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Magnus Wind Turbine: Finite Element Analysis and Control System

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***Abstract*— Due to its special features, the Magnus effect wind turbine allows you to produce energy at a very low speed of the wind. This fact, as well as the growing interest in the of blockchain technology, makes it possible to use this type of wind turbine in private household as part of a distributed energy system in addition to solar panels. The article describes a two blades Magnus wind turbine whose cylinders rotate by means of embedded motors. To avoid a von Karman vortex street effect that occur when the cylinders rotate in the air flow, as well as to ensure maximum power, the optimal ratio between the wind speed and the cylinder rotation speed is determined using finite element analysis. Further, the obtained relations are used in the algorithms of the wind turbine control system.**

***Keywords*— wind, wind turbine, power system, finite element analysis, control system, energy system**

I. Introduction

Nowadays a lot of research focus on distributed energy system [1 - 5] especially on its composition [2,3] and control systems for each part of it [6]. The major idea of conception distributed energy system is using small renewable energy sources in each private houses. Small wind turbines play the major role in this system. The main component that determines the energy efficiency of such wind turbine is generator, which construction is still-open issue [7,8]. The control system of the wind turbine is usually based on the principles of maximum power point tracking [9-11].

The research in area North-East part of Russia and nearest Estonia and Finland has shown that in these area maximum wind gusts is 15 m/s and the mean wind speed is 5,5-7,5 m/s [12]. Fig.1 shows the map with information about wind speed in area mention above. Numerical data of mean wind speed and mean power density in Moscow, Saint-Petersburg, Tallinn and Helsinki are given in Fig.2. It can be seen 6 m/s and 300W is the mean values of wind speed and power density in this area.

For the smooth operation of the three-blade small wind turbine for private houses (see Table I) requires a constant wind speed within 7-13 m/s, which is not acceptable for this area. Due to this fact, it could be most efficient to use a new type of small wind turbine which product maximum power density with a low wind speed around 4-6 m/s. In that context, the concept of new type of wind turbine based on Magnus Effect could be considered as a working prototype.

This work was financially supported by Government of Russian Federation, Grant 08-08.

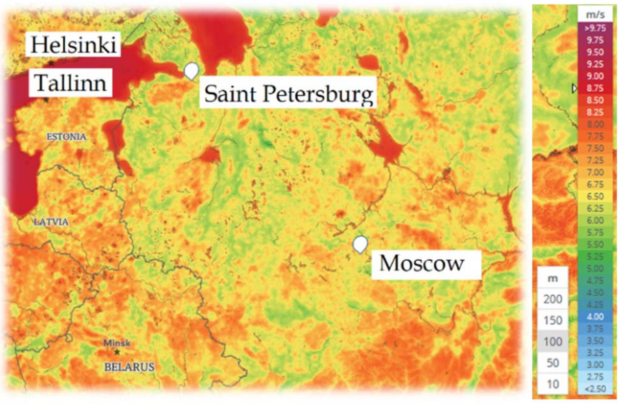
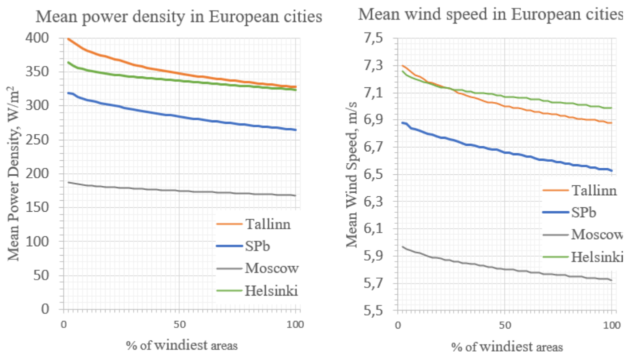


Fig. 1. Wind Energy Layers in Europe and Russia [12]



a) b)

Fig. 2. Mean power density (a) and wind speed (b) in cities

TABLE I. Comparison of Energy Efficiency Small Wind Turbine for Private Houses

Small wind turbine type	Wind Speed Rating [m/s]	Energy Output [W]
WINDMILL 1500W Wind Turbine Generator Kit	13,8	1500
Tumo-Int 1000W Wind Turbine Generator Kit with Wind Boosting Controller	12,5	1000
Happybuy Wind Turbine 600W White Lantern	12	600
Windmax HY400 500 W Residential Wind Generator Kit	12	500
2000-Watt Marine Wind Turbine Power Generator	12,5	2000
2000 Watt 11 Blade Missouri General Freedom II Wind Turbine	6,7	2000

Wind turbines that use the Magnus effect for energy production are a new and most promising direction in the field of wind energy [13]. The main advantage of this type of wind turbines is the ability to generate energy in the range of wind speeds from 2 to 40 m/s compared to 5-25 m/s, acceptable for conventional turbines. These features make Magnus wind turbine is indispensable for microgrid and distributed power systems of private households.

The most complete overview of the Magnus effect and its application in Aeronautics is given in [14]. A description of the nature of the Magnus force origin is given, as well as an analysis of the influence of various parameters on the characteristics of the appropriate system.

The paper [15] provides an overview and analysis of horizontal-axial Magnus wind turbines. As a result of consideration of a large number of sources including patents, the conclusion is made about the prospects of using wind turbines of this type. It is also indicated that one of the ways to increase efficiency is to add ribs and other protruding elements to the cylinder structure, which help to increase the Magnus force.

An extensive study of the Magnus force in relation to wind generators is presented in [17]. The author gives the basics of the theory of the blade element momentum (BEM). This theory is used to analyze the design features of wind turbines, taking into account the highest ratio of lift and drag of rotating cylinders. This parameter largely determines the efficiency of the Magnus wind generator and its competitiveness in the wind generator market.

In [16] BEM theory is used for a comprehensive study of the Magnus wind turbine. In particular, an expression for the power factor is obtained. This method can be used for rough design calculations at the design stage.

A comparative analysis of wind turbines based on the Magnus effect is carried out in [18]. Data obtained from wind turbine model tests in a wind tunnel are used to choose the parameters of wind turbine engines. Experimental data indicate that the maximum efficiency value is reached at wind values up to 8 m/s. The optimal design can be considered a turbine with 6 cylinders, each of which has a length-to-diameter ratio of 15.

Travnicek [19] presents a mathematical model of rotating cylinder with non-symmetric mass transfer. The mass transfer is caused by evaporation from the surface of the cylinder and is aimed at improving lift coefficient. The paper also describes potential flow model and presents visualization of the flow around a rotating cylinder inside a small wind tunnel

Paper [20] describes a modification of the Magnus wind turbine in which spiral ribs were added to the cylinder structure. The turbine was located and tested in the field conditions for a long time. As a result of the tests, low operating noise and the stability of energy production are noted, which is obtained due to algorithms, that take into account value of wind speed.

In [21], a mean lift coefficient of a rotating cylinder is studied. The research shows strong correlation between aspect ratio and lift coefficient of a rotating cylinder affected by a uniform flow. The paper presents a method of estimating mean lift coefficient, supported by experimental data.

Methods of calculating Magnus force are presented in [22]. One method is based on existing equation and allows to calculate irrotational pressure force on the cylinder. The second method is based on a rotational approach and considers centrifugal flow as well as pressure gradient. The comparison shows that the second approach yields 15% higher results than the first one, however, additional research is required to validate this method.

Mara [23] presents a CFD study of a Magnus effect on a rotating cylinder. Different meshing and inflation strategies for model in ANSYS CFX were studied and compared to experimental results provided by Bychkov. Authors suggest using the First Aspect Ratio (FAR20) for mesh inflation around the cylinder and Eddy Viscosity Transport Equation as a turbulence model.

A novel approach to Magnus wind generators is presented in [24]. The author proposes combining Magnus-based turbine and solar panels placed on the surface of the cylinder to increase power output.

Another unconventional approach is proposed by Hably in [25]. The paper describes a crosswind kite power system using magnus cylinder instead of a conventional kite. The Magnus force is used to lift the cylinder and the control system is developed to switch between passive mode (used for climbing) and active mode (used for performing complex oscillating motions and generating power).

There are another implementations of wind turbines based on Magnus effect founded on horizontal configuration named Vertical axis wind turbines (VAWT) [26]. The main advantages of such type wind turbine are easily adjusted its for various wind speeds and easily starting [27]. Also, the mathematical model of VAWT has a simple structure as a low-order cascade model with a dynamic stall model taking into account non-stationary aerodynamic effects [28].

Another implementation of Magnus effect in wind energy devices is Airborne wind energy systems (AWE). It is using wind in high altitude and transfers energy to generator through the drum and cables [29, 30].

II. Structure of Magnus Wind Turbine

a) Magnus effect

The Magnus effect is the occurrence wherein rotary object moving in fluid creates a whirlpool of fluid around itself and arises a force perpendicular direction of motion. The conception is similar to the around an aerodynamic surface with a proliferation which is created by the mechanical rotation, rather than to the airfoil action. In [31, 32] was analyzed Magnus effect in Cylinder based on Computational Fluid Dynamics method.

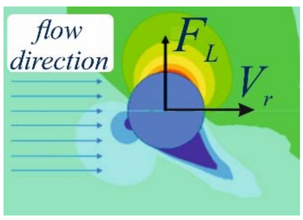


Fig. 3. Magnus force in a rotating cylinder

Magnus effect based on Bernoulli's principle which stipulates that with increasing fluid velocity occurs static pressure decreasing, and fluid's potential energy is decreasing [33]. It can be described as a sidewise force acting on a rotating cylindrical or spherical solid object immersed in a gas or liquid, with the relative movement of them, as shown in Fig. 3.

Kutta–Joukowski theorem was used for finding a lift set up by an airfoil with a sharp trailing edge [34]. Based it, the lift of cylinder can be calculated by Eq. 1.

$$L = \rho \cdot V \cdot G, \tag{1}$$

here L is the lift of a cylinder per unit length, ρ is the air density of a fluid and G is the strength of a vortex, V - fluid velocity.

Calculation of vortex strength G is performed by means of Eq. 2.

$$G = 2 \cdot \pi \cdot r \cdot V_r, \tag{2}$$

here r is the radius of the cylinder and $V_r = 2 \cdot \pi \cdot r \cdot s$ is the angular velocity of the vortex, s is the spin.

b) Wind turbine based on Magnus effect

The wind turbine prototype involves two rotating cylinders rotated by motors. The 3D wind turbine visualization is shown on Fig.4. The lifting (Magnus) force F_L and resistance forces to translational motion and rotation - drag force F_D are affecting on each rotating cylinder. The significant force affecting the cylinder is the Magnus force (or Magnus lift). This force acts in perpendicular direction to the incoming flow. At optimal operation, the Magnus force is higher than the drag force, which generates torque on the rotor, causing it to rotate. Accurate estimation of the drag force is also important for the purpose of modeling deformation of rotor blades and determining the power consumption of DC motors responsible for rotating cylinders.

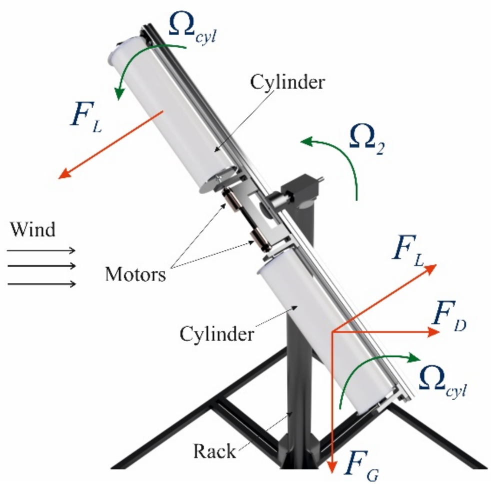


Fig. 4. 3D vizualization of the Magnus Wind Turbine.

For a single cylinder the lift force F_L (Magnus force) and drag force F_D can be written as follows:

$$F_L = \frac{1}{2} \rho S_{cyl} V_r^2 C_L \tag{3}$$

$$F_D = \frac{1}{2} \rho S_{cyl} V_r^2 C_D \tag{4}$$

here V_r - speed of airflow; $S_{cyl} = 2 \cdot \pi \cdot r_{cyl} \cdot l_{cyl}$ - area of the cylinder surface; l_{cyl}, r_{cyl} – respectively length and radius of cylinder. Drag C_D and lift C_L coefficients depends on spinning ratio X_s which can be written as follows:

$$X_s = \frac{\omega_{cyl} r_{cyl}}{V_r} \tag{5}$$

here ω_{cyl} - angular frequency of rotating cylinder.

In [35] was shown that when the ratio of length to diameter of cylinders is low, drag C_D and lift C_L coefficients can be expressed without using Reynolds number (Re):

$$\begin{aligned} C_D &= -0.0211 \cdot X_s^3 + 0.1873 \cdot X_s^2 + 0.1183 \cdot X_s + 0.5 \\ C_L &= 0.0126 \cdot X_s^4 - 0.2004 \cdot X_s^3 + 0.7482 \cdot X_s^2 + 1.3447 \cdot X_s \end{aligned} \tag{6}$$

Figure 5 shows the coefficients calculated from the expressions (5)-(6) [21].

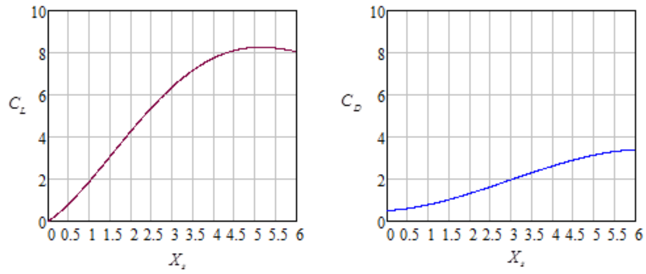


Fig. 5. Dependence drag C_D and lift C_L coefficients on spin ratio X_s

The cylinder rotating in the air flow is affected by the torque:

$$T_{cyl} = \frac{1}{2} \rho S_{cyl} V^2 2 r_{cyl} C_m \tag{7}$$

here C_m – the torque coefficient, which is determined by the cylinder geometry.

III. Control System for Cylinder's Motor

There are a lot of mathematical model of wind turbine. In that paper was used deterministic model due to its portative implementation.

To speed control of cylinders, depending on the wind speed, it is necessary to design closed loop control system. Mathematical model of a wind turbine is described by the following equations [36]:

$$\begin{cases} d\Omega_0 / dt = k_{inv} \cdot u - \Omega_0 / T_{inv}, \\ dT_{cyl} / dt = \beta / T_e \cdot (\Omega_0 - \Omega_{cyl}) - 1 / T_e \cdot T_{cyl}, \\ d\Omega_1 / dt = 1 / J_1 \cdot (T_{cyl} - T_{f1}), \\ d\Omega_2 / dt = 1 / J_2 \cdot (2T_2 - T_{f2}) \end{cases} \tag{8}$$

here Ω_0 - no-load speed; k_{inv}- gain of power converter, T_{inv} - time constant of power converter, u - supply voltage, T_{cyl} - the motor torque, β - the slope of torque-speed characteristic of the motor, T_e - electrical time constant, Ω_{cyl} - the angular frequency of rotating cylinder, Ω_2 - the angular frequency of the shaft of turbine's generator, J_1 - the moment of inertia of cylinder, J_2 - the moment of inertia of the generator shaft, T_2 -

the torque on the generator shaft produced by the lifting force, T_{f1} – friction torque in cylinder's bearing, T_{f2} - friction torque in generator.

In this work, we used a cascade control strategy with an internal torque loop and an external speed loop. The internal torque loop was tuned using a PI controller to a linear optimum to ensure the specified transient with time constant T_t. The speed control system consists of two loops - the internal loop is tuned using the P-controller, and the external loop is tuned using the I-controller. Both loops are tuned on Magnitude optimum:

$$T_{i1} = T_e; \quad K_{p1} = {T_e}/{\beta k_{inv} C_e T_t}; \quad T_{i2} = 4T_{i1}; \quad K_{p2} = {J_1}/{2T_{i1}} \qquad (9)$$

here K_{p1} , T_{i1} – proportional gain and integral time constant of torque controller; K_{p2}– proportional gain of internal speed controller; T_{i2} – integral time constant of external speed controller; C_e - back EMF constant; T_t = $2T_{inv}$ - time constant.of torque loop.

IV. Sumilation and Experimental Results

The photo of Magnus Wind Turbine prototype is shown on Fig.6. The basic dimensions of small wind turbine based on Magnus effect and parameters of imitation modelling, are given in Table II.

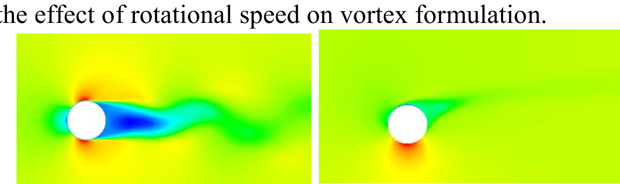
TABLE II. MAGNUS WIND TURBINE DIMENSIONS

Wind turbine parameters	
number of cilinders	2
arm of couple	1.188 m
cilinder dimensions	130 x 545 mm
Parameters Ansys CFX	
Turbulence model	Eddy Viscosity
Inflation Layer Meshing	FLT 20 (3 mm)

Fig. 6. Wind turbine prototype photo

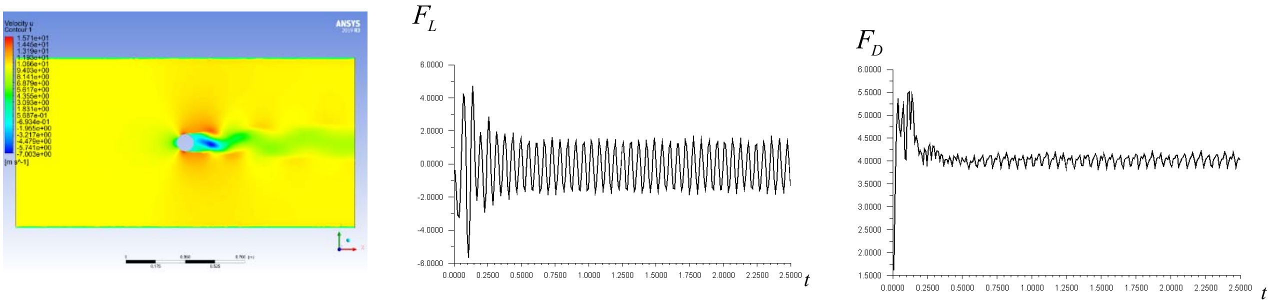
a) Lift force and drag force Magnus Wind Turbine

Study of a Von Karman effect was carried out as shown in Fig.7. The color map shows that vortex formulation intensity decreases with the increase of rotational speed. For each experiment, drag and lift were plotted to further analyze the effect of rotational speed on vortex formulation.



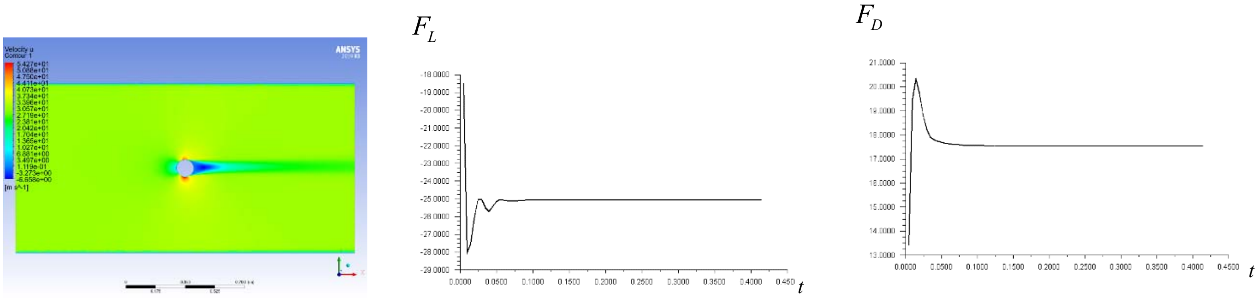
a) b)

Fig. 7. Vortex formation at a cylinder velocity a) ω = 0 rad/s; b) ω = 400 rad/s



a) b) c)

Fig. 8. Sumulation results a) cross-section of cylinder, b) cylinder lift force curve, c) cylinder drag force curve



a) b) c)

Fig. 9. Sumulation results a) cross-section of cylinder, b) cylinder lift force curve, c) cylinder drag force curve

Initial simulations were aimed evaluating Fluent's ability to simulate boundary effects around a rotating cylinder. In the first case, the cylinder was kept stationary in an incoming flow at 10 m/s and the viscosity model was set as laminar. The results are shown on Fig.8. On this flow map, warm colors show higher velocity, while cold colors represent lower velocities. Formulation of Von Karman vortexes caused by asymmetrical separation of boundary layers can be observed on the picture. Force plots are presented on (b) and (c), it is visible that the lift force oscillates significantly around zero. Fig.9. shows the results of a second simulation, carried out at wind velocity of 30 m/s and at a rotational speed of 100 rad/s. In this case, no vortex formulation is visible and neither lift nor drag force show oscillating components.

Further studies of lift and drag force were carried out at a constant wind speed of 8 m/s. 40 simulations were ran with a sample size of 200 measurements for each, or 1 second in real-time. Simulations also shows strong negative correlation between the drag force and cylinder rotational velocity and linear dependency between the lift and rotational velocity. To evaluate the intensity of vortex formulation and its effect on the lift and drag force, a dispersion was calculated for each series. The first 0.25 s of simulations were excluded from this calculation since they have shown transient part of the simulation. Analysis shows that the dispersion of drag force reaches its highest value at the rotation speed of 120-160 rad/s, while the data on the dispersion of the lift force shows that the most significant fluctuations are observed at the speed of up to 180 rad/s. According to these results, it can be estimated that the stable operation of the rotor is possible at velocities higher than 200 rad/s. Another goal of this work was to find correlation between the drag and lift force and the rotational velocity of the cylinder. The linear relationship between the lift and angular velocity can be observed on Fig.10-11.

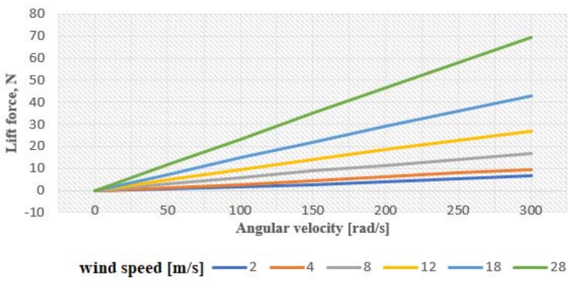


Fig. 10. Curve of lift force depended on cylinder velocity

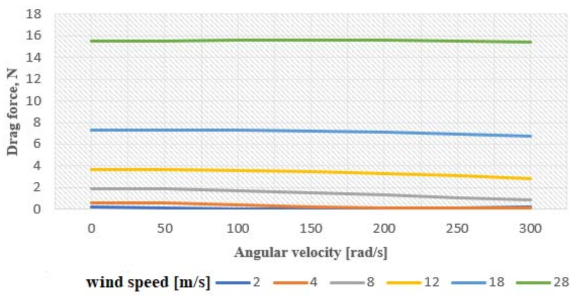


Fig. 11. Curve of drag force depended on cylinder velocity

b) Torque Magnus Wind Turbine

The experimental results were implemented in real environment by using measurements devices. Experiments results are shown on Fig.12. It includes information on torque of the cylinder depending on different wind speed.

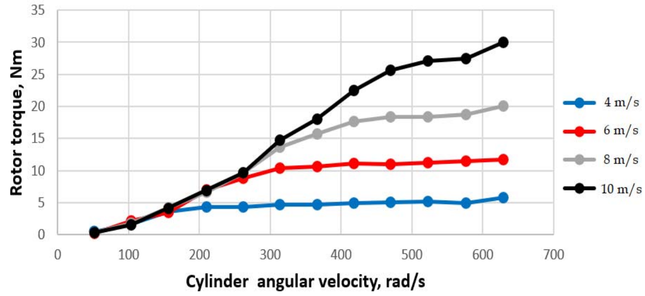


Fig. 12. Relationship between the torque magnitude of the cylinder angular velocity for different wind speeds (EXPERIMENTAL DATA)

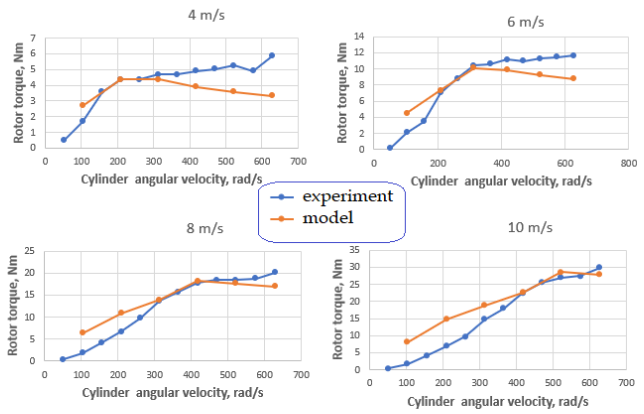


Fig. 13. Relationship between the torque magnitude of the cylinder angular velocity for different wind speeds (Comparison between simulation and experiment)

Figure 13 shows the difference between experimental and simulation data for 3D model of the wind turbine in Ansys CFX. Four series of simulations were carried out for different wind speeds and compared to the experimental data. Results diverge in the quasilinear and saturation areas of the graph, while the position of the saturation point corresponds in both graphs. This shows that the proposed model is an accurate tool for estimating operational range in different environmental conditions for different speeds of cylinders of the wind turbine based on Magnus effect.

c) Power Magnus Wind Turbine

As mentioned above, to ensure stable operation of the rotor, the speed of rotation of the cylinders must be higher than 200 rad/s. The steady-state values of produced and consumed power at reference speed 200 rad/s of the rotating cylinders are shown in Table III. In wind turbine under consideration cylinders' motors have a power of 30W and a nominal voltage of 24V.

TABLE III. SYSTEM POWER PERFORMANCE IN STEADY STATE

Wind speed, m/s	Consumed Power, W	Produced Power, W
2	72.7	83
2.5		104
3		129
8		1250
12		4800

V. Conclusion

The results obtained in this research show the high efficiency of this type of wind turbines, which, in contrast to traditional turbines, can operate in low wind, as well as in the entire range of wind speeds have values of efficiency more than 2 times higher than traditional ones. It was shown that has been linear relationship between lift (Magnus) force and speed of the cylinder that is driven by motor. It is noted that to eliminate the vortex formation caused by Karman's effect, the rotor speed must be higher than 180 rad/s. The simulation results are the same as in the experiment except for the quasilinear and saturation area, where measurement errors and model limitations are high. The model allows to find the saturation point, and, therefore, estimate the operation range. Decreasing mesh element size allows more precise simulation, but at the same significantly increases the simulation time.

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