Evaluation of the energy and environmental potential of a wave self-oscillatory wind turbine

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Abstract. The article describes a new type of wind turbine - wave self-oscillatory wind turbine. The principle of its operation and its inherent advantages are described. An assessment of its energy capabilities and the amount of reduction of harmful emissions into the atmosphere due to its use is given.

Wind energy is one of the fastest growing sectors of renewable energy (RE). Wind energy annually accounts for about a third of all commissioned capacities of RE.

Of all types of renewable energy, wind energy is especially important for Russia, since 70% of the country's territory, where lives 10% of the population, are located in decentralized energy supply zones, which practically coincide with areas of potential wind potential.

The basis of a modern fleet of wind turbines (WT) is made up of devices that use either lifting force or force of aerodynamic drag to drive. Certain advantages and disadvantages are inherent in them, the ideal wind turbine does not exist. This fact stimulates the appearance of new WT the designs of which differ from the designs that have become traditional. Their work can be carried out without usage of traditional forces for the WT [1-5]. Such WT can be called innovative. These WTs may have inherent advantages within which their use may be promising. This type of WT can also include wave self-oscillating WT [6-14].

The wave wind turbine, which is a self-oscillating system (SOS) for converting the energy of wind and water flows [12]. He, like any self-oscillating system, is capable of performing indefinitely undamped oscillations due to an energy source located outside the self-oscillating system, while the periodic oscillation process is created due to a non-periodic energy source.

The equation describing self-oscillations in the most general form can be represented as a second-order differential equation of the form [15-17]:

\[ \ddot{x} + \omega_0^2 x = F(x, \dot{x}) - 2h \dot{x} = f(x, \dot{x}) \]  \hspace{1cm} (1)

For the existence of self-oscillations, it is necessary that:

\[ h < 0, F > 0, \omega^2 > h^2. \]
The working element of the self-oscillating WT is the wing (wings), which, under the influence of the incoming medium flow performs self-oscillating movements. Moreover, the trajectories described by him in space are similar to the trajectories of a body, floating on interface between a liquid and a gaseous medium, but in the case of a self-oscillating WT, oscillations occurs not at the interface between the media, but inside the flow.

The frequency of the oscillations made by the wing is determined by the parameters of the oscillatory system. The oscillations amplitude is affected by the amount of energy, supplied by the flow, and the parameters of the SOS itself. Self-oscillating WTs have such advantages as: environmental friendliness, the ability to work at low wind speeds, convenient design, high wind energy utilization ratio.

Studying the course of self-oscillating processes was carried out on the model of WT, the kinematic scheme of which is shown on Figure 1.

![Figure 1. Kinematic diagram of a self-oscillating wind turbine.](image)

It’s a system of rocker AB and lever OD, interconnected by means of a joint-type coupling BD. Below the hinge is a load of mass \( m_\alpha \). To increase the amount of energy taken from the flow, two wing-shaped planes are installed on the rocker AB. The wing on the lever OD plays the role of an operation controlling element of the WT, performing, together with the joint-type coupling BD, a feedback function.

The description of the WT operation was carried out using the second type Lagrange equation:

\[
\frac{d}{dt} \left( \frac{\partial T}{\partial \dot{\alpha}} \right) - \frac{\partial T}{\partial \alpha} = -\frac{\partial U}{\partial \alpha} - \frac{\partial \Phi}{\partial \dot{\alpha}} + Q(t),
\]

where the coordinate \( \alpha \) – is the deviation angle of the rocker, on which the wings are located from the equilibrium position;

\( T, U \) – kinetic and potential energy of the oscillatory system;
Rayleigh dissipative function that takes into account energy dissipation caused by the presence of internal and viscous friction forces;

$Q(t)$ – time-dependent force acting inside the oscillatory system (OS).

It was shown that the solution to equation (2) is a second-order differential equation in form:

$$\ddot{\alpha} + 2\dot{\alpha} + \omega_0^2\alpha = A \cdot Q(t)$$

(3)

describing the time dependence of the angular coordinate model elements making oscillations for the self-oscillating operating mode, where the coefficients:

$$2h = \frac{\beta(l_1 + l_2)^2}{I_{AB} + I_{OB}},$$

$$A = \frac{1}{I_{AB} + I_{OB}},$$

$$\omega_0 = \sqrt{\frac{k_1l_1^2 + k_2l_2^2}{I_{AB} + I_{OD}}} - \text{cyclic self-oscillation frequency},$$

$$T = \frac{2\pi}{\omega_0} = \frac{2\pi}{\sqrt{\frac{I_{AB} + I_{OD}}{k_1l_1^2 + k_2l_2^2}}} - \text{period of oscillation}.$$

In turn, $\beta$ – is the generalized dissipative coefficient, $I_{AB}, I_{OD}$ – are the moments of inertia of the rocker AB and the lever OD, taking into account the presence of load and wings $k_1, k_2$ – the stiffness coefficients of the corresponding springs, $l$ – the corresponding lengths of the rocker (lever).

The resulting equation (3) corresponds to the general form of the self-oscillation equation (1). Thus, the considered oscillatory system is capable of self-oscillations subject to the necessary conditions, and equation (3) has a solution. It should be noted that in order to synchronize the input of energy into a self-oscillating system, the feedback frequency should be close to the natural frequency of the system. In this case, the self-oscillating system is capable of performing continuous oscillations for an unlimited time. The considered self-oscillating system is an extended system including a wind turbine and a work flow. At the same time, the working flow is at the same time both internal energy sources and the reason for the appearance of feedback regulating the energy supply to the system.

As a result of further experimental studies, the conditions for the appearance of self-oscillations were determined in relation to the equation describing them, as well as the specific form of this equation, for the constructed WT model [13]. A mathematical model of self-oscillating WT was also created, according to which, the calculated parameters of self-oscillations gave good match with the parameters obtained from experiments.

To assess the energy capabilities of a full-scale WT based on a self-oscillating wind turbine, a proportional scaling of the model under study was carried out to the size of the proposed WT. With the length of the wings of the full-scale WT $A=5$ m, the rotation radius of the rocker was $R=2.75$ m, and the area used by the wind flow (covering area) $S=4.56$ m$^2$.

Calculation of the power of a self-oscillating wind turbine was carried out in accordance with the formula (4):

$$P_i = C_p \eta_{me} N_{ni},$$

(4)

where $C_p$ – wind energy utilization ratio (WEUR);
\( \eta_{me} \) – conversion ratio of mechanical energy into electrical energy; \( N_{0i} \) – wind flow power.

Calculation of electricity generation of WT for a period of time \( T \) is made in accordance with the formula (5) [20]:

\[
E = TK_{mg}K_n \sum_{i=1}^{N} P_i \Pi_i ,
\]

where \( K_{mg} \) – ratio of technical readiness (for WT \( K_{mg}=0.96\ldots0.98 \));

\( K_n \) – ratio, taking into account simple WT as a result of icing and sticking of wet snow (\( K_n = 0.96\ldots0.98 \));

\( N \) – number of wind speed gradations;

\( P_i \) – WT power, at the \( i \)-th gradation wind speed and determined by the dependence \( P_i = f(V_{0i}) \);

\( \Pi_i \) – Repeatability of wind speed of the \( i \)-th gradation over time \( T=8760 \) h.

The dependence \( P_i = f(V_{0i}) \) in turn, is determined by the height at which the wind speed was measured, and is related to the height at which the wind turbine works by the ratio:

\[
V_0 = V_u \left( \frac{H_0}{H_u} \right)^m ,
\]

where \( H_u \) and \( V_u \) – measurement height and wind speed at this height;

\( m = 0.125 \div 0.2 \) – ratio taking into account the change in wind speed from height in the surface layers of the atmosphere.

Design features of self-oscillating wind turbines are such that they can be installed on the building’s roofs. The height of a nine-story building is 25–27 m, and a five-story building is half as high.

Thus, the ratio \( \frac{H_0}{H_u} \approx 1 \div 2 \), with the \( \left( \frac{H_0}{H_u} \right)^m \approx 1.0 \div 1.15 \).

Because \( P_i \sim V_0^3 \), then \( P_i \sim \left[ \left( \frac{H_0}{H_u} \right)^m \right]^3 \sim (1.0 \div 1.15)^3 \).

As a result, formula (5) takes the form:

\[
E = (0.96 \div 0.98) \cdot (0.96 \div 0.98) \cdot (1.0 \div 1.15)^3 T \sum_{i=1}^{N} P_i \Pi_i = (0.92 \div 1.46) T \sum_{i=1}^{N} P_i \Pi_i \quad (7)
\]

The electric power of a WT, taking into account repeatability for the Volgograd region, is [18, 19]:

\[
\sum_{i=1}^{N} P_i \Pi_i = 0.7787 \text{kW} .
\]

Value \( P_{sp} \) equal to:

\[
P_{sp} = (0.92 \div 1.46) \sum_{i=1}^{N} P_i \Pi_i = (0.92 \div 1.46) \cdot 0.7787 \approx 0.7 \div 1.14 \text{kW}
\]

represents the average annual capacity of a full-sized WT in real operating conditions of the Volgograd region.

This power value of one full-sized WT, in accordance with formula (5), corresponds to the annual generation of electricity in volume:

\[
E = (0.92 \div 1.46) T \sum_{i=1}^{N} P_i \Pi_i = (0.92 \div 1.46) \cdot 8760 \cdot 0.7787 \approx 6276 \div 9959 \text{kWh} .
\]
For traditional energy, the most important, from an environmental point of view, is the reduction of emissions of water vapor, carbon dioxide, nitrogen oxides.

Water vapor is the main natural greenhouse gas, which is responsible for more than 60% of the effect. The duration of his stay in the atmosphere is estimated at 120 years, and he has a negative impact on several generations ahead.

The greenhouse activity of nitrous oxide is 298 times higher than that of carbon dioxide, in addition, nitrogen oxides can affect the ozone layer as a whole.

According to experts, so that there is no global change in the Earth’s climate, by 2050 it is necessary to reduce CO2 emissions by 60%. Reducing greenhouse gas emissions means making decisions related to energy production - their main source.

About 85% of the world’s energy is generated at thermal power plants. TPP also account for approximately 22% of global CO2 emissions.

The average specific CO2 emission in the Russian Federation per unit amount of generated electric and thermal energy is about 0.414 kg/(kW·h). Such a high result was obtained due to the development of cogeneration and a large (63%) share of natural gas used as fuel in TPPs. Account should also be taken, that a low CO2 emission value corresponds to the average structure of fuel burned at TPPs for the Russian Federation. The emission of CO2 from TPPs operating on solid fuels is approximately 1.7 times higher than on natural gas.

The use of renewable energy sources is currently considered as the most effective way to reduce harmful emissions into the atmosphere.

If we consider that the electricity generated by WT would be produced at thermal power plants by burning one or another fossil fuel, then the amount of harmful emissions generated by this is determined by multiplying the amount of electricity produced by the emission factor characteristic of this type of fuel spent to produce this electricity. When choosing emission ratios, two different approaches can be used:

a) Use the “Standard” emission ratios, in accordance with the principles of the Intergovernmental Panel on Climate Change (IPCC), to assess the risk of global climate change. In this case, only CO2 emissions that occur in connection with energy consumption are taken into account. Standard emission factors are based on the carbon content of each fuel. In this approach, CO2 is the most important greenhouse gas, and other greenhouse gas emissions are not calculated.

b) Use LCA (Life Cycle Assessment) emission ratios, that take into account the overall energy carrier life cycle. This approach includes not only emissions from complete burning, but also all emissions in the product supply chain. In this approach, other greenhouse gases can play an important role. LCA is an international standardized method (ISO 14040 series) and is also used to determine the carbon footprint [21] (table 1).

Table 1. Standard CO2 emission ratios (under the IPCC, 2006) and LCA emission ratios for CO2 equivalents (according to the ELCRD) for typical fuels.

| Energy sources   | IPCC  | LCA     |
|------------------|-------|---------|
|                  | CO2 kg/(kW·h) | CO2-ec kg/(kW·h) | CO2 kg/(kW·h) | CO2-ec kg/(kW·h) |
| Natural gas      | 0.202 | 0.202   | 0.221 | 0.237 |
| Fuel oil         | 0.267 | 0.268   | 0.292 | 0.305 |
| Brown coal       | 0.364 | 0.365   | 0.368 | 0.375 |
| Anthracite       | 0.354 | 0.356   | 0.379 | 0.393 |

The ratios presented in table 1 allows to determine the amount of emissions for the main types of fuel in the production of electricity. Calculations shows that one self-oscillating WT can reduce emissions by approximately one to four tons of CO2 per year.

Results
1. Wind energy is one of the fastest growing sectors of renewable energy.
2. Of all types of renewable energy, wind energy is especially important for Russia. 70% of the country, where 10% of the population lives, are located in zones of decentralized energy supply, which practically coincide with the zones of the implemented wind potential.
3. There is no design for an ideal wind turbine. Designs of innovative WTs differ from designs that have become traditional. Their work can be carried out without the usage of traditional forces for the WTs, and their working elements may not rotate at all. Innovative WTs may have inherent advantages that can create niches for them, within the framework of which their application can be promising.
4. Innovative WTs can also include wave self-oscillating wind motors, which are self-oscillating systems for converting the energy of wind and water flows. The working element of such a WT is the wing (wings), which, under the influence of the incoming medium flow performs self-oscillating movements.
5. Self-oscillating WTs have such advantages as: environmental friendliness, the ability to work at low wind speeds, convenient design, high wind energy utilization ratio.
6. The study of the course of self-oscillation processes was carried out on the WT model, for which a mathematical model was created, according to which, the calculated parameters of the self-oscillations gave a good match with the parameters obtained from the experiments.
7. The average annual electric power of wind turbines based on self-oscillating WT, depending on weather conditions, technical condition, installation height of WT, in the Volgograd region is estimated at 0.7 ÷ 1.1 kW·h, and the annual electricity generation of one wind turbine is approximately 6 ÷ 10 mW·h per year.
8. The use of renewable energy sources, including wind energy, contributes to the limitation of emissions during the works of thermal power plants, along with technical and technological means.
9. The operation of one self-oscillating wind turbine with a capacity of about 1 kW, allows to reduce CO₂ emissions into the atmosphere from one to four tons per year.

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