COMPUTER-AIDED DESIGN SYSTEMS

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COMPUTER-AIDED DESIGN OF WIND POWER SYSTEM WITH COMBINED ROTOR

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Abstract—The paper is devoted to the vertical axis wind turbine combined rotor computer-aided design. It includes the description of main types of vertical axis rotors and their structural parameters. It is solved the problem of combined rotor structural and parameter synthesis.

Index Terms—Combined rotor; wind turbine; vertical axis of rotation; aerodynamics.

I. INTRODUCTION

For the energy independence increase of Ukraine it is necessary to develop wind turbines as a clean energy source.

Today there are wind power turbines with a vertical axis (VA) of rotation, with the following advantages: no need to focus on wind, functioning with variable wind speed, bottom location of generator and multiplier, no turning of the blades, constant section of the blades by length, low-speed, minimal environmental impact, high effectiveness, design simplicity, reliability, environmental clearness, ease of maintenance.

Computer-aided design (CAD) system is intended to automate the design process, resulting in a set of design documentation. Modern CAD systems able to perform the calculation and design of various systems, preparation of financial and design documentation based on the calculations results of estimate. The use of such system can significantly speed up the necessary calculations for the construction of wind turbines with regard to optimization criteria set parameters, eliminate errors due to human factors and reduce the number of personnel involved in the development and design of wind turbines.

II. PROBLEM STATEMENT

The most common types of rotors with a vertical axis of rotation are Savonius (Fig. 1) and Darrieus (Fig. 2) rotors.

The torque of Darrieus rotor is created due to the lift force of blades. The minimal wind speed of classic Darrieus rotor starting is 6 m/s, that is much higher than the average for the majority of Ukrainian territory. At low rapidity Darrieus rotors can sometimes have a negative torque but at higher values of this parameter give a large enough power. Darrieus

rotors are approaching by the conversion coefficient of wind energy into electricity to horizontal axial rotors.

Fig. 1. Savonius Rotor

Fig. 2. Darrieus rotor

Savonius rotors [1] – [3] operate mainly due to the blades drag, so large enough (compared with the same size Darrieus rotor) torque is realized at low

rapidity. With further increasing of it, the torque changes inversely in relation to Darrieus rotor one. Savonius rotor does not provide large conversion efficiency of wind energy into electrical energy.

Therefore, it is reasonable to design combined rotors.

The typical combined rotor (Fig. 3) consists of a Darrieus rotor (main rotor – provides the basic generation of electrical energy) and one or more Savonius rotors (boosters), planted on a common shaft. At low speed of wind stream starting torque is created by Savonius rotors which must be enough to spin-up Darrieus rotor. Further the functioning of wind turbine is supplied basically due to the Darrieus rotor.

To solve the problem of wind turbines combined rotor optimal design it is necessary to choose the criteria of optimization. It is proposed the following criteria: power factor, weight, axial moment of inertia, lift and drag coefficients of blade profile and manufacturing costs.
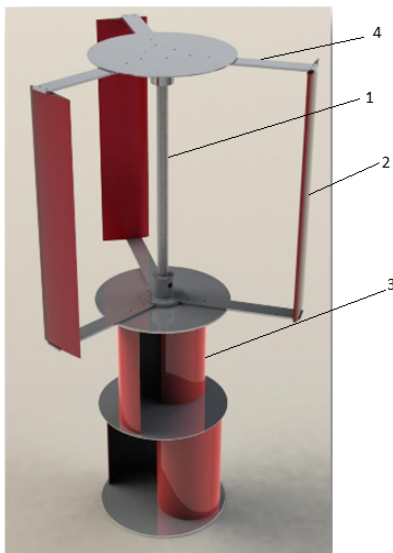

Fig. 3. Example constructive scheme combined rotor with vertical rotation axis: 1 is axle; 2 is Darrieus rotor blades with three straight; 3 is starter (two-stage Savonius rotor with two blades spaced phase); 4 is traverses

Power factor of wind turbine can be written in the following way:

$$J_1 = C_P = \frac{P}{P_{\text{air}}} => \max,$$

where P is useful power on shaft of wind turbine, which is determined because of aerodynamic calculations; P_{air} is the available power of airflow.

$$P_{\text{air}} = \frac{1}{2} \rho V^3 S_{sw},$$

where ρ is air density; V is normalized flow rate of air; S_{sw} is swept rotor area.

The weight of combined rotor can be defined as follows:

$$J_2 = \sum m_i => \min,$$

where m_i is weight of individual elements of wind turbine.

Axial moment of inertia of combined rotor can be defined as:

$$J_3 = \sum \left(J_{0i} + m_i r_i^2 \right) => \min,$$

where J_{0i} are own inertia moments of individual elements; r_i is distance from the centers of mass elements to the rotation axis wind turbines.

The weight decrease and axial moment of inertia influences the start of the combined rotor.

The manufacturing costs of combined rotor can be defined as follows:

$$J_4 = \sum p_i => \min,$$

where p_i is manufacturing cost of wind turbine individual element.

Coefficient C_y of Darrieus blade profile lift must be maximized that can be written down as folows:

$$J_5 = C_y => \max.$$

Coefficient C_x of Darrieus blade profile lift must be minimized, so it can be written as:

$$J_6 = C_x => \min.$$

It should be noted that the optimization criteria are contradictory. For example, to improve the wind turbines efficiency it is necessary to increase the geometric size of the blades, leading to an increase in weight, axial moment and manufacturing costs. According to this, optimization problem can be represented as multi-criteria optimization problem for searching Pareto-optimal points.

The problem of wind turbines with a combined rotor design is divided into two optimization subproblems.

1) Structural optimization is the choice of the optimal:

– relative position of the primary and booster rotors x_{11};

– main x_{12} and booster x_{13} rotors types;

– number of main x_{14} and booster x_{15} rotors;

– number of blades of main x_{16} and booster x_{17} rotors;

– parameter x_{18} is profile of the main rotor blades;

– parameter x_{19} is type of material for constructive elements.

The above-mentioned parameters can be defined as a vector:

$$\mathbf{X}_1 = \{x_{11}, x_{12}, x_{13}, x_{14}, x_{15}, x_{16}, x_{17}, x_{18}, x_{19}\}^{\mathrm{T}}.$$

2) Parametric optimization is determination of the rotors optimal geometrical parameters:

$$\mathbf{X}_2 = \{x_{21}, x_{22}, x_{23}, \ldots, x_{2n}\}^{\mathrm{T}}.$$

The physical meaning of vector parameters $\mathbf{X}_2$ will be explained after explaining of rotors structural schemes

III. Combined Rotor Synthesis

Structural synthesis of combined rotor includes determination [4] – [9] of main and booster rotors relative position, main and booster rotors types, the number of main and booster rotors, number of main and booster rotors blades, profile shape of main rotor blades, type of material for elements production.

A. Relative position of the primary and booster rotors x_{11}

Savonius rotor can be placed coaxially inside the Darrieus rotor. The advantage of this scheme is compact size of combined rotor and occupies less constructive height. However, in this configuration, the inner Savonius rotor is a "aerodynamic shadow" of external Darrieus rotor, that is undesirable for start-up and operation of the combined rotor at low wind speed. Thus, Savonius rotor also reduces the effectiveness of the main rotor.

Savonius rotor located coaxially outside Darrieus rotor. In such configuration negative interactions between rotors are minimal and each rotor works effectively.

B. Type of main x_{12} and booster x_{13} rotors

As the main rotor of vertical axis wind turbine with combined rotor with it is advisable to use Darrieus rotor due to its high coefficient of wind energy use. Structurally Darrieus rotors can have straight (*H*-rotors), spiral or arc-shaped blades.

Whereas booster rotor should be effective at low wind speed, it is advisable to use Savonius rotors. Forms of cross sections of the rotors can be as part of the arc of a circle of a special type.

C. Number of main x_{14} and booster x_{15} rotors

For the combined rotor is advisable to use one Darrieus rotor with optimal geometric parameters for desired power.

Savonius rotor more effective with two or three blades, but this rotor, as noted above, has irregularity of rotation. Therefore, it is advisable to have at least two such rotors with phase spaced blades.

D. Number of main x_{16} and booster x_{17} rotors blades

With the decrease of Darrieus rotor number of blades decreases total working area of the blades, which reduces the power factor and increase the rotation irregularity. With the increase of Darrieus rotor blades number the rotor fill factor increases, but at the same time increasing negative mutual influence of blades. Depending on the length of the blade chord may be optimal three or four-bladed Darrieus rotor configuration.

Similar arguments can be applied in choosing the number x_{14} of Savonius rotor blades. When the number of Darrieus rotor blades increases to four, power factor of rotor significantly reduces and therefore it is appropriate to apply the two- or three-stage rotors with two or three phase spaced blades.

E. Parameter x_{18}, profile forms the main rotor blades

The methodology of choosing the optimal profile shape will be listed in further works.

F. Parameter x_{19}, type of material for elements production

The methodology of choosing optimal materials listed in the further works.

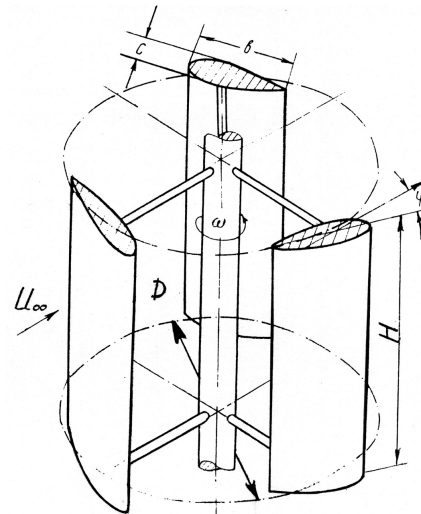The geometrical parameters of Darrieus three-bladed rotor are shown in Fig. 4.

Fig. 4. Geometrical parameters of Darrieus rotor: *H* is height: *D* is diameter; *b* is blade chord; *c* is thickness of the blades; φ is the angle of the blades

Let's mark the optimization parameters of Darrieus rotor as

$$x_{21} = H;\ \ x_{22} = D;\ \ x_{23} = b;\ \ x_{24} = c;\ \ x_{25} = \varphi.$$

The geometrical parameters of Savonius rotor are shown in Fig. 5.

Let's mark the optimization parameters for Savonius rotor as

$x_{26} = H$; $x_{27} = D$; $x_{28} = d$; $x_{29} = e$; $x_{2,10} = a$.

The optimization problem can be written as following:

$$\vec{x}^* = \arg\operatorname*{extr}_{\vec{x}^* \in \mathbf{X}} \mathbf{F}(\vec{x}^*), \qquad \vec{x}^* \in \mathbf{X},$$

where $\mathbf{X}$ is the region of allowable parameters; $\mathbf{F}(\vec{x}^*)$ is the vector of criteria functions.

$$\mathbf{X} = \{\mathbf{X}_1, \ \mathbf{X}_2\}^T;$$

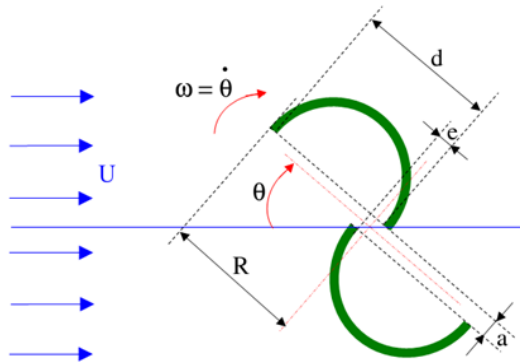$$\mathbf{F} = \{J_1, J_2, J_3, J_4, J_5, J_6\}^T.$$

Fig. 5. Geometrical parameters of Savonius rotor:
H is height; *D is* diameter; *d is* blade chord; *e is* blades overlap; *a is* the gap between the blades

IV. Computer-Aided Design System Structure

Theoretical questions of wind turbines design and their components paid much attention in literature [9], [10]. However, analysis of the literature showed that the there is no methodological basis or systematic approach to the development and optimization of wind turbines parameters.

Proposed approach to VA wind turbines development is based on a sequential (iterative) optimization of component design to improve the parameters of whole turbine based on it study of wind turbines and related components three-dimensional mathematical models in general with the calculation of internal and external influences on wind turbines work.

Block diagram of the methodology for VA wind turbine CAD system design shown in Fig. 6.

Technical and economic need for the creation and implementation of such methodology for the rapid development of wind turbine optimal designs is that the process of research based on experiment is extremely expensive, as it implies the creation of a number of samples of the finished product for tests needs. The progress of computer technology and complex mathematics is one of the quickest and least expensive ways to study the parameters of wind turbines and their optimization is a computer simulation and a comprehensive analysis of physical and mathematical models based on iterative stages, using a number of methods.

Therefore, it seems appropriate to create a combined wind turbine based on Savonius and Darrieus rotors with the methodology whose block diagram is shown in Fig. 7.
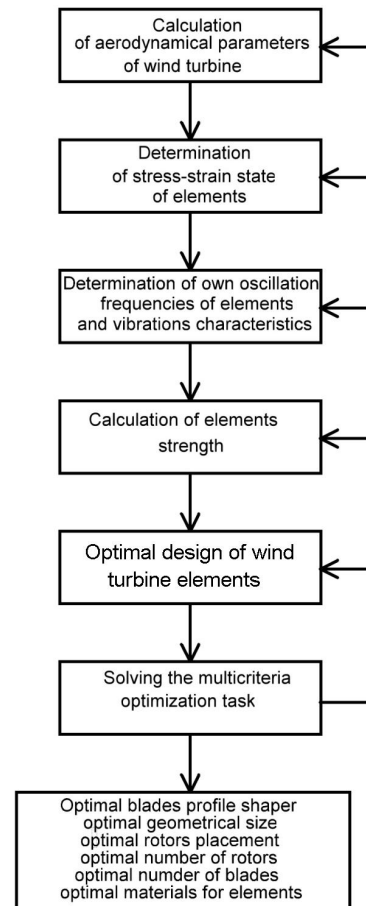

Fig. 6. Block diagram of wind turbine development methodology

Fig. 7. Wind turbine with a vertical axis of rotation

Such methodology is used in newly developed CAD software for vertical axis wind turbines with combined rotors which are effective on the territories with small winds.

V. Conclusions

The developed CAD software allows to perform the design wind turbine with a vertical axis of rotation of the rotor combination, to optimize the parametric rotor, to calculate the strength of the rotor and power plants in general and conduct simulation designed system.

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В. М. Синєглазов, А. А. Зіганшин, М. П. Василенко. Автоматизоване проектування вітроенергетичних установок з комбінованим ротором
Розглянуто проектування автоматизованих вітроенергетичних установок з вертикальною віссю обертання та комбінованим ротором. Описано основні типи роторів з вертикальною віссю обертання та їх структурні параметри. Розв'язано задачу структурного та параметричного синтезу комбінованого ротора.
Ключові слова: комбінований ротор; вітроенергетична установка; вертикальна вісь обертання.

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В. М. Синеглазов, А. А. Зиганшин, Н. П. Василенко. Автоматизированное проектирование ветроэнергетических установок с комбинированным ротором

Рассмотрено проектирование автоматизированных ветроэнергетических установок с вертикальной осью вращения и комбинированным ротором. Описаны основные типы роторов с вертикальной осью вращения и их структурные параметры. Решена задача структурного и параметрического синтеза комбинированного ротора.
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