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Verification of the self-starting problem of a Vertical Axis Wind Turbine with Inclined Blades

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ABSTRACT

In this paper, a theoretical investigation of the impact of varying the blade inclination angle β on the power coefficient of vertical-axis wind turbines equipped with straight blades has been demonstration, where the inclination angle was modified from twenty-five degrees to eighty-five degrees. Within the framework of this study, the term SS-VAWT was assigned to refer to the rotor which is the subject of the research. The "Multi Stream Tube-MST" mathematical model was used after some of its equations were modified to be consistent with the geometrical shape of the SS-VAWT rotor.

A computer program was designed using the "Microsoft Visual Basic" programming language as an application of the mathematical model used, which led to the effectiveness of this program and compared its final results with previous experimental results from other studies, this work was carried out on twelve obligatory SS-VAWT, which are classified into four namely H group which is characterized by rotor high change effect, R group which is characterized by diameter effect, N group which is characterized by number of blades effect and C group influenced by the length of blade chord line.

The results are represented by power curves as a function of tip speed ratio. The behavior of the curves for each case was verified and compared to determine the optimum case. All results were taken in the small range of tip speed ratio λ_0 extending from 0.0 to 2.8. Since the C_p coefficient and the λ_0 coefficient are dimensionless values, the results can be applied to large-sized air rotors, provided that there is geometric similarity. Because they found that the feather's 45-degree tilt and location reduce the problem of starting self-motion.

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دراسة تأثير زاوية ميل الريشة على «مشكلة بدأ الحركة الذاتي» لتوربينات الرياح ذات المحور العمودي

هاشم ابراهيم ابوسنوقة.

ملخص: تم في هذا البحث دراسة تأثير زاوية ميل الريشة على «مشكلة بدأ الحركة الذاتي» لتوربينات الرياح ذات المحور العمودي المستقيمة الريش، تم تعديل ميل الزاوية من 25 درجة إلى 85 درجة، بمقدار 20 درجة. في إطار هذه الدراسة، تم تخصيص مصطلح SS-VAWT للإشارة إلى الدوار موضوع البحث. تم استخدام النموذج الرياضي «Multi Stream Tube» بعد أن تم تعديل بعض معادلاته لتتماشى مع الشكل الهندسي للدوار SS-VAWT، تم تصميم برنامج حاسوب باستخدام لغة البرمجة «Microsoft Visual Basic» كتطبيق للنموذج الرياضي المستخدم، للتحقق من فعالية هذا البرنامج تم مقارنة نتائجه النظرية مع النتائج التجريبية السابقة من دراسات أخرى، تم تنفيذ هذا العمل على اثني عشر تكوينًا لـ SS-VAWT، والتي تم تصنيفها إلى أربع فئات وهي مجموعة H وهي مختصة بتأثير تغير ارتفاع الدوار، مجموعة R و هي مختصة بتأثير القطر ، مجموعة N المختصة بتأثير عدد الريش و مجموعة C المختصة بتأثير طول وتر الريشة. يتم تمثيل النتائج بواسطة منحنيات القدرة كدالة في السرعة النسبية الطرفية، حيث تم التحقق من سلوكيات المنحنيات لكل حالة و المقارنة و المفاضلة فيما بينها لتحديد الأمثل. كل النتائج أستخلصت في مدى λ_0 من 0.0 الى 2.8 و ذلك للتركيز في مشكلة بدأ الحركة.

و بما ان المعامل C_p و المعامل λ_0 هي قيم لا بعدية فإنه يمكن أن تنطبق النتائج على دوارات هوائية كبيرة الحجم بشرط تحقق التشابه الهندسي. من أهم النتائج لهذا البحث أن ميل الريشة بزاوية 45 درجة لها فائدة تقليل مشكلة بدء الحركة الذاتية.

1. INTRODUCTION

Within the context of the wind rotor's rotational motion, determined by the rotation angle (θ), it's important to note that the rotational speed of the wind rotor blade (ω*R) does not align with the speed of the wind (V) flowing through the rotor blade, where ω is angular velocity and R is rotor radius. This disparity between (ωR) and (V) gives rise to what is referred to as the relative velocity (W), resulting in the generation of an angle of attack (α). Consequently, the tip speed ratio (λ_0) which is equal to (ωR/V) plays a pivotal role in influencing (α), as it is a well-established principle in aerodynamics that increasing the angle (α) at which wind flow begins to separate on the blade airfoil enhances the "Lift to Drag" forces ratio (L/D). Consequently, the ratio (ωR/V) significantly impacts the (L/D) ratio of the rotor blade. To achieve optimal aerodynamic efficiency, it is imperative to maintain consistency among the values of (ωR/V), (α), (θ), and (L/D). It is noteworthy that the aerodynamic efficiency of vertical-axis wind turbines exhibits weaknesses at both high and low (ωR/V1) ranges, leading to performance disparities in both scenarios [2][3][4][5]. In contrast to horizontal-axis wind turbines, today's vertical-axis wind turbines encompass a diverse array of engineering designs. These prototypes compete in terms of aerodynamic efficiency, development potential, and production cost [6][7][8][9][10]. Following are a few examples of engineering designs for vertical-axis wind turbines (VAWTs). Darrieus-VAWT, characterized by its parabolic shape, derives its rotational force from lift pressure, but it suffers from several notable drawbacks. Its reliability remains relatively poor, with an efficiency not surpassing 35%, and it is prone to severe vibrations, which, in turn, contribute to an elevated production cost due to excessive structural support requirements for the rotor system [11][12][13][14]. An attempt was made to improve upon this design with the H-Darrieus variant, but it still faces challenges, including significant losses at the blade tips and high bending stresses [15][16][17][18][19]. Similarly, the helical turbine, while intriguing, incurs prohibitive production costs due to the spinning of its blades, and its peak power coefficient falls short of its counterparts [20][21]. All previous iterations of vertical-axis wind turbines shared a common issue known as the self-starting problem [22][23][24][25]. These models were even marketed globally as horizontal wind turbines but gained limited traction [26][27]. Figure 1 illustrates the schematic variables of the SS-VAWT turbine, encompassing parameters such as height (2H), diameter (2R), and blade inclination angle (β). This work primarily focuses on evaluating the impact of these variables, along with blade cord length (C) and the number of blades (N), on the self-starting problem of the SS-VAWT.

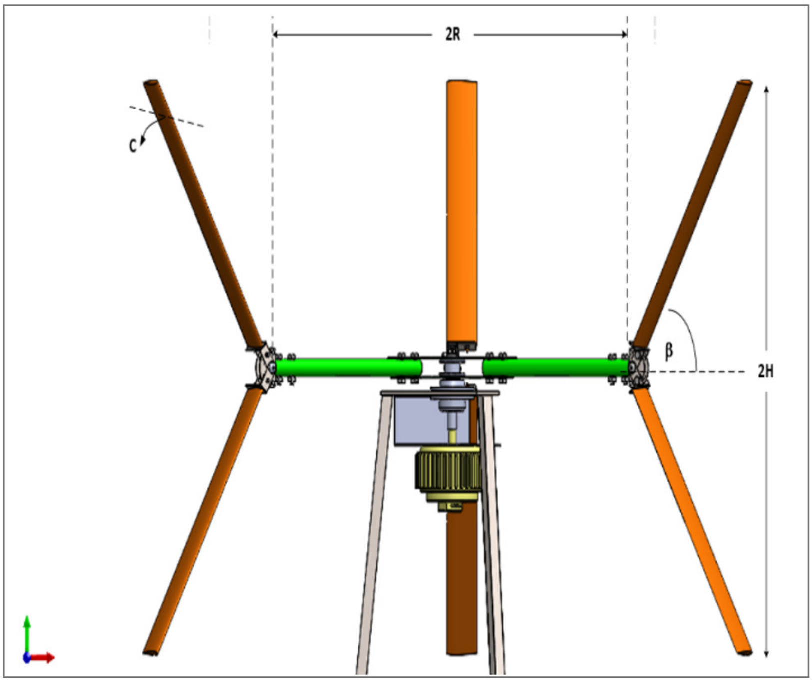

Figure 1: Schematic geometry of SS-VAWT.

2. METHOD

In this analysis, the Multi-Stream Tube Method (MST) was employed with specific adjustments tailored for optimal utilization in the context of the SS-VAWT. This particular modeling approach was selected for its remarkable ability to predict the overall power production of the rotor while being recognized for its efficiency and ease of application when investigating the influence of geometric shape variables on rotor performance. For a concise understanding of this model, as provided by Strickland [28], a brief overview is presented. In this model, the rotor is replaced by what is referred to as an "imaginary actuator disk." This disk is enveloped by a series of "stream tubes," which can be envisioned as tubular structures. The top surface of each stream-tube corresponds to a streamline, ensuring that the velocity vector is tangential across its entire surface. The air's velocity as it traverses these stream tubes undergoes variation, akin to the transition from the "free velocity" value, denoted as V1 in front of the disk, to the air velocity value "V" at the disk's position, and eventually to a velocity of "V2" within the wake area behind the disk. This continuous alteration in disk velocity occurs as a portion of the kinetic energy from the flow it intercepts is extracted [29]. The software underwent rigorous testing using previously gathered experimental data from wind tunnel tests. This software was developed for the analysis of three distinct types of vertical-axis wind turbines: the Darrieus parabolic rotor (Darrieus-VAWT), the straight blades rotor (H-VAWT), and the slant straight blades rotor (SS-VAWT), with the latter being the primary focus of this research paper. The detailed program methodology is elucidated in Figure 2.

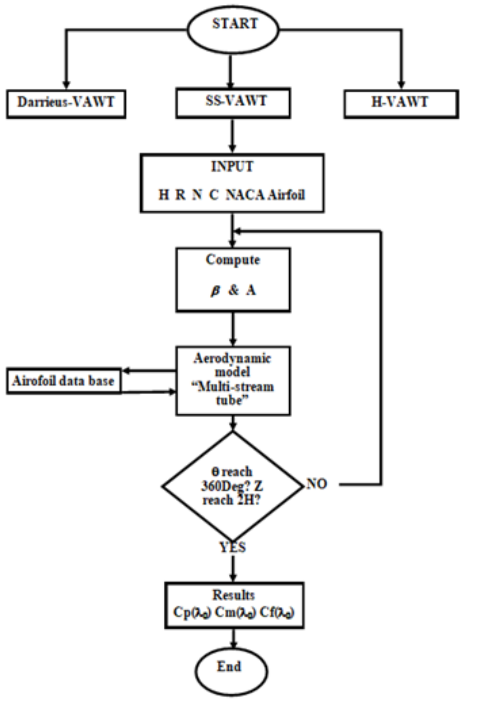

Figure 2: Detailed software methodology.

The study encompasses twelve distinct SS-VAWT configurations, each subjected to an in-depth investigation of their efficiency characteristics, all meticulously documented in Table 1. To express the aerodynamic efficiency while accounting for geometrical variables such as blade inclination angle (β), wind rotor height (2H), wind rotor diameter (2R), number of rotor blades (N), and airfoil chord line (C), power factor curves, often referred to as Cp-curves, were derived from the analysis of these twelve configurations. The rationale for presenting the findings in the form of Cp curves lies in the fact that rotor output data is commonly presented in a non-dimensional format, allowing for the utilization of such data regardless of the scale of the wind rotor, provided that geometrical consistency is maintained across different-sized rotors. Consequently, power coefficient curves in relation to the tip speed ratio λ0 are recognized and employed in the range of small initial values of λ0, in order to reach the goal of this study and verify the problem of the self-starting problem of SS-VAWT rotor. Below, several significant equations from the utilized model are presented for reference.

Table 1: SS-VAWT geometric dimensions.

"H" Group				"N" Group			
N	R	H	C	N	R	H	C
3.0	1.0	0.5	0.12	2.0	1.0	1.0	0.12
3.0	1.0	1.0	0.12	3.0	1.0	1.0	0.12
3.0	1.0	1.5	0.12	4.0	1.0	1.0	0.12
"R" Group				"C" Group			
N	R	H	C	N	R	H	C
3.0	0.5	1.0	0.12	3.0	1.0	1.0	0.06
3.0	1.0	1.0	0.12	3.0	1.0	1.0	0.12
3.0	1.5	1.0	0.12	3.0	1.0	1.0	0.18

- SS-VAWT geometry equation which generated specifically for this research:

$$\left(\frac{r}{R}\right)=\left(\frac{\left(\frac{Z}{H}\right)}{\frac{1}{\left(\frac{H}{R}\right)}\times \operatorname{Tan}\left(\beta\times\frac{\pi}{180}\right)}\right)+1 \qquad ....(1)$$

- The power P is given by:

$$P=\frac{\rho NC}{2\pi}\int_0^H\int_0^\pi W^2 r\frac{\omega C_t}{\sin\beta}d\theta dz \qquad ....(2)$$

- Tip speed ratio relation is:

$$\lambda_0=\frac{\omega R}{V} \qquad ....(3)$$

- The mathematical formula of the power coefficient, Cp, is:

$$C_p=\frac{NC}{\pi A}\int_0^H\int_0^\pi\left(\frac{W}{V}\right)^2\lambda_0\frac{r}{R}\frac{C_t}{\sin\beta}d\theta dz \qquad ......(4)$$

Whereas:
r/R is radius ratio, z/H is Height ratio, ρ is air density and C_t is coefficient of tangential force.

3. RESULTS AND DISCUSSION

All results were taken in the small range of tip speed ratio λ_0 extending from 0 to 2.8 and This will become clear in the following four figures. This is for the purpose of examining the pattern of C_p curves in the region related to the problem of self-starting.

3.1. Verifying the Behavior of C_p When Both β and H Change. [H Group]

Figure 3 illustrates a design group specializing in the study of the impact of changes in β on H. [β=65 H=0.5], [β=65 H=1], [β=85 H=1.5], [β=85 H=1] and [β=85 H=0.5] failed to reduce the movement onset problem, as zero or negative C_p values were recorded along the λ_0 values.
The [β =65 H=1.5] case achieved relative superiority over the previous cases when it reached λ_0 equal to 2, as the C_p values increased significantly.
However, the problem of movement starting became apparent when λ_0 values were less than 2. Looking at the two cases, [β=25 H=1.5] and [β=25 H=1], it appears at first glance that there is a good increase in the C_p values at the lower values of the lambda.
However, the C_p values continue to rise and then fall quickly, and C_p Max does not exceed 0.22, where this pattern is not appropriate to generate electricity, as it reminds us of the Savonius wind turbine, whose rotation depends on the drag force. There are 5 cases left for comparison: [β=25 H=0.5], [β =45 H=1], [β= 45 H=1.5], [β=45 H=0.5] and [β=65 H=1.5], The curves for these cases then take a similar pattern, with growth C_p values increasing directly with increasing λ_0 values. These curves form an acceptable similar to the well-known ideal situation for vertical wind turbines with the highest benefit from significant growth in the market, however it continues to [β =45 H=1.5] is an advantage, as the C_p values versus the smallest values of the λ_0 are greater than the C_p values in the other four cases.
For example, when λ_0 equals 1.8, the C_p values are 0.004, 0.039, 0.19, 0.24, and 0.27, since the last, highest value was taken from case [β =45 H=1.5].

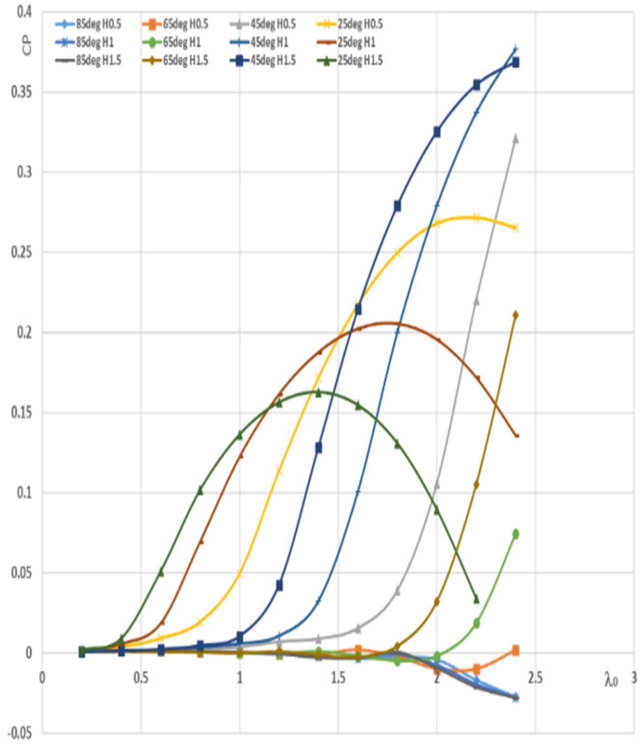

Figure 3: power coefficient behavior in case the angle β changes with the change in height for [H group]

3.2. Verifying the Behavior of C_p When Both β and R Change. [R Group]

In Figure 4, The three cases of β = 85 had negative Cp values in the λ_0 range from 0.0 to 2.0 The optimal engineering configuration were identified as [β = 45 R = 1.5] and [β = 45 R = 1] With the superiority of the latter in terms of, C_p values is higher along λ_0 range, for example C_p equal to 0.2 at $\lambda_0 = 1.8$.

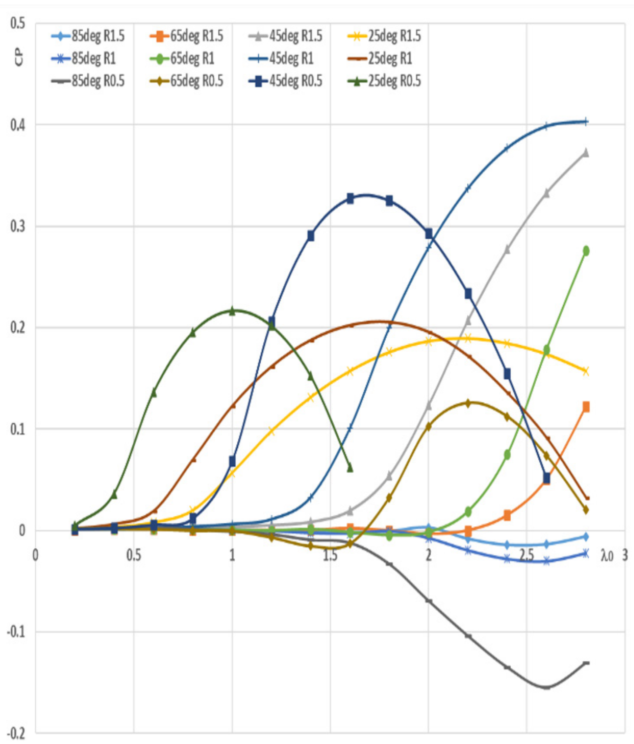

Figure 4: power coefficient behavior in case the angle β changes with the change in radius [R group].

3.3. Verifying the Behavior of C_p When Both β and N Change. [N Group]

Within Figure 5, a distinct classification of curves emerges, delineated by N values of 2, 3, and 4, each subgroup containing four curves corresponding to angles β of 85, 65, 45, and 25 degrees.
A group of β equal to 85 shows the exacerbation of the self-starting problem as the C_p values are negative along the λ_0 values from 0.0 to 3.0 The β=65 group changes the value of N, which does not affect the pattern of the curves much as they are close.
This group is relatively better than the β=85 group in terms of high C_p, but it does not help the problem of starting the movement. In a group of β equal to 25, there is a rapid rise in the C_p values corresponding to very small λ_0 values, and this works in the interest of reducing the problem of starting the movement, but unfortunately the cycle of the curve is completed quickly in a small λ_0 range, where the curves reach the peak and fall quickly, and this pattern is not possible to generates electrical energy.
The β group equals 45 combines two features: the continuation of the rise in C_p values directly with increasing λ_0, and the occurrence of an increase in C_p values early at small values of λ_0.

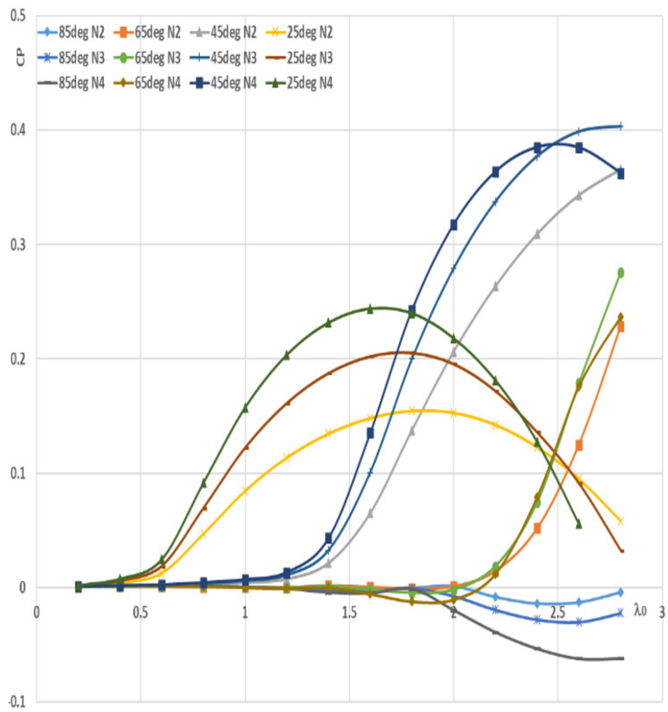

Figure 5: power coefficient behavior in case the angle β changes with the change in blades number [N group].

3.4. Verifying the Behavior of Cp When Both β and C Change. [C Group]

The results regarding the influence of C shifts on rotor efficiency are depicted in Figure 6. Remarkably, the patterns observed in the C_p curves in this instance closely resemble and are nearly identical to those seen in the C_p curves discussed in the preceding section, as illustrated in Section 3.3. Figures 5 and 6 can be characterized as exhibiting a high degree of similarity.

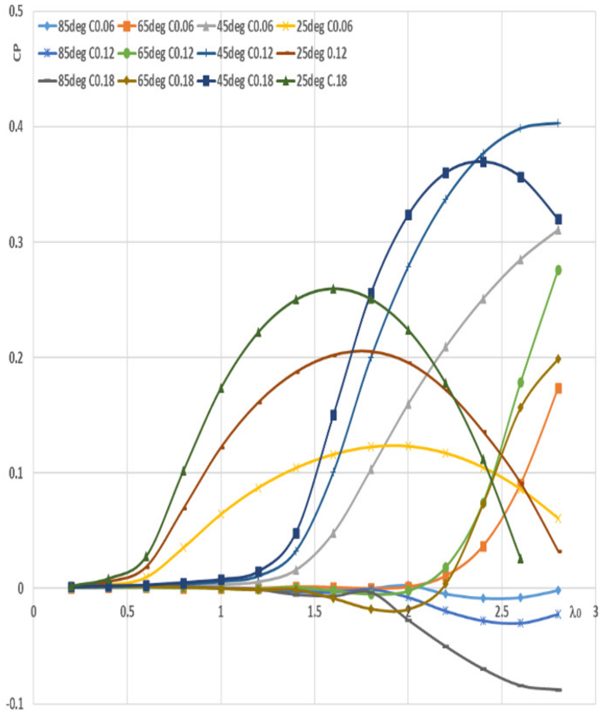

Figure 6: power coefficient behavior in case the angle β changes with the change in cord line [C group].

4. CONCLUSION

In vertical-axis wind turbine with straight-bladed, the best angle of beta is around 45 degrees, as this condition contributed to reducing the problem of the self-starting as explained in the results section.

Within the scope of this research, the results showed that the effect of changing the number of blades (N) is very similar to the effect of changing the blade cross-sectional length (C) in case that the geometric and aerodynamic conditions are similar. Accordingly, when studying the behavior of the power coefficient curves of vertical wind turbines with straight blades and inclined angle theoretically, it is advisable to combine the variables C and N as one variable. Not to mention that they are outside the integration process in equations 2 and 4. Therefore, the number of calculations and the time of analytical operations will be reduced.

This prototype saves effort and money and shortens time during research operations conducted on vertical axis wind turbines, because it is dimensionally variable, meaning it is multi-geometric, and therefore there is no need to manufacture a model for each case study.

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REFERENCES

[1] H. Abusannuga and M. Özkaymak, "Towards Evaluating the Performance of Vertical Axis Wind Turbine Consist of Slant Straight Blades," in 2020 IEEE International Conference on Environment and Electrical Engineering and 2020 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), Madrid, 2020.

[2] B. F. BLACKWELL, "The Vertical-Axis Wind Turbine "How It Works"," Sandia Laboratories, Albuquerque, New Mexico, 1974.

[3] R. Templin, "Aerodynamic Performance Theory for the NRC Vertical-Axis Wind Turbine," National Aeronautical Establishment, LTR-LA-160, Canada, 1974.

[4] Ralph J, Muraca, Maria V, Stephens and J. Ray Dagenhart, "Theoretical Performance of Cross-Wind Axis Turbines with Results For A Catenary Vertical Axis Configuration," NASA Langley Research Center, Virginia, 1975.

[5] P. N. Shankar, "On the aerodynamic performance of a class of vertical shaft windmills," Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences, vol. Vol. 349, no. No. 1656, pp. 35-51, 1976.

[6] Robert E. Sheldahl, Bennie F. Blackwell, "Free-Air Performance Tests of a 5-Metre-Diameter Darrieus Turbine," Sandia Laboratories, New Mexico, 1977.

[7] Paraschivoiu, I., "DOUBLE-MULTIPLE STREAMTUBE MODEL FOR DARRIEUS WIND TURBINES," in Institut de Recherche de l'Hydro-Quebec, Quebec, 1981.

[8] Kumar, P.M., Sivalingam, K., Narasimalu, S., Lim, T.-C., Ramakrishna, S. and Wei, H, "A Review on the Evolution of Darrieus Vertical Axis Wind Turbine: Small Wind Turbines," Journal of Power and Energy Engineering, vol. 7, pp. 27-44, 2019.

[9] Muhammad Bhutta, Nasir Hayat, Ahmed Farooq, Zain Ali, Sh. Rehan Jamil, Zahid Hussain, "Vertical axis wind turbine – A review of various configurations and design techniques," Renewable and Sustainable Energy Reviews, vol. 16, no. 4, pp. 1926-1939, 2012.

[10] T. Dang, "Introduction, history, and theory of wind power," in 41st North American Power Symposium, Starkville, MS, 2009.

[11] Tjiu, Willy & Marnoto, Tjukup & Sohif, Mat & Ruslan, M.H. & Sopian, Kamaruzzaman, "Darrieus vertical axis wind turbine for power generation I: Assessment of Darrieus VAWT configurations," Renewable Energy, vol. 75, p. 50–67, 2015.

[12] Thomas D. Ashwill, Timothy M. Leonard, "Developments in Blade Shape Design for a Darrieus Vertical Axis Wind Turbine," Sandia National Laboratories, Albuquerque, New Mexico, 1986.

[13] Emil G. Kaldlec, "Characteristics of Future Vertical Axis Wind Turbines," Sandia National Laboratories, Albuquerque, New Mexico, 1982.

[14] Willy Tjiu, Tjukup Marnoto, Sohif Mat, Mohd Hafidz Ruslan, Kamaruzzaman Sopian, "Darrieus vertical axis wind turbine for power generation II: Challenges in HAWT and the opportunity of multi-megawatt Darrieus VAWT development," Renewable Energy, vol. 75, pp. 560-571, 2015.

[15] W. S BANNISTER, "Aerodynamic Studies of A Straight-Bladed Vertical-Axis Wind Turbine," in 1ST. B.W.E.A WIND ENERGY WORKSHOP, SPRINGFiElD, VA, 1979.

[16] W. S. BANNISTER, "A Theoretical Analysis Of Small Vertical Axis Wind Turbines," in International Synposium on "Applications of Fluid Mechanics and Heat Transfer to Energy and Environmental Problems, Greece, 1981.

[17] Hara, Y.; Horita, N.; Yoshida, S.; Akimoto, H.; Sumi, T, "Numerical Analysis of Effects of Arms with Different Cross-Sections on Straight-Bladed Vertical Axis Wind Turbine," Energies, vol. 12, no. 11, p. https://doi.org/10.3390/en12112106, 2019.

[18] J. Fadil, Soedibyo and M. Ashari, "Performance analysis of vertical axis wind turbine with variable swept area," in International Seminar on Intelligent Technology and Its Applications (ISITIA), Surabaya, 2017.

[19] Gorlov, A, "Development of the Helical Reaction Hydraulic Turbine," Northeastern University, Boston, 1998.

[20] Han, D.; Heo, Y.; Choi, N.; Nam, S.; Choi, K.; Kim, K, "Design, Fabrication, and Performance Test of a 100-W Helical-Blade Vertical-Axis Wind Turbine at Low Tip-Speed Ratio," Energies, vol. 11, no. 6, 2018.

[21] Rahman, Mosfequr, Salyers, Travis, Ahmed, Mahbub, ElShahat, Adel, Soloiu, Valentin, and Maroha, Emile, "Investigation of Aerodynamic Performance of Helical Shape Vertical-Axis Wind Turbine Models with Various Number of Blades Using Wind Tunnel Testing and Computational Fluid Dynamics," in International Mechanical Engineering Congress and Exposition, Phoenix, Arizona, 2016.

[22] Dominy, R., Lunt, P., Bickerdyke, A., Dominy, J, "Self-starting capability of a Darrieus turbine," Journal of Power and Energy, vol. 221, no. 1, p. 111–120, 2007.

[23] Zhu, J., Huang, H., & Shen, H, "Self-starting aerodynamics analysis of vertical axis wind turbine," Advances in Mechanical Engineering, vol. 7, no. 12, 2015.

[24] Omar S. Mohamed, Ahmed A. Ibrahim, Ahmed K. Etman, Amr A. Abdelfatah, Ahmed M.R. Elbaz,, "Numerical investigation of Darrieus wind turbine with slotted airfoil blades," Energy Conversion and Management: X, vol. 5, no. 100026, 2020.

[25] J. Krishnaraj, Sivakumar Ellappan, M. Anil Kumar, "Additive Manufacturing of a Gorlov Helical Type Vertical Axis Wind Turbine," International Journal of Engineering and Advanced Technology (IJEAT), vol. 9, no. 2, 2019.

[26] IRENA, "Future of wind: Deployment, investment, technology, grid integration and socio-economic aspects," International Renewable Energy Agency (IRENA), Abu Dhabi, 2019.

[27] J. Damota, I. Lamas, A. Couce, J. Rodríguez, "Vertical Axis Wind Turbines: Current Technologies and Future Trends," in International Conference on Renewable Energies and Power Quality (ICREPQ'15), Coruna, 2015.

[28] Strickland, J H, "The Darrieus Turbine: A Performance Prediction Model Using Multiple Streamtubes," Sandia Laboratories, Albuquerque, New Mexico, 1975.

[29] N. Batista, R. Melício, V. Mendes, J. Figueiredo, A. Reis, "Darrieus Wind Turbine Performance Prediction: Computational Modeling," in 4th Doctoral Conference on Computing, Electrical and Industrial, Costa de Caparica, 2013.