International Journal of Energy Production and Management
Vol. 9, No. 3, September, 2024, pp. 151-160
Journal homepage: http://iieta.org/journals/ijepm

Blade Pitch Angle Regulation for H-Type Darrieus Vertical Axis Wind Turbine: A Review

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https://doi.org/10.18280/ijepm.090304

Received: 8 April 2024
Revised: 20 June 2024
Accepted: 11 September 2024
Available online: 26 September 2024

Keywords:
blade pitch angle regulation, coefficient of power, VAWT performance, vertical axis wind turbine, wind energy

ABSTRACT

Wind energy is one of the most widely used renewable energy sources around the world. A considerable research amount was accomplished in the area of performance enhancement for H-type Darrieus VAWT using blade pitch angle regulation. This paper aims to provide a comprehensive information for future research related to performance enhancement of H-type Darrius VAWT using blade pitch angle regulation. By pointing out the current technological development, the main advantages and disadvantages of the blade pitch angle techniques used. This review discusses the main effect of fixed and variable blade pitch angle regulation, blade pitch control techniques, and mathematical modelling. The state-of-the-art on how to improve the H-type Darrieus VAWT performance by using variable pitch angle adjustment was addressed. The active variable blade pitching technique was suggested to enhance the performance of H-type Darrius VAWT as it can increase the lift force and reduce the drag force on the blade during the wind turbine operation. Additionally, DMST model was suggested to be utilized to calculate the power output as it provides relatively accurate results especially at low TSRs.

1. INTRODUCTION

The energy demand is increasing continuously as a result of the world population and economic growth. Renewable sources of energy contribute partially to the market demand, by providing a clean source of energy. For this instance, an affordable and clean source of energy is one of the 17 sustainable development (2030) goals in the United Nations Development Program is an affordable and clean source of energy [1]. Since many decades and in different civilizations energy of wind has been recognized as an energy source; and it's been reported that humans begin have used wind energy almost 4000 years ago. Wind energy was used by King Hammurabi of Babylon in Mesopotamia for irrigation purposes via using wind-powered scoops [2]. Windmills are used to provide energy for many industrial processes, including oil seeds paints, wool, paper, and stone products. VAWT configuration was the mostly used type in the world's oldest wind turbines. Early models were very simple, especially from a construction perspective [3].

For vertical axis wind turbines (VAWTs), the rotational axis of the rotor is perpendicular to the ground and the direction of wind. The VAWTs are comparatively simpler in design and do not require a Yaw mechanism due to the Wind Turbine (WT) blade orientation. The low cut-in speed, low level of noise and ability to be installed in urban areas, make the VAWTs the preferable choice to be used in urban locations [4]. VAWT are usually categorized into two main categories, Savonius WT and Darrieus WT. Savonius WT is a drag force WT, made of two or more semi-cylindrical buckets which capture the wind energy. The Darrieus WT is a lift-type VAWT, and it is equipped with shaped airfoil blades that produce lift force which can rotate the main wind turbine shaft. The Darrieus turbine could be formed in several configurations: Darrieus eggbeater shape, H-type, and Helical blade shape [5].

Most of the development was made on a large scale offshore and onshore WT far away from the city where the wind speed is mostly intense, consistent and constant. In contrast, there is a significant wind energy in the urban areas with considerable potential for energy generation in motorways, high-rise buildings, and on the top of the roofs of local houses [4]. Developing an effective clean energy source of power closer to the consumer place of use in the cities minimize the use of hydrocarbon-based electricity generation. The development of a more efficient VAWT for urban environments is essential to increase the expansion of wind energy usage inside cities and semi-urban areas. The wind characteristics in urban environment experience much more wind fluctuation which makes the prediction of wind behavior under these conditions a challenging task due to terrain obstruction [6]. Therefore, developing a vertical axis wind turbine equipped with adjustable blades based on the available wind will improve the efficiency of energy production. Numerous studies proposed the Variable Pitch (VP) technique to overcome wind fluctuation in urban areas.

The VP-pitch technique aims to keep the VAWT in operating condition between drag and stall angles to reach the highest energy extraction [7].

This paper presents a comprehensive review of the effects of both fixed and variable blade pitch angle regulation, highlighting the blade pitch control techniques used to enhance the performance of H-type Darrius VAWT. Additionally, it covers the mathematical modelling methods for calculating the power output of these wind turbines. The paper also addresses the current challenges faced the by H-type Darrius VAWTs and it suggest recommendations for the future research. The paper mainly provides researchers with insight on how to enhance the performance of H-type Darrius VAWTs. This study found that fixed pitch angle regulation could provide performance enhancement only at the starting stage, and this improvement will have an impact on the overall wind turbine performance especially when the rotational speed increases. On the other side the variable blade pitch angle regulations show better performance; however, this improvement is only limited to a certain TSRs. In order to improve the performance of the H-type VAWT the paper suggests the use of active variable blade pitch angle regulation. This technique can improve the overall performance of the wind turbine in all operational stages (start, normal and overspeed). Moreover, the DMST model was recommended to be used to calculate the rotor power output; this model could provide more realistic results when compared to other models specially at low TSRs.

2. RESEARCH MOTIVATION

The research is motivated by the potential of performance enhancement for the H-type Darrieus VAWTs using blade pitch angle regulation. Since there are more than one technique of blade pitch angle regulation this research will point out fixed and variable blade pitch angle techniques strengths and weaknesses; and will go over the mathematical modelling of H-type Darrius VAWT. The aim of this research is to provide a review of the blade pitch angle regulations techniques, which will be used as a foundation for future recommendations for blade regulation.

3. H-TYPE DARRIEUS VERTICAL AXIS WIND TURBINES

In 1931 Georges Jean Marie Darrieus (a French engineer) developed the Darrieus VAWT [8, 9]. The Darrieus wind turbines are lift force type WT and have the ability to provide more energy and a higher coefficient of power when compared to same scale Savonius WT [4]. Darrieus WT blades move in a circular route; a net force will be developed due to the interaction between the airflow and the airfoil, this net force pushes the turbine blades in which create a torque on the shaft of the wind turbine. Darrieus VAWT rotor blades reduce the turbine bending stress, whereas the blades of this type of turbine mainly experience a tension force [8]. Darrieus turbines are available with two or three blades or more, where blades can be in a straight or curved shape. Self-start ability is a major problem in Darrius turbines, where at the start of the operation the starting torque is very low. Many modifications have been performed on the Darrieus turbine to enhance its performance and expand its adaptation by the market. Most of the developed designs were not considered by the market due to their high cost of manufacturing [10]. One of the best Darrieus turbine designs is the H-type Darrieus VAWT, as it has less complicated design in comparison with the helical shape rotor, and better efficiency when compared to the eggbeater shape Darrieus [9]. The Giromill or H-type Darrieus wind turbine was extensively adopted compared to the other VAWTs in recent years. Also, H-type Darrieus wind turbine shows a high ability for energy generation on different scales especially the domestic and mini-scale turbines [11]. Different studies were conducted to improve the performance of H-type Darrius VAWTs; one of the most effective ways is the blade pitch angle regulation. Recent studies have developed an intelligent blade pitch control system which can adjust the blade pitch angle based on the given parameters [12]. Another way to adjust the blade pitch angle is by using a passive control system which normally shows less performance when compared to the active system [7, 13]. Electro-mechanical actuators have made it more feasible to implement active variable blade pitch angle technique; on the other hand, this adds cost and complication to the H-type Darrius VAWTs. Though many improvements happened to the H-type Darrius VAWTs, it still shows less efficiency compared to the HAWTs within the same scale. Table 1 provides a list of the advantages and disadvantages of H-type Darrius VAWT.

Table 1. List of advantages and disadvantages of H-type Darrius VAWT

Advantages	Disadvantages
It could work in any wind direction; no need for Yaw-mechanism.	Complicated aerodynamics due to the changing in AOA and azimuth position.
Constant radius over the rotor span.	Low ability to self-start due to low starting torque.
Constant blade radius and relatively low Tip Speed Ratio (TSR) provide lower noise during operation.	Power and torque fluctuation (ripple torque) during operation while the blade rotates.
Suitable for the urban environment; as H-type Darrieus VAWT is less affected by changing wind direction.	High bending moment because of centrifugal acceleration, and that is considered a design challenge.
Generators, control systems, and heavy transmission systems are located at the base level.	Ripple torque creates vibrations in the turbine blades and structure.
H-type Darrieus VAWTs could extract energy from the blade wake of other turbines, thus VAWTs can be placed at a closer distance in a wind.	Lower power coefficient and efficiency in comparison with HAWTs of equal scale.

3.1 Performance optimization through blade pitch angle regulation

H-type Darrieus VAWT is a suitable choice for urban environment energy production. However, due to the VAWT rotor orientation, this type of wind turbine suffers because of the changes in the angle of attack (AOA) while the VAWT rotates. Ideal aerodynamic forces could not be obtained in all angles of the rotational azimuth, which led to a weak aerodynamic performance with VAWTs in general. Also, this issue occurs at most azimuth angles as the rotor blades travel from the lift region to the drag region [14]. Moreover, fluctuating lift force creates a considerable fluctuation in the generated torque and power [15]. Many researchers mentioned (see Table 2), H-type Darrieus VAWT blade pitching as the blades move around the path has the ability to reduce these issues to some extent [11, 14, 15]. Blade pitch angle regulation usually tries to keep the AOA in the optimum or close to the optimal orientation for most azimuth positions.

Table 2. Studies mentioned VP-angle effect on the performance of the VAWT

VP Effect on the Performance	Pitch Angle Value	TSR	Author(s)
20%	-12°	5	Schönborn and Chantzidakis [16]
25%	9°	2	Hwang et al. [17]
35%	9°	2.35	Erickson et al. [18]
12%	5°	2-2.5	Chougule and Nielsen [19]
10%	-3°	2.5	Sagharichi et al. [20]
18.9%	Value changing from 3° to -3°	5	Zhao et al. [21]

3.2 Effects of fixed pitch blade angle regulation on the performance of H-type Darrieus vertical axis wind turbine

Fixed blade pitch angle regulation is a powerful method used to enhance the power generation of H-type Darrieus VAWT. During this process, the blade will be rotated either inside or outside the circle trajectory. The angle in between the chord of the blade and tangent to the rotor azimuth rotating path is called the pitch angle and it's usually presented using the Greek letter (β). A positive pitch angle is defined when the leading edge of the airfoil's is inside the circular path of the blade. The negative pitch angle occurs when the leading edge of the blade's is outside of the circular path, Figure 1 illustrates the blade pitch angle [22]. In the VAWT, the blade AOA experiences substantial changes; therefore, studying appropriate pitching angle is essential to improve the performance of this type of WT [23].

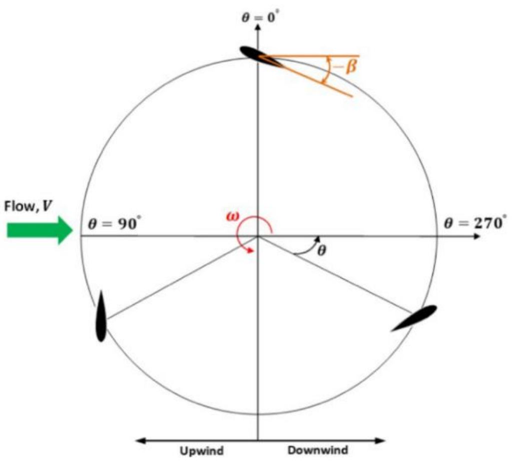

Figure 1. Illustration of Blade pitch angle [22]

At blade negative pitch angle, the AOA will be reduced in the upwind part of the wind turbine, however, the AOA will be raised in the downwind region. Fixing the angle by a fixed amount is most likely to be a translation of the AOA either by curve up or curve down with a constant amount. The dynamic stall of the blade is delayed if the AOA is decreased in the upwind region, leading to more torque at a larger portion of the azimuth [24, 25].

Different Studies [25-29] reported that the negative blade pitch angle can rise the torque of H-type Darrieus VAWT. And mentioned that the negative blade pitch angle can enhance the WT self-staring ability and decrease the starting time. Sagharichi et al. [7] reported the effect of the fixed blade pitch angle on the power output generation of the H-type Darrieus WT. The study presents that the maximum coefficient of torque can be obtained at β = -3° as shown in Figure 2. A β = -3° fixed pitch angle increases the torque generated by the blade because of the increasing in the lift force, which creates a positive effect on the performance of the wind turbine. This creates a delay in the dynamic stall of the blade in the upstream part of the rotor. A positive pitch angle adjustment will have negative impact on the performance of the wind turbine. As the pitch angle increases towards higher positive value of pitch, less torque is generated due to the increasing drag force. The study also found; the extracted power in the downstream region (180 < ϴ < 360) of the rotor is higher by a small amount for the positive blade pitch angle of β = 9°. This happens as a result of, WT extracting less wind energy on the upstream side (0 < ϴ < 180). This tells us that, usually, there is a balance between the power extracted in the upwind and downwind halves of the WT. This result is been supported by Akay et al. [30] as well, where it was mentioned more kinetic energy extraction from the upstream region of the rotor will result in less momentum reaching the downstream region, thus a smaller amount of power is generated in the downstream region and vice versa.

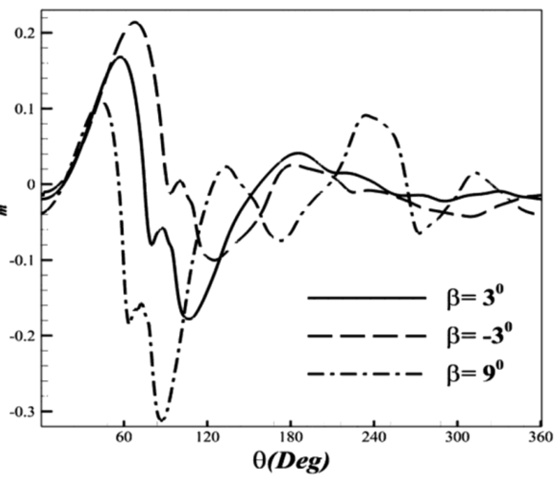

Figure 2. Torque coefficient (CM) against Azimuth angle (ϴ) for various blade fixed pitch angles [7]

3.3 Effects of variable blade pitch angle regulation on the performance of H-type Darrieus vertical axis wind turbine

A tiny negative blade angle pitching increases the power generated and delays the blade dynamic stall in the upstream phase, on the other hand, the negative pitch angle provides bigger AOA which result in increase in the dynamic stall in the downstream phase of the wind turbine. To overcome that barrier, a sinusoidal pitch angle technique could be applied to increase the performance of the H-type Darrieus WT [7, 31, 32]. A sinusoidal blade pitch technique is utilized to make the blade pitch almost zero, where small power or toque is generated; and then return to optimal pitch angle when the blade gets near to Θ = 90° azimuthal angle, in which the maximum torque is developed [23]. This technique in the blade pitching movement can reduce the AOA variation in the upwind and downwind phases of the wind turbine, thus minimizing the unwanted dynamic stall impact at the azimuthal points where the rotor blade suffers dynamic stall. Pawsey [33] stated that using a variable pitch technique at low TSR will improve the self-start capability of the WT. Sagharichi et al. [7] examined the variable pitch angle effect on the power generation of the H-type Darrieus wind turbine, the study considered four different pitching amplitudes (β = 3°, β = 10°, β = 20°, β = 36°) using sinusoidal relation in Equation 2, to identify the effects of these amplitudes on the WT performance. Figure 3 compares the fixed and variable pitch angle regulation technique for different pitch amplitudes. As a result of variable pitch angle regulation, the blade will face less dynamic stall during rotation; which improves the aerodynamic performance of the WT [7].

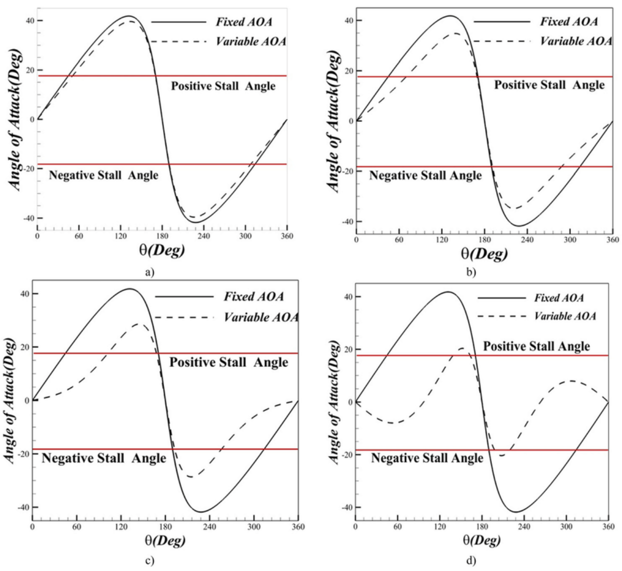

Figure 3. Blade pitch angle effect on the AOA at TSR = 1.5 (a) β = 3°; (b) β = 10°; (c) β =20°; (d) β = 36° [7]

Zouzou et al. [34] presented a study of a VAWT using variable pitch blade angle regulation at low TSR for H-type Darrieus VAWT; which is recommended to reduce the noise and improve the WT performance. The Aerodynamic performance is studied using Computational Fluid Dynamics (CFD) modelling and wind tunnel experiments. The Eddy simulation approach was used to generate a 3D flow field over the blade. The simulation of VP is created by utilizing the sliding mesh method, where a special program was used to adapt the blade pitch angle based on the azimuthal position while the WT is rotating. The findings showed that the VP turbines have the ability to generate a higher Coefficient of Power (C_P). Also, VP reduces the torque fluctuations while the wind turbine is rotating compared to the Fixed Pitch (FP) scenario; therefore, the aerodynamic load is minimized which provides less vibrations on the turbine structure. One of the main disadvantages with the variable pitch control mechanism is that will increase the cost and the complication within the rotor.

Sun et al. [35] examined the effect of passive blade pitching amplitude on the performance of the H-type VAWT; where the study validates the numerical analysis using experimental testing. The experimental testing includes a gear-linkage mechanism which integrated into the design of the rotor in order to achieve the changing in the pitch angle. The numerical results confirm that the passive blade pitch angle positive effect on the turbine performance; an increment in the extracted power when compared to the zero-pitch angle is obtained by 39.01%, 25.83% and 15.78% at 3, 6 and 9 m/s. The study also claims that the passive pitching can reduce the blade vortices and eliminate the effect of the blade wake. The experimental results of the study validate the numerical results found. On the other side, adding a gear-linkage to the rotor system will create more resistance at the start of the turbine, which reduce the self-start ability of the H-type Darrius VAWT. Also, the passive mechanical control system can provide improvements to the wind turbine performance only in certain TSRs and under certain wind conditions.

3.4 Variable blade pitch control techniques

The Darrieus H-type VAWT blade experiences cyclical changes in the AOA and the Wind Speed (VW) while the turbine rotates. Performance enhancement could be achieved through blade pitch regulation by optimizing the AOA value at each position of the azimuth [18]. Any enhancement to the angle of attack might be formed in a cyclical manner as presented in Figure 4 [36]. Therefore, a standard blade pitch angle curve for variable pitch technique is represented by Eq. (1) and Eq. (2):

$$\beta = A_C \sin \theta \tag{1}$$

$$A_C = A_S - (A_S \frac{TSR}{X_O}) \sin \theta \tag{2}$$

where, Θ: azimuthal angle, β: blade pitch angle, TSR: Tip Speed Ratio, AC: maximum pitch angle for specific TSR, AS: maximum pitch angle at all TSRs, and XO: TSR of max coefficient of power at zero Ac.

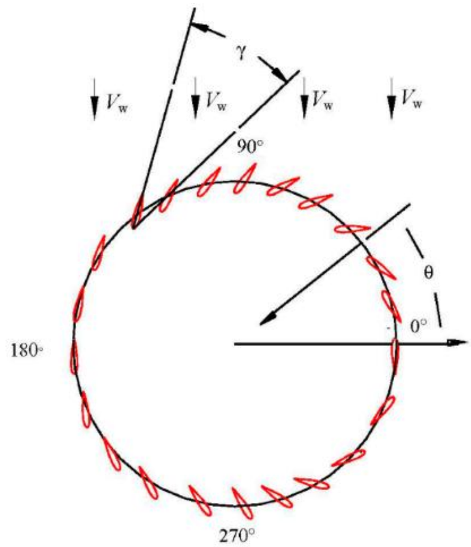

Figure 4. Representation of cyclical VP technique [36]

On another conventional variable pitch blade angle regulation technique of Darrieus H-type VAWT, the blade rotates on its own axis based on the uniform rotational motion of the WT. By taking a section view of the WT, at a given point (P) the lines normal to the airfoil chord at each blade position intersect during one revolution as shown in Figure 5 [36]. The blade pitch angle changes based on the azimuth angle are presented in Eq. (3):

$$\beta = A_C \sin\theta - tan^{-1}\frac{\sin\theta}{\cos\theta + TSR} \qquad (3)$$

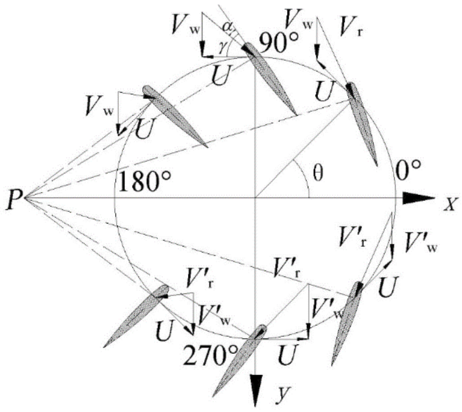

Figure 5. Cycloidal variable pitch [36]

Zhao et al. [36] considered a stall angle of attack around 10°, as illustrated in Figure 6. For low TSRs or at the start of the WT, the maximum AOA is exceeding the stall angle value by a considerable amount (see Figure 6 (a)), where the blade lift force is reduced, and the drag force is increased. In similar occasions, to prevent the dynamic stall, the blade will be rotated either clockwise or anti-clockwise using variable blade pitch techniques. Both of the methods were used by Zhao et al. [36] to achieve the same target. For the first method, the pitch angle control will be active only at the points where AOA is higher than the dynamic stall value, where the AOA is adjusted to be just below the stall angle value [36-38] as presented in Figure 6 (b). The technique used allows the WT to operate with the optimal angle of attack in a wider azimuthal zone which counts as an advantage of this method. On the other hand, as a disadvantage, the pitch angle change, shown as a dashed line in Figure 6 (b) is limited to a few positions only. A sudden dynamic load might occur as a result of the rapid change in the pitch angle; this can cause significant change in the torque value leading to a possible fatigue in the long run. The second method of variable pitch control is changing the blade pitch angle using a sinusoidal function as presented in Figure 6 (c). The beauty of this practice is that the blade pitch angle changes continuously and in a smooth manner. Also, this technique has a higher possibility of implementation in comparison with the first technique. To rise the peak coefficient of power at large TSRs, the blade pitch angle needs to be moved in the direction which increases the AOA as presented in Figure 6 (d), but the improvement will be very limited due to the little change that happens to the AOA towards maximum amplitude.

Zhao et al. [21] proposed a new variable pitch technique that is mainly designed for performance improvement. This new strategy in blade pitching aims to reduce the azimuthal range with low or poor performance and increase the high-performance range. As mentioned earlier 0° and 180° azimuthal points are transformation spots between positive and negative angles of attack, therefore the pitch angle effect should be zero at these points. The strategy divides the blade's azimuthal path into five regions, where at each region the blade pitch angles have a special tendency of variation. According to Zhao et al. [21], this new approach will allow the blade to have more lift and will widen the maximum lift curve in the upstream phase. Also, in the downstream phase of the rotor, it will increase the lift at 4.5 TSR but at 5.5 TSR it will reduce the lift. The proposed technique shows an increment in the efficiency of VAWT at 4.5 TSR by 18.9%. The main obstacle for that system will be the feasibility of that control system, such a control system will require special programming and electro-mechanical actuators which can highly increase the cost of manufacturing.

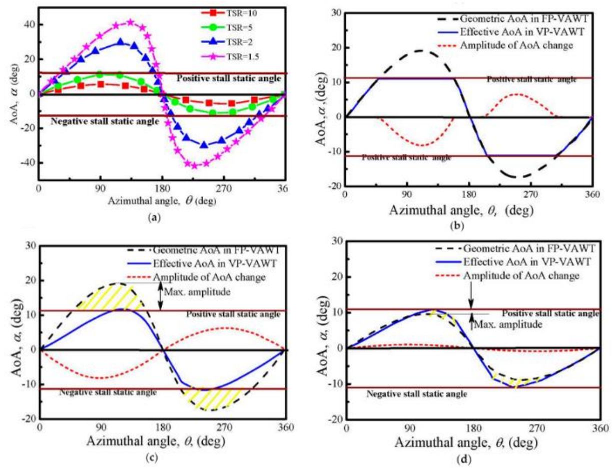

Figure 6. (a) AOA at different TSRs; (b) Pitching technique one (low TSR); (c) Pitching technique two (low TSR); (d) Pitching technique two (high TSR) [36]

Abdalrahman et al. [12] designed and developed an intelligent blade control system using the variable blade pitch angle adjustment to enhance the performance and self-start ability of H-type Darrius VAWT. The study used an intelligent blade pitch control technique based on artificial neural network. A DC motor used to change the blade pitch angle based on the mathematical calculation which used a sinusoidal equation. Different pitch angle values will be entered in the CFD simulation and MATLAB Simulink to select the optimum angle during operation. The results present that better self-start ability is obtained by the rotor using this active intelligent control system in comparison with fixed blade system. Also, 22% improvement on the overall turbine performance is achieved. The intelligent blade control system is a promising method to increase the performance of H-type Darrius VAWTs. This method can offer performance enhancement at different TSRs; unlike the passive adjustment method which normally improves the performance at certain stages of the wind turbine operation such as the staring stage.

Karimian and Rasekh [39] determined the aeroacoustic and aerodynamic effect of blade pitch angle regulation on the H-type Darrius VAWT. The study used CFD SST k-ω turbulence model to simulate the flow field and Flows Williams-Hawkings (FW-H) acoustic analogy method and to predict the noise generated during the operation of the rotor. The results obtained validated using experimental testing. To discover the effect of pitch angle on different situation the TSR range has been covered. In this study, it's been found that at the optimum TSR a pitch angle setting equal to -1° increase the power output by 4.2%; and its claims that at the lowest TSRs more power enhancement could be obtained by adjusting the pitch angle. Unlike the negative pitch angle, the positive pitch angle will reduce the performance of the H-type VAWT except at the very low TSRs cases. For the noise, a reduction of 1.8 dB in the overall pressure level sound is achieved by sitting the pitch angle equal to 1° or 3°. The study concludes by indicating the importance of using simple mechanism for changing the bade pitch angle for different operational conditions.

Kavade and Ghanegaonkar [40] explored the efficiency enhancement of H-type VAWTs by using optimal pitching. The study target self-starts and power improvement across different TSRs. The paper used aerodynamic analysis and simulations based on the SST model and BEM theory. The research identifies the best pitch angle positions for the wind turbine blades at different azimuth positions. A MATLAB program was utilized to predict the turbine performance at different pitch angles. The paper found that optimum blade pitch angle varied with the TSRs, where the maximum power coefficient of 0.49 occur at 2.5 TSR with a 15° pitch angle. A higher pitch angles between 40° to 45° are effective at low TSRs, on the other hand lower angles between 10° to 30° is more suitable for higher TSR. The research mentioned that variable blade pitch angle can significantly enhance the performance of H-type Darrius VAWTs. The paper mentioned different optimum pitch angle values for different TSRs; this presents the need of active variable blade pitch angle regulation which can change the pitch angle based on the TSRs or rotational speed.

Miliket et al. [41] developed a low-cost model to evaluate the performance of H-type Darrius VAWTs. The paper highlights the rotor power optimization using variable blade pitch angle. A DMST model was used to calculate the power output and to select the optimum pitch angle at different TSRs. 2D unsteady computational fluid dynamics (CFD) was utilized to describe the flow of the rotor. The result of power coefficient for the DMST model was (0.464) compared to the CFD simulation results (0.4537). The results for zero pitch angle only were validated with the wind tunnel experiment found in the literature. The study found that an improvement of 37.2% was obtained using variable pitch blade regulation. The improvement on the power is matching to the previous numbers in the literature; however, to select the optimum pitch angle values for different TSRs there will be an essential need to apply experimental testing to validate the results. On similar case, Manfrida and Talluri [42] studied the optimization of H-type VAWTs using dynamic blade pitch adjustment to enhance the performance. The DMST was used, and the results validated with a commercial wind turbine for the zero pitch angle values only. The study also mentioned that in order to apply dynamic pitch angle there is a high need to have fast response actuators to be able to apply the change of the pitch angle at the time required. In fact, there is an essential need for the system to be tested experimentally with actuators to ensure the power enhancement as well as the structure stability of the rotor.

4. MATHEMATICAL MODELLING OF BLADE PITCH ANGLE REGULATION

Mathematical modeling is the process of creating mathematical representation of an actual scenario. For Darrieus H-type VAWT mathematical modeling normally used to predict the power output using different models such as SST (Single Streamtube Model) or DMST (Double Multiple Streamtube Model). Dai et al. [43] developed a mathematical model to calculate the power output of H-type Darrieus VAWT, the results were validated using CFD simulation. The mathematical model was built based on the Blade Element Theory (BEM). The author mentioned that the power calculation using the developed mathematical model needs to be revised. This occurs as the BEM only considers the forces on the blade, and it neglects the effect of the blade wake in the downstream. Similar approach was taken by Han et al. [44], but on helical blade H-type Darrieus VAWT, the results found could a good match between the mathematical model and the experimental test. Kumar et al. [45] discussed the use of different aerodynamic models used in mathematical modeling of H-type VAWT; where the author mentioned that a reliable mathematical model is essential to optimize different design parameters. The developed mathematical model used DMST as it is the most suitable option among other aerodynamic models and validated using wind tunnel experiment. The paper claims that DMST will be less accurate when applied to a small model of H-type Darrieus VAWT. Biadgo et al. [46] highlighted the progress made in the aerodynamic model particularly in streamtube model. The paper used DMST model and compared it to CFD simulation, the results found by DMST were a bit higher than the simulated results which is expected. For low TSR the results show a negative torque which shows the wind turbine inability to self-start as the author mentioned. Aytai et al. [47] optimized the DMST by including the effect of base section in the wake, where the new approach requires to rescale the wake velocities to ensure mass continuity. The study used 30 streamtubes for both convectional and new DMST, which represents a typical convergence plot. This new approach improves the accuracy of DMST at high and moderate axial induction factors for a heavy loaded wind turbine (high TSR).

The process of mathematical modeling is not only limited for fixed blade Darrieus H-type VAWT; researchers employ mathematical modeling with the help of aerodynamic models such as SST or DMST to calculate the power output of H-type VAWT that equipped with variable blade pitch angle regulation. Kushwaha et al. [48] used the DMST model to enhance the power output of variable pitch H-type Darrieus rotor for relatively high TSR in range between 4 to 5.5. The AOA was increased manually for each TSR. The study found that more accurate results will be found at high TSR; conversely Islam et al. [49] stated that the DMST model validity normally reduced at high TSR. Increasing the results manually could result in better performance within the rotor, however these changes are not always mechanically feasible and at some point, it might create high vibration rate as mentioned by Zhao et al. [21]. Also, the paper did not precisely point out how effective this approach is with low TSR. Other research paper by Chougule and Nielsen [19] proposed the VP technique to improve the VAWT H-type Darrieus self-start ability and the overall performance. A certain value of VP was applied to the mathematical model in each run of the simulation system (Using MSC software tool). The mathematical model was built based on the DMST. The study targets the TSR between 0.5 to 2.5, and it's been found that a 12% increment on the overall performance is achieved at 5 degrees pitch angle. Although 12% enhancement show the effect of the VP, the mechanical technique used to adjust the blades of the turbine was not mentioned. As Zouzou et al. [34] claimed that sinusoidal pitch angle regulation technique which will vary the value of pitch angle at each azimuthal point will help to have more energy balance between the upstream and downstream; where this will have a positive effect on the performance.

Zhang et al. [50] proposed an individual blade pitch angle control by applying different values of pitch angle for each blade only in the upstream region; where in the downstream the fixed pitch control was applied with no change on the pitch angle. The power output was calculated using mathematical modelling based on the DMST model. The paper proved that individual active blade pitch control improves the aerodynamic performance (lift force) of the H-type Darrieus VAWT by almost the double comparing to the fixed pitch. Also, the torque and the power coefficient have been greatly increased. Such a system will improve the performance in the upstream part only, however in the downstream part of the rotor these changes might not be the optimum. As extracting more energy in the upstream part will lead to less wind passing to the downstream, which might affect negatively on the performance, and this could increase the vibration in the WT. The performance of the downstream part of the rotor was not considered by this study. A similar approach was taken by Zhao et al. [21], the mathematical model based on DMST was used to calculate the power output of a novel proposed technique for the variable pitch angle blade regulation. The new technique could improve the power coefficient by 18.9% at 5 TSR.

Hernandez et al. [51] utilized the mathematical modelling based on the DMST to determine the torque curve against the angle of attack for different azimuthal positions in the upstream and downstream halves of the rotor. The DMST simulated results show that torque could be improved with a selection of the appropriate AOA, where this give an indication on the best pitch angle should be selected for the whole 360 degrees of the rotor azimuth. Setting a fixed pitch angle could increase the torque generated almost by four times; however, this achievement is only in theory. In order to apply such a method experimentally it will require a lot of design work. Also, this approach was mentioned by other authors and it shows a smaller improvement about 10% [20].

Shah et al. [52] compared 1KW FP and VP H-type Darrieus VAWT, numerical and experimental results. The aim of the study is to maximize the power output and the torque of the VAWT. The mathematical modelling was performed using BEM in particular SST; the model was mainly applied to help in the selection of the wind turbine design parameters. Thus, from one side the mathematical model will help to select the optimum values of the design parameters such as aspect ratio, solidity, dimension of the turbine, and swept area. And from the other side CFD simulation will be used to calculate the power output of the rotor for FP and VP VAWT. The comparison results present that 43.17% increment in the power output was obtained using VP blade regulation in comparison with the FP blade regulation. The power increment occurs due to the variable blade pitch adjustment need to be validated using experimental testing as well. The study validated only the zero pitch angle results using experimentation; and the variable pitch results were validated with the CFD model. The big enhancement on the performance could not be accurate as the SST model is not considering the wake of the blade. A blade pitch adjustment could result in creating more wake generated by the blade, which can lead to considerable reduction in the rotor rotational speed leading to less power generated.

Mathematical modeling was also used by researchers to determine the power output of H-type Darrieus VAWT which is equipped with variable blade pitch angle. Komass [53] developed a mathematical model using SST, the aim of the research was mainly to calculate the power output for the rotor with and without the variable pitch angle. MATLAB SIMULINK was used to simulate the mathematical model developed. The study aims to find the best pitch angle that could deliver the highest torque. Two different ways were utilized to reach this aim, the first is to calculate the best angle by selecting the angle of attack which has the highest lift/drag coefficient. The second was by trying different values of pitch angle until the system selects the angle that will allow for the highest torque. The study presents that 10% improvement on overall torque occurs while using the pitch angle regulation. Moreover, it recommends the second way of finding the pitch angle as this will allow for increment in the maximum torque about 18.4%, and the lift/drag coefficient way will provide an increment in the maximum torque about 14%. Though the study shows an improvement on the torque generated, more validation needs to be applied to ensure the improvement in the real-life situation. Also, the value suggested by the MATLAB SIMULINK was applied as a fixed pitch angle all over the azimuth line, which was less recommended by other authors [7, 21]. Using a variable value of blade pitch angle will result in more energy balance between the upstream and the downstream regions. In addition to that, the SST model is less accurate when compared to the DMST; as the SST is not considering the change in the wind speed between the upwind and downwind side of the rotor. The improvements of using the blade pitch angle will only be applied for normal operational stage of the WT, and that will leave a mysterious question on what will be the effect on the self-start and overspeed stage.

5. CURRENT CHALLENGES AND FUTURE PERSPECTIVES

H-type Darrieus VAWTs turbines typically exhibit lower starting torque compared to other VAWT designs, due several factors such as aerodynamic imbalance, stall behavior and inefficient blade Design. In comparison, to the HAWT usually VAWT are less efficient. However, in urban environment the vertical axis wind turbine is proven to be a suitable choice due to its low cut in wind speed and its ability to rotate in any direction of wind. A blade pitch angle regulation is suggested by many researchers as mentioned previously in this paper; blade adjustment shows a considerable amount of improvement for the performance of H-type Darrius VAWT in general. However, fixed pitch technique has a negative effect on the performance of the turbine if the speed of the rotor was not in the ideal range as the blade will be adjusted for optimum stage of operation only. Also, this technique will mainly maximize the torque generated in the upstream, where most of the torque is generated, while the downstream part is mostly neglected. On the other side, fixed pitch angle mechanism is less complicated in term of design and fabrication when compared to the variable pitch angle mechanism.

Variable pitch angle adjustment will provide more balance in the torque generated in the upstream and downstream halves of the rotor. Moreover, better performance is obtained using variable pitch angle regulation in comparison with fixed pitch angle regulation. However, the design of the variable pitch angle will be more complicated. Also, the system will require a mechanical mechanism in order to move the blade according to the azimuth position. The extra mechanics required for that type of pitch angle usually will need additional torque to move the blade which can affect negatively on the rotor performance especially at the self-start. Other solutions provided by Abdalrahman et al. [12], suggest the use of DC motor was to control the blade pitch angle. Nonetheless, adding an extra control system to the H-type VAWT, might increase the cost of manufacturing for these types of turbines.

The technique used in blade pitch angle regulation can vary based on the available operating conditions. Techniques might have different target such as enhancement of overall performance, self-start, or it could be creating more balance to avoid vibrations. Understanding and measuring the operational parameters such as rotational speed, wind speed, rotor design, and airfoil design will allow for better technique modelling. Researchers like Zhao et al. [21] and Abdalrahman et al. [12] used mathematical modelling to predict the effectiveness of the new variable blade pitch angle regulation technique used to improve the performance of H-type Darrius VAWTs. Using a mathematical modeling for predicting the performance of H-type Darrius VAWTs is effective and low cost when compared with CFD especially for low TSRs turbines. However, once the rotor reaches high speed the accuracy of the momentum models which are normally utilized will be reduced. On the other side, mathematical models can be used to select the optimum pitch angle that will enhance the performance of a wind turbine based on the available operational conditions. Also, mathematical modelling can be utilized for testing different blade pitch angle regulation techniques; however, the accuracy of the results will mainly depend on the model accuracy and limitations.

Selecting the optimum blade pitch angle can positively affect the H-type Darrius VAWT in term of self-starting ability and the overall performance. Future research in this filed might be conducted to overcome the previously stated challenges. The research might include real-time adjustment mechanism through advance control algorithms using DMST model, use of machine learning, and enhanced sensor technology for accurate data collection and validation through experimental testing. The development of such adaptive control mechanisms could optimize blade pitch angle regulation process based on real-time wind conditions and hence enhance the overall wind turbine performance.

6. CONCLUSION

Performance improvement of the VAWT remains one of the most challenges in the turbine industry. The wind in urban environments normally experiences a rapid and unexpected wind fluctuation, this made a major drawback in the power output consistency. The studies in this this review mentioned that using a variable blade pitch angle regulation increase the H-type Darrieus vertical axis wind turbine performance. The blade pitch angle regulation is divided to two major categories fixed and variable blade pitch regulation. The fixed angle pitching targets a constant change in the pitch angle; this technique provides limited improvement to the rotor performance. As it focusses mainly on certain TSR vale or certain operational stage. On the other side, variable blade pitch angle adjustment aims to create balance between the energy extraction in the upstream and the downstream halves of the wind turbine by applying various pitching techniques. At variable blade pitching, the value of change in the pitch angle usually varies based on the azimuth position. This technique shows better turbine self-start and overall performance; however, improvement was also limited to a specific TSR as the system is passively adjusted. Other studies stated in this review present the use of intelligent blade pitching system, which is a dynamic system that can change the pitch angle based on the given parameters. The results achieved significant enhancement on the overall turbine performance at different TSRs; however, the blade pitch angle selection process was made using CFD simulation which is a time-consuming process that cannot be used for active system during operation. This paper suggests the use of active blade pitch angle technique which can use DMST model to calculate the optimum blade pitch angle value based on the operational parameters for instance the wind and the rotational speed. Such a system will improve the turbine overall performance in all operational stages (start, normal and overspeed). Limited number of studies found in the recent published work in the literature used DMST as a model to select the optimum pitch angle for performance enhancement of H-type Darrius VAWT.

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NOMENCLATURE

AOA	Angle of Attack
BEM	Blade Element Momentum
CFD	Computational Fluid Dynamics
DMST	Double Multiple Streamtube
FP	Fixed Pitch
HAWT	Horizontal Axis Wind Turbine
SST	Single Streamtube
TSR	Tip Speed Ratio
VP	Variable Pitch
VAWT	Vertical Axis Wind Turbine
WT	Wind Turbine

List of Symbols

C_P	Coefficient of power
V_W	Wind velocity

Greek Symbols

β	Pitch angle
Θ	Azimuth angle
ω	Angular velocity