International Journal of Scientific Engineering and Applied Science (IJSEAS) - Volume-1, Issue-7,October 2015
ISSN: 2395-3470
www.ijseas.com

Wind Power Unit with the New Type Wind Turbine and Electric Generator

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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 electric generator magnetic field with permanent magnets and braking torque depending 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 performed.

Keywords: *wind turbine of Darrieus type, controlled blades, electric generator, permanent magnets, electromagnetic torque.*

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 power units are the wind generators with a horizontal or vertical axis of rotation, the electric generator for converting mechanical energy on the rotor shaft into electric and the tower for the placement of these generators. At present, for utilization of wind energy the horizontal axis wind turbines (HAWT) with capacity from hundreds watts to several megawatts are widely used. The essential components of such wind turbine construction is the vertical tower with height from 10 to 150 meters, the mechanisms for orientation the area of wind turbine rotation perpendicular to the direction of wind flow.

Vertical axis wind turbines (VAWT) do not need special arrangements of orientation relative to the direction of the wind and allow two-bearing rotor mounting system. The electric generator may be placed in the base of the unit, which simplifies its construction. The important advantage of VAWT is the relative simplicity of blades construction and the relatively small area required for the placement of wind turbines [1]. One of the main disadvantage of Darrieus type VAWT with rigidly fixed blades relative to the horizontal crosspieces is a high-speed wind flow, at which there is the self-starting of VAWT to rotate, and large values of the variable mechanical load on the shaft. As it turned out both of these disadvantage can be eliminated by using special methods of control the position of the blades on its circular trajectory.

2. Darrieus type VAWT with straight controlled blades

When moving in a circular path the blade of VAWT 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 turbine 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 flow stall and big decrease of the value of the useful component of the aerodynamic forces, so that the blade even brakes wind turbine in some parts of the trajectory. However, if it is possible to turn the blade in such a manner that the flows are at the optimal angle of attack around of the blade profile, the produced value of torque on the VAWT shaft can be significantly increased.

The test of turbine models in water [2-3] and the full-scale prototypes of VAWTs in the air [4-5] have shown considerable increase the power coefficient $C_p = 2P/\rho V^3 S$ (P – capacity of wind turbine, ρ – density of air or water, V – velocity of air or water flow, S – swept area of wind turbine) as well as a significant decrease in the average load on the turbine 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 value of coefficient C_p was received equal 0.45.

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

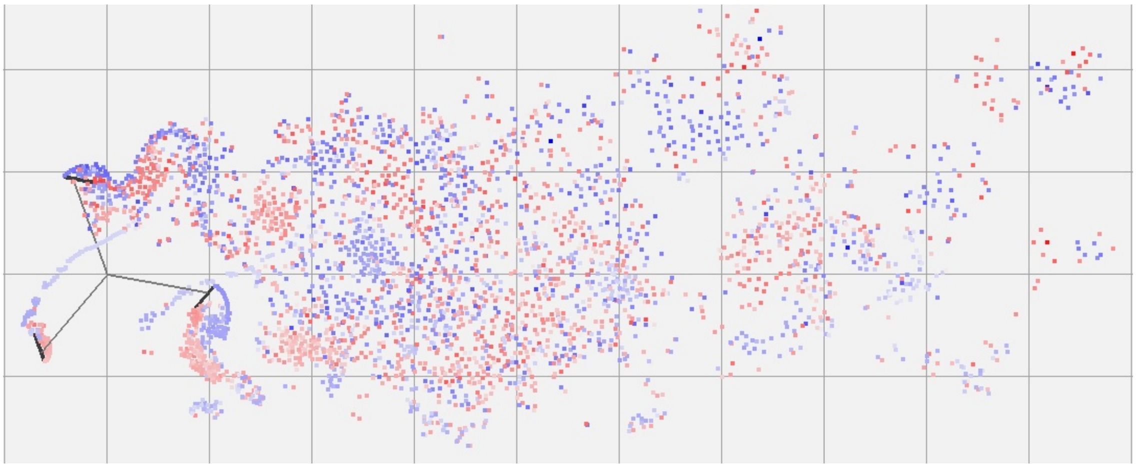
Darrieus type VAWT with straight controlled blades (Fig. 1) had the following parameters: blade length l_{blade} = 1.6 m, the chord length of the blade b = 0.25 m, the profile of the blade is symmetrical NACA 0015, the blade aspect ratio AR = l_{blade}/b = 6.4, radius of blade rotation R = 0.7 m, the average diameter of the control track D = 0.4 m, the VAWT swept area $S = 2Rl_{blade} = 2.24 m^2$, the solidity $\sigma = 3b / 2R = 0.54$. The blades were made of carbon plastic and one blade weighed 2.7kg.

Mechanism for blades control have cylindrical track of the special form in plan and 8 mm thick, placed below the lower crosspieces of the VAWT, on both sides of which three pairs of rollers moved. The pair of rollers 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 lower end of the blades. The control track was attached to the bottom support rigidly.

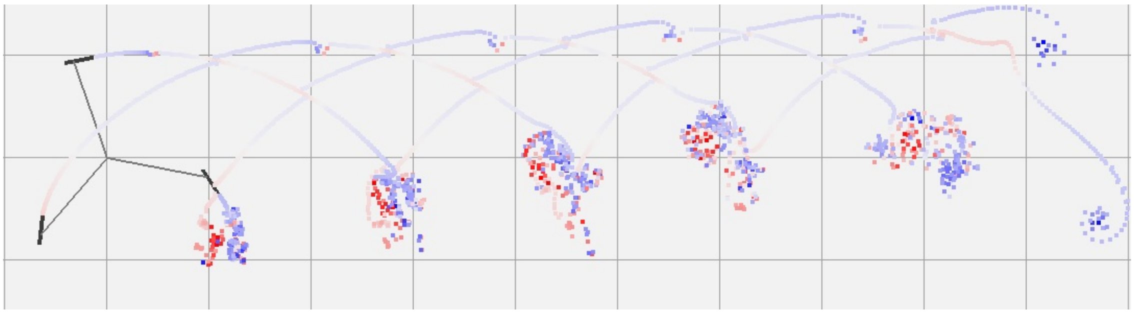
To determine the shape of the cylindrical track was used computer modeling of the flow around the VAWT. A modified method of discrete vortices was used for modeling. This method based on the model of inviscid incompressible fluid [6]. A variable nature of the flow around blades is a feature of this modification: a flow around blade is unseparated at subcritical angles of attack of blade, at supercritical angles of attack a flow separate on leading edge of blade.

The used method of computer modeling allows to view the time evolution of the vortex trail behind VAWT and to get instantaneous and integral dynamic characteristics of VAWT. The presence of numerical flow visualization helps to better understand the physics of the processes and identify patterns that can not be identified solely by instrumental measurements.

The results of numerical visualization of a vortex flow behind VAWT with fixed (*a*) and controlled (*b*) blades at tip speed ratio $\lambda p = 2\pi n R/V = 1.2$ are shows in Fig.2 (the clockwise-rotating vortices are blue, counterclockwise rotating vortices are red, more intensive vortices are more brighter). It can be seen that for VAWT with fixed blades the trail has a pronounced turbulent character that adversely affects the dynamic characteristics of the VAWT. For the VAWT with controlled blades highly visible vortex trail is formed and a this trail leads to the improvement of dynamic characteristics of the VAWT. Note that such a marked difference vortex trail occurs precisely at tip speed ratio λp = 1.2, which was selected for controlling track optimization. By change λp in upward or downward from this value the vortex trail behind the VAWT quickly loses its orderly appearance and the positive effect of the control blades loses also.



a)



b)

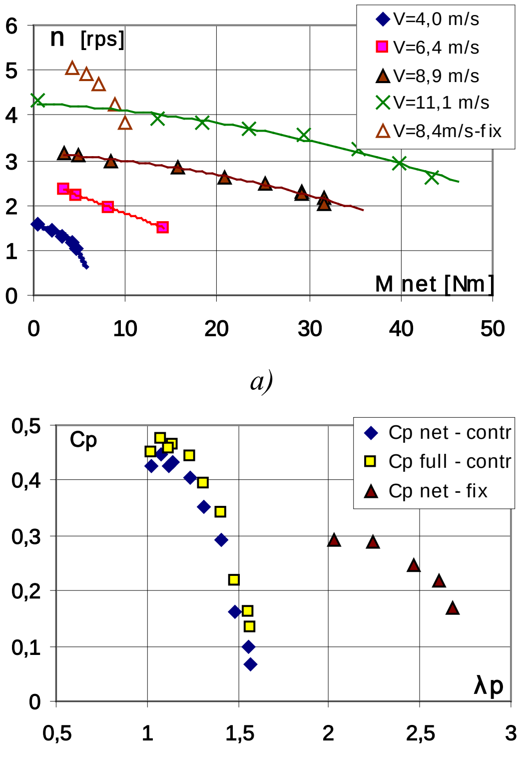
Fig. 2. Numerical visualization of a vortex flow behind VAWT with fixed (*a*) and controled (*b*) blades at tip speed ratio λp = 1.2

The lower end of the turbine 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 VAWT was placed on the shaft, and the shaft through gear box 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), VAWT self-started when the wind flow velocity was V = 2,5 ÷ 2,8 m / sec, without load (i.e. the coupling is removed) the VAWT self-started when the wind flow velocity was V = 1,8 ÷ 2 m/sec. The same VAWT 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 velocity V = 3,5 ÷ 3,8 m / sec.

Dependence of the rotation speed of the VAWT ***n*** from the useful torque M_{net} on the shaft at various velocity of wind flow V is shown in Fig. 3,*a*. The maximum power on shaft was obtained at the lowest rotation speeds of the VAWT. The control of blades allows to get a torque on the shaft almost three times superior than the VAWT with blades rigidly fixed, thus almost twice the speed of rotation decreases (Fig. 3,*a*).

This is clearly seen in Fig. 3,*b*, where the maximum of power coefficient C_p of the VAWT with controlled blades obtained by tip speed ratio λp = 1,1, and the maximum of power coefficient C_p of the VAWT with blades which are rigidly fixed obtained by λp = 2.1. At the same time the power coefficient Cp_{net} of the VAWT 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°, which agrees with the data obtained at the Institute of McMaster in Canada [7] while purging of the VAWT with sizes l_{blade} x D = 3 x 2.5m (Cp_{full} was received experimentally and was not more than 0.33).



a)

б)

Fig. 3. The dependences of the VAWT rotation speed ***n*** from the torque M_{net} on the shaft at various speeds of wind flow V (*a*) and the dependence of the energy coefficient C_p from the value of tip speed ratio λp (*b*) at wind flow V = 9 m / sec.

Thus, the use of simple constructive and technological control blades mechanism of the wind turbine with vertical axis allows using it effectively in small (6-8 m/sec) wind speeds, reducing the value of wind load on the wind turbine 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 power. There are many types of electric generator constructions as disk type construction [8], salient pole type construction [9] and construction with slotted stator [10].

It was designed the electric generator with permanent magnets and slotted stator for the wind power unit described in this paper. It was used a stator taken from a standard asynchronous motor for a lowering designed generator price.

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

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

At the predesign stage of electric 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. 4 shows the sector of the electric 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.

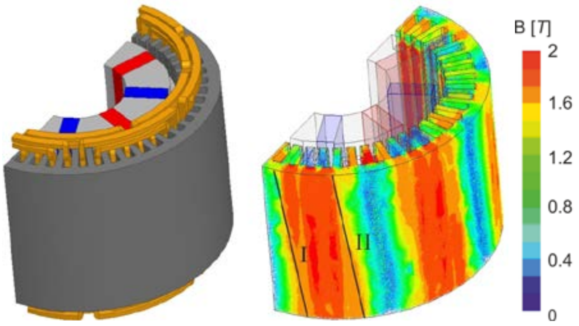


Fig. 4 The magnetic flux density distribution in the stator core.

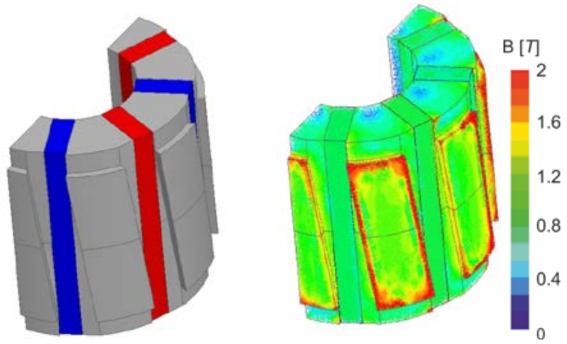


Fig.5. The magnetic flux density distribution in the rotor.

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 from steel ST2211 (with taking into consideration the nonlinearity of material). The ferromagnetic concentrators are made from 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. 6 shows the pattern for the cross section of the magnetic field at a distance of 1/2L_z from the front face of the rotor.

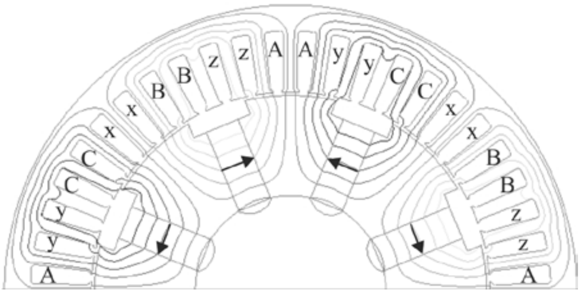


Fig.6. Magnetic field distribution 2D.

As shown by the results of studies (Fig. 7), the value of the electromagnetic torque T 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. Fig. 7 shows the dependence of the electromagnetic torque T (Nm) on the rotor turn angle θ (in geometrical degrees).

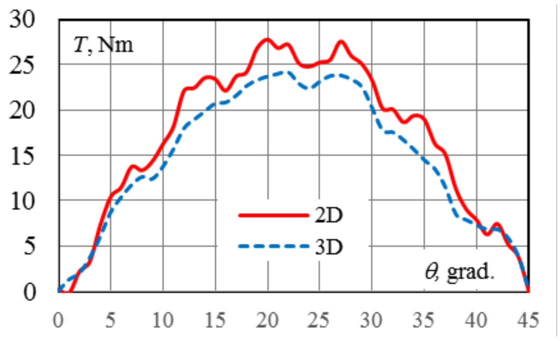


Fig.7. The electromagnetic torque dependence from rotor position for 2D modeling and 3D modeling.

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.8 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 on the value of current in the load. Load characteristics are represented by dependencies of ***Udc*** (direct voltage was measured at load) on ***Idc*** (direct current was measured in 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 on the temperature.

In the Fig.8 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.

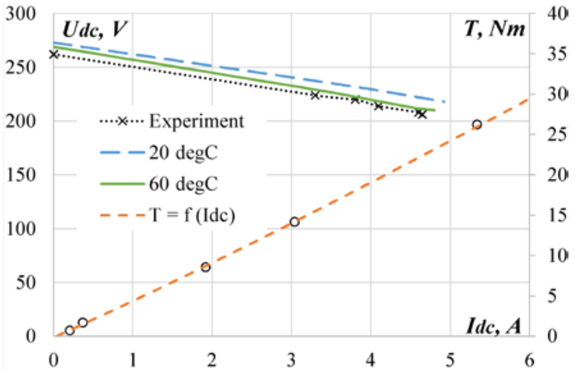


Fig. 8. Characteristics of electric generator.

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%.

4. Conclusions

The Darrieus type wind turbine with straight controlled blades was designed and was built. The results of turbine tests 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 VAWT 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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