1]. The analysis of the existing WPI shows that they are efficiently applied in areas with an average annual speed of wind from 7 m/s and above. However, in areas with an average annual speed of wind of 4-7 m/s the high-speed, low-bladed WPI calculated on rapidity of $Z = 6–9$ to work in the calculated mode from 152 to 720 hours or from $2$ to $8\%$ per year, and multi-blade about 1000 hours work with rapidity of $Z = 1.5–4$. The main requirements imposed to WPI include the need to ensure operational stability of a power station even at weak speeds of wind (4-4.5 m/s). Now, researches of a possibility of application of various designs of accelerators of a stream for increase in effectiveness of WPI in relation to regions of low wind activity are relevant.

In this regard, the aim of the article is development of the methods providing an effective use of wind power that is lower than the minimum speed of wind at which the rated power develops, that is in the wind turbine capacity shortage mode.

2. Materials and methods

Operation of the wind-receiving device (WRD) with the maximal wind power capacity factor $\xi$ (WPCF) is necessary for ensuring maximal development of $A_\xi$ energy. It is known what $\xi_{max}$ is provided during the work of WRD in a natural wind stream and variable speed of rotation of the wind-
receiving device when keeping a condition of \( Z=Z_n = \text{const} \), where \( Z \) and \( Z_n \) – are the current and normal rapidity of WRD respectively [2]. The dependence of the speed of rotation of the wind-receiving device on the speed of a wind stream when keeping the specified condition changes in proportion to a square of speed of its rotation, \( M = M_n \left( \frac{n}{n_n} \right)^2 \), where \( M \) and \( M_n \) – current and nominal values of a torque of the wind-receiving device; \( n \) and \( n_n \) – the current and nominal values of speed of rotation of the wind-receiving device. These dependencies are valid at preservation of a condition of \( Z = Z_n \) in all working range of speed of rotation of the wind-receiving device. For this purpose, it is necessary that the torque of the resistive force as well as the moment, of the developing WRD, changed in proportion to the speed of rotation squared. Workload with such characteristic of change of the section modulus call ideal. According to the approximate formula for the power rating of WRD [3], P’s max power developing on the wind-receiving device under the ideal workload can be calculated according to the formula

\[
P_{\text{max}} = \frac{D^2 N_n Z_n}{2080} V^3
\]

where \( D \) – diameter of WRD, \( \overline{M_n} \) – the normal moment received from aerodynamic (relative) characteristics of the wind-receiving device, \( V \) – wind speed in m/s.

The minimum value of the speed of wind at which rated power develops is called the rated speed of the \( V_p \) wind. WPI are usually used in such modes that at \( V > V_p \) the developed power does not increase significantly in spite of the fact that the most admissible working speed of \( V_{\text{max}} \) of wind can exceed \( V_p \) by multiple times. On the other hand, at \( V > V_p \), WPI power sharply decreases. The lower limit of speed of wind at which productive work of the wind turbine is still possible corresponds to the minimum working speed of \( V_{\text{min}} \) of wind. For wind turbines, \( V_{\text{p}} \) is chosen usually ranging from 8 up to 10 m/s [4]. Calculation of the development of energy is carried out by taking into account the characteristics of the repeatability of speeds of wind [5]. In the calculation, accept that the working range of speeds of wind begins with \( V_0 = 4 \) m/s which corresponds to characteristics of the modern wind turbines [6]. For areas with average annual speeds of the wind \( V = 4; 5; 6 \) m/s these repeatability of working speeds of wind are specified in table 1.

**Table 1.** Repeatability of working speeds of wind for areas with various mean annual speeds of wind.

| Mean annual speed of wind, \( V \), m/s | 0–3 | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 |
|-------------------------------------------|-----|----|----|----|----|----|----|----|----|----|
| 4                                         | 50  | 16 | 12 | 9  | 5  | 4  | 2  | 1  | 1  | 0  |
| 5                                         | 37  | 15 | 12 | 10 | 8  | 6  | 4  | 3  | 2  | 3  |
| 6                                         | 28  | 13 | 12 | 11 | 9  | 7  | 5  | 4  | 3  | 8  |

Calculation of development of energy for a year of work is made on a formula:

\[
A_\Sigma = P_{V=4} \cdot T_{V=4} + P_{V=5} \cdot T_{V=5} + \cdots + P_{V=V_p} \cdot T_{V=V_p}
\]

where,

\( P_V \) – the power calculated by formula 1 for each value of speed of wind;

\( T_V \) – number of business hours in a year at a speed of wind of \( V \) (\( T_V \) was chosen with the use of the table 1).
3. The analysis of the existing models of accelerators of a wind stream

Today, a large number of offers on applications in wind turbines, concentrators of a stream and flow-accelerating elements is developed for increase in effectiveness of use of wind energy. The common difference of these installations is that for an organized supply and withdrawal of an airflow to the impeller and from it, flow control devices or concentrators of a stream which represent the converging devices accelerating an airflow are used in various types. Contractors establish in front of the wind-receiving device to receive increase in a flow rate in its narrow part i.e. on WRD. It is supposed, that use of concentrators of a stream will considerably increase WPI power.

However, the task of concentration of airflows wasn’t simple. Even such simple devices as converging devices were ineffective [2]. The installed capacity utilization factor (ICUF) of these installations is very small owing to the formation of an airbag on an entrance to a bell at the expense of an air skid, created by WRD, and an airflow leak from a cone on its external surface. Besides, designs of these wind turbines are very heavy and consume a lot of metal.

4. Modeling of work of axial accelerators of wind flow

The theory of the ideal wind-driven generator does not consider factors of influence of an external stream of air on the air stream departing from WPI. In practice, the environmental fast stream of air washes away the departing stream and accelerates it. Acceleration causes pressure to drop down which is then transferred to the back side of blades and gives additional padding power. Thus, the concentrators directing streams of fresh fast air in the departing slow stream cause increase in WPCF [7]. According to the classical theory of the ideal wind-driven generator, loss of speed in the plane of the wind-receiving device is equal to one third of speed of wind, and the total loss of speed of wind for WRD is twice more than loss of speed in the plane of its rotation. Thus, wind speed in the WRD plane is an arithmetic average from wind speeds ahead of the wind-receiving device and speed of wind for WRD

\[
V = \frac{V_1 + V_2}{2}
\]

where \(V_1\) – wind speed before VPU; \(V_2\) – wind speed after VPU.

We replaced the wind-receiving device with the circular, passing air disk (figure 1) and accepted that in the disk section, so much energy is taken away by the wind, that the speed behind a disk reaches only the size \(V_2 = \frac{1}{3}V_1\) (ideally).

![Figure 1. Schematic representation of work of the disk which is passing air.](image)

Before WRD the speed of air decreases, at the same time there is a pressure rises. For obtaining larger energy on the wind-receiving device it is necessary to reduce first of all kinetic pressure for WRD by increasing speed. It is known that the interior of the wind-receiving device of all traditional wing wind turbines remains unused owing to design reasons and poor coefficient of efficiency (the wind stream before WRD is bends, changes an angle of attack and, therefore, the coefficient of
efficiency falls). Therefore, accept that 1/3 real radiuses of the wind-receiving device are not used [8]. According to a formula [3] to increase speed in disk \( V_d \) section, it is necessary to increase the wind speed behind the disk \( V_2 \). For this purpose in the center of a disk we establish a pipe with diameter of \( d=D/3 \) and blow in a disk with a wind stream of the same speed of \( V_1 \) (figure 2).

![Figure 2. Schematic representation of the work of the disc with the pipe.](image)

In this case the pipe will not interfere with the easy access of a wind stream, therefore, at the exit its flow rate of \( V_3 \) will only be a little bit more than \( V_1 \). Thus, in an airflow, the speed gradient, at the same time thanks to the viscosity (existence of coupling of particles with each other)of the layers of air will be moving faster, carry layers which are moving more slowly, there is an increase in speed behind the disk \( V_2 \) and, therefore, speed in disk \( V_d \) section will increase.

In figure 3, the test stand for imitation of operation of the wind-receiving device is presented. The test stand represents the disk which is passing an airflow through express cuts with the changing sizes. With the increase or reduction of the sizes of cuts the drag coefficient of a stream of the wind-receiving device changes. In the course of the experiment the disk is blown by a wind stream in the mode "without pipe" (the central part is closed by diameter of \( d=D/3 \)) and in the mode "with a pipe" (the central part is open) and by means of an anemometer reading of the speed of wind behind the disk \( V_2 \) at various drag coefficient are taken. The experiment showed that in the "with a pipe" mode there is an increase in speed of \( V_2 \) in comparison with a "without pipe" mode at the same drag coefficient.

![Figure 3. The test stand for the imitation of work of a disk in the mode "without pipe" (a) and in the mode "with a pipe" (b).](image)
One of the objectives of our study is to create a new design of the WRD [9, 10]. Figure 4 shows the experimental model of the WRD with an aerodynamic wind flow accelerator located in the center of the device.

Field tests of the wind-receiving device, with the following principal specifications were carried out: the number of blades – 8 pieces; Ø WRD – 1200 mm, Ø of the axial aerodynamic accelerator – 350 mm. For imitation of the range of speed of a wind stream the WRD was established on a truck (figure 5). In the course of field tests the central part of the wind-receiving device where the aerodynamic accelerator was installed, closed with a lid, for imitation of the traditional WPI. During the experiment, results of the speed of a wind stream at the different modes were received (with the closed central part, with the accelerator of a wind stream). Results are presented in table 2.
Table 2. Test data of WRD with the closed and open center. CC - the closed VPU, OC center - the WRD open center with accelerator of a wind stream

| V wind stream, m/s | CC | OC | CC | OC | CC | OC | CC | OC | CC | OC |
|-------------------|----|----|----|----|----|----|----|----|----|----|
| 2.2               | 2.5| 2.6| 2.6| 2.4| 4.3| 4.2| 4.2| 4.3| 4.8| 4.8|
| 3.5               | 2  | 2.6| 2.6| 2.4| 4.3| 4.2| 4.2| 4.3| 4.8| 4.8|
| 4.3               | 2  | 2.6| 2.6| 2.4| 4.3| 4.2| 4.2| 4.3| 4.8| 4.8|
| 4.8               | 2  | 2.6| 2.6| 2.4| 4.3| 4.2| 4.2| 4.3| 4.8| 4.8|
| 5                 | 2  | 2.6| 2.6| 2.4| 4.3| 4.2| 4.2| 4.3| 4.8| 4.8|
| 6.5               | 2  | 2.6| 2.6| 2.4| 4.3| 4.2| 4.2| 4.3| 4.8| 4.8|

The comparative analysis of efficiency of work of traditional WPI and WPI with the accelerator of a wind stream is presented in table 3 where the average annual value of speed of wind undertakes as a constant, 4 and 5 m/s respectively. And speeds of the wind \( v = 3, 4, \ldots, 10 \) undertake in hours as the repeatability periods. So, for example, time period when a wind has the speed of 6 m/s at an average annual speed 5 m/s will be 10% of an annual cycle or 876 hours.

Table 3. The comparative analysis of efficiency of work of traditional WPI and WPI with the accelerator of a wind stream.

| Wind speed \( v \), m/s | Amount of energy in a year at an average annual speed of wind 4 m/s, kWh | Amount of energy in a year at an average annual speed of wind 5 m/s, kWh |
|--------------------------|---------------------------------------------------------------------|---------------------------------------------------------------------|
|                          | Traditional 3-bladed WPI | WPI with the accelerator of a wind stream | Traditional 3-bladed WPI | WPI with the accelerator of a wind stream |
| 3                        | 0                      | 342                                  | 0                      | 210                                  |
| 4                        | 112.7                  | 966                                  | 101.15                 | 867                                  |
| 5                        | 117.9                  | 1048                                 | 130.05                 | 1156                                 |
| 6                        | 144.45                 | 963                                  | 181.5                  | 1210                                 |
| 7                        | 700                    | 700                                  | 465                    | 930                                  |
| 8                        | 492                    | 492                                  | 548                    | 685                                  |
| 9                        | 350                    | 350                                  | 500                    | 500                                  |
| 10                       | 280                    | 280                                  | 394                    | 394                                  |
| Total                    | 2197.05                | 5141                                 | 2319.7                 | 5952                                 |
| ICUF                     | 25%                    | 58.7%                                | 26.4%                  | 67.6%                                |

\( v = 4 \text{ m/s} \) \( \Delta = 2944 \text{ kWh} \) \( v = 5 \text{ m/s} \) \( \Delta = 3632.3 \text{ kWh} \)
5. Conclusion
As a result of the conducted researches it was shown that use of WPI with vortex accelerators of a wind stream leads to increase in power production in the annual mode up to 400% depending on the average annual speed of wind in comparison with traditional WPI. Also, use of the offered WPI with the axial aerodynamic accelerator of a wind stream allows the raise of the installed capacity utilization factor (ICUF) to 52%.

Acknowledgements
This work was supported by Federal State Budgetary Scientific Institution "Federal Scientific Agroengineering Center VIM".

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