3D Analysis of Vertical Axis Wind Turbine with Enclosure

Michal Petruželа, Vojtěch Blažek, Jan Vysocký Stanislav Mišák
Department of Electrical Power Engineering, Faculty of Electrical Engineering and Computer
VŠB – Technical University of Ostrava
17. listopadu, Ostrava, Czech Republic
michal.petruzela@vsb.cz, vojtech.blazek@vsb.cz, jan.vysocky@vsb.cz, stanislav.misak@vsb.cz

***Abstract*—Appropriate method to analyse aerodynamic flow in wind turbine is Computational fluid dynamics (CFD). This is the reason why we choose this method to analyse the effect of turbine enclosure on static torque characteristics of vertical axis wind turbine (VAWT) with straight blade. Analyses are realized by use of Ansys CFX software. At first, we carried out simulations of turbine without an enclosure. Next step was to find out a dimensions of the enclosure that increase the torque of the turbine. From the analysis results we selected the enclosure that had overall highest increase of average torque over the turbine without any enclosure at wind speed 5 and 10 m/s. Analysis at two wind speeds are performed for a reason to find out how the effect of the enclosure on turbine torque changes.**

Keywords— Computational fluid dynamics, CFX, vertical axis wind turbine, Darrieus turbine, straight blade, static torque, enclosure.

I. INTRODUCTION

Due to continuously growing emphasis on renewable energy sources, there is also increased focus on research on these sources, among which belongs wind power. Wind power attractiveness lies in its low maintenance cost. Horizontal axis wind turbine (HAWT) is currently most widespread design for electric energy generation from wind, this type of turbine has output power ranging from 1 kW to units of MW. Although there are various types of construction of HAWT, there can be found several factors that are common for proper functionality [1] and [2]. For optimal operation of HAWT is typical higher wind velocity and to that is related necessity of yaw mechanism that is responsible for the orientation of wind turbine towards wind. According to [3] and [4] efficiency of HAWT is low at low wind velocity, so the wind power plant isn't fully utilized.

Vertical axis wind turbine (VAWT) is more appropriate for areas with lower wind velocities. Generally power output of VAWT is lower and ranges from hundreds of W to units of kW, there are some experimental turbines that have bigger power output, for example Sandia 34-M rated at 500 kW [5]. VAWT's independence of wind direction is one of its advantages, due to this there is no need for complex and expensive equipment for adjusting blade direction. Darrieus [6] revealed his concept of VAWT in 1931 and it is area of research to this day. For example, Gorlov [7] and his patent of improved Darrieus turbine. Gorlov turbine had 2 blades twisted in angle of 180 degrees, it is also called Gorlov helical turbine. Because of blade curvature, the airfoil surface is evenly distributed over turbine's circumference. Which means there are no abrupt changes of lift and drag forces which leads to the smoother torque curve, less vibrations and noise.

Thanks to availability of sufficient computing power, there is growing number of three-dimensional (3D) simulations. Howell et al. [8] compared two-dimensional (2D) and 3D simulations to the manufactured model with following outcome, 3D simulations are in reasonably good agreements with experimental measurements in a wind tunnel. Eagle et al. [9] did experiments in the wind tunnel and analysed the effect of different enclosures on straight blade VAWT with airfoil or simple flat blades but investigated only changes of rotational speed. Enclosures have greater effect on simple flat blades than on airfoil and in a few cases the enclosure had negative effect on the rotational speed of the turbine with airfoil. Archinal et al. [10] also did tests in wind tunnel but analysed only one type enclosure, used Savonius VAWT and investigated changes of output torque respectively power. Enclosure caused major decrease of output. Chong et al. [11] proposed and analysed effect of omni-directional shroud composed of five guide-vanes on VAWT with five straight blades. Four different azimuthal angles of oncoming wind were analysed with quite different results, lowest torque increment was 106% and highest was 287%.

II. ANALYSIS DESCRIPTION

First, we describe characteristic dimensions of analysed turbine shown in Fig. 1. Turbine of diameter 1500 mm composes of three Wortmann FX 60-126 airfoils with chord length 400 mm and shaft with diameter 150 mm, last dimension that isn't shown in Fig. 1 is height, turbine is 2200 mm tall. Other than that Fig. 1 shows direction of incoming wind, azimuthal angle ϑ of blade and enclosure defined by its radius R_{enc} and angle β that is symmetric about the y axis and tells us how big portion of the turbine is enclosed.

In analysis the turbine is located in the centre of fluid domain

This paper is supported by the following projects: LO1404: Sustainable development of ENET Centre; SP2018/58 Students Grant and TACR TH02020191, Czech Republic.

in our case material of domain is air at 25 °C. This domain is 15 m long, 15 m wide and 2 m tall. One face of this domain is set as air inlet, here we define a speed of the wind. Other 5 faces are set as opening with relative pressure 0 Pa, this means wind can freely flow in and out through these faces. Turbine itself is set as a wall with no-slip condition.

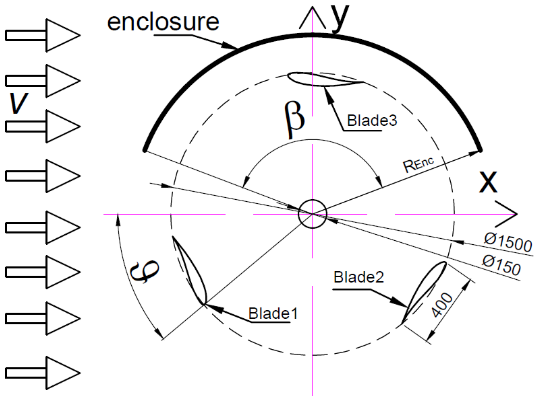

Fig. 1 2D layout of analysed turbine

Before finding enclosure radius R_{Enc} and angle β of the enclosure that increases the output of the turbine, we had to analyse the turbine without any enclosure. With assumption that the turbine has three fold rotational symmetry, we analysed azimuthal angle ϑ in a range from 0° to 110° with step 10°. This was conducted for wind speed 10 m/s. When we got results we calculated average torque and started to analyse the turbine with enclosure, starting point was radius R_{Enc} 950 mm and angle β 180° and in every consecutive step angle was decreased by 5°. We kept doing the steps until it was unlikely that the further decrease of the angle β would yield increase of average torque, in our case it is situation when an enclosure doesn't sufficiently redirect wind flow on a blade that moves against wind and therefore not decreasing braking torque generated by this blade. Next step was change R_{Enc} enclosure radius and repeat procedure with angle β, smallest possible radius R_{Enc} is 825 mm, this is given by the analysis setup where the blades are in rotating domain and enclosure is in stationary domain. This whole procedure was also applied to the analysis with wind velocity 5 m/s, due to a simple reason, to find out if there are any enclosures that increase average torque of wind turbine at both wind speeds. Torque of each blade is acquired by using function described in [12]. Equation (1) is turbine torque at given azimuthal position:

$$M(\vartheta) = M_{Blade1}(\vartheta) + M_{Blade2}(\vartheta) + M_{Blade3}(\vartheta) \quad (1)$$

where M is torque in (Nm) and ϑ is azimuthal angle in (°). Total amount of torque in wind flowing through turbine is calculated by following equation:

$$M_{Wind} = 0{,}5 \cdot \rho \cdot v_{Wind}^2 \cdot A_S \cdot R \quad (2)$$

where ρ is air density in (kg/m^3), v_{wind} is wind speed in (m/s) and A_s is swept area in (m^2) in our case it is product of rotor height and diameter, R is rotor radius in (m).

Step size of every parameter is chosen with respect to that the results have to contain all inflexion points and a simulation time of one setup, which can vary from 20 minutes to 1 hour. In total 864 simulations were carried out.

III. Analysis Results

Table 1 shows the results of the analysis of three enclosures at both wind speeds that have best results. Enclosure 3 has biggest increase of average torque over the turbine without enclosure at wind speed 5 m/s and at wind speed 10 m/s it's Enclosure 2.

TABLE I. AVERAGE TORQUE COMPARISON.

Setup	R_{Enc} (mm)	β (°)	v (m/s)	Average M (Nm)	Average torque increase (%)
No enclosure	-	-	5	0.817	-
Enclosure 1	875	145	5	0.926	13.37
Enclosure 2	875	150	5	0.993	21.51
Enclosure 3	875	155	5	0.998	22.22
No enclosure	-	-	10	3.298	-
Enclosure 4	825	145	10	3.600	9.166
Enclosure 5	825	150	10	3.658	10.903
Enclosure 2	875	150	10	3.560	7.935

Fig. 2 and Fig. 3 show percentual change of average turbine torque as a function of enclosure radius R_{Enc} and angle β at wind speeds 5 and 10 m/s respectively.

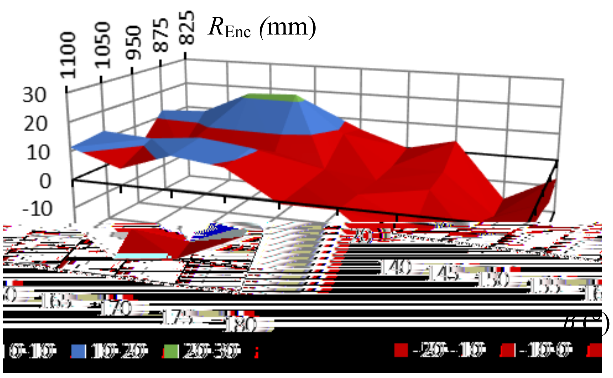

Fig. 2 Percentual change of average turbine torque for all enclosures at wind speed 5 m/s

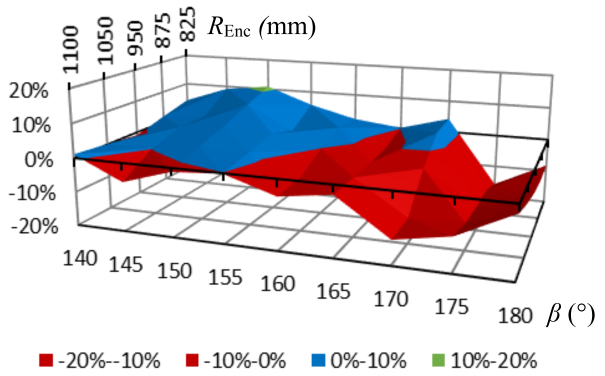

Fig. 3 Percentual change of average turbine torque for all enclosures at wind speed 10 m/s

Fig. 4 and Fig. 5 show turbine torque of setups mentioned in Tab. 1 as a function of azimuthal position at wind speeds 5 and 10 m/s. In legend trace names are given by enclosure dimensions, for example 150 (875) means angle β = 150° and radius R_{Enc} = 875 mm. Due to clarity and assumption of three fold symmetry both plots show only 1/3 of revolution. At these figures we see the enclosure doesn't increase maximal torque but shifts the shape of torque characteristics the way it doesn't reach as big negative value of a torque as turbine without the enclosure. In range of azimuthal angle from 20° to 55° it almost completely removes negative torque, on the other hand in range from 60° to 90° decreases torque and at some point even generates negative torque but not as big as the turbine without any enclosure. Effect of the enclosure aside from the increase of average torque should be shrinking the band of azimuthal positions where torque negative and thus the turbine is unable to start-up.

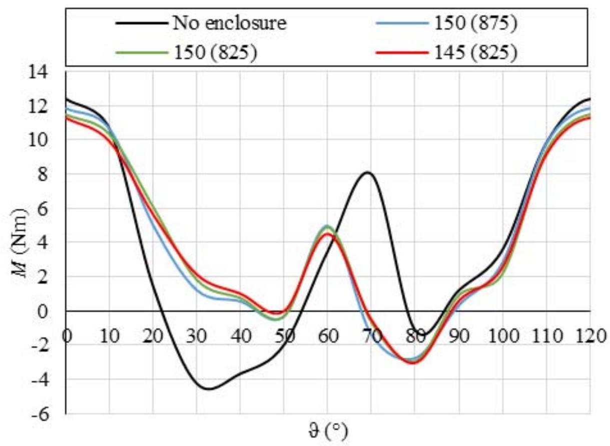

Fig. 4 Turbine torque with different enclosures over 1/3 of revolution at wind speed 10 m/s

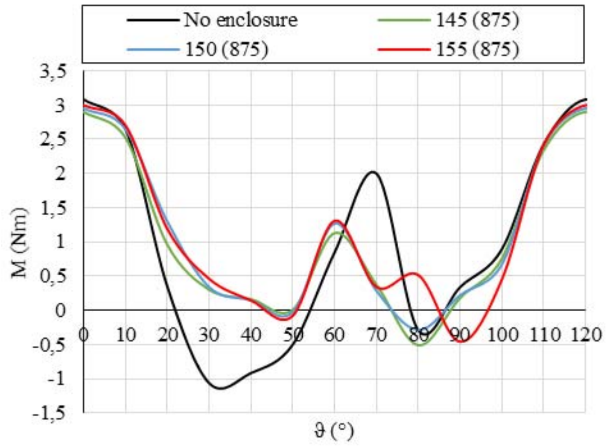

Fig. 5 Turbine torque with different enclosures over 1/3 of revolution at wind speed 5 m/s.

Based on the results we assume the Enclosure 2 is best choice because noticeably increases torque of the turbine at both wind speeds and when compared to Enclosure 3 at wind speed 5 m/s it has smoother torque curve. Torque of the turbine with this enclosure is portrayed in Fig. 4 and 5 as a blue trace. Fig. 6, Fig. 7, Fig. 8 and Fig. 9 show turbine with and without enclosure at two azimuthal angles where the positive respectively negative effect of the enclosure is most significant.

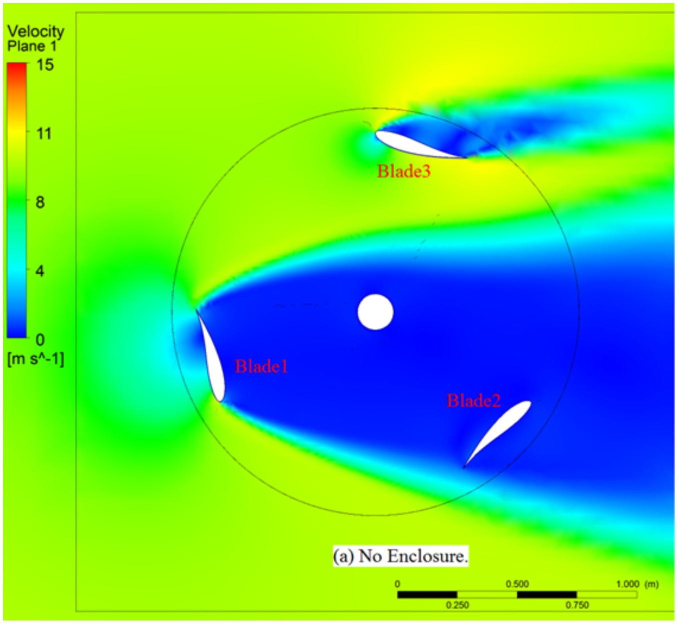

Fig. 6 Wind velocity contours at azimuthal angle 30° for turbine with (a) No enclosure

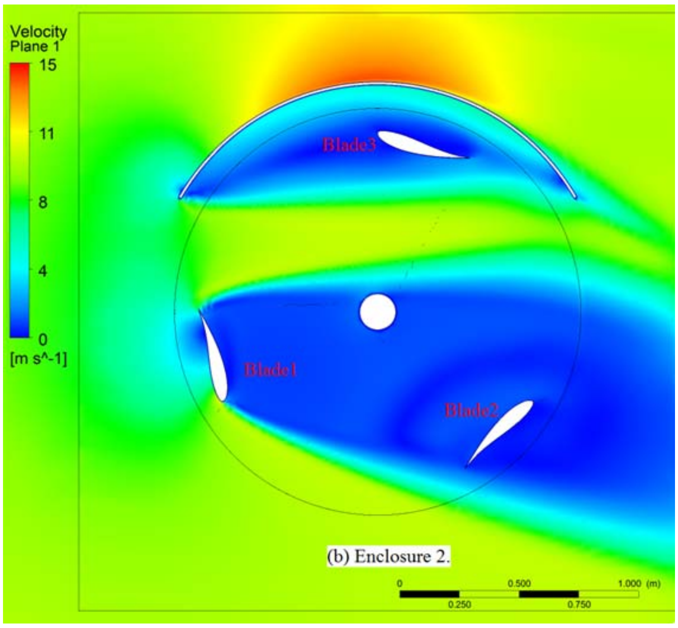

Fig. 7 Wind velocity contours at azimuthal angle 30° for turbine with (b) Enclosure 2

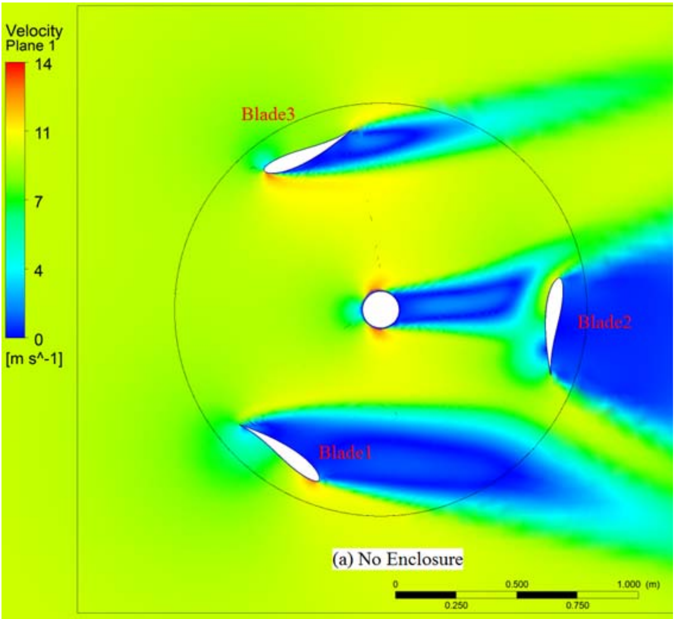

Fig. 8 Wind velocity contour at azimuthal angle 70° for turbine with (a) No enclosure

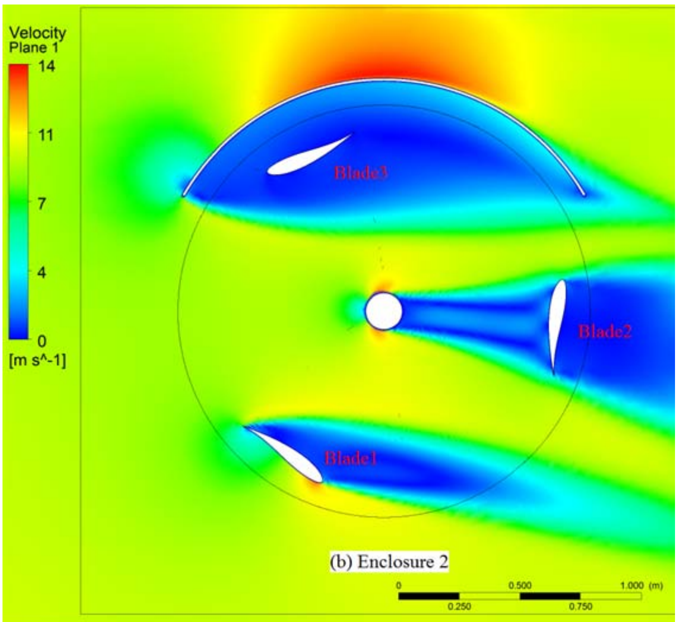

Fig. 9 Wind velocity contour at azimuthal angle 70° (b) Enclosure 2

TABLE II. PARTIAL AND TOTAL TORQUE VALUES AT TWO AZIMUTHAL ANGLES.

		Torque (Nm)			
Setup	ϑ (°)	Total	Blade1	Blade2	Blade3
No enclosure	30	-4.250	0.898	0.037	-5.185
Enclosure 2	30	1.811	0.828	0.048	0.936
No enclosure	70	7.998	-1.249	6.100	3.147
Enclosure 2	70	-0.671	-1.465	0.759	0.035

Table 2 contains results at two azimuthal angles where the Enclosure 2 has biggest negative and positive effect. First case where Enclosure 2 has greatest positive effect is at azimuthal angel 30° where it completely removes negative torque from Blade3 but also removes positive torque from Blade1. Second case is at azimuthal angle 70° where Enclosure 2 has biggest negative effect on torque, it nullifies torque from Blade1, Blade2 and causes negative torque to be generated on Blade3.

IV. Conclusion

We analysed effect of the enclosure on static torque characteristics of VAWT with straight blades. At first, we had to analyse turbine without any enclosure, these results are used to calculate if the effect of an enclosure is positive or negative. Next step was to find suitable enclosures that has most positive effect on average output torque of the turbine at wind speeds 5 and 10 m/s, for each wind speed we selected 3 enclosures with best results and presented them in Table 1. From these results we decided that the Enclosure 2 with following parameters - enclosure radius R_{Enc} = 875 mm and angle β = 150° is more suitable than the Enclosure 3 because average value of the torque increments at wind speeds 5 and 10 m/s is higher and has smoother torque curve at wind speed

5 m/s. Average torque of straight blade VAWT with Enclosure 2 was increased by 21.5% at wind speed 5 m/s and by 7.9% at wind speed 10 m/s, this leads to the conclusion that the turbine with the enclosure should improve its ability to start-up at lower wind speeds.

Future research lies in analysing effects of the selected enclosures on power curve, applying same procedure on VAWT with helical blades and examining how inaccurate orientation of the enclosure towards the wind affects the torque.

REFERENCES

[1] M. R. Patel, Wind and solar power systems. New York: CRC Press, 1999. ISBN 0-8493-1605-7.

[2] J. Manwell, J. McGowan and A. Rogers. Wind energy explained: theory, design and application. New York: John Wiley & Sons, 2009. ISBN 978-0-470-1500-1.

[3] I. Paraschivoiu, Wind turbine design with emphasis on Darrieus concept. New York: John Wiley & Sons, 2002. ISBN 2-553-00931-3.

[4] S. Eriksson, Direct driven generator for vertical axis wind turbines. Uppsala: Acta Universitatis Upsaliensis, 2008. ISBN 978-91-554-7264-1.

[5] H. Sutherland, J. D. E. Berg and T. D. Ashwill. A retrospective of VAWT technology. Albuquerque: Sandia National Laboratories, 2012.

[6] G. Darrieus, Turbine having its rotating shaft transverse to the flow of the current. U.S. Patent 1835018, 8 December 1931.

[7] M. A. Gorlov, Unidirectional helical reaction turbine operable under reversible fluid flow for power systems. U.S. Patent 5451137, 19 September 1995.

[8] R. Howell, N. Qin, J. Edwards and N. Durrani. Wind tunnel and numerical study of a small vertical axis wind turbine. Renewable energy. 2010, vol. 35, iss. 11, pp. 412-422. ISSN 0960-1481. DOI: 10.1016/j.renene.2009.07.025

[9] J. M. Eagle, D. Olinger, J. O'Shaughnessy. Enclosed vertical axis wind turbines. Worcester, 2012. Project. Worcester Polytechnic University.

[10] P. Arichnal, J. Lee, R. Pollin and M. Shooter. Partially enclosed vertical axis wind turbine. Worcester, 2014. Project. Worcester Polytechnic University.

[11] W. T. Chong, A. Fazlizan, S. Y. Yip, K. H. Wong, L. F. Sim, S. C. Poh and W. P. Hew. Design and numerical study of the integration of omni-directional shroud with vertical axis wind turbine, 3rd IET International Conference on Clean Energy and Technology (CEAT) 2014, Kuching, Malaysia, ISBN 978-1-78561-069-1, pp. 1-5, 2014.

[12] CFX Manual, ANSYS Release Version 15.0, Reference guide; ANSYS Inc.: Canonsburg, PA, November 2013.