A Review On The Types Of Vertical Axis Wind Turbines And The Methods Of Their Performance Study

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***Abstract*— Wind energy became one of the most significant renewable energy resources in the last decades. A wind turbine is used to harvest kinetic energy from wind and convert it into electrical energy. The electricity generated by the wind turbine is transmitted directly into transmission lines as in the case of wind farms or stored in batteries as in the case of individual turbines. Wind turbines are classified according to their rotating axes into Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). Various Experimental, numerical and analytical methods have been introduced in scientific researches to study the performance of wind turbines. This review paper introduces the different types of wind turbines and their methods of performance calculation.**

Keywords— Renewable energy; wind power; Wind turbine designs; vertical axis wind turbines; numerical calculation of VAWTs

I. INTRODUCTION

The need to substitute fossil fuel resources by clean and renewable energy resources started in the late 20th century. The emerged interest in renewable energy resources has significantly affected Co2 emission rates. Several renewable energy resources including biomass, solar, geothermal, hydroelectric, and wind have been used. Through these available renewable resources, the world has massive possibility of wind energy that can be used for electricity generation [1]. A Wind turbine is a device used to transform kinetic energy of wind into a more beneficial electrical energy form. Inclusive research efforts were performed in order to improve the technology of electricity generation from wind turbines.

A. Different Types and Configurations of Wind Turbines

In general, wind turbine design can be classified into two categories, Horizontal Axis Wind Turbines (HAWTs) and Vertical Axis Wind Turbines (VAWTs) [2]. HAWTs have become extremely common in the current market, they work by transforming the kinetic energy of the wind into electric energy by rotating a shaft with an axis parallel to the wind direction. Regarding VAWTs, the rotor axis has a vertical position, and they deal with the wind from any direction so that they do not need a yaw mechanism [1], [2].The template is used to format your paper and style the text. All margins, column widths, line spaces, and text fonts are prescribed; please do not alter them. You may note peculiarities. For example, the head margin in this template measures proportionately more than is customary. This measurement and others are deliberate, using specifications that anticipate your paper as one part of the entire proceedings, and not as an independent document. Please do not revise any of the current designations.

The performance of an individual HAWT is higher compared to an individual VAWT having the same size; however, current studies show that VAWTs can be installed in closer vicinities compared to HAWTs. Hence, the power density (power per unit area) for VAWT farms is higher than that of HAWT farms by three to ten times. It is also worthy to mention that VAWTs are appropriate for electricity generation in the conditions where HAWTs are incapable to perform efficiently such as urban areas with lower wind speed and high turbulent wind flows [1], [3]. Other studies show that the VAWTs have more merits than the HAWTs as VAWTs work with a smaller tip speed ratio, which causes lower noise levels. That is why VAWTs have protruded again as a possibility unit to the need, after being stockpiled by wind turbine companies in the late 1980s because of success of HAWTs[4]. Moreover, from the economic point of view, the VAWTs are more favorable because they do not need high towers, which reduce the cost of production and maintenance. Another major advantage is the easiness of assembly and accessibility, where the turbine generator is mounted at lower levels near the terrain. VAWTs is classified into two main types; Savonius rotor (drag type) and Darrieus rotor (lift type) shown in figure (1-a) and figure (1-b), respectively. The main contribution of the power generated by Savonius-type VAWTs is the drag force applied on the blades. Their main advantage is the simple construction; however, they generate low power, and they are often used as a wind-speed measuring device [1], [2],[5]. The Darrieus-type VAWT was invented by a French engineer George Jeans Mary Darrieus in 1931, It contains a specific number of vertical blades having an airfoil shaped cross-section rotating around a vertical axis and depends mainly on lift force for torque and power generation [5].

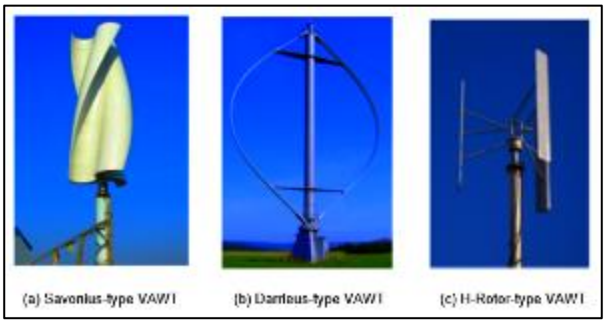

Fig. (1) Modern VAWT types[6]

In order to solve the problem of low starting Sun et al. introduced a numerical simulation for a hybrid turbine making benefit of both the drag-type and the lift-type VAWTs as shown in figure (2). Numerical results indicate that the power coefficient of this lift drag hybrid vertical axis wind turbines declines when the distance between its drag type blades and the center of rotation of the turbine rotor increases, whereas its starting torque can be significantly improved. Studies also show that unlike the lift-type vertical axis wind turbines, this lift drag hybrid-type vertical axis wind turbines could be able to solve the problem of low start-up torque [7].

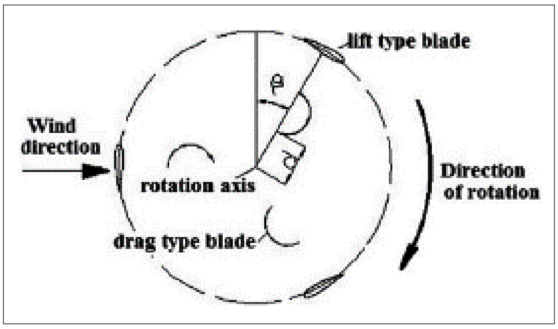

Fig. (2) The Physical Model for a Hybrid VAWT [7]

Belmili et al. have designed, analyzed, and manufactured Savonius-rotor vertical axis wind turbine of the hybrid kind. The results proved that the system was effective and could be manufactured [8]. Hosseini et al. suggested a hybrid VAWT modeled as a combined Savonius-type Bach turbine and a 3-bladed H-rotor Darrieus wind turbine. The system was analyzed utilizing computational fluid dynamics. The study showed that the hybrid turbine shown in figure (3) has a self-starting feature and power coefficient enhancement up to 40% [9].

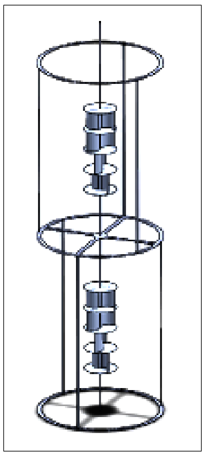

Fig. (3) Hybrid VAWT [9]

This review paper introduces comprehensively study on Darrieus-type straight-bladed VAWT (H-rotor type) shown in figure (1-C). This configuration is classified into two main types: fixed pitch and variable pitch Darrieus turbines [5], [10]. The fixed pitches VAWTs have problems in self-starting, low power coefficient, and the small band of the tip speed ratio. The variable pitch controlled VAWTs overcome the hurdles of fixed pitch VAWTs improving the aerodynamic characteristics and enhancing the power extracted by sustaining optimum pitch angle allover azimuth positions of the blades. Experimental and numerical analysis show that the pitch amplitude ranging between ± 20o to ± 25o enhanced the efficiency of a VAW. The change of the pitch angle of VAWT throughout its operation is achieved by either active pitch control or passive pitch control methods [3], [11], [12], [13].

B. Method for Variable Pitch Control

1) Active variable pitch VAWT:

In active pitch VAWTs the blade angle is controlled by the definition of a cyclic blade motion as a function of azimuth position proportional to the wind direction and the utilization of mechanical systems such as cams or gears to prescribe this predefined pitch motion [10], [11], [13], [14] as shown in figure (4).

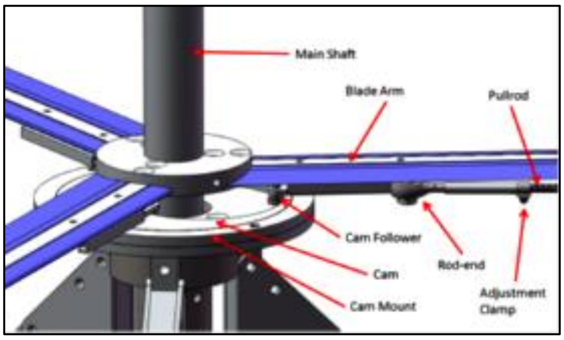

Fig. (4) Cam Mechanism of Variable Pitch VAWTs [14]

Studies to improve the performance of VAWTs are achieved by optimizing the pitch angle versus the azimuth using a four-link mechanism shown in figure (5), the cyclic change for the orientation of the turbine blades achieved a power increase of 35% in addition to self-starting capability enhancement.

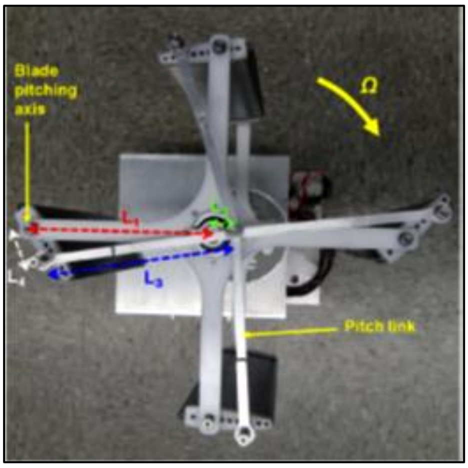

Fig. (5) Four link-mechanism for VAWT Sinusoidal Pitch Control [3]

For variable pitch VAWT, the optimum tip speed ratio (where the maximum power coefficient is achieved) is shifted to a lower value compared to the fixed pitch configuration, decreasing blade centrifugal loading and permitting more cost-effective designs as shown in figure (6) [14], [15], [16].

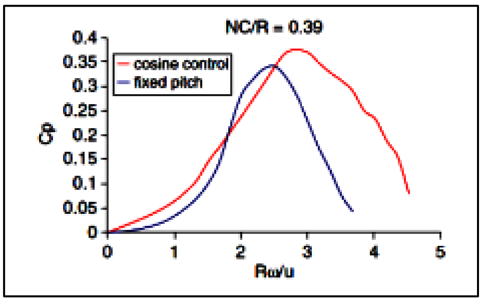

Fig. (6) The power coefficient for Cyclic controlled Variable Pitch VAWT compared to fixed Pitch VAWT at different tip speed ratios [16]

The variation of the amplitude of sinusoidal blade pitch results in a wider range of tip speeds operation with maximum performance as shown in figure (7) [16], [17].

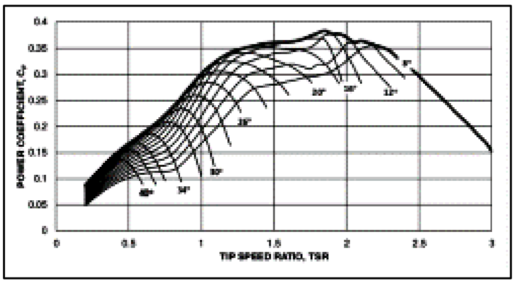

Fig. (7) Blade Pitch at different Tip speed ratios [17]

Active pitch control is subdivided into collective and individual pitch control. The Collective pitch control adjusts the pitch of all rotor blades to the same angle at the same time [16]. Liang et al. have improved the performance of straight blade VAWT to enhance the self-starting ability by utilization collective and individual pitch control method Compared to experimental data and numerical results [18]. Zhang et al. presented a mathematical and dynamic model for VAWT individual active blade pitch control, the maximum power coefficient is promoted about twice as great as that of the fixed-pitch VAWT that in addition to improvement of starting torque as shown in figure (8) [19].

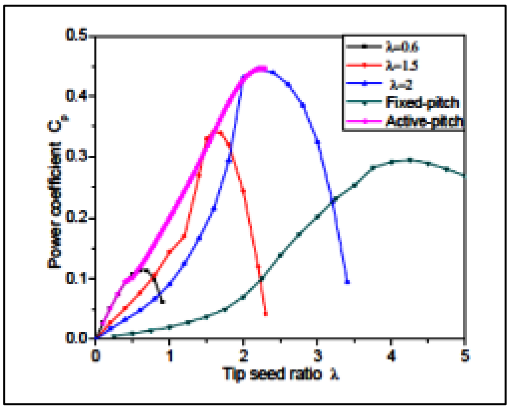

Fig. (8) Power Coefficients Curve by using Individual Active Pitch Control [19]

2) Passive variable pitch VAWT:

The active systems are complicated in their structure because of the need of cam or mechanism system for variable pitch control. In addition, some gauges and control systems are required in order to sense wind speed with respect to rotor speed. In the passive variable pitch systems, the blade is free to pitch about a vertical axis positioned close to its leading edge under the action of wind forces [13], [20].

Pawsey has evaluated a number of passive variable-pitch blade mechanisms in order to improve performance of straight-bladed VAWT shown in figure (9). The common elements between the different passive variable-pitch designs are represented in free blade rotational (Pitch), changes in the blade pitch angle to reduce the angle of attack by the action of aerodynamic forces, the existence of a certain regulating moment about the pitch axis that produces pitch response having an appropriate phase and amplitude for improved blade performance.

Figure 9 (a) shows the general designs consisting of the blade as the rotating mass, a torsion spring for moment regulation and damping. Figure 9 (b) shows employing the inertial load to play the role of the torsion spring. In figure 9 (c) the radial centrifugal load is taken through a bearing. However, in figure 9 (d) the radial centrifugal load be taken through a torsion spring. Figure 9 (e) the radial constraint on the axis of the blade is removed, while retaining the tangential constraint. Figure 9 (f),(g) shows the idea of designing a mounting piece made from an appropriate elastomer and shaped to produce the desired stiffening effect. By constraining the piece within a radial slot, tangential loads are transmitted to the rotor without affecting the blade pitch [20].

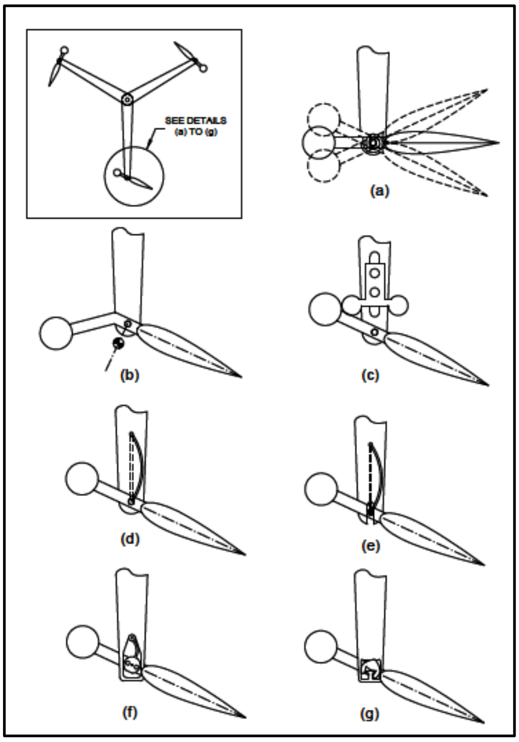

Fig. (9) Passive Variable-Pitch Design Concepts [20]

Hantoro et al. introduced a passive variable-pitch blade mechanisms to develop the performance of a three straight-bladed vertical axis ocean current turbines [21]. The pitch of the blade is restricted by stoppers to keep it in a margin of ±10o as shown in figure (10).

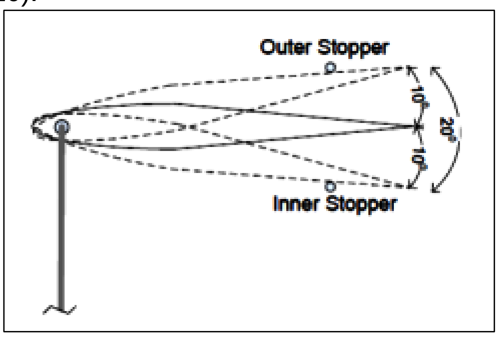

Fig. (10) Fixed pitch and passive pitch position at foil [21]

Kirke et al. measured the performance of a vertical axis wind turbine with passive variable pitch control shown in figure (11) compared to fixed pitch [22]. He utilized both double multiple stream tube analytical model and a two dimensional unsteady Reynolds-averaged Navier–Stokes computational fluid dynamics simulation. The self-start torque was enhanced by three times compared to fixed pitch.

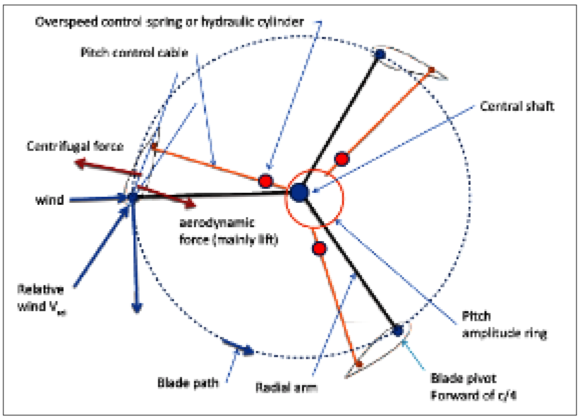

Fig. (11) Schematic representation of pitch control mechanism [22]

C. Different Methods to Calculate VAWTs Performance:

The performance of VAWts is determined according to literature survey, general researches, and best-supported models by one of the following five models: Momentum model, Vortex model, Cascade model, Computational Fluid dynamics model, and Experimental measurements [5].

1) *Momentum Model (Stream Tube Model):*

The entire turbine is assumed to be enclosed within a stream tube. Different momentum models: Blade Element, Momentum or Blade Element Momentum models are considered, all of them are based on the calculation of change in velocity across turbine. Newton’s 2nd law is used to equate the stream wise aerodynamic forces acting on the turbine blades with the rate of change of in linear momentum. Stream tube approaches include single, multiple and double multiple stream tube models shown in figure 12.

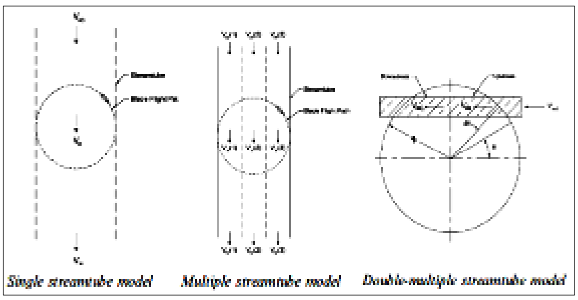

Fig. (12) Schemes of Momentum stream tube models [5]

Islam et al. studied some aerodynamic models to improve performance prediction and design analysis of straight-bladed Darrieus type VAWT. The double-multiple stream tube model, free-vortex model and the cascade model are evaluated. The results showed that each of these three models has its advantages and disadvantages. The vortex is found to be the most accurate models compared to experimental data, however the model needs high computational resources and it experiences convergence problem. The double-multiple stream tube model is found to be inadequate for high tip speed ratios and high-solidity VAWT. Furthermore the Cascade model has smooth convergence even in high tip speed ratios and high solidity VAWT with quite feasible accuracy [5]. Jakubowski et al. presented a kinematic computation model for of an H-type VAWT with a controlled pitch angle based on the Blade Element Momentum theory for improving the power output. The results showed an increase in the turbine efficiency by 22.6% [10]. Soraghan et al. calculated the rotor performance and aerodynamic blade forces for a straight bladed VAWT with variable pitch. The model used the double multiple stream tube method and compared the results with experimental data. The results showed that the model produces accurate predictions for induction factors, blade forces and power production for VAWTs with variable pitch angle as shown in figure 13 [23].

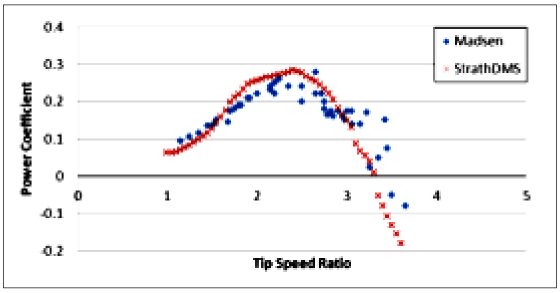

Fig. (13) Power coefficient against tip speed ratio [23]

Brahimi et al. developed a model capable of predicting the aerodynamic loads for Darrieus rotors in a turbulent wind based on double-multiple stream tube method. Results illustrated that the calculation aerodynamic loads have been enhanced by involving stochastic wind into the aerodynamic model [24]. Kozak et al. presented results from a simulation of a baseline VAWT computed utilizing Star-CCM+, a commercial finite volume method (FVM) compares to data obtained from a multiple-stream tube model. The study has Focused on dynamic stall characteristics and wake production which have the almost greater effect on turbine performance. A model was developed to produce blade wake interaction joint at higher tip-speed ratios and improved the accuracy of obtained from blade element momentum model as shown in figure 14 [25].

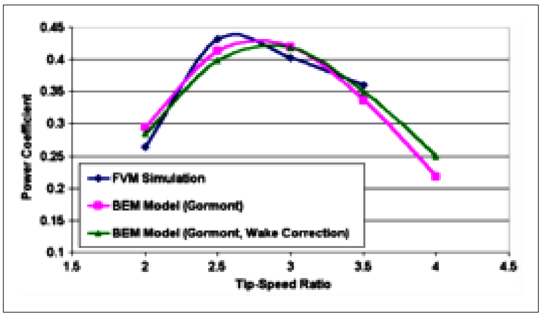

Fig. (14) Cp for FVM, BEM, and BEM Model with Blade Wake Correction [25]

Vallverdu developed a double multiple stream tube models code based on blade element method VAWT using MATLAB program. The results showed the easiness and fast convergence of the blade-element momentum theory [6]. Sharma et al. used QBlade software to review the performance of VAWT which utilizing Blade Element Momentum (BEM) method based on double multiple stream tube for the simulation and design of VAWTs. The results showed the inclusive performance of QBlade as a tool for wind turbine design [26].

2) Vortex model:

The Vortex models are based on potential flow models, which calculate the velocity in the flow field around and the influence of vortices in the wake of the blades. The turbine blades are represented a bound vortex filament called substitution vortex filament or a lifting line whose strengths are specified from airfoil coefficients and calculated relative flow velocity and angle of attack as shown in figure 15 [5].

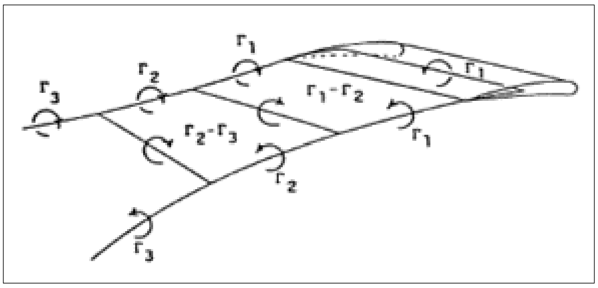

Fig. (15) Vortex system for a single blade element [5]

Marten et al used nonlinear lifting line free vortex wake code integrated into the wind turbine simulation software QBlade [27]. The study compared the lifting line theory (LLT) results with U-RANS and Double Multiple Stream tube (DMS) simulation results showing reasonable results for steady state performance as shown in figure 16. However, the code was lacking a dynamic stall model.

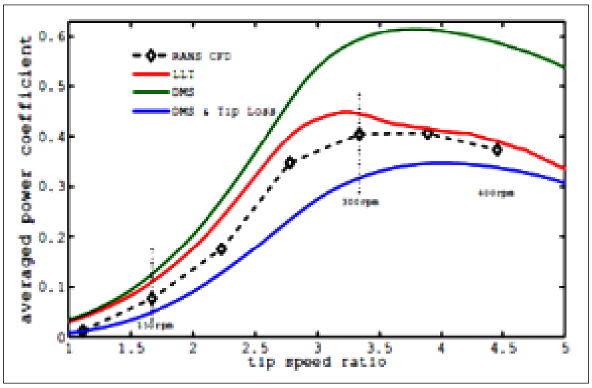

Fig. (16) Cp at Different TSR with One Bladed Configuration [27]

McIntosh et al. examined the performance of a swept bladed VAWT utilizing a Lagrangian based two dimensional free vortex model [28]. The model showed good agreement compared to 2-bladed VAWT wind tunnel experimental data carried out at West Virginia University (WVU) as shown in figure 16.

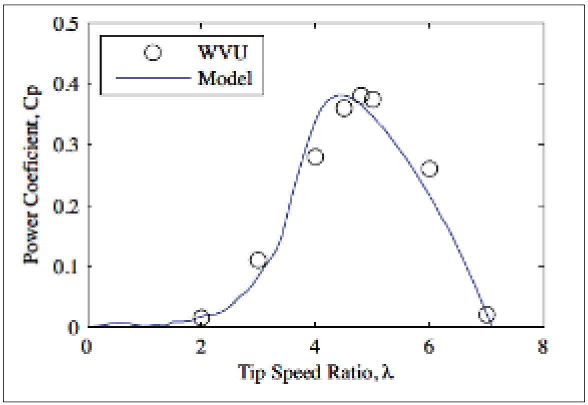

Fig. (16) Steady Validation for 2D Vortex Model [28]

Balduzzi et al perfromed a 3D numerical computational fluid dynamic (CFD) simulation on a single blade Darrieus VAWT and compared the results with those obtained by an open source code based on a Lifting Line free vortex wake the LLFVW Model [29]. The comparison illustrated high agreement between the results. Ponta et al. combined the free vortex model with a finite element analysis (FEVDTM) to calculate aerodynamic characteristics of the flow around the blades. The combined model does not use airfoil coefficient data in order to avoid quasi-steady problems. The model includes pitching circulation effect, and the apparent mass effects are included in the momentum equation. However, it does not include stall phenomena [30]. The results shown in Figure 17 confirm the advantages of FEVDTM compared against the earlier models in predicting instantaneous blade forces as well as wake constitution.

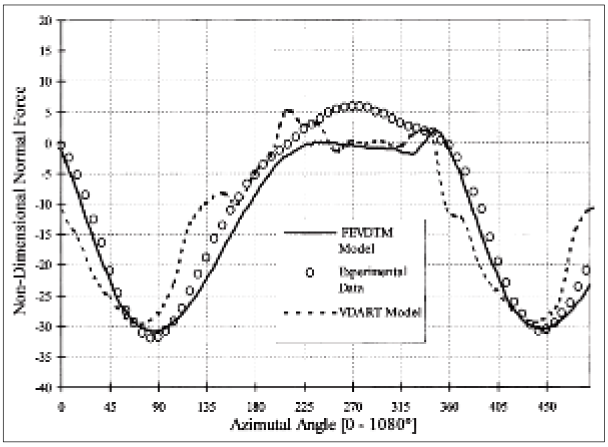

Fig. (17) Non-Dimensional Normal Force against Azimutal Angle, Comparison of Experimental Data, V–DART And FEVDTM Predictions [30]

Strickland et al. calculated an aerodynamic prediction for two and three-dimensional Darrieus VAWT using a vortex lattice of analysis [31]. Analytical and experimental were in good agreement with regard to the normal force (Fn) is quite. The vortex models are capable with some degree of confidence in predicting the dominant aerodynamic force component related to the structural integrity of the rotor. A comparison between rotor power coefficients predicted by the simple momentum model (strip theory) and the vortex model presented by Strickland for a one-bladed two-dimensional rotor is shown in Figure 18 on the left, the right figure shows the power coefficients for a three-dimensional rotor predicted by the two models and compared to experimental measurements.

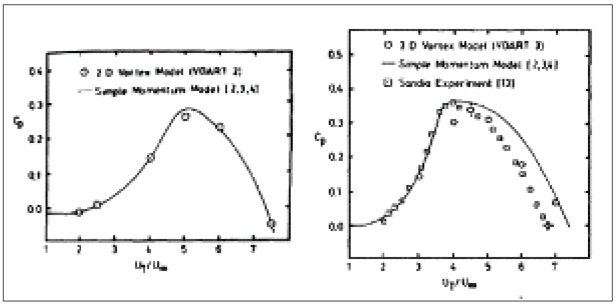

Fig. (18) 2D and 3D Rotor Performance [31]

Yang et al. calculated the effect of tip vortex on the downstream region of VAWT using (CFD) simulations. Wind velocity curves calculated by CFD simulations are consistent with Laser Doppler Velocity (LDV) measurements [32].

3) *Cascade model:*

The periodical equidistant arrangement of blades or vanes of turbo-machines are called a cascade [5]. The Cascade model proposed by Hirsch et al [33] for the analysis of VAWTs, in this model the blade airfoils of a turbine are assumed to be positioned in a plane surface with the blade interspace equal to the turbine circumferential distance divided by the number of blades as shown in figure 19.

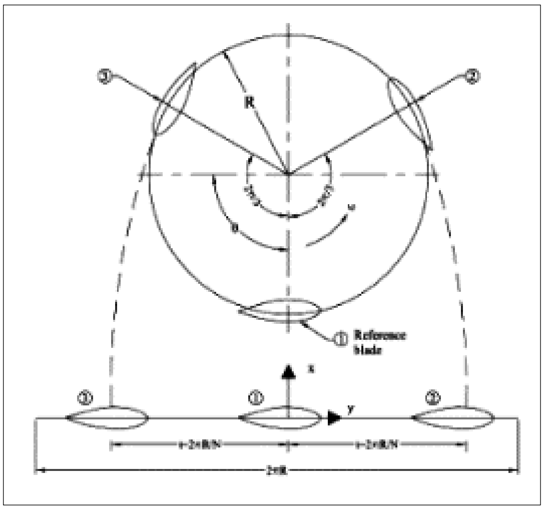

Fig. (19) Cascade Configuration [5]

Islam et al. used the cascade theory to design a 1 kW straight-bladed vertical-axis Darrieus wind turbine [34]. The model included dynamic stall and flow curvature effects, this lead to higher Cp values as shown in figure 20.

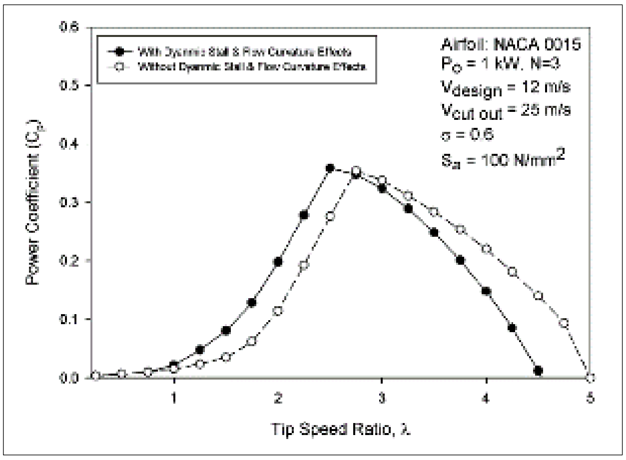

Fig. (20) Power Coefficient at Different λ [34]

Dhar performed a theoretical investigation of aerodynamic performance and design for a Darrieus VAWT using multiple stream tube theory and cascade theory and applying thin airfoil theory for choosing lift and drag coefficients of a cambered blade profile [35].

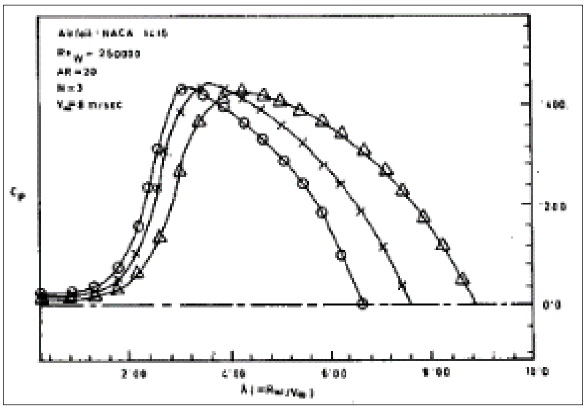

Fig. (21) Cp Vs. λ at Various Solidities (Calculated by Cascade Theory) [34]

The calculated results showed that the momentum theory could not give reasonable performance prediction at higher tip speed ratios and at higher solidities by. However, cascade theory gave reasonable correlation with experimental results at Various Solidities as shown in figure 21.

4) Computational Fluid Dynamics (CFD) (Numerical Method):

Computational fluid dynamics (CFD) is one of the most common methods for solve numerically Navier-Stokes equations for viscous flow or Euler equations for inviscid flow. The method is characterized by the availability of all the information required for the calculated fluid field and it can simulate a full-scale model [36]. Alaimo et al. simulated 2D-3D dimensions for a straight blade VAWT and a helical blade using Ansys fluent to solve the Reynolds averaged Navier–Stokes (RANS) equations [37]. He found that the helical blades have an average torque coefficient increased by equal to 8.75% compared to the straight bladed turbine. Comparing three-dimensional with two-dimensional results showed that the generation of the tip vortices reduces the turbine efficiency, this effect is less relevant in the helical VAWT as shown in figure 22.

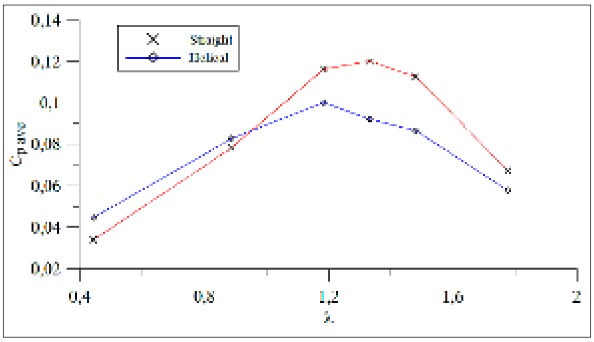

Fig. (22) Cp Vs. λ for Straight and Helical Three-Dimensional Turbines [37]

Xisto et al. studied the effect of a high-solidity on the performance of variable pitch VAWT low tip speed ratios using a numerical approach based on finite-volume discretization of two dimensional domain [38]. The unsteady Reynolds-averaged Navier–Stokes (URANS) equations are solved using multiple sliding mesh for simulating the turbine blade rotation and pitching, the results are validated against experimental data as shown in figure 23.

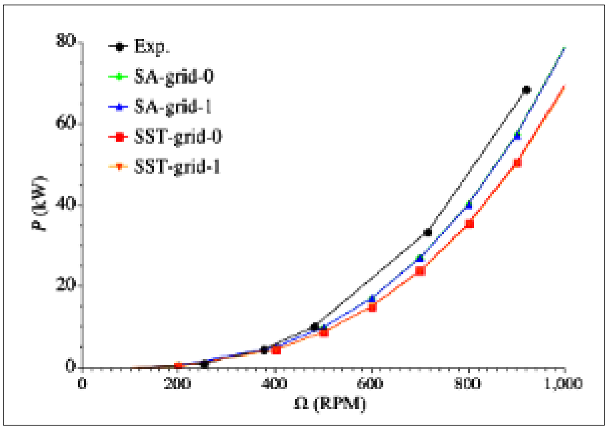

Fig. (23) Variation of Power with Rotational Speed [38]

Bianchini et al. analyze the wake characteristics of small-size straight-blade Darrieus VAWT using a two-dimensional U-RANS computational model [39]. A good agreement is shown in the comparisons between simulations and experiments. A Structure analyses is performed for the turbine wake in addition to correlation for the main macro-structures of the flow to the local aerodynamic features of the airfoils in cycloidal motion as shown in figure 24.

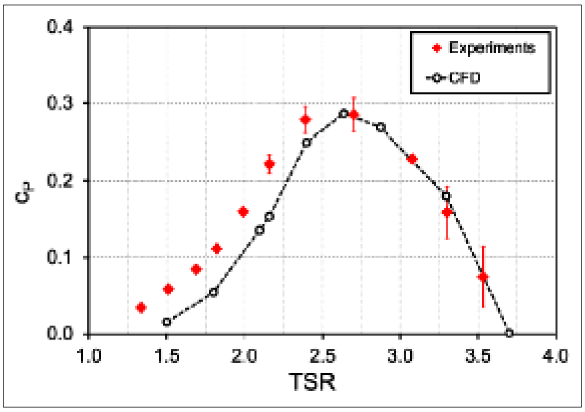

Fig. (23) Cp Vs. TSR: Experiments and Simulations [39]

Rezaeiha et al. performed simulations of VAWTs at different tip speed ratios and solidities and evaluated the results of moment and power coefficients against wind tunnel measurements as shown in figure 24. The unsteady Reynolds-averaged Navier-Stokes (URANS) are solved and a 4-equation transition SST turbulence model is used [40]

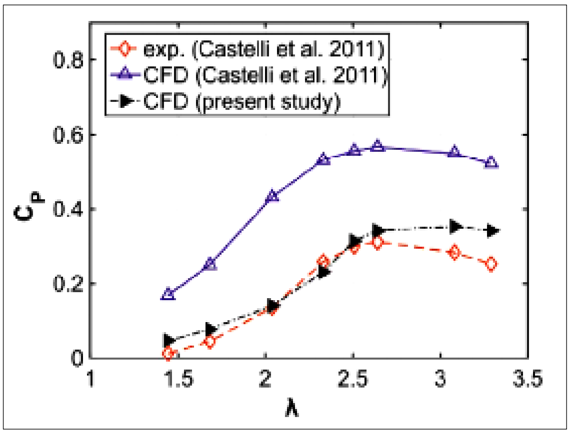

Fig. (24) Cp Vs. λ Experimental and Numerical Results [40]

5) *Experimental method:*

Experimental analysis is one of the conventional methods used to evaluate VAWTs performance. There are mainly two types of experimental testing: wind tunnel testing, and Particle Image Velocimetry testing (PIV) [41]. The wind tunnel is a passage through which air flows at specified velocities against wind turbines under experimental testing as shown in figure 25.

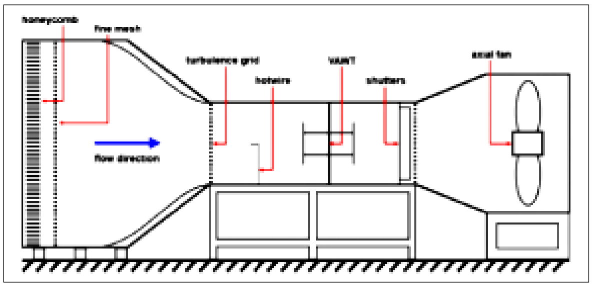

Fig. (25) Wind tunnel Testing [41]

During this process, the torque and power are measured in order to obtain the operating characteristics of the VAWT at different tip speed ratios as shown in figure 26

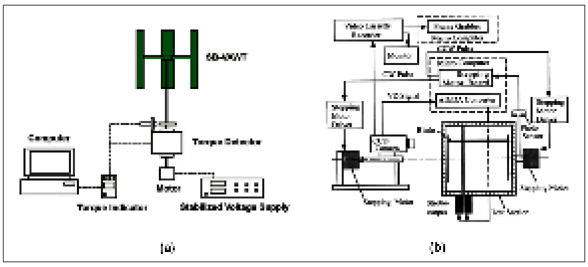

Fig. (26) Torque measurement in wind tunnel and PIV [41]

Sunny et al. achieved an aerodynamic modeling, manufacturing, and performance evaluation of VAWT, a prototype model is tested in subsonic wind tunnel to analyze the power coefficient of the rotor under different wind speeds ranging from 4.38 m/s to 22.38 m/s as shown in figure 27. The test results show reliable and efficient performance [42]

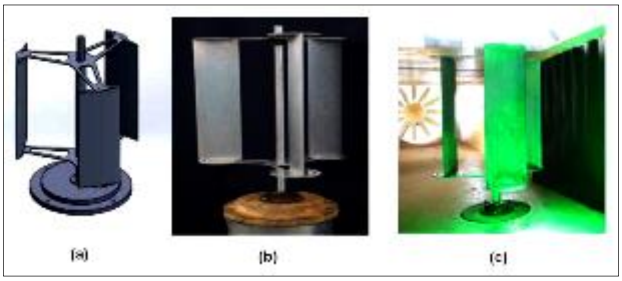

Fig. (27) (a) modeling, (b) Prototype Fabrication and (c) Wind tunnel testing of VAWT [42]

Rahman et al. fabricated and tested physical models of NACA 7510, NACA 5510, and semicircular VAWTs in a subsonic wind tunnel at three different speeds as shown in figure 27 [43]. Dynamic torques measured experimentally showed that the model with NACA 7510 blade has the best result among all models at high tip speed ratio as shown in figure 28.

Fig. (28) Experimental setup of the Wind Tunnel [43]

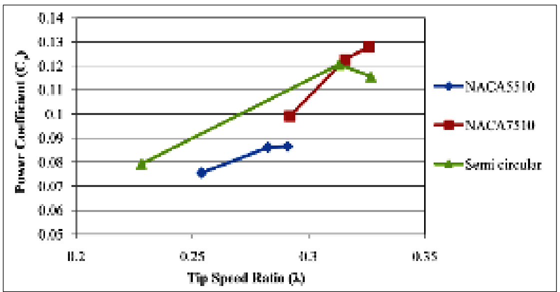

Fig. (28) Experimental Power Coefficient vs. tip speed ratio for Three Different Three Bladed Models [43]

The Particle Image Velocimetry (PIV) is the measurement of the flow of a fluid by tracking particles introduced into the flow. Fujisawa et al. showed that the dynamic stall results of flow separation on the pressure surface of the blade followed by generation of vortices on the suction surface using PIV measurement as shown in figure 29 [44].

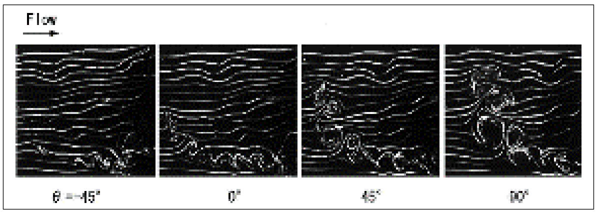

Fig. (29) Flow Visualization of Dynamic Stall of Darrieus Wind Turbine in a Stationary Frame of Reference [44]

Tescione et al. observed wake flow using stereoscopic PIV in an open-jet wind tunnel for a VAWT, and showed shed vortices around the blade as shown in figure 30 [45].

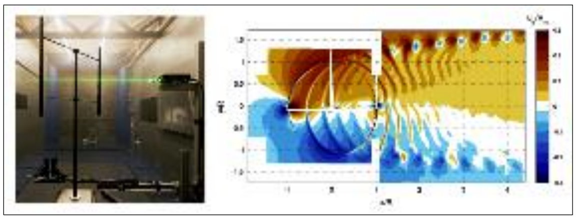

Fig. (30) Flow Analysis by PIV and Velocity Contours [45]

Rolin et al. immersed a small scale VAWT in a boundary layer in a wind tunnel and used stereo PIV is to quantify the 3D characteristics of the wake as shown in figure 31 [46].

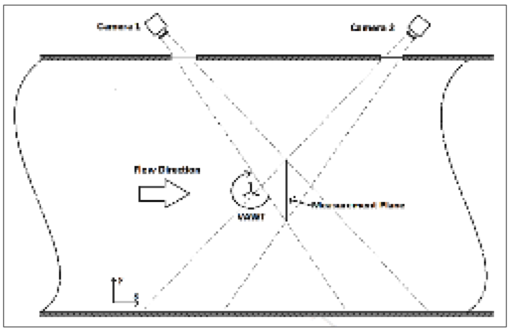

Fig. (31) Top-Down View of Stereo-PIV Arrangement [46]

The measurements showed that the wake is strongest behind the sector of the rotor that turns into the wind, and comparing the velocity deficit to the position of the rotor indicates that the far wake is deflected towards the negative-y direction, and recovers more momentum above the rotor mid span than below as shown in figure 32.

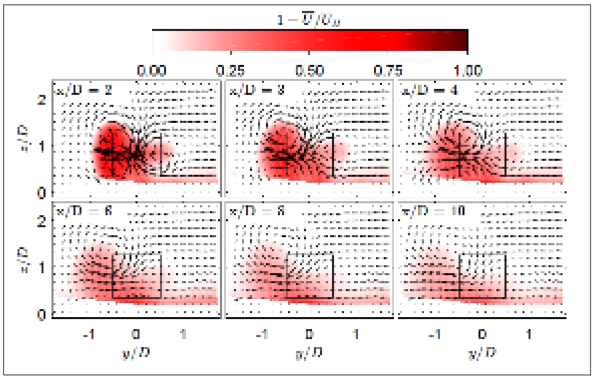

Fig. (32) Contours of Stream Wise Velocity Deficit at Different Downstream Positions Normalized by Incoming Wind speed Midspan [46]

II. SUMMARY

This paper introduces a survey on VAWTs, introducing their different type and configurations. Although HAWTs are extremely common in the market and the performance of an individual HAWT is higher compared to an individual VAWT having the same size, current studies show that VAWTs can be installed in closer vicinities compared to HAWTs in order to increase the power density for a wind farm by three to ten times.

The paper discussed active pitch control for VAWTs introducing cyclic blade motion as a function of azimuth position proportional to the wind direction and the utilization of mechanical systems such as cams or gears to prescribe this predefined pitch motion to achieve a power increase of 35% in addition to self-starting capability enhancement. Also the passive variable pitch systems are introduced where the blade is free to pitch about a vertical axis positioned close to its leading edge under the action of wind forces reducing the angle of attack and improving the blade performance.

Different methods to calculate VAWTs Performance are introduced which are analytical (Momentum model, Vortex model, Cascade model), numerical (computational fluid dynamics) and experimental methods. Each methods introduced was shown to have its own strength and weakness and it suitability for different purposes.

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