ISSN 2278-3091
Volume 8, No.1.3, 2019
International Journal of Advanced Trends in Computer Science and Engineering
Available Online at http://www.warse.org/IJATCSE/static/pdf/file/ijatcse1881.32019.pdf
https://doi.org/10.30534/ijatcse/2019/1881.32019

Investigation of Self-Starting Mechanism on the Performance of Darrieus Rotor

Djamal Hissein Didane[1], Nurhayati Rosly[2], Syariful Syafiq Shamsudin[3]
[1]Department of Thermofluid Engineering, Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Batu Pahat, Johor, Malaysia, djamal@uthm.edu.my
[2]Department of Aeronautical Engineering, Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), 86400 Parit Raja, Batu Pahat, Johor, Malaysia, djamal@uthm.edu.my

ABSTRACT

Currently, the Darrieus rotor is receiving more interest as it can be more favorable and perform better in low wind speed regimes. However, the symmetrical NACA airfoil suffers from low starting torque. Thus, in the present study, a passive method is adopted to enhance the self-starting difficulties while improving the performance of the rotor. Four typical conditions were studied including a rotor with six semicircle PVCs (case 4), a rotor with three semicircle PVCs at the bottom arms of the rotor (case 3), a rotor with three semicircle PVCs at the top arm (case 2) and a rotor without any semicircle PVCs (case 1). The results indicated a significant improvement in terms of self-start characteristic and performance output. Case 3 showed the highest output, while, case 4 showed the least with regard to the cases with PVCs. The system has also enhanced the self-starting behavior by allowing the model to self-start at a wind speed of as low as 5 m/s and increased to 8 m/s without any semicircle PVCs. Such improvement of the proposed approach confirms the effectiveness of this method and could hopefully provide a simple and low-cost mechanism of enhancing self-starting difficulties in Darrieus H-type VAWTs.

Key words : H-type Darrieus rotor; Self-starting; Torque coefficient; Wind energy.

1. INTRODUCTION

Today, wind energy conversion technologies development is found in a fast pace all over the world so as to realize all the advantages that wind energy could offer [1]. The Darrieus H-type vertical axis wind turbine (VAWT) has gained much interest in the last few decades as among the reliable devices for wind energy conversion techniques particularly in the urban environment [2]. As they are simple in terms of design, fabrication, emits low noise due to its low rotational speed and better maintenance accessibility [3], [4]. However, such airfoil suffers from two significant issues; low starting torque particularly at low rotational speed and low power output [5, 6]. This low starting torque is owed to the aerodynamic stall which leads to an inability to self-start [7].

Thus, in the recent years, there has been a great deal of extensive and intensive research to explore the possibilities of improving the self-start characteristics and performance of the H-type design. Both active and passive methods were adopted while seeking to improve the self-starting capabilities of this rotor. However, most of the approaches were based on an active method by optimizing the static geometrical parameters such as rotor solidity, thickness, camber, pitch angle, blade aspect ratio, etc. While few others, were passively focusing on the turbine design itself, thus by combining Savonius and Darrieus rotor together.

The term self-start is defined as the capability of the turbine to accelerate from not moving to a state where a useful output is extracted, according to Ebert and Wood [8] and Krike [9]. However, Lunt [10] and Dominy *et al.*[11] considered that self-starting is a function of tip-speed ratio (TSR) where the wind turbine is capable to reach a TSR of more than a unity.

In essence, the Darrieus-type wind turbine is a lift type. Thus, in order to produce a useful lift force, the angle of attack has to always remain smaller than the stalling angle of the blade, or else it will face difficulties to self-start. It is usually enhanced by incorporating external devices or power (passive method) which usually increases not only the cost but also adds some complications on the design [6]. Rossetti and Pavesi [12] introduced the aspects that contribute to the self-starting inabilities. They found that the blade profile, Reynolds number, secondary flows and three-dimensional aerodynamic effects are the main causes for self-start difficulties.

In the early 90^{th} Nahas [6] introduced a mechanism to improve the self-starting capability of the Darrieus-type straight (symmetrical) blade. He started by increasing the pitch (span) of the airfoils in order to reduce the angle of attack which eventually avoids stalling and therefore the generation of torque and power at low-speed were possible. Several years later, Miau *et al.* [13] adopted a similar approach and found a pattern that confirms the previous results of Nahas [6].
Few researchers [14] – [16] combined Savonius-Darrieus type

wind turbine to improve the self-starting difficulties which resulted in more complex design although it enhanced the self-start capability. Similarly, Mohamed [17] adopting a hybrid system and confirmed that the combination of drag and lift type indeed improves the self-starting capability. The author also suggested that increasing the solidity improves the self-start ability and efficiency of the H-rotor Darrieus wind turbine. Moreover, Lee and Lim [18] also confirmed this finding and provided more detailed results. They found that higher solidity increases the power at low TSR, while lower solidity increases the power at higher TSR. Likewise, Singh *et al.* [3] also improved the self-starting capability by increasing the solidity while adopting unsymmetrical (cambered) blade. However, although, Singh *et al.* [3] Benedict *et al.* [19] declared that cambered airfoil generally improves the performance of VAWT, Beri and Yao [20] argued that the power coefficient obtained using cambered airfoil is lower compared to symmetrical blades.

While other authors including Gupta and Biswas [21] used the blade twisting technique to improve the self-starting ability of the Darrius rotor. It was found that self-start could be attained with blade twist of 30˚ at chord ends. Likewise, Alaimo *et al.* [2] performed 3D simulations to account for the aspect ratio effect and dynamic stall for a symmetrical airfoil, while testing various twisting angles. It was indicated that the increase of the twisting angle gives better performance in terms of power output and torque. Nevertheless, there were several disadvantages associated with a higher twisting angle such 90˚ in terms of weight, manufacturing and installation. Thus, it was concluded that 60˚ angle was regarded optimal considering all the aforementioned characteristics.

However, Dominy *et al.* [11] indicated that self-starting for Darrieus rotor is possible for two-bladed turbine without the inclusion of any external devices or the modifications of the blade. After all, it is a matter of obtaining the angle of attack smaller than the stalling angle of the airfoil. Moreover, Howell *et al.* [22] suggest that in terms of power performance, adding more blades while maintaining the same chord length has a negative effect on the power produced, not to mention the cost associated with it. Furthermore, a great number literature including Howell *et al.* [22] also pointed out that thicker symmetrical blade produces higher starting torque compared to thinner ones. However, in an experimental study performed by Singh *et al.*[3] believe that adopting unsymmetrical blade and increasing the rotor solidity could be an effective approach to overcome the self-starting problem. The same conclusion was also drawn by Beri and Yao [20] using computational fluid dynamics (CFD) simulations.

Recently, Didane *et al.* [23] performed an experimental study on a counter-rotating VAWT while adopting semicircle PVCs to enhance the self-starting capability of the two rotors. Their findings indicated the effectiveness of this approach on improving the self-start capability. Inspired by their work, the current study similarly seeks to adopt semicircle PVCs on a single rotor wind turbine (SRWT) with different installation positions and numbers while enhancing the performance of the symmetrical H-type Darrieus rotor.

2. METHODOLOGY

2.1 Principle of operation

The wind turbine power is extracted from the wind as a result of the interaction between the rotor and the wind as shown in Fig. 1. Theoretically, according to Betz's limit, an ideal wind turbine can extract about 60% power from the existing energy (lift type) [24]. However, for a drag type wind turbine rotor, this efficiency drops to about half (29.6%) [25]. This limit is owed to the aerodynamic effects that shrink the conversion efficiency of rotors.

The extractable power available in a wind stream, P is proportional to the cube of the velocity and it is given as in Equation 1 below:

$$P_{ex} = C_p \frac{1}{2} \rho A V^3 \qquad (1)$$

where ρ is air density, A swept area, V is the freestream wind speed and C_p is power coefficient or efficiency of the turbine and it is denoted as following:

$$C_p = \frac{P_{ex}}{P_w} = \frac{P_{ex}}{\frac{1}{2}\rho A V^3} \qquad (2)$$

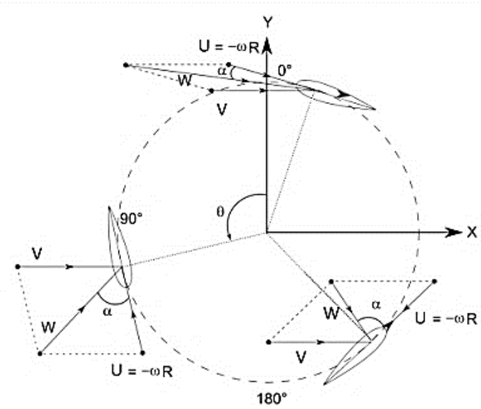

Figure 1: Velocity acting in a Darrieus rotor for various azimuthal positions

In wind turbine performance evaluation, it is equally important to determine the rotor torque so that a suitable shaft that can withstand the load being subjected (structural strength) is selected [26]. It is also used as a prime quantity to verify and validate the analytical model besides the output power. Such measurement of torque also ensures the accuracy of the results obtained and the validity of the assumptions that were made throughout the study [27].

The thrust force experienced by a rotor (F) can be expressed as:

$$F = \frac{1}{2} \rho_a A V^2 \qquad (3)$$

Hence, the rotor theoretical torque (T) can be represented as:

$$T = \frac{1}{2}\rho_a A V^2 R \quad (4)$$

Furthermore, the ratio between the actual torque developed by the rotor and the theoretical torque is termed as the torque coefficient(C_T). Thus, the torque coefficient is given by:

$$C_T = \frac{2T_T}{\rho_a A V^2 R} \quad (5)$$

2.2 Semicircle PVC

The entire document should be in Times New Roman. The font sizes to be used are specified in Table 1. Polyvinyl chloride (PVC) pipes are typically used in construction to convoy fluids. However, in this study, the purpose is different. Given that the Darrieus airfoils have low starting torque [6, 7, 28], they are used as a simple mechanism to overcome the self-starting difficulties. Thus, in order to improve the inherent self-starting difficulties of the symmetrical NACA blade airfoil, semicircle PVCs were installed at each supporting arm in an effort to help the blade to self-start, as illustrated in Fig. 2. The diameter and length of the semicircle PVCs are 10.5 cm and 23 cm, respectively with the thickness of 2 mm as in Fig. 2.

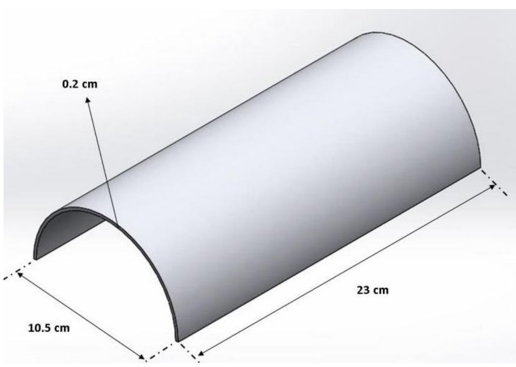

Figure 2: Details of the semicircle PVC

2.3 Blade selection, fabrication and setup

The airfoil profile used in this study is the straight-bladed four-digit NACA 0021. The blades of the rotor are fabricated from pinewood material. Given that the weight of the blade has a significant effect on the performance of the rotor, pinewood is chosen for blade material due to its relatively lightweight properties and low cost. The airfoil has a chord length of 10 cm and a diameter and height of 80 cm and 50 cm, respectively. The central shaft is made of aluminum rod with 10 mm diameter. The supporting arms are hollowed mild steel bars with the dimension of 10 mm × 10 mm each as shown in Table 1.

Table 1: Geometrical details of model

Parameter	Detail
Blade profile	NACA 0021
Chord, c [m]	0.1
No. of blades [-]	3
Diameter, D [m]	0.8
Height, H [m]	0.5
Rotor solidity [-]	0.75

The rotor consists of six semicircle PVCs; three at the top position of the rotor and the other three at the bottom as shown in Fig. 3. Each of the semicircle PVC is mounted at the middle of the supporting arms which is 40 cm long. The incoming wind speed is measured using a vane anemometer while, the rotational speed of the rotor is measured using a digital tachometer. The performance of the rotor is tested at four different conditions while observing the effectiveness of these semicircle PVCs on the improvement of the system. At the initial condition (case 1), the rotor is tested without any semicircle PVC and then followed by three at the top (case 2) and then at the bottom (case 3) and finally with all semicircle PVCs on the rotor (case 4) as shown in Table 2 while aiming to provide an effective, easy to install and low cost method of improving the self-starting mechanism of the rotor.

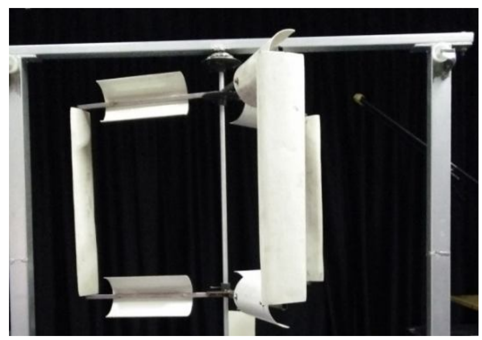

Figure 3: Actual photograph of the prototype

Table 2: Details of the experimental cases

Case	Number of PVC	Position
1	-	-
2	3	Top
3	3	Bottom
4	6	Top and bottom

3. RESULTS AND DISCUSSION

3.1 Evaluation of torque

This section reveals and ties together the performance of the current model with regard to mechanical torque while varying the position and number of the semicircle PVCs being installed. Four different ceases have been examined including the condition where all semicircle PVCs were mounted on the rotor, only the top PVCs, the bottom PVCs and with no PVC. This is done in effort to observe the effectiveness of incorporating the semicircle PVCs in the rotor and the effect of the position of the PVC on the performance of the rotor in terms of self-starting mechanism. As such, case 1 was tested first and its effect was observed afterwards. The output analyses are presented in terms of torque as it typically used in the studies of wind turbine concerning aerodynamic performance. Thus, in each case, the model was subjected to a wind speed in the range of 5 m/s to 12 m/s.

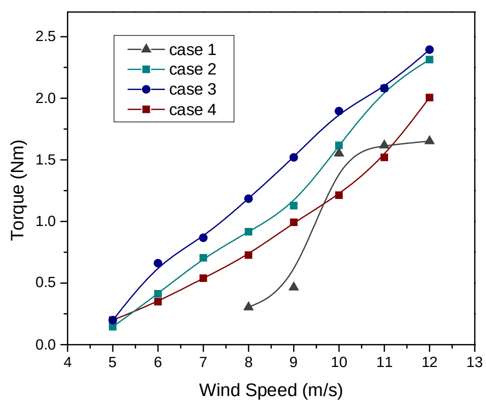

Figure 4: Variation of torque against wind speed

It was found that the free-stream wind speed has a great effect on the self-starting capability of the wind turbine. The consistent increase in the rotational speed has led to a tremendous increase in the amount of torque produced at all cases studied. However, at the condition where the semicircle PVCs are installed at the bottom position (case 3) showed better results compared to the other cases, with the condition all PVCs (case 4) to be the least output. It is also to be noted that at the condition where there was no any PVC installed (case 1), the rotor was able to self-start at 8 m/s as oppose to 5 m/s at the other three cases. This huge difference in the starting speed is a result of the presence of the semicircle PVC which denotes the effectiveness of this mechanism and the enormous output that this might have created in term of torque as shown in Fig. 4. More interestingly, such starting speed also signifies that regions with moderate and low speed with as low as 5 m/s could also take advantage of this simple and effective mechanism. Moreover, the existence of the PVC also contributed to the performance output of the wind turbine and not only the self-start behavior, notably at low wind speed conditions. However, at higher wind speeds beyond 10 m/s, it was found that the case without PVCs performed slightly better and generated more torque output compared to case 4. This could be owed to the fact that the weight and the shape of the PVC may have generated some aerodynamic drags on the rotor in which contributed to the low performance at higher speeds as was also found by Didane *et al.* [23].

However, although the rotor performed quite well at the three cases where semicircle PVC installation took place, it is recommended that only case 3 should be used for further development as it has shown better results in terms of both self-start and output performance.

3.2. Evaluation of torque coefficient

It is equally important practice to assess the behavior of the system with respect to dimensionless aerodynamic quantity such as torque coefficient[28]. This is because parameters such as optimum or rated wind speed and optimum TSR are better expressed and identified using these parameters. As such, this section embodies the performance analysis of the torque coefficient for all the four cases with respect to the operating wind speed involved in this study.

Fig. 5 is quite reveling in several ways. First, the performance coefficients of all conditions exhibited almost a similar trend. At the beginning, the torque coefficient with respect to wind speed tends to increase with the operating speed and then decreases as the speed increases. Second, as was expected, case 3 has shown a higher conversion efficiency compared to the other conditions. Followed by case 2 and then case 4 where all semicircle PVCs were presented. In case 1, the rotor self-started at 8 m/s and showed lower conversion efficiency. Moreover, a higher torque coefficient at low speed indicates that the rotor has a high tendency to self-start which is exactly what happened during the experiment. As it is always important to strive for high coefficient when dealing with H-type Darrieus wind turbine for greater accomplishment, these outputs provide strong evidence for the usefulness and efficacy of incorporating semicircle PVCs in system while enhancing self-starting and performance output of the VAWT.

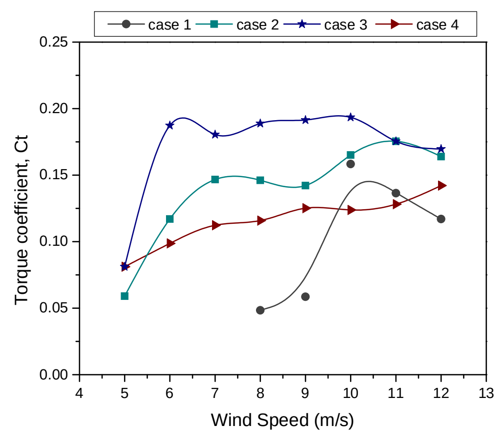

Figure 5: Torque coefficients as a function of wind speed

4. CONCLUSION

In this study, a passive method of improving self-starting behavior of a straight-bladed Darrieus VAWT has been studied. Four typical conditions including rotor with semicircle PVCs installed at the top and bottom position (case 4), bottom position (case 3), top position (case 2) and without semicircle PVC (case 1) were tested while enhancing self-start character and performance out of the turbine. At the beginning the model was tested without mounting any semicircle PVC in the system and then the effect of installing them at different position and number were then observed. The performance analyses have shown the effectiveness of this method and its usefulness in improving the self-start characteristics of the symmetrical Darrieus wind turbine. Among the four cases, case 3 performed better compared to the other conditions. The rotor was able to self-start at 5 m/s for all the cases with semicircle PVCs (case 2, case 3, case 4), and increased to 8 m/s without them which was in case 1. This difference is considered significant and indicates the efficacy of this method. It also shows a wider range of site application including low and moderate wind speed terrains using this method.

ACKNOWLEDGEMENT

The authors wish to express their sincere gratitude and gratefully acknowledge the financial support received from Universiti Tun Hussein Onn Malaysia (UTHM) under research grant IGPP U416.

REFERENCES

1. D.H. Didane, A. Ab Wahab, S.S. Shamsudin, N. Rosly, **Wind as a sustainable alternative energy source in Malaysia -** a review, ARPN J. Eng. Appl. Sci. 11 (10) (2016).
2. A. Alaimo, A. Esposito, A. Messineo, C. Orlando, and D. Tumino, "**3D CFD analysis of a vertical axis wind turbine,**" Energies, vol. 8, no. 4, pp. 3013–3033, 2015. https://doi.org/10.3390/en8043013
3. M. A. Singh, A. Biswas, and R. D. Misra, "**Investigation of self-starting and high rotor solidity on the performance of a three S1210 blade H-type Darrieus rotor**," Renew. Energy, vol. 76, pp. 381–387, 2015. https://doi.org/10.1016/j.renene.2014.11.027
4. F. Balduzzi, A. Bianchini, R. Maleci, G. Ferrara, and L. Ferrari**, "Critical issues in the CFD simulation of Darrieus wind turbines,"** Renew. Energy, vol. 85, pp. 419–435, 2016. https://doi.org/10.1016/j.renene.2015.06.048
5. F. Ottermo and H. Bernhoff, **"Resonances and aerodynamic damping of a vertical axis wind turbine,"** Wind Eng., vol. 36, no. 3, pp. 297–304, 2012. https://doi.org/10.1260/0309-524X.36.3.297
6. M. N. Nahas, **"A self-starting darrieus-type windmill," Energy,** vol. 18, no. 9, pp. 899–906, 1993. https://doi.org/10.1016/0360-5442(93)90002-U
7. A. Untaroiu, H. G. Wood, P. E. Allaire, and R. J. Ribando, **"Investigation of Self-Starting Capability of Vertical Axis Wind Turbines Using a Computational Fluid Dynamics Approach,"** J. Sol. Energy Eng., vol. 133, no. 4, p. 41010, 2011. https://doi.org/10.1115/1.4004705
8. P. R. Ebert and D. H. Wood**, "Observations of the starting behaviour of a small horizontal- axis wind turbine," ~ Pergamon Renew. Energy**, vol. 12, no. 3, pp. 245–257, 1997. https://doi.org/10.1016/S0960-1481(97)00035-9
9. B. Kirke, **"Evaluation of self-starting vertical axis wind turbines for stand-alone applications,"** Vasa, pp. 281–285, 1998.
10. P. A. V Lunt, **"An aerodynamic model for a vertical-axis wind turbine,"** MEng Proj. Report, Sch. Eng. Univ. Durham, UK, 2005.
11. R. Dominy, P. Lunt, A. Bickerdyke, and J. Dominy, **"Self-starting capability of a Darrieus turbine,"** Proc. Inst. Mech. Eng. Part A J. Power Energy, vol. 221, no. 1, pp. 111–120, Feb. 2007. https://doi.org/10.1243/09576509JPE340
12. A. Rossetti and G. Pavesi**, "Comparison of different numerical approaches to the study of the H-Darrieus turbines start-up,"** Renew. Energy, vol. 50, pp. 7–19, 2013. https://doi.org/10.1016/j.renene.2012.06.025
13. J. J. Miau, S. Y. Liang, R. M. Yu, C. C. Hu, T. S. Leu, J. C. Cheng, and S. J. Chen, **"Design and Test of a Vertical-Axis Wind Turbine with Pitch Control,"** Appl. Mech. Mater., vol. 225, pp. 338–343, 2012. https://doi.org/10.4028/www.scientific.net/AMM.225.338
14. T. Wakui, Y. Tanzawa, T. Hashizume, and T. Nagao, **"Hybrid configuration of darrieus and savonius rotors for stand-alone wind turbine-generator systems,"** Electr. Eng. Japan (English Transl. Denki Gakkai Ronbunshi), vol. 150, no. 4, pp. 13–22, 2005. https://doi.org/10.1002/eej.20071
15. R. Gupta, A. Biswas, and K. K. Sharma, **"Comparative study of a three-bucket Savonius rotor with a combined three-bucket Savonius-three-bladed Darrieus rotor,"** Renew. Energy, vol. 33, no. 9, pp. 1974–1981, 2008. https://doi.org/10.1016/j.renene.2007.12.008
16. B. K. Debnath, A. Biswas, and R. Gupta**, "Computational fluid dynamics analysis of a combined three-bucket Savonius and three-bladed Darrieus rotor at various overlap conditions,"** J. Renew. Sustain. Energy, vol. 1, no. 3, p. 033110–(1–13), 2009. https://doi.org/10.1063/1.3152431
17. M. H. Mohamed**, "Impacts of solidity and hybrid system in small wind turbines performance,"** Energy, vol. 57, pp. 495–504, 2013. https://doi.org/10.1016/j.energy.2013.06.004
18. Y. T. Lee and H. C. Lim, **"Numerical study of the aerodynamic performance of a 500W Darrieus-type vertical-axis wind turbine,"** Renew. Energy, vol. 83, pp. 407–415, 2015. https://doi.org/10.1016/j.renene.2015.04.043
19. M. Benedict, V. Lakshminarayan, J. Pino, and I. Chopra, **"Fundamental Understanding of the Physics of a Small-Scale Vertical Axis Wind Turbine with Dynamic Blade Pitching: An Experimental and Computational Approach,"** 54th AIAA/ASME/ASCE/AHS/ASC Struct. Struct. Dyn. Mater. Conf., pp. 1–21, 2013. https://doi.org/10.2514/6.2013-1553
20. H. Beri and Y. Yao, **"Effect of Camber Airfoil on Self Starting of Vertical Axis Wind Turbine,"** J. Environ. Sci. Technol., 2011. https://doi.org/10.3923/jest.2011.302.312
21. R. Gupta and A. Biswas, **"Computational fluid dynamics analysis of a twisted three-bladed**

H-Darrieus rotor," J. Renew. Sustain. Energy, vol. 2, no. 4, 2010.
https://doi.org/10.1063/1.3483487

22. R. Howell, N. Qin, J. Edwards, and N. Durrani, **"Wind tunnel and numerical study of a small vertical axis wind turbine,"** Renew. Energy, vol. 35, no. 2, pp. 412–422, 2010.
https://doi.org/10.1016/j.renene.2009.07.025
23. D. H. Didane, N. Rosly, M. F. Zulkafli, and S. S. Shamsudin, **"Performance Evaluation of a Novel Vertical Axis Wind Turbine with Coaxial Contra-Rotating Concept,"** Renew. Energy, 2017.
https://doi.org/10.1016/j.renene.2017.08.070
24. A. Betz, **"Windenergie und ihre Amcendung dureh Windmuhlen," Gottingen Vanderhoeck Rupr**., 1942.
25. B. G. Newman, "**Actuator-disc theory for vertical-axis wind turbines,"** J. Wind Eng. Ind. Aerodyn., vol. 15, no. 1–3, pp. 347–355, 1983.
https://doi.org/10.1016/0167-6105(83)90204-0
26. S.-Y. Lin, Y.-Y. Lin, C.-J. Bai, and W.-C. Wang, **"Performance analysis of vertical-axis-wind-turbine blade with modified trailing edge through computational fluid dynamics,**" Renew. Energy, vol. 99, pp. 654–662, 2016.
https://doi.org/10.1016/j.renene.2016.07.050
27. R. E. Akins, D. E. Berg, and W. T. Cyrus, **"Measurements and Calculations of Aerodynamic Torques for a Vertical-Axis Wind Turbine,**" no. SAND86-2164, 1987.
28. M. Ahmadi-Baloutaki, R. Carriveau, and D. S.-K. Ting, **"Straight-bladed vertical axis wind turbine rotor design guide based on aerodynamic performance and loading analysis,**" Proc. Inst. Mech. Eng. Part A J. Power Energy, vol. 228, no. 7, pp. 742–759, 2014.
https://doi.org/10.1177/0957650914538631