Defining the Main Parameters of a Darrieus Type Wind Turbine with a Power of 1 kW

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Abstract: *Utilizing huge amounts of cheap wind requires efficient, predictable, environmentally friendly conversion systems. Vertical-axis wind turbines are an area of less investigated wind energy conversion systems. Thanks to advantages over horizontal-axis wind turbines, vertical-axis wind turbines are becoming convenient for certain distinct regions, especially in urban and suburban areas. The article presents the argumentation of the geometric parameters of the blade with aerodynamic profile through numerical simulations, the development of a vertical-axis wind turbine and the investigation of its basic parameters.*

Keywords: *Wind turbine, vertical axis, aerodynamic profile*

1. Introduction

Wind energy has been used by humans for thousands of years. For over 3000 years, windmills have been used for grinding and pumping water. Even today, in the century of computer science, nuclear energy and electricity, thousands of windmills on various continents are used for pumping water and oil, for irrigation, for production of mechanical energy in order to operate low-power mechanisms.

Nowadays, the phrase "use of wind energy" means, first of all, non-polluting electricity produced on a significant scale by modern "*windmills*" called *wind turbines*, a term used to try to emphasize the similarity with steam or gas turbines, which are used to produce electricity, and at the same time to distinguish between their old and new destination.

The first attempts to obtain electricity from the wind date back more than a hundred years, starting with the end of the 19th century. But a real flourishing of this technology is attested only after the oil crisis of 1973. The sharp rise in oil prices has forced the governments of developed countries to allocate substantial financial resources for research, development and demonstration programmes. Over the course of 20 years, a new technology, a new industry and, de facto, a new market - the Wind Energy Conversion Systems (WECS) market - have been created worldwide.

If in 1973 the main incentive for the development of the WECS was the high price of oil, today a second one has been added - the tendency of mankind to produce "clean" or "green" electricity with no or with low carbon monoxide emissions. Of the EU's total greenhouse gas emissions, 79% come from the use of fossil fuels for energy production [1]. The year 1993 was marked as the beginning of a wind boom, which is characterized by an annual increase of over 20% of installed capacity. Thus, in 2000 the cumulative world capacity reached 650 GW. In the last 25 years, energy efficiency has doubled, with the cost of one kWh produced falling from 0.70 euros to about 0.32 euros today [2].

The world leader in installed capacity is the European Union, with a share of 65%, followed by China, the USA and India. No other sector of the world industry knows such a spectacular development. EU Energy Commissioner A. Piebalgs said at the launch of the European Wind Energy Technology Platform [1]: „*Wind energy is certainly one of the fastest growing technologies and it plays an important role in helping create a sustainable and competitive energy policy in Europe*".

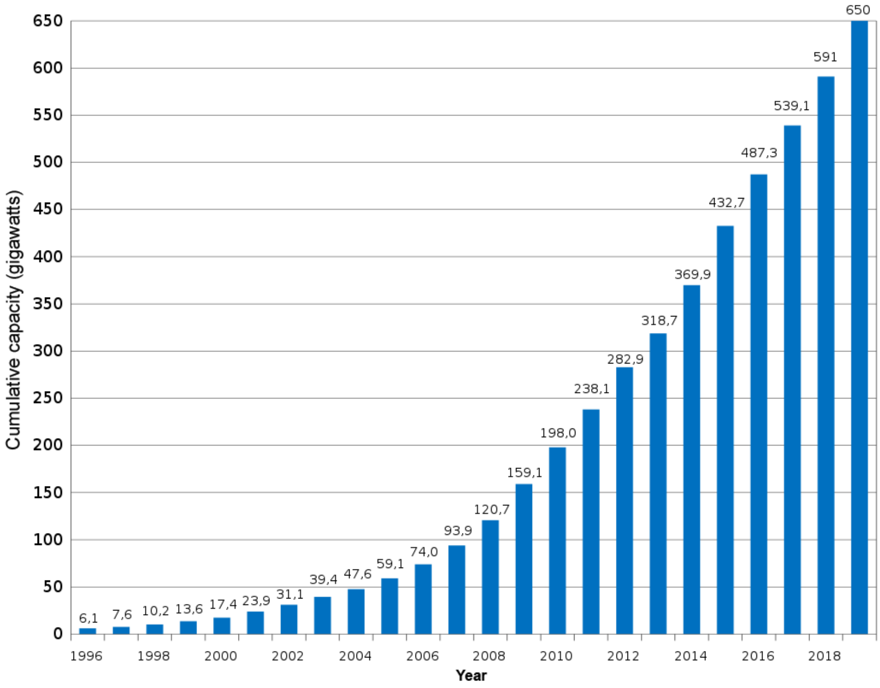

Fig. 1. Wind power: world installed capacity 1996 - 2020

To understand fully the technology of converting wind energy into electricity, knowledge is needed in various fields, including meteorology, aerodynamics, electrical engineering, mechanical engineering and civil engineering.

Depending on the orientation of the rotor axis, wind turbines are divided into horizontal-axis (HAWT) and vertical-axis wind turbines (VAWT). The latter are, in turn, divided into two basic types: the Darrieus turbine, invented by the French engineer George Darrieus; and the Savonius turbine, invented in 1920 by the Finnish engineer Sigurd J. Savonius [3].

Even though horizontal-axis wind turbines (HAWT) are much more widespread, vertical-axis wind turbines (VAWT) still have some advantages [4]: simpler construction; do not require the orientation of the rotor in the wind direction; a recent analysis, using an evolutionary algorithm, showed that the Betz limit, equal to 59.3% for HAWT, is approx. 6% higher at VAWT, because the principle of energy conversion of a VAWT turbine is different from that of a HAWT turbine; in an urban or suburban environment VAWTs are more competitive compared to HAWTs.

2. Parameters of the designed vertical-axis wind turbine

The vertical axis wind turbine was developed based on the technical solution, which was in the patenting stage [5]. The CAD model of the rotor (figure 2, a) was developed with SolidWorks software, and later imported into ANSYS simulation software. To reduce the degree of unevenness of the rotational movement, a rotor with helical blades was developed. The helical angle (of inclination of the blades) has the value of 30°, fact that ensures the coverage of a segment of approx. 60° (for each blade) on the circumference of the rotor projection on the plane. In the cross section of the blade, the Wortmann FX 63-137 aerodynamic profile was adopted with a maximum thickness of 30.9% of the rope length and a maximum curvature of up to 53.5% of the chord length, recommended for vertical-axis wind turbine rotors. The angle between ***AC*** (profile chord) and ***DE*** (axis of the blade fixing arm with the rotor) is 92° (fig. 2, b). The angle between ***AB*** (the axis joining the end points of the profile A and B) and ***DE*** is 93° (fig. 2, c). The length of the chord is 350 mm.

The estimated calculation of the power and geometric parameters of the elaborated vertical-axis wind turbine was performed in the MathCAD application.

Estimated power for yield $c_p = 0.33$:

$$Ar := H_t \cdot D_t = 3.78\ m^2. \quad (1)$$

$$P := \frac{\rho_{aer}\,Ar}{2} \cdot cp \cdot V_{ind}^{3} = 1016\ W. \quad (2)$$

Tangential speed: $V_t := \lambda \cdot V_{ind} = 3.5 \times 11 = 38.5$ m/s. (3)

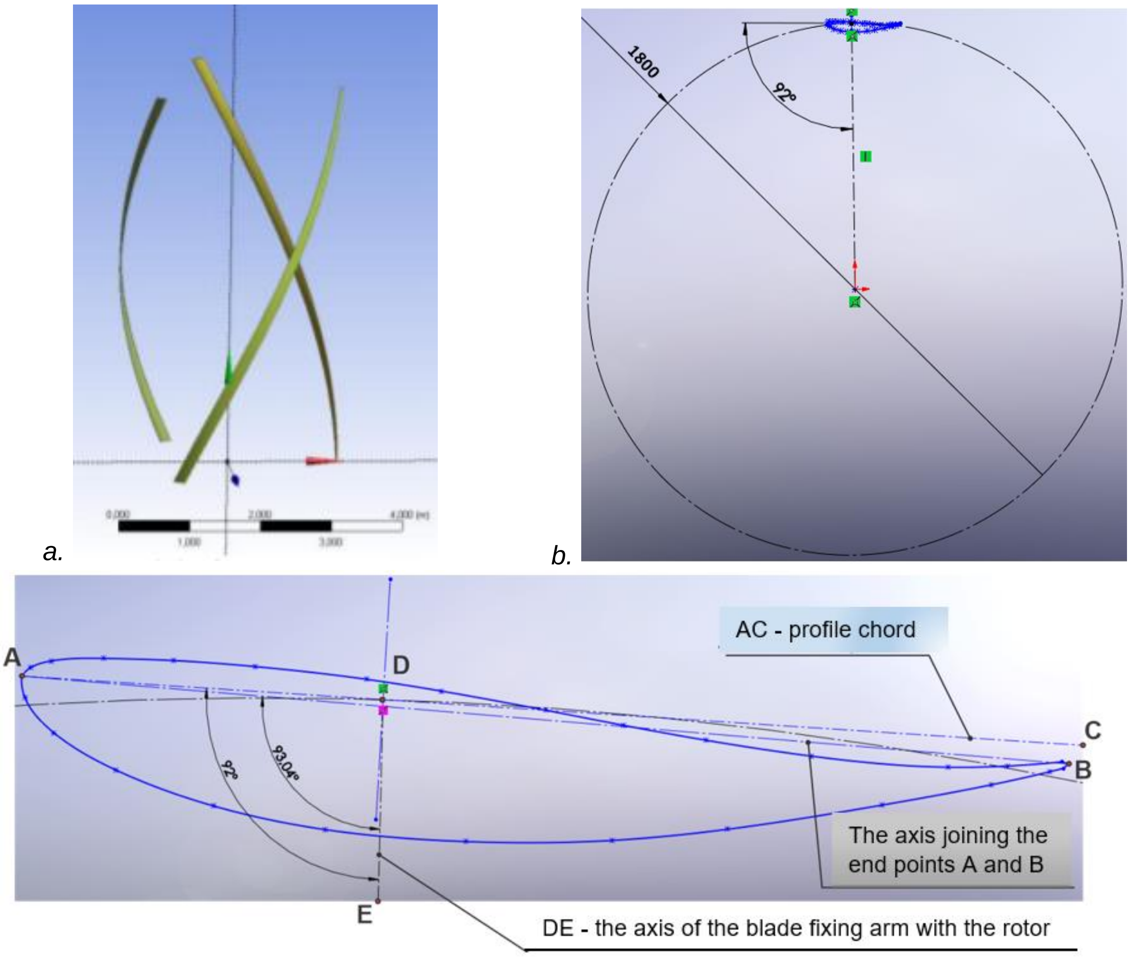

Fig. 2. CAD model of the helical rotor (a), the projection of the rotor in the plane (b) and the parameters of the aerodynamic profile of the blade

Angular velocity: $\omega := \frac{V_t}{R_t}$ = 30.8 s^{-1} (4);

Rotor speed $n := \frac{\omega \cdot 30}{\pi}$ = 294 min^{-1} (5);

Solidity $\sigma := \frac{N_p \cdot Lp \cdot c_p}{H_t \cdot D_t}$ = 0.42 (6);

Kinematic viscosity: $\nu := 1.460 \cdot 10^{-5} \frac{m^2}{s}$ (7);

Table 1: Rotor construction parameters

Parameter	Symbol	Value
Height, m	H_t	2.1
Turbine diameter, m	D_t	1.8
Length of the blade, m	L_p	2.25
Rapidity	λ	3.5
Aerodynamic profile chord, m	c_p	0,35
Blade number	N_p	3
Wind speed, m/s	$V_{inf.}$	11
Air density, kg/m³	r_{aer}	1.225
Estimated power for yield 0.33, W	P	1016

Angle of attack (fig. 3): $\alpha(\theta) := \operatorname{atan}\left(\frac{V_{ind} \cdot \sin(\theta)}{V_{ind} \cos(\theta) + R_t \cdot \omega}\right)$, θ = 0deg, 1...360 deg. (8)

Relative speed: $W_{rel}(\theta) := \sqrt{\left(V_{ind} \cdot \sin(\theta)\right)^2 + \left(V_{ind} \cdot \cos(\theta) + R_t \cdot \omega\right)^2}$; θ = 0deg,1...360 deg. (fig. 4). (9)

Load (C_l) and resistance (C_d) coefficients were determined using JavaFoil simulations (fig. 5).
Normal and tangential coefficients:

$$Cn_i := Cl_i \cdot \cos\left(\alpha\left(\theta 1_i\right)\right) + Cd_i \cdot \sin\left(\alpha\left(\theta 1_i\right)\right) \quad (10)$$

$$Ct_i := Cl_i \cdot \sin\left(\alpha\left(\theta 1_i\right)\right) - Cd_i \cdot \cos\left(\alpha\left(\theta 1_i\right)\right) \quad (11)$$

The parameters of the vertical-axis wind turbine are shown in Table 1 above.

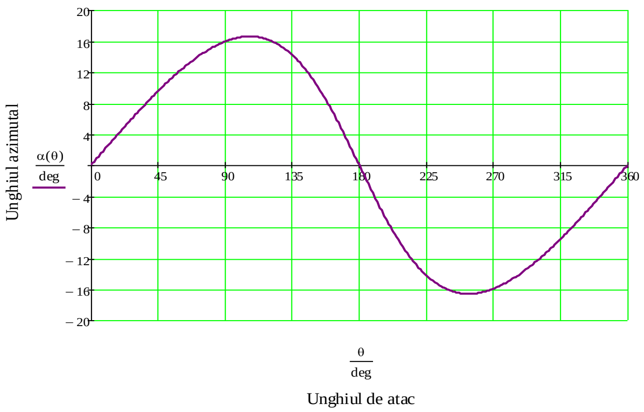

Fig. 3. Angle of attack as a function of azimuthal angle

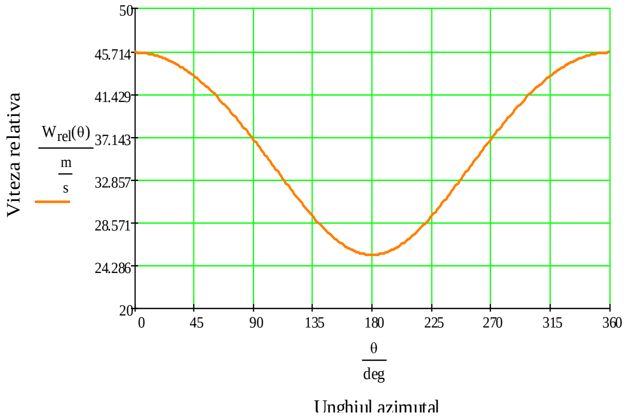

Fig. 4. Relative velocity as a function of azimuthal angle

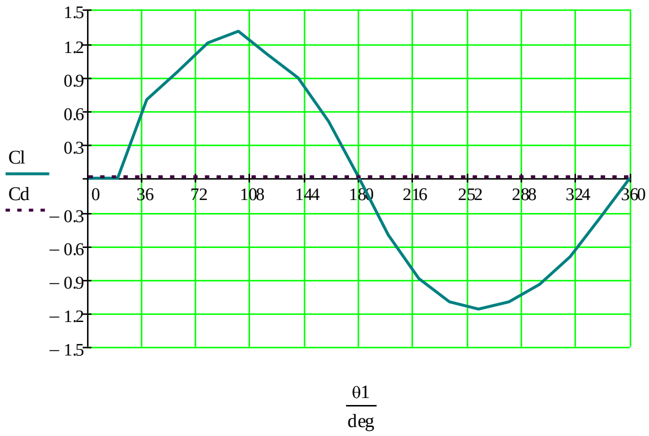

Fig. 5. C_l şi C_d as a function of azimuthal angle

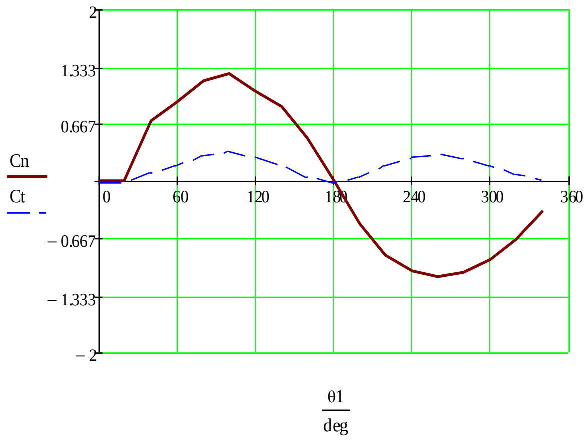

Fig. 6. C_n şi C_t as a function of azimuthal angle

3. CAD modeling of the rotor

ANSYS CFX software was used for the numerical simulation of the "*blade-fluid*" interaction. The mathematical model in the ANSYS CFX software is based on the continuity and momentum equations that are solved using the *k-epsilon* turbulence model (*solving the non-stationary Navier-Stokes equation*). The mathematical model used in the QBlade application is Double-Multiple Streamtube (DMS). This model was developed by Ion Paraschivoiu for the analysis of the performance of Darrieus type rotors. CAD models of the rotor, domain of the rotor (rotary domain) and fluid domain (static domain) were made using SolidWorks and then imported into ANSYS. Domain sizes are set, using the recommendations of the cited source [6]. The dimensions of the fluid domain are: length - 30 m, width - 18 m, height - 8 m (fig. 7, a). The dimensions of the rotor domain are: height 2.5 m, diameter 2.1 m. The rotor is placed at a distance of 5 m from the entry and in the middle compared to the four sides (fig. 7.b). To facilitate the setting of border conditions, the following named selections are created: entry, exit and openings. The three surfaces of the rotor domain are also defined, i.e., the caps and the cylindrical surface. The surfaces of the blades are also defined. This is done when making the CAD model of the rotor. These lines are very useful for setting placement dimensions around the blade. An interface is created between the rotor domain and the fluid domain (Fluid-Fluid). The mesh for the rotor domain and fluid domain is made separately (figure 7.c). The mesh for the fluid domain is as follows: the maximum face size and the Tet size for the fluid domain is 350 mm; The weaving method is automatic; Inflation is made at the interface with the rotor domain: height of the first layer - 120 mm, maximum layers – 6, and grow rate is 1.12. The size of the element of interface surface between the rotor and the domain is 90 mm. The number of items is 585632.

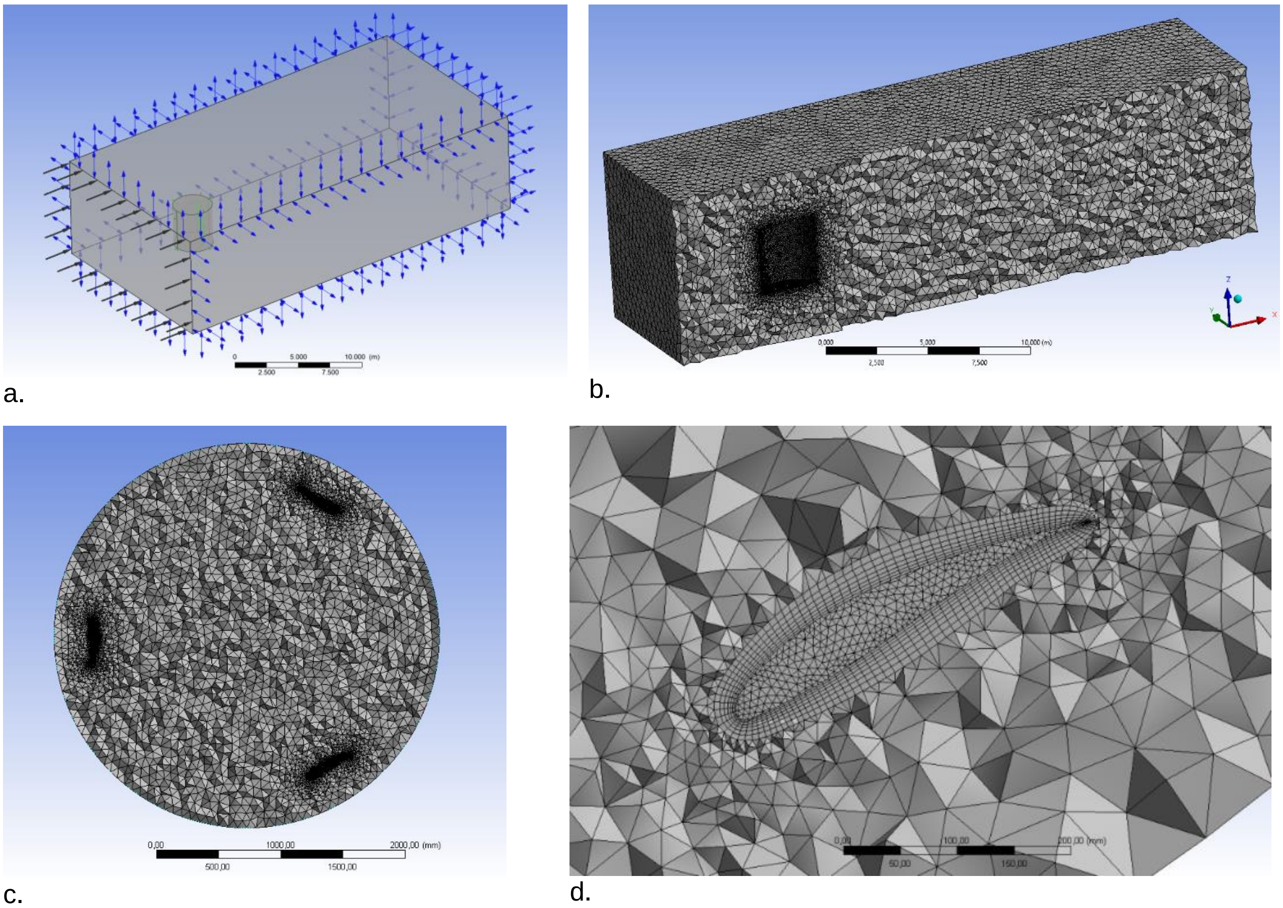

Fig. 7. Discretization of the domain around the blade (a), domain of the rotor (b), domain of the stator (c), and model of the computational domain of the vertical-axis wind rotor.

For the rotor domain, the maximum face size and Tet size of the element is 120 mm. The size of the element on the surfaces of the blades is 3 × 6 mm. In order to reproduce the phenomenon of the boundary layer on the blade surface, where strong fluctuations of the fluid velocity occur, prismatic finite elements were generated by extending them from the blade surface to the outside. This was achieved through the "*Inflation Layer*" process, which was imposed on the surface of the blade with the option "*Total Thickness*" with number of layers = 8, grow rate = 1.1 (relative thickness of two adjacent layers) and type of grow rate = geometric. Height of the first layer = 1 mm (fig. 7.d). The total number of elements is 5684368. When checking the quality of the meshes obtained, asymmetry and orthogonality are the most important. The recommendation is to have a maximum asymmetry less than 0.95 and a minimum orthogonality greater than 0.15.

The domain was discretized, using the "*Triangles*" method with maximum element dimensions of 16 mm. The "*Edge Sizing*" procedure with an element size of 0.8 mm was used for the perimeter of the aerodynamic profile. The "*Inflation*" procedure was also applied with the "*Total thickness*" option: "*Number of layers*" - 11; *Grow rate* - 1.17; "*Maximum thickness*" - 4 mm. A maximum limit of 2.5 mm has been set for interior domain elements. At the Setup stage, the "*Pressure-Based*" computational model in steady flow conditions ("*Steady*") was adopted. The "*K-epsilon Standard*" model with the "*Standard wall function*" option was used to simulate turbulence.

The reference areas for which the boundary conditions were specified (Inlet, Outlet, Internal, Walls) are indicated in figure 7. For Inlet the speed of 16 m / s was adopted, and for Outlet - Gauge pressure (Pascal) - 0. For the maximum residual values of the equations, available in the "*Monitors - Residual - Absolute Criteria*" section, a maximum value of 0.0001 has been set.

4. CFD solutions and results

The simulation results, displayed in Figure 8, show the current lines and the velocity distribution around the blade profiles. It is obvious that the blade, which passes through the descending area, will reduce the rotor torque, as the air flow speed decreases. One can note that the power lines form vortices behind the blades, which must be taken into account when placing wind turbines in wind farms. The power curve was obtained based on the simulations in the ANSYS CFX program (wind speed of 11 m / s, 294 rpm) (fig. 9). The convergence of power results was attested by monitoring the variables of interest. For a better illustration of the dependence on the wind speed, figure 10 shows power curves for V = 7, 8, 9, 10, 11, 12 m / s. The power curves were sketched using the average value of the resulting power for the corresponding wind speed.

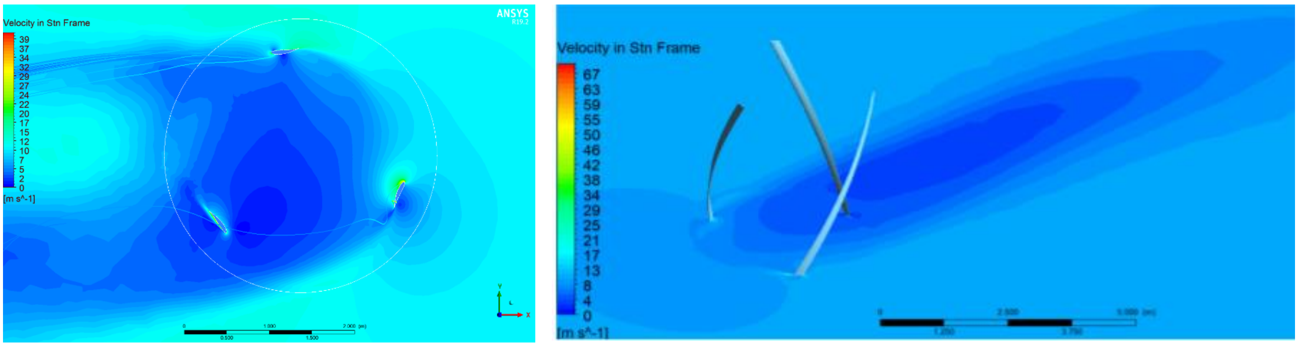

Fig. 8. Fluid velocity distribution around the rotor

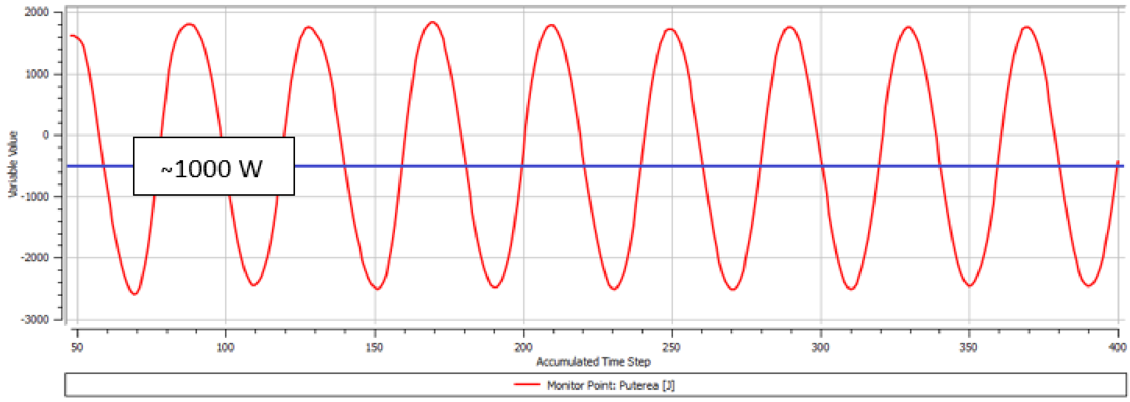

Fig. 9. Power curve obtained by simulations in the ANSYS CFX software (wind speed 11m / s, 294 rpm)

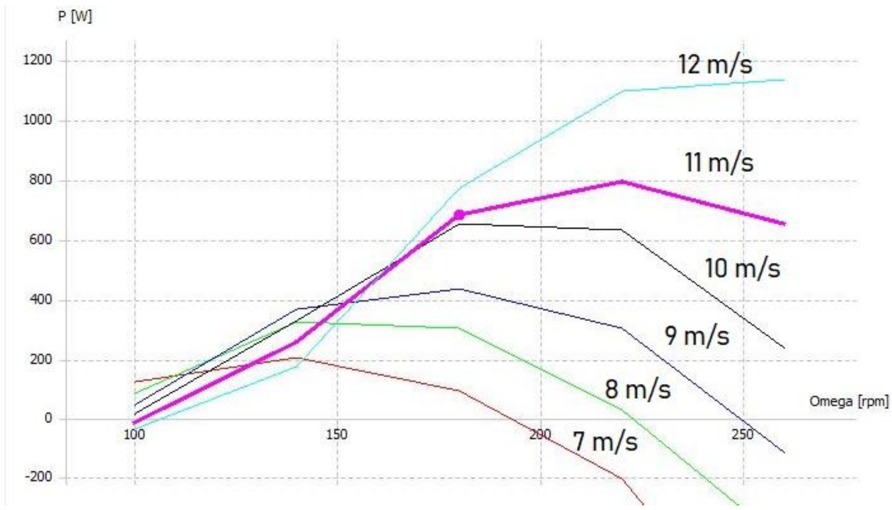

Fig. 10. Comparative power curves obtained based on simulations in the Qblade application

Based on the results of the calculations and CFD simulations performed, the hybrid experimental model of a vertical-axis wind turbine with helical-blade rotor (Figure 11) was designed and manufactured. The blades of the Darrieus and Savonius rotors were made of composite material, ensuring low mass and the required mechanical strength parameters. The Savonius rotor, installed inside the Darrieus rotor, has the function of a starter, thus lowering the starting speed of the Darrieus rotor to approx. 3-4 m / s, therefore ensuring the increase of the turbine efficiency at low wind speeds. The experimental model of the turbine was blown in a wind tunnel, validating, in the rough, the results obtained by CFD simulations and calculations.

Fig. 11. Experimental model of the Darrieus + Savonius hybrid vertical-axis wind turbine

5. Conclusions

- Vertical-axis wind turbines are advantageous compared to horizontal-axis wind turbines, especially in urban and suburban environments;
- The results of the simulations performed in the ANSYS CFX fluid flow dynamics analysis software indicate a very good accordance with the results obtained in the dedicated QBlade application;
- The use of helical blades ensures a low degree of unevenness of the rotor speed;
- The use of the Savonius rotor ensures the lowering of the starting speed of the Darrieus rotor.

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