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Research Article

WIND TURBINE OPERATION PARAMETER CHARACTERISTICS AT A GIVEN WIND SPEED

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ABSTRACT
This paper discusses the results of the CFD simulation of the flow around Vertical Axis Wind Turbine rotor. The examined rotor was designed following patent application no. 402214. The turbine operation is characterised by parameters, such as opening angle of blades, power, torque, rotational velocity at a given wind velocity. Those parameters have an impact on the performance of entire assembly. The distribution of forces acting on the working surfaces in the turbine can change, depending on the angle of rotor rotation. Moreover, the resultant force derived from the force acting on the oncoming and leaving blades should be as high as possible. Accordingly, those parameters were individually simulated over time for each blade in three complete rotations. The attempts to improve the performance of the entire system resulted in a new research trend to improve the performance of working turbine rotor blades.

Keywords: wind turbine, renewable energy, computational fluid dynamics, numerical analysis.

INTRODUCTION

Numerical investigations unlike experimental ones enable the validation of design intents at the design stage. Accordingly, costly preparation of model or prototype for stand testing can be avoided. CFD methods can be applied to compare aerodynamic characteristics of the forces acting on the working rotor surfaces and determine the parameters of its operation, including torque or power generated by the turbine system. If various design changes are made, one can explore their impact on characteristics and improve the entire system. If the geometry of wind turbine blades is modified, numerous aerodynamic phenomena are triggered.

Turbine performance depends largely on the pressure distribution on its working surface. The challenge is to achieve the best possible recovery of kinetic energy derived from the wind by blade shaping so that the oncoming blade could show the smallest possible drag coefficient at the possible highest drag coefficient of the leaving blade as defined in the following relation [1, 4].

$$P = P_1 - P_2 \tag{1}$$

$$P = c_{x1} \cdot \frac{A \cdot \rho}{2} \cdot (v - u)^2 - c_{x2} \cdot \frac{A \cdot \rho}{2} \cdot (v + u)^2 \tag{2}$$

where: P – resultant force acting on the turbine rotor;
A – front surface of the turbine blade;
ρ – density of the agent flowing around the rotor;
c_{x1} – leaving blade drag coefficient;
c_{x2} – oncoming blade drag coefficient;
u – peripheral speed of the blade tip;
v – wind speed

The resultant force P as a difference of the component forces P_1 and P_2 is a driving force of the entire rotor. Actually, that force determines rotor torque. This study identifies the forces acting on the blade during its entire rotation range.

MODELS FOR THE SIMULATION STUDIES

The geometrical model of the rotor that is numerically simulated is a construction according to patent application no. 402214 (Figure 1). The rotor consists of blades that enable us to change an active surface, i.e. that can receive the kinetic energy of wind. Principally, its operation involves adjusting the angle α between the top and bottom part of the blades mounted on the assembly axis (Figure 2). Increasing the angle of opening α between the upper and lower part can increase the active surface which absorbs kinetic energy of wind.

This study is part of the large research and refers to the calculations for a single angle of blades, i.e. a = 90° only. Moreover, the relation in [1] was applied to modify the blade working surfaces to improve their performance. The geometric model of the turbine assembly was developed in CATIA v5. Its size was defined by the size of the wind tunnel used to verify the CFD results. The measurement chamber is 292×292 mm (cross-section). The geometry applied in the simulation reflects the wind tunnel conditions. The turbine under study was in the space of transverse dimensions corresponding to those in a wind tunnel.

The values of the parameters of the rotor and their indications as in Figure 4 are given in Table 1.

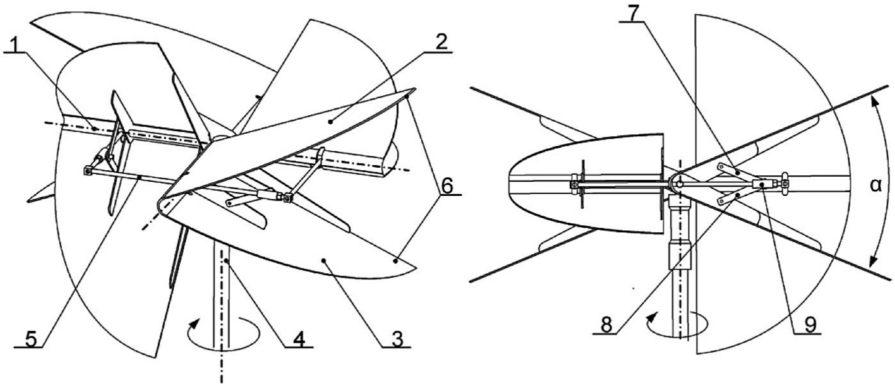

Fig. 1. Isometric view of the rotor with adjustable blade working position (left) and side view of the rotor with adjustable blade working position (right) [5]: 1 – assembly axis, 2 – upper part, 3 – lower part, 4 – bearing axis, 5 – leading axis, 6 – blade, 7, 8 – linkage connecting the sleeve with the upper and lower blade part, 9 – sleeve to adjust spacing blade elements, **α** – angle between the upper and lower blade part

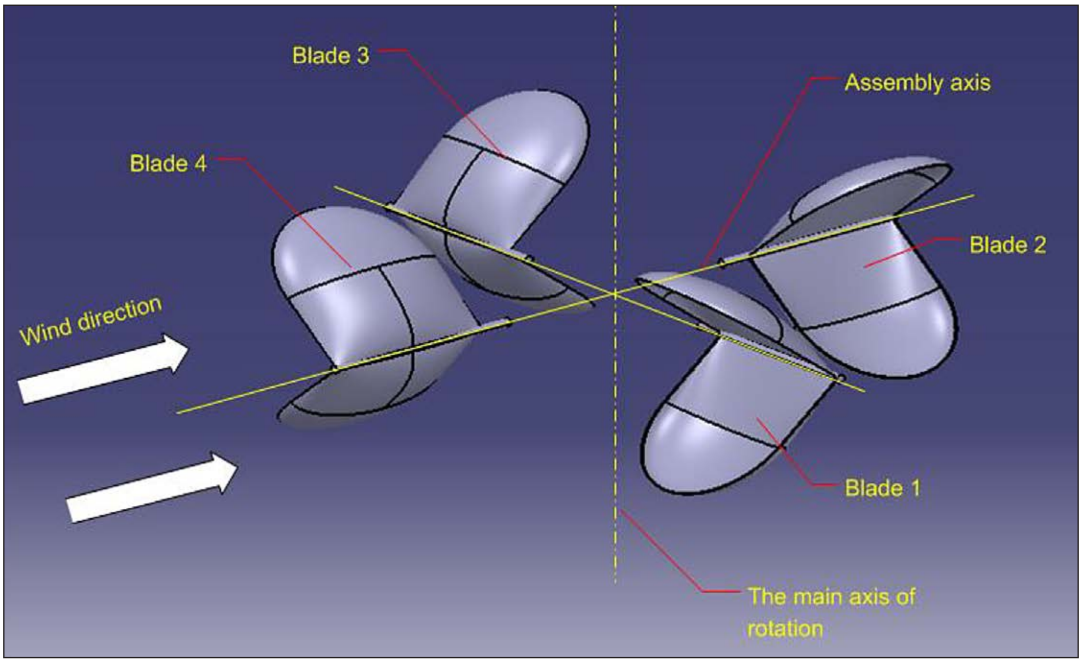

Fig. 2. Notations for the rotor under study

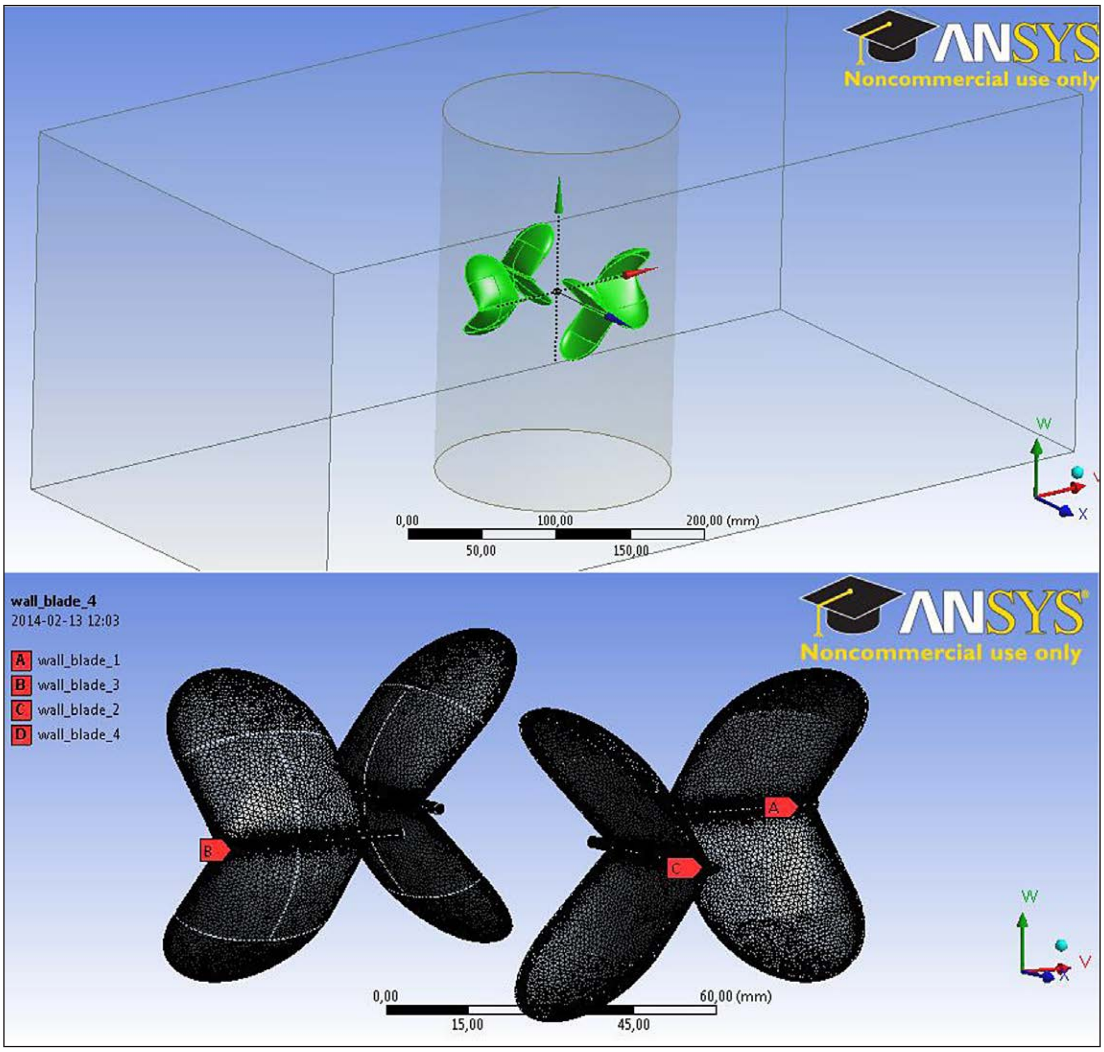

Fig. 3. A sample method of preparing a model of flow around a wind turbine (above) in the wind tunnel measurement chamber and the blade surface mesh density (below)

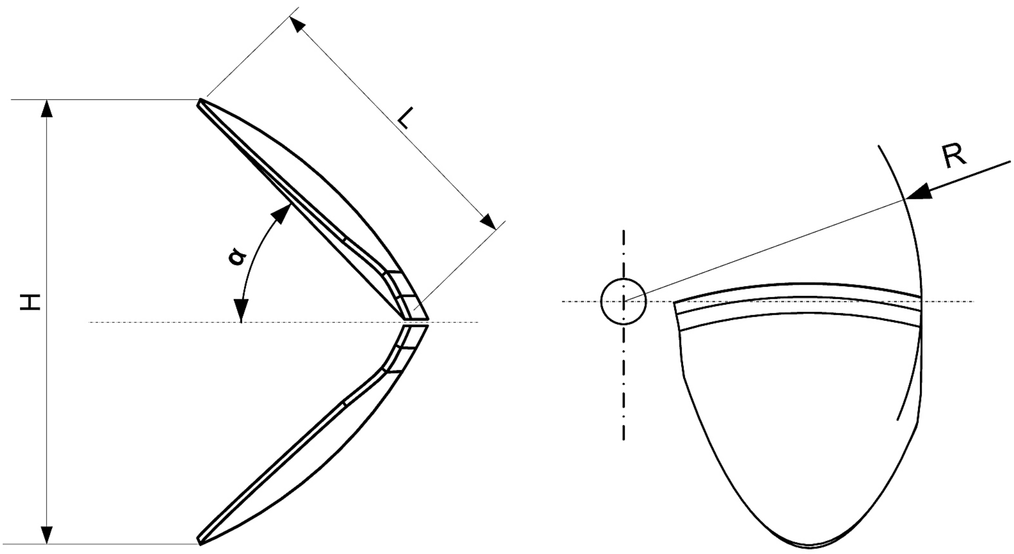

Fig. 4. Diagram of the geometric sub-model of the wind turbine rotor blade, **α** – angle of blade opening as the angle between the upper or lower blade part and the horizontal surface, R – blade radius [mm], L – blade length [mm]

Table 1. Volumes of rotor parameters

No.	Name	Indication	Value	Unit
1	Opening angle	α	45	[°]
2	Blade radius	R	65	[mm]
3	Blade pitch	H	55	[mm]
4	Blade length	L	39	[mm]

RESEARCH DESCRIPTION

The tests were done for several rotational velocities but identical wind velocity. Three complete rotations were simulated to record the changes in blade loading as a function of a rotation angle and rotation repeatability. Accordingly, Table 1 summarizes the auxiliary quantities which are the solver computing settings. If rotational velocity changes, time for a complete rotation changes, too. If the same number of time steps is to be maintained, the value of a single step for each velocity is calculated.

The research scope includes determining the coefficients of the torque for the blades (for each blade) and the entire rotor based on the sum of components. The torque coefficient is defined by the relation in (3), [3].

$$C_m = \frac{T}{0,5 \cdot \rho \cdot v^2 \cdot A \cdot Lc} \qquad (3)$$

where: T – torque [Nm],
ρ – air density [kg/m^3],
v – wind velocity [m/s],
A – reference surface [m^2],
Lc – reference length [m].

Range of the quantities under study that describe the turbine rotor:

- torque coefficient – blade 1,
- torque coefficient – blade 2,
- torque coefficient – blade 3,
- torque coefficient – blade 4,
- torque coefficient – rotor,
- torque [Nmm] – rotor
- rotor power [mW],
- wind power [W]
- efficiency [%].

The calculations refer to the reference quantities that were used to calculate torque coefficients C_m. The values of those coefficients were obtained from the calculation solver. Having converted them according to (3), the change in torque at time T(t) for the entire rotor system was specified. The rotor power P was determined from equation (4).

$$P = (T \cdot n_m)/9550 \qquad (4)$$

The performance of the system under study was calculated from the comparison of the value of rotor power P and wind power P_w for a given rate flow [4].

$$P_w = 0.5 \cdot \rho \cdot A\, v^3 \qquad (5)$$

The numerical calculations were done with computational solver Ansys/Fluent. Turbulence model k-ω SST was employed in the calculations because it is best for this type of research as claimed in [6]. It combines two other models. The basic and most common k-ε model fails in near-wall flow modeling and reflecting the phenomena that occur in the near-wall layer. The

Table 2. Auxiliary data for the numerical computations

Rotational velocity n_m [rpm]	Rotational frequency ω [rad/s]	Rotational velocity n_s [rps]	Time for three rotations [s]	Number of time steps [-]	Value of a time step [s]
0	0	0	0	540	0
50	5.233	0.833	3.600		0.00667
100	10.467	1.667	1.800		0.00333
150	15.700	2.500	1.200		0.00222
200	20.933	3.333	0.900		0.00167
250	26.167	4.167	0.720		0.00133
300	31.400	5.000	0.600		0.00111
350	36.633	5.833	0.515		0.00095
400	41.867	6.667	0.450		0.00083
450	47.100	7.500	0.400		0.00074
500	52.333	8.333	0.360		0.00067

Table 3. Reference quantities in the simulations

Name	Symbol	Value	Unit
Reference surface	A	32.6	[cm²]
Reference radius	L	46.5	[mm]
Air density	ρ	1.2257	[kg/m³]
Air flow rate	v	6	[m/s]

results obtained from that model are reliable when the flow is slow with a turbulent area in the whole area that is far away from the near-wall layer. Wilcox k-ω model can replace the k-ε model because it can give satisfactory results for the near-wall flows. Combining those two models, a new one, i.e. k-ω SST is created which uses Wilcox k-ω model for the near-wall flows and k-ε model for flows in areas far away from the walls of the object under study so the numerical results are more reliable and comparable with the real results.

RESEARCH RESULTS

First, the values of torque coefficients for each of the blades as a function of time are compared. Notice that time [s] is the reference quantity. Despite the fact that the calculations were done for the same number of time steps, their values vary depending on velocity. Hence, the time courses of quantities such as power, torque and performance given in Figures 10, 11 and 12 are shorter for higher velocities.

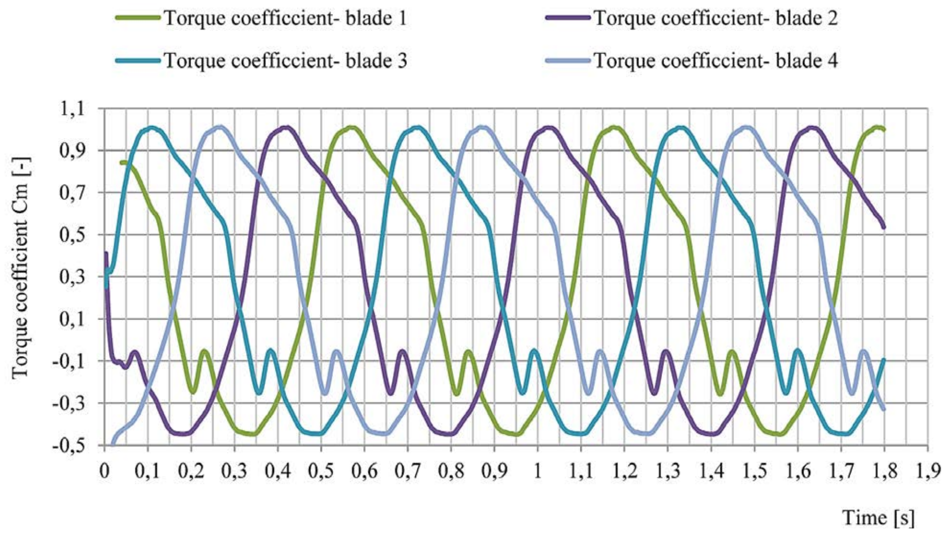

Fig. 5. Time courses of torque coefficient C_m [-] as a function of time for each wind turbine rotor blade for three complete rotations at an angle of 90° and a rotational velocity of 100 rpm

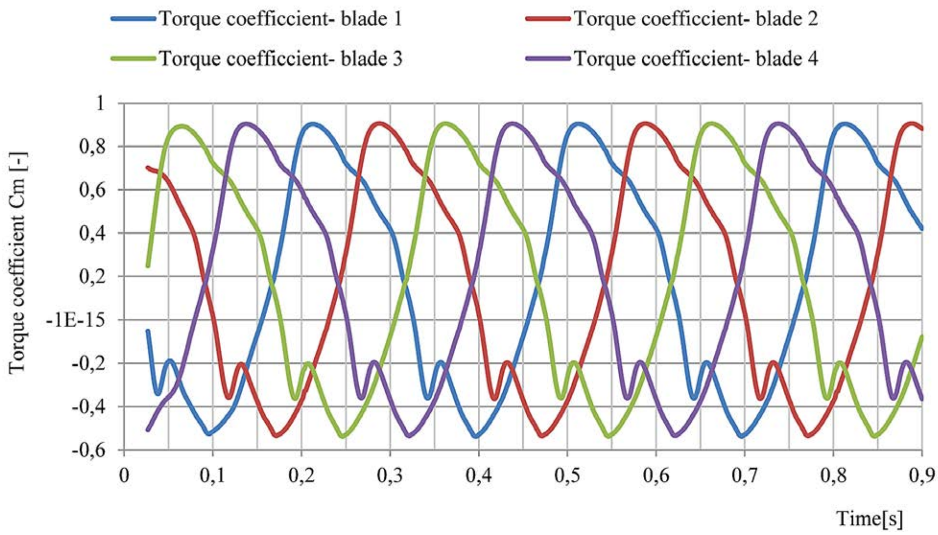

Fig. 6. Time courses of torque coefficient C_m [-] as a function of time for each wind turbine rotor blade for three complete rotations at an angle of 90° and a rotational velocity of 200 rpm

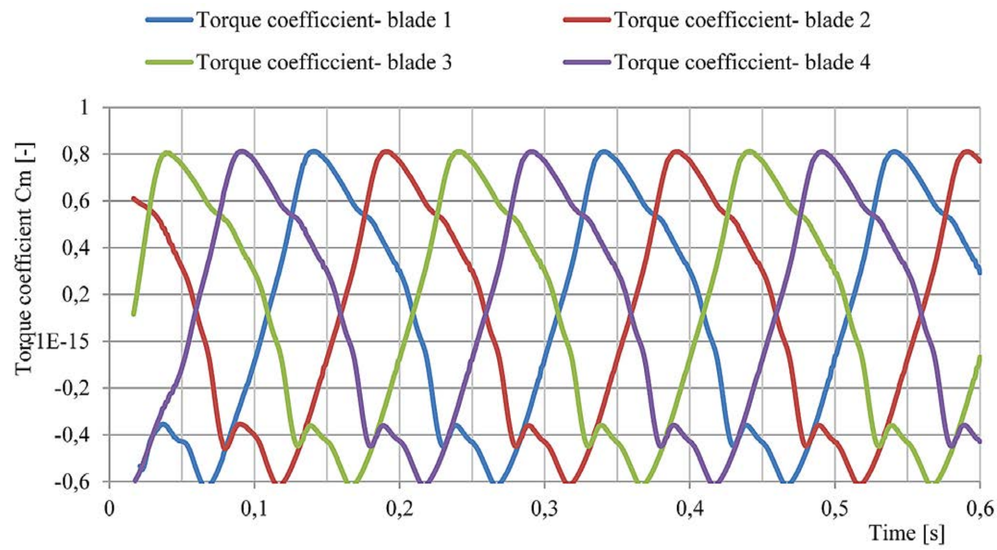

Fig. 7. Time courses of torque coefficient C_m [-] as a function of time for each wind turbine rotor blade for three complete rotations at an angle of 90° and a rotational velocity of 300 rpm

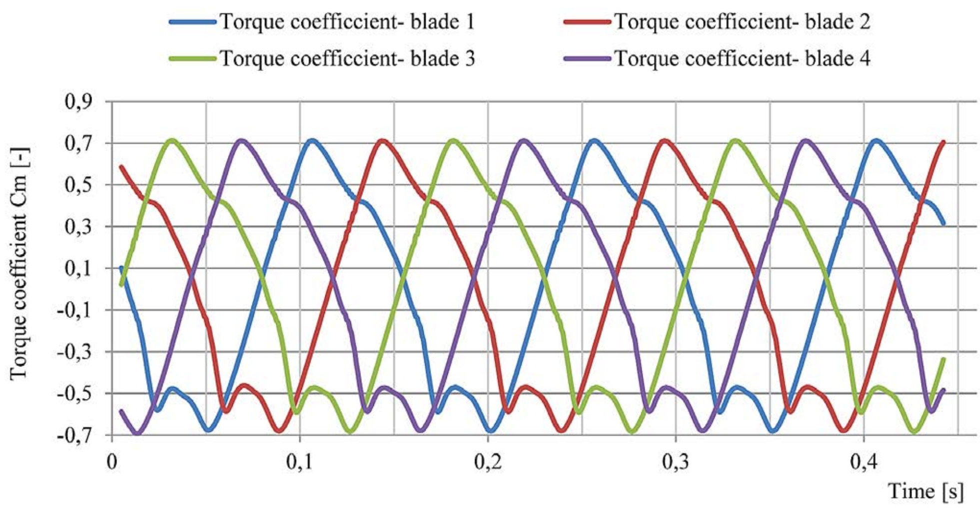

Fig. 8. Time courses of torque coefficient C_m [-] as a function of time for each wind turbine rotor blade for three complete rotations at an angle of 90° and a rotational velocity of 400 rpm

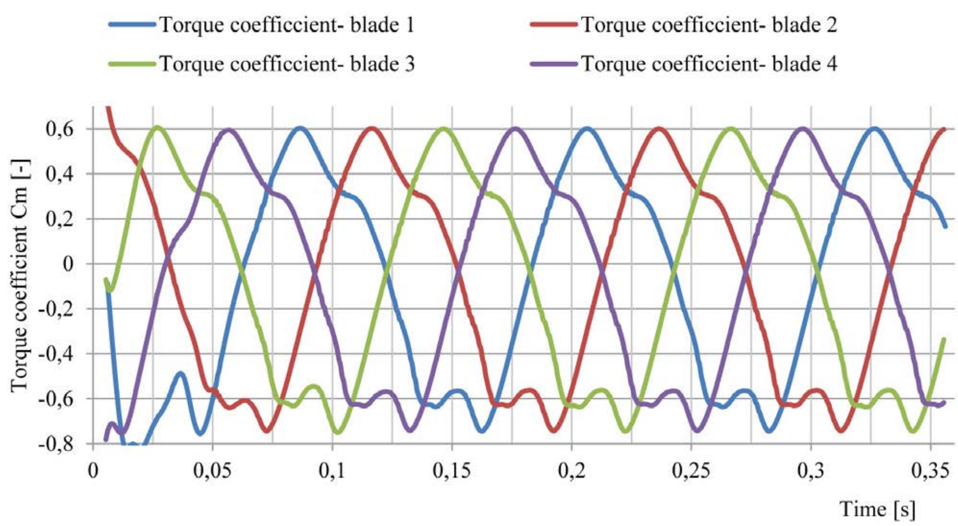

Fig. 9. Time courses of torque coefficient C_m [-] as a function of time for each wind turbine rotor blade for three complete rotations at an angle of 90° and a rotational velocity of 500 rpm

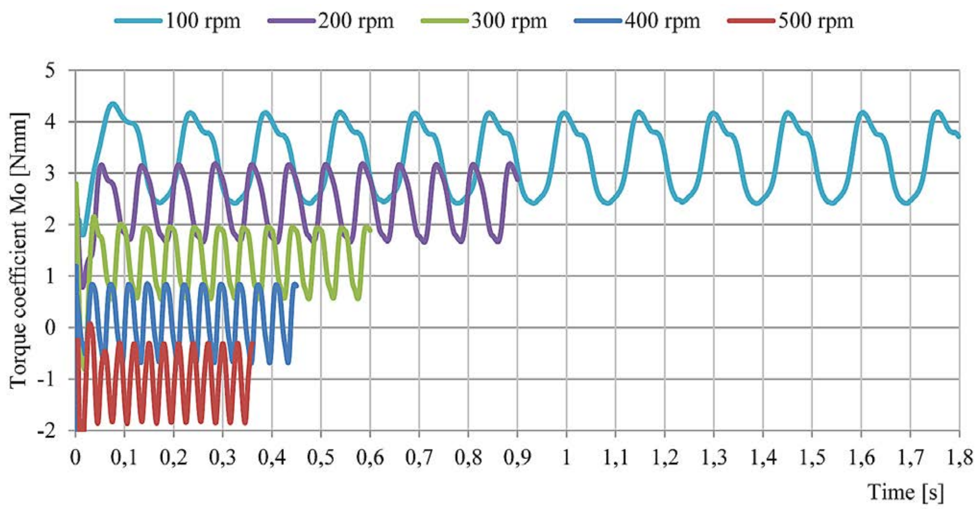

Fig. 10. Torque coefficient for the entire wind turbine rotor [Nmm] as a function of time for three complete rotations at an angle of opening of 90° and varied velocities

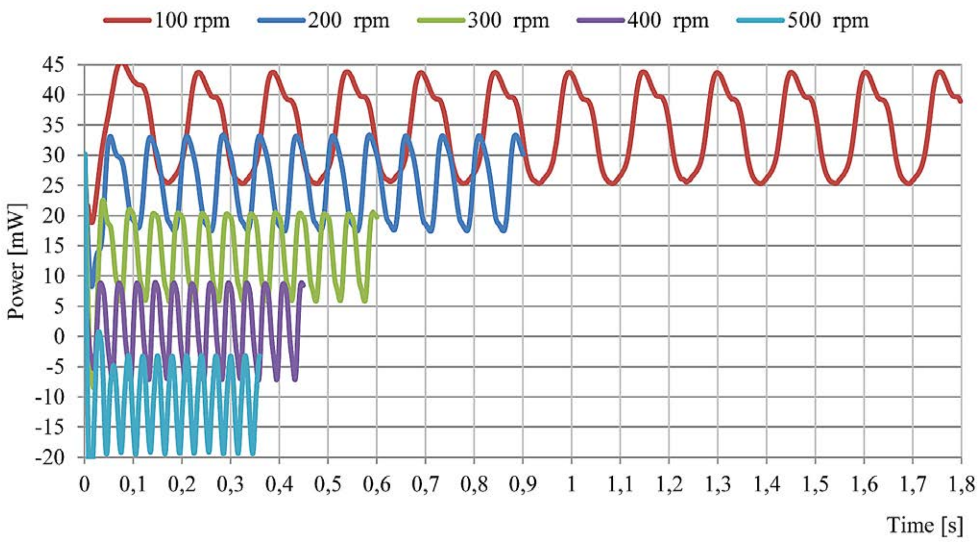

Fig. 11. Power generated by the entire wind turbine rotor [mW] as a function of time for three complete rotations at an angle of opening of 90° and varied velocities

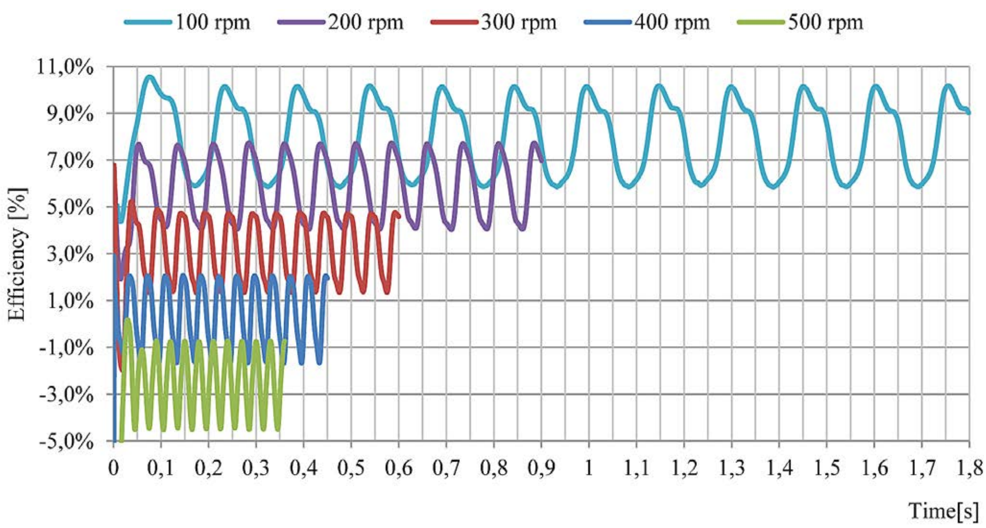

Fig. 12. Efficiency e of the entire wind turbine rotor [mW] as a function of time for three complete rotations at an angle of opening of 90° and varied velocities

SUMMARY

Torque values over time oscillate with a certain amplitude whose boundary values depend on rotor rotation frequency. Also, the coefficient of torque decreases with increasing velocity, which is triggered by a rise in oncoming blade drag. As soon as the velocity boundary value is exceeded, the coefficient C_m reaches a negative value, which means that the oncoming blade at such high speed reaches the instantaneous drag force larger than that of the leaving blade. Actually, this comes from the sum of the linear velocity of a point on the blade and wind velocity. The leaving blade loses its drag as the result of the reduced wind velocity by the linear velocity of a point on the blade. C_m of each blade over time reaches different values depending on the angle of rotation. The largest absolute values are achieved by the extreme blades, i.e. 2 (leaving) blades and 4 (oncoming) blades as in Figure 2. For the oncoming blades, those values are negative (adverse effect). The total coefficient C_m of the entire rotor needs to be positive. That coefficient is almost 0 at a velocity of about 400 rpm, whereas at higher velocities it begins to be negative. This means that it should be given power to run at such high velocities. That need is also confirmed by the negative rotor performance. The maximum instantaneous performance of the system studied is more than 10% at a velocity of 100 rpm while the average one is about 8%. The suggested changes in the structure to continue the investigation on improving the performance refer to avoiding losses due to pressure leak near the assembly axis. Also, a more concave shape in that area is recommended in order to achieve high ratio drag coefficient of the leaving blade to oncoming blade.

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