Numerical and Experimental Efficiency Evaluation of a Counter-Rotating Vertical Axis Wind Turbine

Ion Malael
CFD Department
National Research and Development Institute for Gas Turbines COMOTI
Bucharest, Romania
ion.malael@comoti.ro

Valeriu Dragan
CFD Department
National Research and Development Institute for Gas Turbines COMOTI
Bucharest, Romania
valeriu.dragan@comoti.ro

***Abstract*—This paper investigates the concept of a concentric counter-rotating vertical axis wind turbine (VAWT), consisting of a two stage vertical H-type turbine with three blades on each stage. The model has an inner and an outer stage, rotating in opposition to each other. Both numerical and experimental tests have been performed in order to validate this new concept. Numerical analysis is based on the use of 2.5-dimensional, unsteady simulations using a DOF type of analysis which allows for the two stages to self-adjust their rotation speed. Sliding mesh conformal interfaces are defined between these subdomains to minimize numerical artifacts such as artificial relations or entropy changes. Fully turbulent URANS were carried out in Ansys Fluent software. One key outcome was the momentum coefficient for each stage at different tip wind speed values. Another, more qualitative, outcome is the analysis of vortex shedding, impingement and overall interaction between the stages at different positions and scenarios. Ultimately, the numerical results have been validated using a scaled experimental device which was analyzed in the wind tunnel at different free stream speeds.**

Keywords-CFD; counter rotating; wind tunnel; wind turbine

I. INTRODUCTION

Concerns regarding global warming have favored the interest of researchers for innovation and research in the field of renewable energy. Wind energy is emerging as a renewable alternative to conventional power plants. In Romania, the proportion of wind power peaked at 20% of national requirements in January of 2017, surpassing nuclear power sources. Both vertical and horizontal axis wind turbines are currently employed, with a heightened interest for VAWTs for urban areas. VAWTs represent a major part of urban sustainable energy landscape for several decades, mostly due to their robustness in terms of wind orientation although they suffer from self-starting lack, requiring start-up assistance to reach a self-sustained operation point. While offshore wind farms make use of the larger, but less versatile, axial wind turbines, the VAWT independence of the inflow makes them ideally suited for urban environments where flow patterns can be often unpredictable [1]. Constructively, the Savonius types [2] are limited to a TSR of one unit, making them inefficient when compared against the Darrieus types [3]. On the other hand, Darrieus VAWTs have difficulties during rotation starting, making high torque applications difficult. Recent years have seen a significant number of VAWT variations, deviating from the classical Savonius and Darrieus types to hybrids [4-6] or rigid [7] and flexible [8] combinations of the two prime configurations. The focus of this paper is to provide a concept of an original variation of the Darrieus [9] configuration, where two stages are assembled coaxially and in series. Other counter-rotating configurations, such as stacking two H-types on top of one another, have been proposed earlier [10], offering constructive advantages in terms of their linkage to the electric generator. However, having the two half-turbines counter rotating and in parallel does little to further the aerodynamics of the machine, leaving the classical relation between the tip speed ratio and power coefficient unaltered. By placing the secondary stage in series, a significant part of the wind power that would otherwise be inaccessible is converted into motion and hence to electric power. This way, the proposed VAWT can approach Betz's limit [11].

II. CFD SIMULATION

In profiling the blades of this new wind turbine design we considered the NACA 0021 airfoil which has the advantage of being well understood by its use in other single stage similar applications. Table I presents the geometric features of this wind turbine. By inverting the leading edge and trailing edge position of the turbine blades we achieve the counter rotating effect. The CAD assembly of the embodiment studied in this paper is presented in Figure 1, where the three blades and the supporting system can be observed.

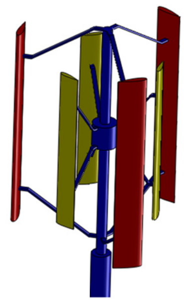

Fig. 1. 3D Wind turbine model

TABLE I. GEOMETRY OF THE COUNTER-ROTATING IN-SERIES VAWT

Parameters	Value		Units
	Inner Turbine	Outer Turbine	
Blade chord	45	70	mm
Turbine diameter	225	450	mm
Airfoil	NACA 0021		-
Turbine height	500		mm
Blade number	3		-
Velocity	10÷16		m/s

For the numerical analysis, a computational domain has been defined divided in four subdomains: stator for the inner subdomain, rotor for the inner turbine, rotor for the outer turbine and stator for subdomain for around of the turbine concept. Three fully conformal interfaces have been defined between the subdomains, which connect the rotors to the stators and vice-versa. Figure 2 shows the structured mesh generated as well as a detail of the interface between the two stages. To resolve the probable No.s in the boundary layer, the y+ value has been set to no more than 1, and the growth ratio of the elements was set to 1.1.

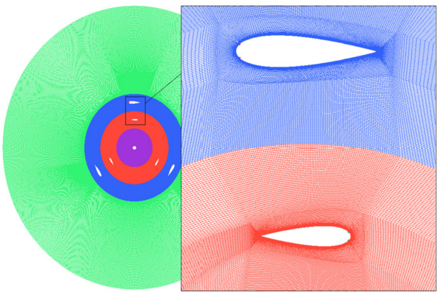

Fig. 2. Mesh of the CR-VAWT concept

For this numerical study three structured meshes were used. The coarse mesh has around 500k elements, the medium around 850k and the fine one around 1200K. The CFD numerical models work by solving the Navier-Stokes system of equations. The state of the art in the wind turbine CFD simulations is very complex. Authors in [12] studied the blade-vortex interactions showing that the flow pattern is highly dependent on the flow time history not just the current flow characteristics that are being considered in constant TSR (tip speed ratio) CFD studies [13]. The instantaneous rotational speed of the turbine is dependent on the torque, but the moment coefficient is non-uniform throughout a full rotation, making the constant rotational speed analysis less accurate [14]. The CFD simulations of the counter rotating wind turbine concept, rely on the degree of freedom (DOF) method, which works by selecting momentum inertia for each wind turbine rotor in order to determine the operational point of the turbine. In this way, the self-starting characteristics of the turbine can be analyzed. This regime is very important-particularly to Darrieus configurations-since the turbine works at high angles of attack [15]. Meaning that, from airfoil polar diagram, only the post stall region will be used where the lift-drag ratio is typically low [16]. Since this is an inherently inefficient regime, traditional H-types have difficulties attaining self-sustained operation, hence making this regime an interesting optimization topic. In the DOF method, the parameters of the analysis were the wind velocity and the moment of inertia, allowing the software to compute the characteristics of the turbine at every time step, until the simulation converged to the optimal point. For CR-VAWT the momentum inertia is presented in Table II for each turbine stage.

TABLE II. GEOMETRY OF THE COUNTER-ROTATING IN-SERIES VAWT

Parameters	Value		Units
	Inner Turbine	Outer Turbine	
Mass	192.21	264.41	g
Momentum inertia	0.003767	0.013386	kgm^2

Due to the time-dependent characteristics of the simulation, the unsteady Reynolds averaged Navier-Stokes based model SST, was used in this study, because of its successful track record of accurately predicting the performance of wind turbines [17-18]. This model is a combination of the standard k-ε model and the k-ω model, using k-ε model for the free flow area, which is considered fully turbulent, and the k-ω for the boundary layer [19]. The transition between the two models is insured by the use of connecting functions, which have the purpose of activating each of the models, depending on the area of interest. These connecting functions have another role of introducing a diffusive term in the transport equation of ω. The transport equation for the kinetic turbulent energy (k):

$$\frac{\partial k}{\partial t}+\bar{u}\frac{\partial k}{\partial x}+\bar{v}\frac{\partial k}{\partial y}+\bar{w}\frac{\partial k}{\partial z}= =\frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(\Gamma_k\frac{\partial k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_k\frac{\partial k}{\partial y}\right)+\frac{\partial}{\partial z}\left(\Gamma_k\frac{\partial k}{\partial z}\right)\right] +\tilde{G}_k-Y_k. \quad (1)$$

The transport equation of the specific rate of dissipation (ω):

$$\frac{\partial \omega}{\partial t}+\bar{u}\frac{\partial \omega}{\partial x}+\bar{v}\frac{\partial \omega}{\partial y}+\bar{w}\frac{\partial \omega}{\partial z}= \frac{1}{\rho}\left[\frac{\partial}{\partial x}\left(\Gamma_\omega\frac{\partial \omega}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_\omega\frac{\partial \omega}{\partial y}\right)+\frac{\partial}{\partial z}\left(\Gamma_\omega\frac{\partial \omega}{\partial z}\right)\right] +G_\omega-Y_\omega+D_\omega \quad (2)$$

III. EXPERIMENTAL SETUP

In order to validate the counter rotating vertical axis wind turbine a scale wind turbine model was manufactured using carbon fiber for all six blades. Since dimensional precision is important, a molding method was used inside an autoclave. The curing cycle was established based on the material datasheet and previous experimental work made with the same material, thus consisting in a heating stage from room temperature up to 120°C (~2°C/min), temperature was held constant for 90 min, followed by cooling at room temperature. To use this technology two molds with NACA 0021 were from CNC milled Al 4.0 Cu 1.2 Pb 1.1 Mg 0.8 Mn aluminum alloy. The mold is presented in Figure 3. Tests were conducted in the closed loop wind tunnel of the Romanian Research and Development Institute for Gas Turbine - COMOTI by exposing the wind turbine concept to various levels of the stream velocity. The experimental model is connected to a one of the kind permanent magnet generator with a purpose built configuration.

Fig. 3. Blades molds for inner turbine

This PMG [20] was designed for this wind turbine concept, meaning it has two rotors which spin in opposite directions. Figure 4 shows a cross section of this PMG. In order to quantify the power generated by the turbine, the generator was connected to an electric circuit which acted as a resistor. In Figure 5 the main parts of this permanent magnet generator are presented, showing the armatures of the coils, the shaft, casings and the bearings.

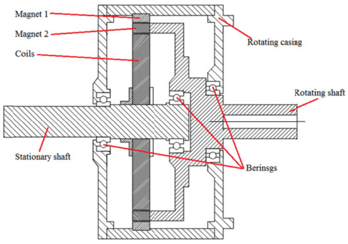

Fig. 4. PMG cross section

Fig. 5. PMG main parts

In order to determine the internal efficiency of this PMG several experimental tests were carried out on the testing bench. The configuration of this testing bench in presented in Figure 6. With the results from PMG tests an electric efficiency map was defined. Figure 7 shows this PMG map.

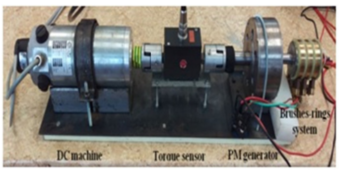

Fig. 6. PMG testing bench

To find the mechanical power generated by the wind turbine rotors the relation between the measured electrical quantities, torque and rotational speed were determined. In order to determine the PMG efficiency, the torque was measured with a digital torque detector. In Figure 8 the schematic diagram of the experimental system [21] is presented.

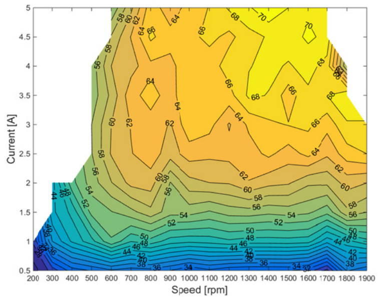

Fig. 7. Efficiency map of the PMG

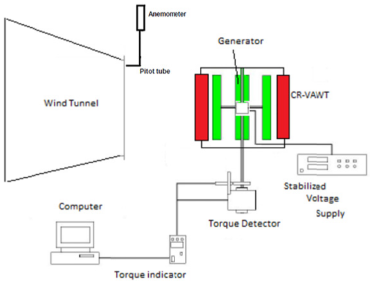

Fig. 8. Schematic diagram of experimental system

Typically, wind turbines can generate electric power only when a certain wind speed is reached, therefore the tests were carried out at 4 wind speeds, with the maximum of 20m/s. A static Pitot tube is fixed on the 3-D traversing system alone for the velocity measurements to determine the flow velocity from wind turbine upstream and double check the wind tunnel internal settings. In the experimental model design the bearing system was a challenge because the friction should be minimized in order to have little impact on the efficiency of the concept. In this embodiment, the bearing system consists of six ball bearings. To support the turbine a casing was manufactured. In Figure 9 the experimental model is shown.

Fig. 9. Experimental model

IV. RESULTS

In order to determine the nominal point of this counter rotating vertical axis wind H type Darrieus turbine, several simulations were carried out, using a URANS DOF method. To estimate the evolution of the turbine, the vorticity for different positions of the turbine blades, has been plotted. This makes it easier to observe the recirculation areas that have a negative impact on the overall performance of the wind turbine. In Figures 10-13 the vorticity magnitude variation for the case where the stream velocity was 12m/s is presented.

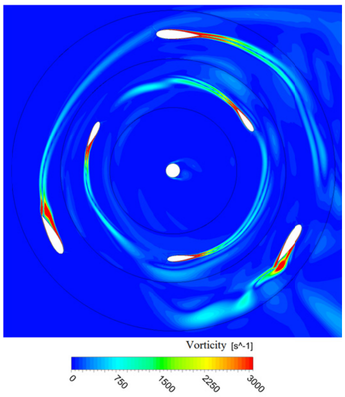

Fig. 10. Vorticity magnitude for theta 0 degrees, for V=12m/s

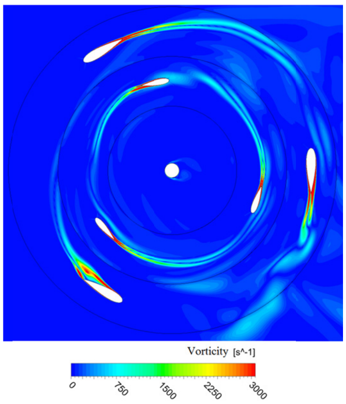

Fig. 11. Vorticity magnitude for theta 30 degrees, for V=12m/s

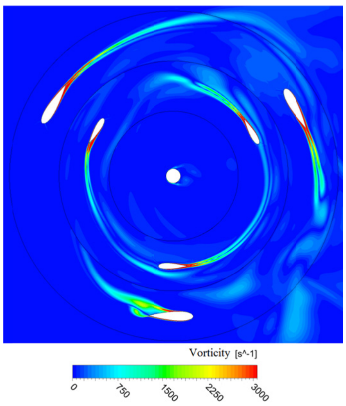

Fig. 12. Vorticity magnitude for theta 60 degrees, for V=12m/s

Figures 14-15 show the variation of the torque coefficient of outer and inner turbine for different velocity values. The maximum value is obtained at V=12m/s, where the contribution of the inner turbine in the concept efficiency is the highest. The numerical data was validated in wind turbine where the experimental model was investigated for velocity values between 10m/s and 16m/s. In the chart from Figure 17 the power coefficient for numerical simulation and for experimental tests is presented.

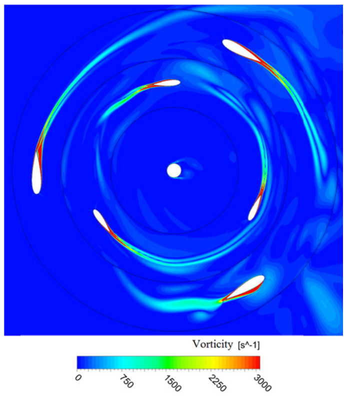

Fig. 13. Vorticity magnitude for theta 90 degrees, for V=12m/s

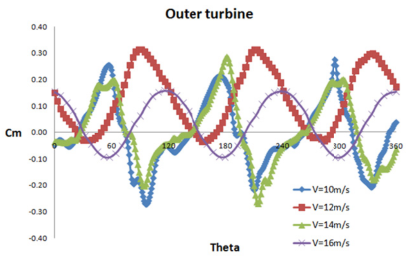

Fig. 14. Momentum coefficient variation for the outer turbine

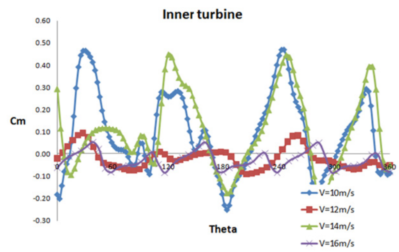

Fig. 15. Momentum coefficient variation for the inner turbine

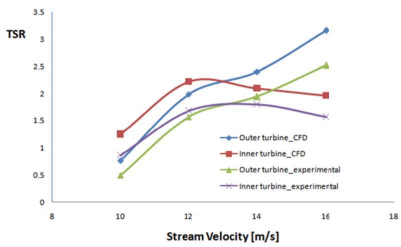

Fig. 16. Tip speed ratio variation within stream velocity

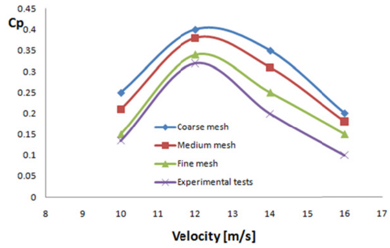

Fig. 17. Power coefficient variation within stream velocity

V. CONCLUSION

A new concept for VAWT was proposed, consisting of a two stage, in series H-type Darrieus turbines. The envisioned advantage regarding the power extraction capabilities was tested both in CFD and wind tunnel with good results. Aerodynamic modeling of counter rotating straight bladed VAWT model was done using DOF methods since it was found that the natural rotating rate of the two stages differs and cannot be easily predicted through classical calculations. With this method, only an inertial momentum is specified for the two rotors, leaving the acceleration to aerodynamic effects computed using the unsteady SST RANS model. Experimental tests of the concept feasibility were also conducted with a PMG manufactured specifically for this application. The experimental results from wind tunnel showed acceptable performance but an aerodynamic optimization is needed. In this optimization the blade airfoil selection and the ratio between the inner and outer turbine diameter will be taken into consideration. A better understanding of the relation between stage solidity and specific speed will lead to furthering this concept towards its full potential. Future work will focus on the experimental model where a magnetic bearing system will provide less friction, allowing more focus to be placed on the aerodynamics of the concept.

ACKNOWLEDGMENT

This work was carried out within National Research and Development Institute for Gas Turbines COMOTI research funds on wind turbine field.

REFERENCES

[1] P. A. Costa Rocha, J. W.Carneiro de Araujo, R. J. Pontes Lima, M. E.Vieira da Silva, D. Albiero, C. F. de Andrade, F. O. M. Carneiro, "The effects of blade pitch angle on the performance of small-scale wind turbine in urban environments", Energy, Vol. 148, pp. 169-178, 2018

[2] T. Wenlong, M. Zhaoyong, B. Zhanga, Y. Li, "Shape optimization of a Savonius wind rotor with different convex and concave sides", Renewable Energy, Vol. 117, pp. 287-299, 2018

[3] R. Gupta, A. Biswas, K. K. Sharma, "Comparative study of a three-bucket Savonius rotor with a combined three-bucket Savonius–three-bladed Darrieus rotor", Renewable Energy, Vol. 33, No. 9, pp. 1974-1981, 2008

[4] J. Gavalda, J. Massons, F. Diaz, "Experimental study on a self-adapting Darrieus—Savonius wind machine", Solar & Wind Technology, Vol. 7, No. 4, pp. 457-461, 1990

[5] A. Ghosh, A. Biswas, K. K. Sharma, R. Gupta, "Computational analysis of flow physics of a combined three bladed Darrieus Savonius wind rotor", Journal of the Energy Institute, Vol. 88, No. 4, pp. 425-437, 2015

[6] K. Sahim, D. Santoso, D. Puspitasari, "Investigations on the Effect of Radius Rotor in Combined Darrieus-Savonius Wind Turbine", International Journal of Rotating Machinery, Vol. 2018, Article ID 3568542, 2018

[7] Y. Kyozuka, "An Experimental Study on the Darrieus-Savonius Turbine for the Tidal Current Power Generation", Journal of Fluid Science and Technology, Vol. 3, No. 3, pp. 439-449, 2008

[8] X. Liang, S. Fu, B. Ou, C. Wu, C. Y. H. Chao, K. Pi, "A computational study of the effects of the radius ratio and attachment angle on the performance of a Darrieus-Savonius combined wind turbine", Renewable Energy, Vol. 113, pp. 329-334, 2017

[9] I. Paraschivoiu, O. Trifu, F. Saeed. "H-Darrieus wind turbine with blade pitch control", International Journal of Rotating Machinery, Vol. 2009, Article ID 505343, 2009

[10] D. Horia, A. Dumitrache, F. Frunzulica, A. Pal, V. Turbatu, "TORNADO concept and realisation of a rotor for small VAWTs", NCAS Bulletin, Vol. 5, No. 3, pp. 69–75, 2013

[11] M. J. Werle, W. M. Presz, "Ducted wind/water turbines and propellers revisited", Journal of Propulsion and Power, Vol. 24, No. 5, pp. 1146-1150, 2008

[12] S. Ivanell, J. N. Sorensen, D. Henningson, "Numerical computations of wind turbine wakes", in: Wind Energy, Springer, pp. 259-263, 2007

[13] D. Hartwanger, A. Horvat, "3D modelling of a wind turbine using CFD", NAFEMS Conference, Cheltenham, UK, June 10-11, 2008

[14] M. R. Castelli, A. Englaro, E. Benini, "The Darrieus wind turbine: Proposal for a new performance prediction model based on CFD", Energy, Vol. 36, No.8, pp. 4919-4934, 2011

[15] F. Balduzzi, A. Bianchini, R. Maleci, G. Ferrara, L. Ferrari, "Critical No.s in the CFD simulation of Darrieus wind turbines", Renewable Energy, Vol. 85, pp. 419-435, 2016

[16] W. A. Timmer, R. P. J. O. M. Van Rooij, "Summary of the Delft University wind turbine dedicated airfoils", Journal of Solar Energy Engineering, Vol. 125, No. 4, pp. 488-496, 2003

[17] I. Malael, V. Dragan, G. Vizitiu, "The vertical axis wind turbine efficiency evaluation by using the CFD methods", Applied Mechanics and Materials, Vol. 772, pp. 90-95, 2015

[18] H. Dumitrescu, V. Cardos, I. Malael, "The physics of starting process for vertical axis wind turbines", in: CFD for Wind and Tidal Offshore Turbines, pp. 69-81, Springer, 2015

[19] G. Naccache, M. Paraschivoiu, "Parametric study of the dual vertical axis wind turbine using CFD", Journal of Wind Engineering and Industrial Aerodynamics, Vol. 172, pp. 244-255, 2018

[20] M. Dranca, M. Chirca, V. Zaharia, S. Breban, "Permanent magnet generator for counter-rotating vertical axis micro-wind turbine", 52nd International Universities Power Engineering Conference, Heraklion, Greece, August 28-31, 2017

[21] R. Howell, N. Qin, J. Edwards, N. Durrani, "Wind tunnel and numerical study of a small vertical axis wind turbine", Renewable energy, Vol. 35, No. 2, pp. 412-422, 2010