POWER MACHINERY

UDC 621.548.5:533.69(045)
DOI:10.18372/1990-5548.70.16755

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AUTOMATION DISIGN OF HYBRID VERTICAL-AXIAL ROTORS

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Abstract*—The paper proves the need to create vertical-axial rotors of wind power plants in the city strip, which can be placed on roofs, which makes it possible to increase their energy efficiency by 60-70%. It is shown that the placement of such rotors on the roofs has its own characteristics, which is the need to take into account the relief of the roof of the house, its surface area, rose and wind speed over it and others. Examples of wind farms are considered and it is proved that their energy efficiency can be increased by using hybrid vertical-axial rotors, which consist of a combination of Darrieus and Savonius rotors, where the Darrieus rotor is the main source (s) of wind energy conversion. in electric, while the rotor (s) of Savonius provide acceleration of Darrieus rotors. In order to improve the quality of design, an automated design system was developed, which includes the following blocks: determining the forces affecting the rotor, choosing the type of main and accelerating rotors, determining the optimal number of blades, optimal rotor placement, calculation of dynamic rotor characteristics, analysis of probable wind speed characteristics and strength calculation.*

Index Terms—Aerodynamics; controlled deflection angles; rotor Daria; wind turbine; incompressible; viscous.

I. INTRODUCTION

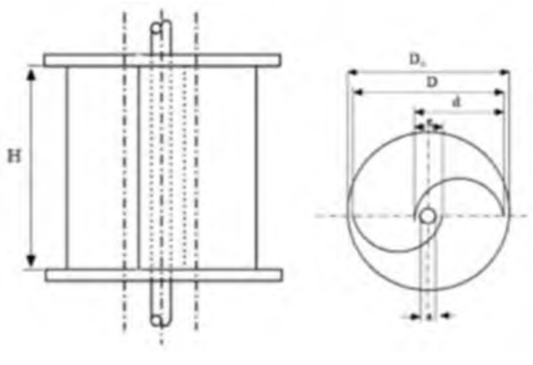
Today, much attention is paid to wind energy around the world, for example: in Germany – 25%, China – 52% in the US – 31%, and the vast majority of wind energy is converted into electricity through the use of horizontal-axis wind farms, which are dangerous in terms of health impact for humans, animals, birds, so there are restrictions on their placement near homes, etc. Vertically axial wind farms do not have such restrictions and therefore they are promising for placement in urban areas, especially on the roofs of high-rise buildings. Due to their use, it is possible to significantly increase the production of clean energy for urban lighting, illuminated advertising, ensuring the operation of traffic lights, lighting ancillary premises in buildings.

II. CLASSIFICATION OF VERTICAL-AXIAL ROTORS

Vertical-axial rotors can be divided into the following: Savonius rotor, Darrieus rotor (Figs 1, 2) and hybrid [1].

In turn, the Savonius rotor is determined by such parameters as (Fig. 1): height (*H*), rotor diameter (*D*), shaft diameter (*c*), blade length (*d*).The article deals

The Darrieus rotor also has several types, namely: D-type D-rotor, helical, or ordinary Darrieus rotor (Fig. 2). Darrieus rotor is characterized by parameters (Fig. 3): height (*H*), rotor diameter (*D*), blade length (*c*).



a) b)

Fig. 1. Scheme of the Savonius rotor: (a) front projection; (b) horizontal projection

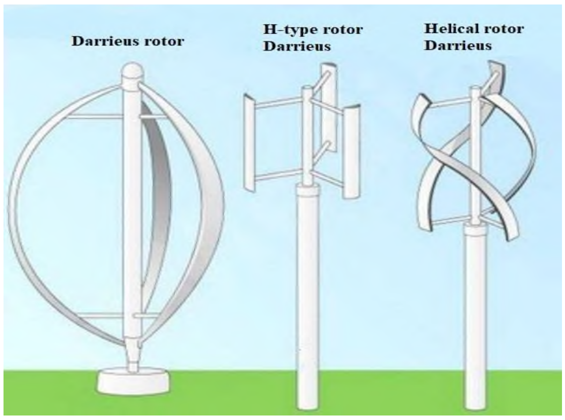


Fig. 2. Types of Darrieus rotor

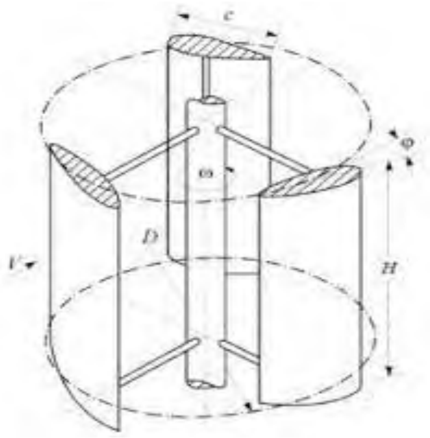


Fig. 3. Scheme of three blades Darrieus rotor

Hybrid vertical-axis rotors consist of Darrieus and Savonius rotors. Let's consider features of a design:

1) Savonius rotor, which is located on the shaft of the Darrieus rotor in the middle (Fig. 4).

2) The Savonius rotor is located above the Darrieus rotor (Fig. 5).

3) The Savonius rotor is located below the Darrieus rotor (Fig. 6).

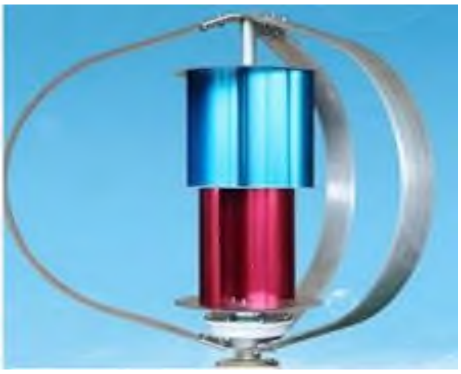


Fig. 4. Hybrid rotor with three blade Darrieus and double rotor Savonius in the middle

Fig. 5. Hybrid rotor with five blades H-type Darrieus and Savonius on the top

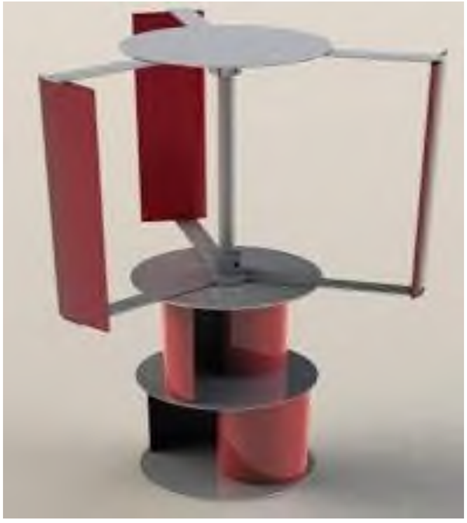


Fig. 6. Hybrid rotor with 3 blade H-type Darrieus and double rotor Savonius below

It can be concluded that the hybrid rotors of Darrius and Savonius differ from each other by the types of rotors by their placement on the shaft, as well as the number of blades.

III. Mathematical Models of Darrieus and Savonius Rotors

The numerical solution of the Navier–Stokes equation for a combined rotor is a rather complex computational procedure, which is why this paper proposes an iterative procedure consisting of alternating aerodynamic calculations of the Darrieus and Savonius rotors that make up the combined rotor [2]. We solve the problem of flow around each rotor separately, taking into account the mutual influence of the rotors through the boundary conditions (GU) in the sections I-I and II-II between the rotors (Fig. 7).

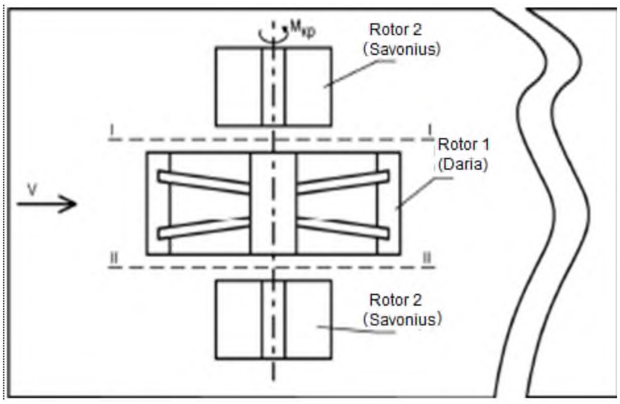


Fig. 7. Aerodynamic scheme of the combined rotor

The modeling uses a viscous gas flow model with averaging of turbulent characteristics (Reynolds-averaged Navier–Stokes equations for incompressible fluid). In compact form:

$$\frac{\partial u_j}{\partial x_j} = 0,$$

$$\frac{\partial u_j}{\partial t} + \frac{\partial (u_j u_i)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[v_{eef}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right],$$

where x_i, i = 1, 2 are Cartesian coordinates (x, y); t is the time; u_i is the projections (u, v) of the average velocity on the Cartesian coordinate axis; p is the pressure; ρ is the density; $v_{eef} = v + v_1$ $P_{availeble.\max} = 1/2\left(\rho A v^3 Cp\right)$ is the effective coefficient of kinematic viscosity; v and v_t is the molecular and turbulent coefficients of kinematic viscosity.

In this regard, it can be concluded that to obtain the desired power results, it is necessary to find the optimal parameters of the hybrid rotor, namely: the type of rotors, their placement on the axis, the number and type of blades.

IV. Setting Objectives

The task is to develop optimal designs of hybrid rotors according to the following criteria: power, cost.

The search for the optimal design is to determine the structure of the rotor (number of Darrieus Savonius rotors, choice of type of Savonius Darrieus rotors (blade shape, their mutual placement,) and its parameters, number of blades, height, blade width, profile shape).

V. Overview of Design Approaches

Approaches to construction of hybrid rotors are considered in the works.

The following optimization blocks for finding the parameters of hybrid rotors are given in the literature:

1) Finding the optimal parameters using the method of swarming particles.

2) Using the Navier–Stokes equation.

3) Use the method of calculating hydrodynamics (CFD).

4) Using a genetic algorithm.

VI. Automation of Design of Hybrid-Vertical Axial Rotors

To solve the problem related to design automation, it is necessary to develop an automated design system, the strict scheme of which is shown in Fig. 8.

VII. Algorithm for Calculating Hybrid Rotors of Wind Power Plants

Given the problem of designing hybrid vertical-axial rotors, we can conclude that this problem is multi-criteria, because in its solution it is necessary to optimize two criteria, on the one hand to maximize power and minimize cost. A multi-criteria genetic algorithm is used to solve this problem.

VIII. Genetic Algorithm

The use of genetic algorithms to solve multi-criteria optimization problems eliminates the main disadvantages of classical methods, as genetic algorithms are suitable for large-scale problems and are able to capture Pareto-optimal points even when running the algorithm once. By supporting a population of solutions and applying the concept of Pareto-optimality, genetic algorithms can find different Pareto-optimal solutions in parallel [4].

Thus, unlike most classical approaches to solving multicriteria optimization problems, when to obtain each individual point it is necessary to run a separate algorithm for finding Pareto-optimal solutions, using an evolutionary approach to vector optimization, due to the inherent parallelism in genetic algorithms, it is possible to obtain different points of the Pareto set with one run of the algorithm. The scheme of execution of this algorithm can be shown in Fig. 9.

IX. Theoretical Foundations

The main equations that were used to build the mathematical model of VAWT will be presented in detail in this section [3]. The relative blade speed can be written as:

$$\omega = V_\infty - R_\omega,$$

where V_∞ is the speed of intact air; R_ω is the speed of the blade at the radius of the equator; ω is the speed of rotation of the blades.

Significant speeds when using the DMS calculation approach are:

1) V_∞: the flow rate of undisturbed free flow.

2) V: wind-induced velocity due to energy extraction from the blades on the front half of the rotor.

3) V_e: equilibrium velocity that appeared in the plane between the upper and lower halves of the rotor, indicating the speed of the front rotor disk (keel wave) and the flow rate of the rotor disk downstream.

4) V': wind-induced velocity due to the extraction of blade energy in the lower half of the rotor.

5) V'': wake rate of the entire double disc.

The first step in the calculation process is to determine these speeds, and then the parameters of the traction energy in the upper and lower halves of the rotor can be determined as follows:

$$u = \frac{V}{V_\infty}, \qquad u' = \frac{V'}{V_e}.$$

Fig. 8. Automated design system

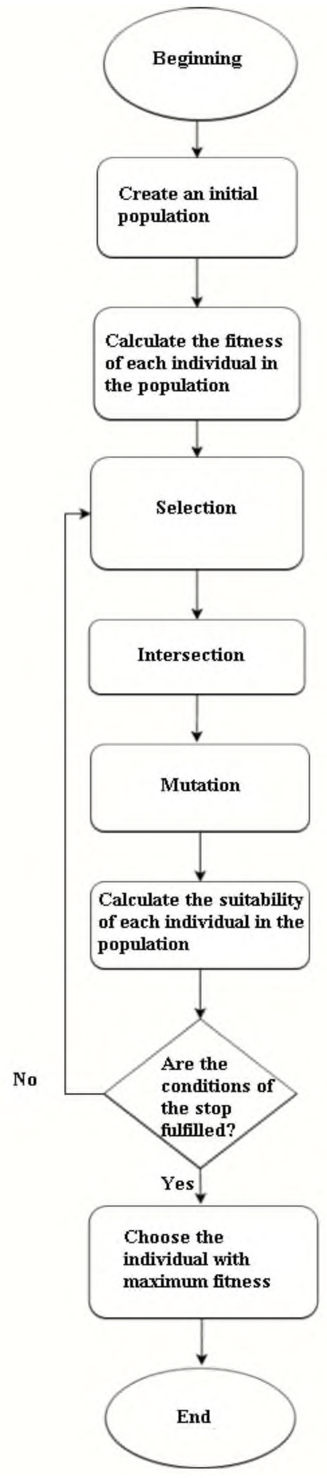


Fig. 9. Block diagram of the genetic algorithm

This circumstance is an obvious advantage of the evolutionary approach to solving multicriteria optimization problems over traditional methods of solving them.

The total speed ratio is the relative speed of rotation (VAWT):

$$TSR = \frac{R_{\omega}}{V_{\infty}}.$$

In addition, the simulation of the turbine allows you to determine the profile of the tidal wind. There are three potential options:

1) Uniform speed profile (as rotor modeling).
2) Forces law:

$$V_{\infty}(z) = v_{ref}\left(\frac{z}{z_{ref}}\right)^{a},$$

where V_{ref} is the simulated wind speed, Z_{ref} is the equator of the turbine and α is the roughness index.

3) Logarithmic approach:

$$V_{\infty}(z) = v_{ref}\left(\frac{\log\left(\frac{z}{z_0}\right)}{\log\left(\frac{z_{ref}}{z_0}\right)}\right)^{a}; \qquad (8)$$

where Z_o depends on the environment of the wind turbine (for example, Z_o = 0.2 mm for flat landscape, Z_o = 2 m for high-rise areas).

X. CALCULATIONS OF ELECTRICITY PRODUCTION

The power produced by the wind turbine at some time depends mainly on the air mass rising from the rotor blades. Increasing the speed coefficient of the tip reduces the lifting mass and affects the output power. The maximum power that a turbine can receive depends on the design of the turbine, including the aerodynamic profile of the blade, and the angle of inclination. Figure 2 shows the details of the developed approach used in this research to analyze and optimize the vertical axial wind turbine.

The power generated by the wind turbine is determined on the basis of the power factor (*Cp*) including the tip speed factor (λ) and the angle of inclination (β) parameters. The tip speed coefficient λ is often adjusted over time as it is determined by the angular velocity of the turbine rotor. Feedback from the turbine rotor to the tip speed ratio can be created in a closed loop.

The available kinetic wind energy, which can be converted into mechanical energy, does not exceed 59% of the total value (theoretically), as stated in Betz's law, where the extracted power is usually less than 45% of the available energy. Taking into account the field covered by VAWTs, area $A = r_l$, air velocity = v, blade length VAWT = l, air density = ρ, and Betz's theoretical limit Cp = 0.59 output power. Then the maximum power (P) available can be calculated as follows:

$$P_{availeble.\max} = 1/2\left(\rho A v^3 Cp\right), \qquad (9)$$

where *A* is the area of rotation of the blades, ρ is the density of air, *B* is the speed of air and *Cp* is the power factor.

XI. CONCLUSIONS

The paper substantiates the need to use an automated design system to obtain the optimal configuration of wind turbines with a vertical rotor of the hybrid type. It is shown that such a rotor should consist of a combination of Darrieus and Savonius rotors, the number of which, the mutual displacement and the size of the blades are determined based on the use of genetic multicriteria algorithms.

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Received September 28, 2021

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В. М. Синєглазов, О. В. Station Станіславчук. Автоматизація проектування гібридних вертикально-осьових роторів

В роботі доведено необхідність створення в міській смузі вертикально-осьових роторів вітроенергетичних станцій, які можуть розміщуватися на дахах, що дає можливість підвищити їх енергопродуктивність на 60-70%. Показано, що розміщення таких роторів на дахах має свої особливості, що полягає в необхідності враховувати форму рельєфу даху будинку, його поверховість, розою та швидкістю вітрів над ним та іншим. Розглянуто приклади реалізації вітростанцій та доведено, що їх енергоефективність може бути підвищено за рахунок використання гібридних вертикально-осьових роторів, які складаються з комбінації роторів Дар'є та Савоніуса, де ротор Дар'є є головним джерелом перетворення енергії вітру в електричну, тоді як ротори Савоніуса забезпечують розгін роторів Дар'є. З метою підвищення якості проектування в роботі розроблено систему автоматизованого проектування, до складу якої входять наступні блоки: визначення сил, які впливають на ротор, вибір типу основного та розгінного роторів, визначення оптимальної кількості лопатей, оптимального розміщення роторів, розрахунок динамічних характеристик ротора, аналіз ймовірних характеристик швидкостей вітру та розрахунок міцності.

Ключові слова: аеродинаміка; керовані кути відхилення; ротор Дар'є; вітрова турбіна; нестискувальний; в'язкий.

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В. М. Синеглазов, А. В. Станиславчук. Автоматизация проектирования гибридных вертикально-осевых роторов.

В статье доказана необходимость создания вертикально-осевых роторов ветроэнергетических установок в полосе города, которые могут быть размещены на крышах, что позволяет повысить их энергоэффективность на 60–70%. Показано, что размещение таких роторов на крышах имеет свои особенности заключающиеся в необходимости учета рельефа кровли дома, площади ее поверхности, высоты и скорости ветра над ней и др. Рассмотрены примеры реализации ветроэнергетических установок и доказано, что их энергоэффективность может быть повышена за счет использования гибридных вертикально-осевых роторов, состоящих из комбинации роторов Дарье и Савониуса, где ротор Дарье является главным источником преобразования энергии ветра в электрическую, тогда как роторы Савониуса обеспечивают разгон роторов Дарье. В целях повышения качества проектирования в работе разработана система автоматизированного проектирования, в состав которой входят следующие блоки: определение сил, влияющих на ротор, выбор типа основного и разгонного роторов, определение оптимального количества лопастей, оптимального размещения роторов, расчет динамических характеристик ротора, анализ вероятных характеристик скоростей ветра и расчет прочности.

Ключевые слова: аэродинамика; управляемые углы отклонения; ротор Дарье; ветровая турбина; несжимаемый; вязкий.

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