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A WIND TURBINE OF A NEW TYPE

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Abstract: The results of studies on possibility of increasing efficiency in the use of wind energy and improving the dynamic characteristics of Darrieus wind rotor with straight blades are described. It is shown how the values of torque on the rotor shaft may be optimized by controlling the orientation of the rotor blades relative to the oncoming flow. The ability of the rotor with controlled blades to self-start at a very low speed of wind flow as well as a significant increase in utilization factors of energy flow and torque on the shaft of wind rotor compared with the same rotor with rigidly fixed blades are shown. The results of calculation of the magnetic field inside the electric generator with permanent magnets and the dependence of electromagnetic torque on the position of the rotor relative to the stator are presented. Also, the results of calculation of the dynamic characteristics of electric generator and the comparison of calculated values with experimental ones are shown.

Streszczenie: W artykule przedstawiono wyniki badań dotyczących możliwości podwyższenia efektywności wykorzystania energii wiatru oraz poprawy charakterystyk dynamicznych wirnika wiatrowego Darrieusa z łopatami prostymi. Pokazano, że przez regulację orientacji łopat wirnika w stosunku do kierunku przepływu wiatru można zoptymalizować wartość momentu obrotowego na wale wirnika. Pokazano zdolność wirnika z łopatami regulowanymi do rozruchu przy bardzo niskich prędkościach przepływu wiatru oraz znaczną poprawę współczynników wykorzystania energii przepływu i momentu obrotowego na wale wirnika wiatrowego w porównaniu z analogicznym wirnikiem z łopatami sztywno ustalonymi. Przedstawiono wyniki obliczeń rozkładu pola magnetycznego w generatorze elektrycznym z magnesami trwałymi oraz zależność momentu elektromagnetycznego od pozycji wirnika względem stojana. Przedstawiono także wyniki obliczeń charakterystyk dynamicznych generatora, porównano wartości obliczone z otrzymanymi w trakcie badań.

Keywords: *Darrieus wind rotor, electric generator, permanent magnets, electromagnetic torque*
Słowa kluczowe: *wirnik wiatrowy Darrieusa, generator elektryczny, magnesy trwałe, moment elektromagnetyczny*

1. Introduction

As it is known, all over the world, the technologies have been intensively developed using renewable energy sources, including kinetic energy of wind and water flows. The main types of the wind turbines are the wind rotors with a horizontal or vertical axis of rotation, equipped with the electric generators for converting mechanical energy on the rotor shaft into electric energy and the tower for the placement of these generators.

At present, for utilization of wind energy the wind turbines with a horizontal axis of rotation and with wattage from hundreds of watts to several megawatts are widely used. The essential components of such wind turbine construction is the vertical tower of height from 10 to 150 meters, the mechanisms for orientation the area of wind rotor rotation perpendicular to the direction of the wind. Wind turbines with a vertical axis of rotation do not need special arrangements of orientation relative to the direction of the wind flow and allow two-bearing rotor mounting system. The generator may be placed in the base of the unit, which simplifies its construction. The important advantage of the wind turbines with a vertical axis of rotation is the relative simplicity of construction of the blades and the relatively small area required for the placement of wind turbines [1]. One of the main disadvantages of Darrieus wind rotor with rigidly fixed blades relative to the horizontal crosspiece is a high-speed wind flow, at which there is the self-starting of the rotor to rotate, and large values of the variable mechanical load on the shaft. As it turned out both of these drawbacks can be eliminated by using special methods of controlling of the blades position during rotation of wind rotor.

2. Darrieus wind rotor with controlled blades

When moving in a circular path the blade of Darrieus wind rotor operates in a periodically changing unsteady flow. As the typical wing profiles are used in the construction of blades, the main parameter determining the value and direction of the forces acting on the profile is the angle of attack. The nature of blades movement in the rotor with fixed position of blades is such that the angle of attack becomes supercritical at a very large part of its trajectory [2]. This leads to stall of flow and big decrease of the value of the useful component of the aerodynamic force, so that the blade even brakes wind rotor in some parts of the trajectory. However, if it is possible to rotate the blade in such a way that the flowing around of the blade profile is at the optimal angle of attack, the produced value of torque can be significantly increased on the rotor shaft. The test models of rotors in water [2-3] and the full-scale prototypes of the rotors in the air [4-5] have shown considerable increase the power coefficient C_p, as well as a significant decrease in the average load on the rotor shaft and its amplitude pulsations [3-4]. The last prototype of the series of the wind rotors was created and tested in 2011-2013 and showed a stable and reliable performance during the tests in the wind tunnel, and the coefficient C_p was equal 0.45. Darrieus wind rotor with straight controlled blades (Fig. 1) had the following parameters: blade length l_{blade} = 1.6 m, the chord length of the blade b = 0.25 m, the profile of the blade is symmetrical NACA 0015, the blade aspect ratio $\lambda = l_{blade}/b = 6,4$, radius of blade rotation R = 0,7 m, the average diameter of the control track D = 0.4 m, the swept area S = 2,24m^2, the solidity $\sigma = 3b / 2R = 0,54$. The blades were made of carbon plastic and one blade weighed 2,7kg.

Controlling mechanism of the blades are cylindrical track of the special form in plan and 8 mm thick, placed below the lower crosspieces of the wind rotor on both sides of which three pairs of rollers moved, connected by special carriages, which in its turn were pivotally connected to the rods disposed within the lower horizontal crosspieces. Another ends of the rods were pivotally connected to the control axes at the end of the blades. The control track was attached to the bottom support rigidly.

Fig. 1. The wind rotor with controlled blades in the wind tunnel

The lower end of the rotor shaft went under the floor of the wind tunnel, where on the shaft the disc with the 60-hole for measuring the speed of rotation of the wind rotor was placed on the shaft, and the shaft through reducer with conic gears connected to the electromagnetic powder brake coupling (mod.14.512.08.1.2). The range of brake torque of coupling is 3 ÷ 80 Nm in increments of 2 Nm. Under the initial load on the shaft of 3 Nm (resistance coupling with the power supply disconnected), the wind rotor self-started when the wind flow speed was V = 2,5 ÷ 2,8 m / sec, without load (i.e. the coupling is removed) the wind rotor self-started when the wind flow speed was V = 1,8 ÷ 2 m/sec. The same wind rotor without control mechanism (i.e. the blade are rigidly fixed to the crosspieces) and without load on the shaft self-started when the wind flow speed V = 3,5 ÷ 3,8 m / sec. Dependence of the rotation speed of the wind rotor **n** from the useful torque M_{net} on the shaft at various speeds of wind flow V is shown in Fig. 2a. The maximum shaft power was obtained at the lowest rotation speeds of the wind rotor. The control of blades allows you to get a torque on the shaft almost three times superior than the wind rotor with blades rigidly fixed, thus almost twice the speed of rotation decreases (Fig. 2a).

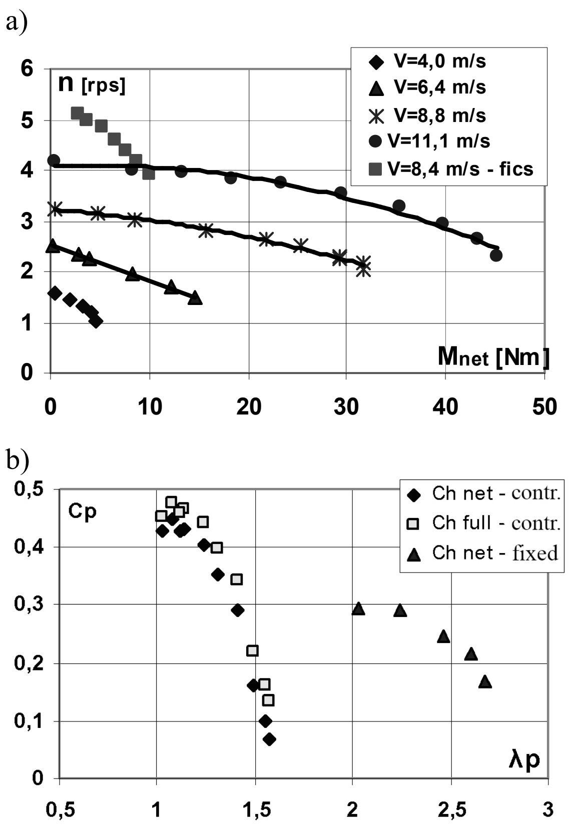

*Fig. 2. The dependences of the rotation speed of wind rotor **n** from the value of torque M_{net} on the shaft at various speeds of wind flow V (a) and the dependence of the energy coefficient Cp from the value of tip speed ratio λp (b) at a speed of wind flow V = 9 m / sec*

This is clearly seen in Fig. 2b, where the maximum efficiency of the rotor with controlled blades obtained by tip speed rate $\lambda_r = 2\pi nR/V = 1{,}1$, and the maximum of efficiency of the rotor with blades which are rigidly fixed obtained by λr = 2.1. At the same time the energy coefficient Cpnet of the rotor with controlled blades almost 1.5 times higher than the same with rigidly fixed blades. At rigid attachment of blades the angle of the blades placement on the crosspiece was 8^o, which agrees with the data obtained at the Institute of McMaster in Canada [6] while purging of the wind rotor with sizes H x D = 3 x 2.5m (Cp_{full} was received experimentally and was not more than 0.33).

Thus, the use of simple constructive and technological control blades mechanism of the wind rotor with vertical axis allows using it effectively in small (6-8 m/sec) wind speeds, reducing the value of wind load on the wind rotor shaft, and significantly improving the performance characteristics.

3. Electric generator

Synchronous electric generators with permanent magnets are used very often for wind power units with low wattage. There are many types of electric generator constructions as disk type construction [7], salient pole type construction [8] and construction with slotted stator [9].

For the wind power unit described in this paper the electric generator with permanent magnets and slotted stator was designed. A stator taken from a standard asynchronous motor was used to decrease a price of designed generator.

The results of wind rotor examination are following: if wind speed is between 6 and 12 meters per second the rotor rotation frequency is 2-5 revolution per second or 120-300 rpm with load torque M_{net} = 10÷40 Nm i.e. generator power must be P ≤ 1 kW.

During electrical generator designing it was composed the model of electric generator with permanent magnets of 1 kW power. The modeling results were compared to the results of experimental examination of physical model.

At the predesign stage of electrical generators with permanent magnets, it is necessary to pay attention to way of magnetic flux density distribution in the air gap along the poles and to the analysis of dynamic processes in the loaded generator. Whereas the electromagnetic processes are nonlinear, the analytical methods which are used for classical electrical machines design cannot accurately describe the processes in electrical machines with permanent magnets, so the modern special software should be used. Comsol Metaphysics and Infolytica Magnet were used for these purposes.

Fig. 3 shows the sector of the electrical generator. The stator outer diameter is D_a = 168 mm. The stator slot number is Z = 48. The inner stator diameter is D_i = 117 mm. The stator core axial length is L_z = 100 mm.

The stator of standard asynchronous motor AIR100B8 was used for this project. The rotor has 8 poles with permanent magnets magnetized in tangential direction. The dimensions of permanent magnets are 10x25x100 mm. The air gap thickness is δ = 1 mm. There are ferromagnetic poles (concentrators) between permanent magnets. It is necessary to make the skew of the poles for electromagnetic torque ripple decreasing [8].

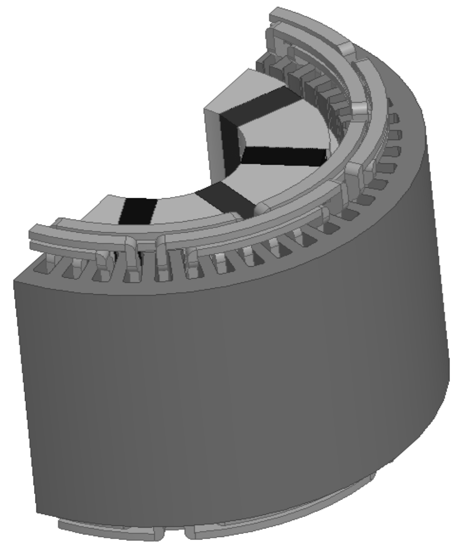

Fig. 3. Electrical generator model

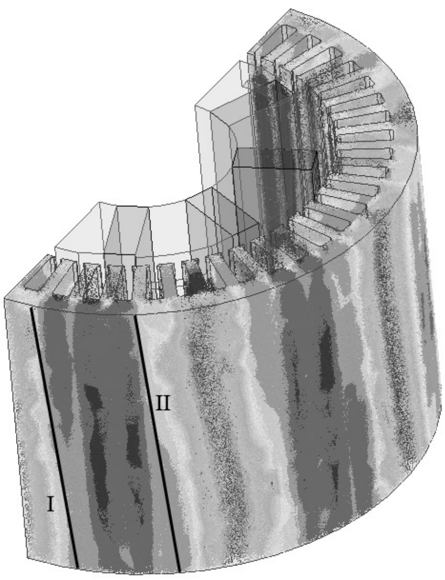

Fig. 4. The magnetic flux density distribution in the stator core

For all calculations the residual magnetic flux density of permanent magnets is B_r = 1,23 T and coercive force is H_c = 955 kA/m. The stator is laminated and made of steel ST2211 (with taking into consideration the nonlinearity of material). The ferromagnetic concentrators are made of construction steel ST20 (with taking into consideration the nonlinearity of material).
The magnetostatic calculations were executed for the moment when the phase currents are ***Ia*** has max value with forward direction, ***Ib*** has max value and backward direction and ***Ic*** is 0. According to slot filling ratio K_f = 0,5 the phase current density is J = 5 A/mm^2.

There were composed 3D model and 2D model. Fig. 4 shows the magnetic flux density distribution in the stator core. The pole skew affects to the stator field and it can be seen between line **I** and line **II** in the fig. 4.
To take into account the pole skew in 2D model it is necessary to compose 3 models according to 3 sections of magnetic system of electrical machine. The planes of these sections should be perpendicular to the rotor shaft and should be placed at following distances from rotor core face $1/6L_z$, $1/2L_z$ and $5/6L_z$. The total electromagnetic torque is arithmetical mean value between electromagnetic torques of these models.
Fig. 5 shows the pattern for the cross section of the magnetic field at a distance of $1/2\boldsymbol{L_z}$ from the front face of the rotor.

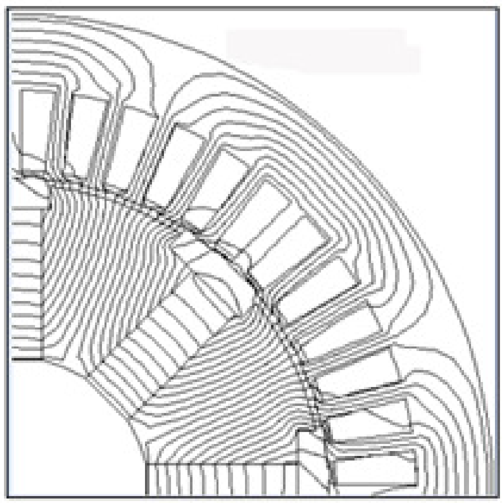

Fig. 5. Magnetic field distribution 2D

As shown by the results of studies (Fig. 6), the value of the electromagnetic torque in the 3D model is somewhat smaller than the 2D. This is explained by the fact that in 2D are not considered an end field dissipation.
It should be noted the 3D modeling time is much higher than 2D modeling time that is why at predesign stage it is better to use 2-Dimentional modeling by 3 cross sections with following 3D modeling of the final magnetic system.
The dynamic characteristics modeling of the generator under load was executed in Matlab Simulink. For such modeling, it is necessary to calculate the electromagnetic torque and magnetic flux linkage for various phase currents and rotor positions.

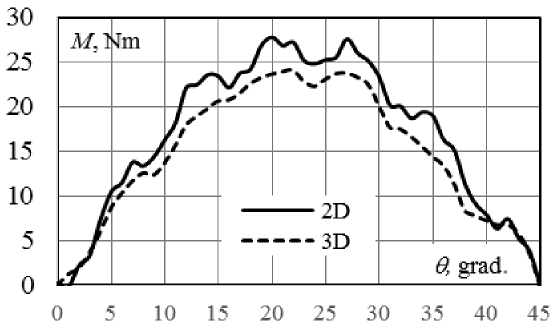

Fig. 6. The electromagnetic torque dependence from rotor position for 2D modeling and 3D modeling

Fig. 7 shows the load characteristics of the investigated generator, obtained experimentally and the calculated one for speed of rotation n = 275 rpm when the generator was loaded by resistor, as well as the calculated dependence of electromagnetic torque from the value of current in the load. Generator windings are connected in a "star". The load is connected to generator through 3-phase rectifier (Larionov bridge). The calculated values were obtained taking into account demagnetization curve of the magnets depending from the temperature.

In the Fig. 7 the load characteristics of generator for 60 degrees temperature is represented by solid line, for 20 degrees – by dashed line and for real experiment – by pointed line. It should be noted the difference between 20 and 60 degrees of permanent magnets temperature is insignificant. The difference between experimental and calculated data is less than 7%.

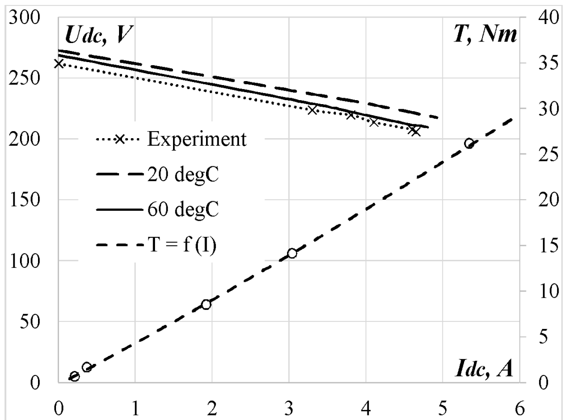

Fig. 7. Characteristics of electrical generator

4. Conclusions

The Darius turbine with straight blades of controlled position was designed and was built. The results of turbine examination in wind tunnel approved the efficiency of this turbine as the wind or water energy converter is 1.5 times higher than the best world samples.

The electric generator model was composed for wind power unit based on Darreius wind rotor with controlled blades. The calculated results were compared to experimental results. The mean difference between these results is not higher than 7%.

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