1. Introduction

Charging wind power plants, wind-solar, wind-diesel and wind-solar-diesel complexes of guaranteed power supply (WDC GPS, WSDC GPS) with low-power horizontal-axis turbines (HAWT) and vertical-axis wind turbines (VAWT) that have drawn a lot of interest over the last 15–20 years can be efficiently used for power supply of remote settlements, agricultural farms, small industrial enterprises, radio communication systems and other objects located in regions with stable winds with an average annual wind speed exceeding (4.0–5.0) m/s. According to the data of the World Wind Energy Association (WWEA) of 2017, in 2011, out of 327 companies engaged in production of low-power wind turbines, 74% companies produced HAWT, 18% companies manufactured VAWT, and 6% companies produced wind turbines of both designs [1]. The average power of VAWT is 7.4 kW, and the most commonly used turbines generate power of 2.5 kW. Among the 157 VAWT models, 88% of the models exhibit a capacity of less than 10 kW, and the capacity of 75% of the models is less than 5 kW, which quite reliably shows the market demand for vertical-axis wind turbines. The average power generated by VAWT in 2011 was 1.6 kW [1].

In recent years, both abroad and in Russia, there has been an increased interest in VAWT with a guide vane (GV) since they show almost noiseless operation and a higher utilization rate of wind energy due to the GV used, a slightly complicated design and increased cost. For a long time, these turbines have been developed and produced with some difference in design by Russian companies, such as Windc Scientific and Engineering Center together with GKNPTs named after M.V. Khrunichev (Figure 1a) [2, 3], and OOO Enexis [4] (Figure 1b). Foreign companies involved are GUAL Industrie, Belgium [5] (Figure 2a) and Bioplan company, Germany [6] (Figure 2b), which has recently started manufacturing and selling wind turbines of this class and is the leader.
Figure 1. Vertical-axis wind turbines with a guide vane by Russian enterprises: a) wind turbine aerodynamic scheme by Windec, design by GKNPTs named after M.V. Khrunichev; b) wind turbine by OOO Enexis.

Figure 2. Vertical-axis wind turbines with a guide vane a) by GUAL Industrie, Belgium, b) by TE 20 by Bioplan, Germany.

Figure 3 shows the characteristics of the 1 kW Bioplan T 20 wind turbines.
VAWT contains a stator with guide vane plates and a wind wheel (WW) that consists of blades attached to a shaft rotating in two stator end shields (Figure 1) [2,3]. Wind wheels are designed based on the Savonius scheme. The aerodynamic scheme of the VAWT developed by Windecc is shown in Figure 4.

The primary advantages of the VAWT are the absence of the wind orientation system and a current collection device to transfer energy from the generator to the load, two-point fastening of the WW shaft to eliminate WW shaft (rotor) deformation even at high wind speeds, an increased wind energy
conversion coefficient due to airflow concentration by GV, and low noise level (less than 25 dBA). In addition, the turbines are ornithologically safe, which is a very important environmental factor for this WT.

VAWT enables aerodynamic control of the WW rotation speed by changing the airflow rate to the WW blades through regulation of the change in the angular position of the guide vane plates [7].

The wind turbines presented in Figures 1 and 2 differ in design, in particular, the number of WW blades, and the size and number of GV plates. In [2], a simplified model of similar WT with flat WW blades and flat GV plates was analyzed, and it was shown that the maximum wind energy conversion coefficient of this simplified design is $\zeta=0.19$. The results of the experimental and theoretical study of the VAWT model with curved blades and guide vanes are reported in [8]. The aerodynamic scheme of the model is shown in Figure 4, where $\alpha$ is the blade angle between the blade chord and the radius passing through the end blades, and $\beta$ is the guide vane blade angle – the angle between the chord of the guide blade and the radius passing tangentially through the anterior toe of the blade.

This technique was used to manufacture a VAWT physical model (Figure 5), which was tested in the wind tunnel, and a mathematical model was developed for digital modeling based on the solutions of the Navier-Stokes equations.

![VAWT physical model](image)

**Figure 5.** Physical model of the VAWT: (a) Wind turbine stator and rotor; (b) Wind turbine with guide plates.

The numerical simulation results are presented in Figures 5–8.

2. **Research and development problem statement**

To develop a series of VAWT, a method should be developed to design a module and a concept should be elaborated to construct a structural diagram of the wind turbine based on individual modules.

The initial data for wind turbine designing are typically as follows:

1. Estimated power.
2. Estimated speed.
3. Nominal output voltage.
4. Working range of wind speeds.
5. Storm speed.

These data should be used to determine the VAWT geometric dimensions. The WW rotation speed can be controlled by turning the guide plates to limit the airflow.

This paper discusses the issues of the VAWT design with a guide vane with WW blades and a guide vane of an ‘arc’ profile, which can significantly reduce the production cost of the WW blades.
and GV plates in comparison with full-profile blades and guide vane plates and, thus, significantly reduce the cost of the wind turbine as a whole.

The WW output power depends on its geometric dimensions and is equal to \([9,10]\)

\[
P = C_P \rho \eta \frac{S_T V^3}{2} = C_P \rho \eta \frac{D_T H V^3}{2},
\]

where \(P\) is VAWT power,
\(V\) is airflow rate, m/s,
\(C_P\) is wind energy conversion coefficient;
\(\eta\) is generator efficiency;
\(\rho = 1.225\ kg/m^3\) is specific air density at \(t=18\ °C\);
\(S_T\) is the maximum cross-sectional area and rotor, m²;
\(D_T\) is WW diameter
\(H\) is wind turbine height, m.

Introduce a dimensionless design parameter that characterizes the ratio of the WT height to the WW diameter – \(k_h\).

\[
k_h = \frac{H}{D_T}
\]

In this case, the WW area will be calculated using the equation

\[
S_T = k_h D_T^2
\]

Based on the constructive design, we take \(k_h = 1.4–1.6\). The WW area and power depend on this coefficient. Accept that \(k_h = 1.5\).

The WW diameter \(D_T\) is calculated using equations (1), (2) and (3),

\[
D_T = \sqrt{\frac{2P}{C_P \rho \eta k_h V^3}} = 1.4 \sqrt{\frac{P}{C_P \rho \eta k_h V^3}}
\]

The WT height \(H\) is calculated using equation (2), and based on the optimal ratio that was obtained in the study, the diameter of the guide vane \(D_{WT}\) is determined.

The GV diameter is related to the coefficient \(k_{WT}\) through the coefficient of the ratio of the GW diameters to the WW diameter by equation (5).

\[
K_{WT} = \frac{D_{WT}}{D_T}
\]

The choice of the \(k_{WT}\) value depends on the WT operating conditions, that is, wind characteristics. The higher the wind speed, the lower the \(k_{WT}\) values should be. The results of the WT study [5] showed that \(k_{WT} = 2.25–2.5\) yields the maximum values of the conversion coefficient \(\zeta = 0.2\). It should be noted that at high wind speeds the diameter should be reduced to \((1.5–2) \ D_T\) in order to minimize the age of WT, and the power generation will not decrease due to higher wind speed during VAWT operation.

There is a relation between the wind energy coefficient \(C_P\), speed \(Z\), and relative torque \(\overline{M}\)

\[
C_P = \overline{M}^* Z
\]

The torque developed by the turbine is calculated using the equation

\[
M = \frac{N}{\omega} = \frac{30N}{\pi n} = \frac{30C_P \rho \eta RH V^3}{\pi n}
\]

where \(\omega = \pi n/30\) is WW angular speed, rad/sec;
\(n\) is WW rotation speed, rpm.

The VAWT rate \(Z\) is found using the equation

\[
Z = \frac{\omega R}{V} = 0.4
\]

The VAWT rotation speed is calculated using the equation

\[
n = \frac{30RZ}{\pi V}
\]

Figure 6 shows the dependences of the wind energy conversion coefficient \(C_P\) for different VAWT models. Figure 6a illustrates the effect of the number of wind turbine blades. Figure 6b shows the effect of the relative width of the WW blades on \(C_P\) with regard to the rate for different number of WW blades and their relative width to the WW radius.
It was found that the VAWT speed is 0.4.

**Figure 6.** Dependence of the wind energy conversion coefficient on the WW speed of the VAWT for different number of WW blades; (b) different ratios of the chord length of the WW blades and the wind turbine radius.

Figure 7 shows the dependences of the relative starting torque of the WW of the VAWT on the wind turbine-to-wind wheel diameter ratio, as well as the angles of incidence of the GV plates for different numbers of WW blades – from 8 to 24.

**Figure 7.** Characteristics of the VAWT (a) dependence of the relative starting torque on the ratio of the VAWT diameter with respect to the ratio of the WT outer diameter to the rotor diameter; (b) dependence of the relative starting torque of the WW on the angle of incidence of the GV plates $\beta$.

Figure 8 shows the dependence of the effect of the number of WW blades on the wind energy conversion coefficient. It can be seen that the $C_p$ value is optimal when the number of WW blades is equal to 12 and the number of GW blades is equal to 8.
The wind energy conversion coefficient $C_P$ depends on both the blade chord length $b$ and the incidence angle. The developed WW torque depends on the incidence angle $\alpha$. Figure 8a shows the dependence of $C_P$ on the $b$ to the WW radius $R$ ratio, at the optimal blade incidence (35–50)\%.

Figure 9b presents the dependence of the relative starting torque on the blade incidence $\alpha$. Analysis of the Figures 8b shows that the optimal $C_P$ is yielded at $\alpha=25^\circ$.

The size of the profile boom for WW blades is (15–20)% of the blade width (Figure 10). The size of the profile boom for the GV plates is (8–10)% of the GV plate width.

![Figure 8. Dependence of the wind energy conversion coefficient on the number of wind wheel blades for eight guide vanes](image)

![Figure 9. VAWT characteristics: (a) dependence of the wind energy conversion coefficient on the blade chord to the WW radius ratio; (b) dependence of the WW starting torque on the WW blade angle $\alpha$.](image)

![Figure 10. WW blades of the VAWT: (a) WW blade; (b) GV plate.](image)
In accordance with the recommendations chosen, the geometric parameters of the VAWT with a capacity of 0.2 kW to 10 kW were calculated.

Table 1 shows the geometrical dimensions of the WW and GV of the VAWT of different capacity, and the WW rotation speed.

| No. | Parameter          | VAWT power, kW |
|-----|--------------------|----------------|
|     |                    | 0.2 | 1  | 2.5 | 5   | 10  |
| 1   | WW diameter, m     | 0.65| 1.44| 2.28| 3.23| 4.57|
| 2   | WW height, m       | 0.97| 2.17| 3.42| 4.84| 6.85|
| 3   | GV diameter, m     | 1.29| 2.89| 4.57| 6.46| 9.13|
| 4   | WW rotation speed, rpm | 142.1 | 63.5 | 40.2 | 28.4 | 20.1 |

3. Analysis of the design results
1. It is most reasonable to manufacture VAWT of a modular type with power of 0.2 kW, 1.0 kW and 2.5 kW.
2. VAWT with power of 5 and 10 kW have significant dimensions and low rotation speeds of wind wheels, which will require installation of multiplexers, since the cost of the generator of low rotation speeds is high and its mass is large.
3. The use of modular structures can increase the WT capacity. VAWT with a capacity of 0.2, 1.0 and 2.5 kW can be used as basic modules.
4. It is most expedient to double modules and to use four modules. In this case, the generator can be placed either on each wind module or on a double module.
5. The WT capacity can be improved through increased number of parallel operating double or quad modules.
6. The optimal number of WW blades \( i = 12 \).
7. The optimal WW blade angle \( \alpha = -30^\circ \).
8. The optimal WT–WW diameter ratio is 2…2.25.
9. The optimal GV plate angle \( \beta = 25^\circ \).
10. The maximal wind energy conversion coefficient in the VAWT is about 0.2.
11. The speed of the VAWT with an ‘arc’ profile blade \( Z = 0.4 \).
The aerodynamic scheme considered above (Figure 4), the obtained results and the developed design technique were employed to design and manufacture the VAWT with four separate modules connected in series with each other and with the electric generator. The entire structure was installed on a metal rack 4 m high. The rigidity and reliability of the VAWT was secured with cable ties (Figure 11). VAWT testing confirmed the theoretical computation and adequacy of the design to the results obtained in the study of the model.

4. Conclusions
A method for designing vertical-axis wind turbines of low power supplied with a guide vane with a technologically simple profile of the wind wheel (rotor) blades and guide vane plates was developed based on the studies of the physical model (Figure 5) in the wind tunnel and a digital model made according to the aerodynamic scheme shown in Figure 4.

Despite a relatively low value of the utilization rate of wind energy of such wind turbines, they are advantageous since they do not depend on wind orientation, function without a current collector, they are virtually silent, ornithologically safe, and operate efficiently in a wide range of wind speeds and different climatic conditions. If necessary, they can be supplied with a system to control the rotation speed through regulation of the guide plates.

Wind turbines are easy to manufacture and technologically advanced. They have a modular design, which makes it possible to increase their power by installing several independent modules on one rack to efficiently use wind energy and increase the overall reliability of the energy complex that includes several modules, since in case of failure of one of the modules others continue to operate.

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