Review of Effect of Specific Geometrical Parameters on the Performance of Small Straight Blade –Vertical Axis Wind turbine (SB-VAWTs) of Darrieus-type

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Abstract- The aim of the study was to examine the effect of specific geometrical parameters on the performance of small Straight Blade –Vertical Axis Wind Turbine (SB-VAWT) of Darrieus-type. The study processes involve selecting fixed and different geometrical parameters for turbine and predicting performance of the turbine based on the selected parameters. Double-multiple stream-tube model was selected to examine the performance of the prototypes of VAWT. The performances of prototypes of VAWT with a specific anticipated maximum power were investigated under the different design parameters i.e., rotor aspect ratio, rotor solidity, and blade pitch angles. The results show that an increase in aspect ratio enhances the value of Tip Speed Ratio (TSR) at which the maximum power coefficient is achieved. In addition, an increase in rotor aspect ratio leads to greater maximum power coefficient. Add to that, an increase in solidity enhances the value of TSR at which the maximum power coefficient is achieved. Furthermore, a negative blade pitch angle leads to greater maximum power coefficients compared to a zero or positive blade pitch angle. Based on the findings, the study provides the recommendations of using the findings in relation to rotor aspect ratio, solidity, and blade pitch angle to guide the design of VAWT to harvest energy from wind.

Keywords Review, SB-VAWTs, Darrieus-type, Geometrical Parameters.

1. Study background

Attention has been paid to relatively low intensity energy sources that can be used in small electrical applications such as lighting roads in rural areas, in order to overcome the lacking of illumination that represent one of the main reason of accident on highways. One way to take advantages of relatively low intensity energy sources e.g., wind energy from moving vehicles and low wind speed in particular areas is to install small wind turbine. Installing small wind turbine to generate electricity is particularly important in rural areas in which centralized electricity generation is not available. However, there is a need to study the geometrical characteristics of the turbine for optimum performance.

Mainly, there are two types of wind turbines, horizontal and vertical axis wind turbines. Horizontal Axis Wind Turbine (HAWT) is a turbine that has the central rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind, while Vertical Axis Wind Turbine (VAWT) is a type of wind turbine in which the central rotor shaft is set crossways to the wind while the main components are positioned at the base of the turbine. The selection of the wind turbine depends of the requirements of its use. There are several characteristics of wind turbine that determine its uses. For instance, HWAT has the advantages of collecting great amount of energy through pitching the blades, the lift force in this type of turbine contribute in collecting large amount of energy, and it is popular source of energy [1].

However, when there are high wind velocities and unstable wind stream. VAWTs would be the appropriate solution [2].In addition, VAWTs have a unique advantage that they do not need yawing device [2]. VAWT accepts wind from any direction. Furthermore, the existence of the main turbine components e.g., generator at the base of the turbine would simplify the turbine's design, construction, and maintenance cost, accordingly lessen the turbine overall cost [3].VAWT can function still when the wind is very unsteady, such characteristic make VAWT appropriate to be used in urban and small-scale applications [4]. In addition, VAWT is easier to install and produce less noise [3]. Add to the previously mentioned advantegs of VAWT, VAWT has low tip speed ratio [5].

The use of small wind turbines (SWTs) have the potintial of providing alternative power for devices taht operate on electrcity [6].The standard SB-VAWT is one of the most common types of SB-VAWT of Darrieus-type. As its structure shows it is easy to manufacture. Small VAWTs, which operate at low wind speed and produce limited amount of energy, is becoming more popular for several reasons that include its physical proximity, the independence between the performance of the VAWT and the direction of the wind, and the physical proximity of most of VAWT's components and the ground, where that make VAWT easy to maintain and manage [7].

Based on the previous discussion, the current study examined the effect of specific geometrical parameters on the performance of small Straight Blade –Vertical Axis Wind Turbine (SB-VAWT) of Darrieus-type. The following sections discus some significant geometrical parameters of SB-VAWTs of Darrieus-type, operational parameters of SB-VAWTs of Darrieus-type, the analysis methods of performance of the SB-VAWT, and brief overview of previous studies related to the topic.

1.1. Geometrical parameters of SB-VAWTs of Darrieus-type

1.1.1. Number of blades

There is more than one option for selecting the number of blades of SB-VAWTs of Darrieus-type. SB-VAWTs of Darrieus-type can have 2, 3 and 4 blades. The optimal number of blades for SB-VAWTs is suggested to be three based on the previous study [8]. The number of blades would directly influence the solidity of the turbine that represent a relation between the blade area and the turbine swept area and it has great affect the performance of SB- VAWT. In addition, the number of blade affects revolution speed compared to the wind velocity and produced power, three blades represent an optimal choice to acquire self starting VAWT and have stable power coefficient, mainly under low wind speed condition [9]. Furthermore, SB-VAWTs with three blades run smother than SB-VAWTs with two blades since the energy fluctuations are lower in each revolution, where the repeated disparity in torque and resultant force acting on the rotor are much smaller [8]. In addition, SB-VAWTs with three blades would have better self-starting ability compared with two-bladed SB-VAWTs [10].

1.1.2. Rotor aspect ratio

Another important geometrical characteristic of VAWT is turbine's rotor aspect ratio (AR) as the ratio between blade height and rotor diameter [8] as in eq. 1.

$$AR = H/D \tag{1}$$

Selecting appropriate value for rotor aspect ratio depends on the purpose of the turbine and the effect of the rotor aspect ratio on the power efficacy of the turbine. However, the recommended rotor aspect ratio for SB-VAWT is between 0.5 and 2 [8].

1.1.3. Rotor solidity

An important design geometrical characteristic of VAWT is its rotor solidity that can be defined as the ratio of area of the blades to swept area [11]. The solidity (σ) of VAWT rotor is dimensionless parameter that is a function of on the number of blades (N_b), airfoil chord length (c) and rotor radius (R) as in eq. 2.

$$\sigma = \frac{N_b c}{R} \tag{2}$$

Research studies adopted the definition of solidity that replaces the rotor diameter with the rotor radius as shown in the previous equation [8]. The solidity has integral effect on the performance and the self starting ability of the SB-VAWT. For instance Reference [12] reported that self starting turbine can be achieved when using high rotor solidity (e.g., $\sigma \geq 0.4$) of a turbine.

1.1.4. Blade pitch angle

Blade pitch angle is one of the basic parameters of the SB-VAWT. It represents the angle between the chord line and the direction of the blade speed (tip speed) that represent the result of the product of Ω the angular velocity of the rotor and its radius (RΩ) of the blade. The chord line for the airfoil can be defined as the straight line drawn from the leading to trailing edges of the airfoil. The blade pitch angle of the VAWT can be zero, negative or positive, see Fig. 1.

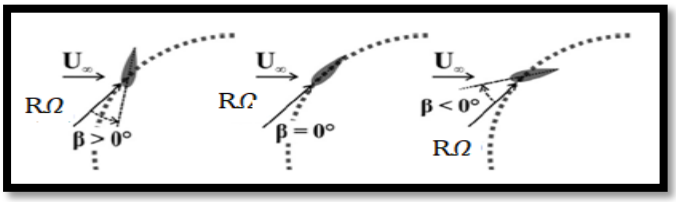

Fig. 1: The pitch angle for a VAWT blade [13, p.133].

Blade pitch angle has effect on power coefficient of the wind turbine through directly affecting the air flow around the blade that would affect pressure distribution on the blade surface and that might change in the lift-to-drag ratio [13].

For instance, Reference [13] found that a small negative pitch angle by two degrees would increases turbine power coefficient for 6.6% compared to 0 degree pitch angle. Furthermore, the blade pitch angle has an effect on the self starting ability of the VAWT. For instance, it has been found that fixed pitch angle of -2.5 degrees would make the VAWT having faster self-starting time [14].

1.2. Operational parameter of SB-VAWTs of Darrieus-type

1.2.1. Power coefficient

Wind turbine rotor performance is usually characterized by its power coefficient, CP that represents the ratio between rotor power and the power available in the wind as in equations 3 and 4. The maximum theoretically possible power coefficient for wind turbines is called Betz limit and it is equal to 59.3%. The Betz limit was discussed in details in the following sections. The range of power coefficient for SB-VAWT is 0.15 to 0.5, depending on the geometrical parameter of the turbine [8].

$$C_p = \frac{\text{Rotor power}}{\text{Avaliable power in the wind}} \quad (3)$$

$$C_p = \frac{\text{Rotor power}}{(1/2)\rho A U^3} \quad (4)$$

$$\text{Where } A = H * D \quad (5)$$

Where:

A is the projected frontal area of turbine in m2.

H is the height of turbine in meter.

D is the rotor diameter in meter.

U is the air stream velocity (Wind speed) in m/s.

1.2.2. Tip Speed Ratio (TSR)

The tip-speed ratio λ can be defined as the ratio between the tangential speed of the tip of a blade and the actual speed of the wind λ=ΩR/U, where Ω is the angular velocity (in radians/sec) of the wind turbine rotor, R is the radius of the wind rotor, and U is the free stream velocity (Wind speed). The power coefficient C_P can generally be expressed as a function of the tip speed ratio as a measure of the performance of the total rotor. The CP – λ curve can be used to specify the rotor power for any grouping of wind and rotor speed, where this curve offer data on the highest power coefficient and optimum TSR [11].

1.2.3. Reynolds number

Another important parameter that has effect on the aerodynamic forces on VAWTs is Reynolds number. Reynolds number is directly related to the geometrical characteristic of SB-VAWTs of Darrieus-type i.e., chord length. Reynolds number is a non-dimensional parameter that used to define the characteristics of fluid flow conditions. It assess of the viscous performance of air, where it is the ratio between inertial force and viscous force as in eq. 6 [11], where

$$R_e = \frac{Uc}{v} = \frac{\rho Uc}{\mu} = \frac{Inertial\ force}{Viscous\ force} \quad (6)$$

Where

Re is the Reynolds number, which is unit-less.

ρ is the fluid density in kilograms-per-cubic-meter typical value of ρ for air is ((1.225 kg/m^3)

U is the fluid velocity in meters-per-second (wind speed)(m/s)

c is length in meters (chord length) (m)

μ is the viscosity of the fluid in Pascal-seconds (Pa.s)

v kinematic viscosity, equal to (μ/ρ) typical value of v for air is (1.562* 10^{-5} m^2/s) at temperature of 25 C

As it can be seen in the equation of the Reynolds number, the parameter that can be designed for VAWT is the chord length c. Reynolds number has affect on the produced power of the VAWT and its self starting ability, where increasing the Reynolds number increased the power coefficient of a given VAWT and increase its self starting ability [15].

In the context, it is important to distinguish between the free stream Reynolds number and the local Reynolds number. In the free stream Reynolds number, the used fluid velocity is the free stream velocity, while in the blade Reynolds number, the used fluid velocity is the relative velocity of the air to the blade. The relative velocity of the air can be estimated as in eq.7, λ is tip-speed ratio, a is the induction factor that accounts for the deceleration in the wind as it passes through the turbine rotor, and ϕ represent the azimuth angle.

$$\frac{U_{rel}}{U} = \{\lambda + (1-a)sin(\phi)\} \quad (7)$$

The relative velocity can be estimated through the use of TSR value (λ) at which a turbine reaches peak performance (λ_C_{pmax}) in addition the blade Reynolds number can be estimated from free stream Reynolds number as in eq. 8 [4, 16]. For the small VAWT that used to generate electricity from low wind speed, the Re is typically in the low range.

$$Re_{Local} = \lambda_{Cpmax} * Re_{Free\ Stream} \quad (8)$$

1.3. Analysis methods of performance of the SB-VAWT

The analysis of the aerodynamics performance of the SB-VAWT can be made through different methods [8, 11, 17, 18]. Generally, in order to analyze the aerodynamics performance of wind turbine there are two methods: the experimental method and theoretical method. Mainly, the experimental methods involve using wind tunnel, visualization and field experiment [17]. On the other side the theoretical methods include aerodynamic computational models and numerical simulation. Figure 2 shows the main theoretical methods for analyzing SB-VAWT.

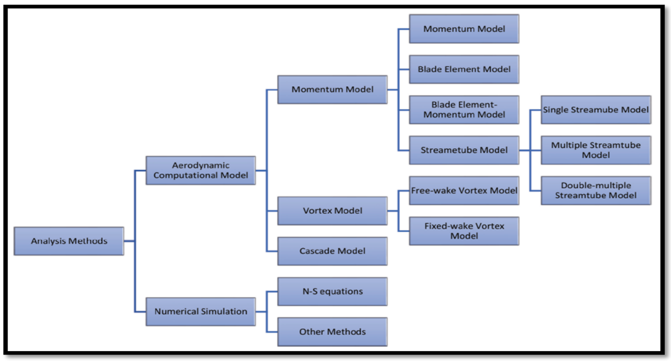

Fig. 2: Main theoretical methods for analyzing SB-VAWT [17, p.5].

Based on the previous literature, among the proposed theoretical methods for analysis of aerodynamics performance of the wind turbine, the momentum models are the most common models for analysis. For analyzing the aerodynamics performance of SB-VAWT, stream-tube models, which are based on Blade Element Momentum (BEM) model, is the most commonly used method [17]. BEM model is based on the Momentum Model (MM) and Blade Element (BE) Model. Several research studies, that examine the aerodynamics performance of SB-VAWT, showed that the experimental data quantitatively agrees with the theoretical data that result from using different stream-tube models, where this particularly true for small SB-VAWT [19].

The stream-tube models include the Single Stream-tube (SST) model, the Multiple Stream-tube (MST) model, and the Double Multiple Stream-tube (DMST) model [20]. These three models were commonly found in the literature that examines the design and performance estimation of small SB-VAWTs of Darrieus type [20, 21].

2. Previous studies

There are several research studies that focused on the use of SB-VAWT to generate electricity [4, 8, 18, 22, 23, 24] These studies examined different aspects of the VAWT. Some of these studies focused on the geometrical characteristic of SB-VAWT. For instance, Reference [8] examined the optimum range of the design parameters for prototype construction of small SB-VAWT with 3 blades. The researcher used DMST analytical approach to determine the optimum range of the design parameters. They found that the rotor solidity factor should be between 0.2 and 0.6; and rotor aspect ratio should be between 0.5 and 2. In addition, they provide a range of values for the maximum power coefficient for the first design iteration to be between 0.15 and 0.45. Furthermore, Reference [4] conducted a study that aimed to examine the aspect ratio affects the turbine's performance through the use of MSTM. They used SB-VAWT with two blades with NACA 0018 airfoil. They showed that as aspect ratio decreases, the Reynolds number increases which enhance wind turbine performance. Decreasing the aspect ratio means increasing the turbine radius and that cause decrease in the solidity for the same chord length. That cause to increase the value of the optimum tip speed ratio.

In another study that provide different findings; Reference [18] experimentally examined the effects of set of small SB-VAWT's parameters that include solidity, blade profile, pitch angle, surface roughness, and aspect ratio on the turbine self-starting and performance. The researchers used asymmetric and symmetric profiles. The results show that symmetric profiles namely NACA0021 has better self-starting capability compared to asymmetric profiles that failed to self-start. In addition, the results show that turbine with high solidity ($\sigma \geq 0.81$) has started faster than turbine with low solidity due to the increased flow blockage. But the researchers recommended balancing between stronger self-starting capability and larger peak power output when selecting turbine's solidity. Furthermore, the results shows that at low and small and negative blade pitch ($\beta \geq -2°$) would result in more torque generated.

In a study, with different findings regarding the effect of foil shape on the self-starting ability of the rotor, Reference [22] conducted a study that focused on some small VAWT's design parameters that include blade number (2 and 3) and airfoil camber line (comparing symmetrical and asymmetrical profiles). A Blade Element-Momentum (BE-M) model was used to predict the performances of the different designs. The findings indicate that using three-bladed wind turbines would result in improved performance, and lower variation of both torque and thrust compared to two-bladed wind turbines. In addition, the results shows that the asymmetrical profile would help in overcoming the start-up problems of VAWT, but asymmetrical profile showed limitation in its performance at low and medium wind speeds.

In another study, reference [23] examined the performance of VAWT through the use of numerical simulation based on different solidity values that were 1, .5 and .3. They found that the reduction of solidity would increase the range of the operating tip-speed ratio λ; however the reduction of solidity would reduce the maximum power coefficient. Furthermore, reference [24] conducted a study that developed a simulation model, via Ansys/Fluent, to investigate the effects of pitch angle and blade camber on flow characteristics and performance of small-size SB-VAWT. They used different airfoil shape with different campers that include (NACA0012, NACA2412 and NACA4412) and they used pitch angle that increases from β = -10 to β = 10. They found that the larger the camber of the blade, the better was the self-starting ability of the VAWT. In addition, they found that initial acceleration was inversely related to the pitch angle. In another study, reference [25] conducted a study that aimed to investigate the effects of pitch angle on performance of VAWT. They used Computational Fluid Dynamics (CFD) for the analysis. The results show that out-offset blade pitch angles showed better results than in-offset blade pitch angles.

The previous studies show various results regarding the effect of the design parameters on the performance and operational factors of the VAWT. The previous studies have focused on the effect of one or two design parameters on the performance SB-VAWT using different analysis method. The current study took advantages from the previous in setting the ranges of the design parameters. The current study add to the previous studies through examining the effect all the examined design parameters in the previous studies on the performance SB-VAWT using only one analysis method that is MSTM.

3. Methodology

In the current study, theoretical design procedures were followed. The design process involved several interrelated steps. First of all, the desired ranges of rated power output of the turbine were determined. Then, based on the examined literature specific design parameters e.g., structure for a turbine, number of blades, rated wind speed, and rated power coefficient were determined. In addition, a range of design parameters e.g., rotor aspect ratio, rotor solidity, and blade pitch angle were determined. After that the performance of the turbine was predicted theoretically based on the pre-determined turbine design parameters based on specific method of analyzing of the performance of the designed turbine.

The following sections provide a description of the selected design parameters and the justification for the selection. In addition, the chapter provides description of theoretical modeling of the examined turbines based on the design and calculate parameters as well as the theoretical method of analyzing of the performance of the designed turbine.

3.1. Design parameters of the VAWT and selected performance analyzing method

The first step of the design procedure was selecting the rated desired power. The anticipated maximum power is 30 watt. Such rates of power would meet the required power for small rural application e.g., street light. After that, geometrical design parameters were selected for the turbine's prototypes. Two geometrical design parameters i.e., number of blades and rotor type/blade inclination were fixed in the analysis of the performance of the turbine's prototypes. The selected topology was the Straight Blade (SB)-VAWT of Darrieus-type with three blades. The selection of SB-VAWT with three blades was based on the major advantage (SB)-VAWT of Darrieus-type of being easy to manufacture.

Different values of three geometrical design parameters i.e, solidity factor, rotor aspect ratio, and blade pitch angle, were used in the analysis of the performance of the turbine's prototypes. Table 1 shows a description of different design parameters of the turbine's prototypes.

In the current design, asymmetrical airfoil was selected i.e., NACA4415 that has a camper. The airfoil represents cross-sectional shape of blade that affects the operational variables of the turbine and its aerodynamics behavior. The reason behind selecting this airfoil that Asymmetrical profiles has better performance than symmetric profile for VAWT's performance

Another design parameter for the VAWT is the rotor solidity of the wind turbine; the selected values of solidity factor of a turbine's rotor were between low to high solidity, i.e., 0.2, 0.4, 0.6, 0.8 and 1. The reason behind selecting these values is to compare the effect of varying solidity factor on the VAWT's performance. Selecting these values was based on the previous discussion of the optimal solidity factor and the recommendation of similar studies that examined the optimal solidity factor wind turbine as in [8, 12, 22].

An additional design parameter for the VAWT is the turbine rotor aspect ratio. The selected values of turbine rotor aspect ratio were between low to high aspect ratio, i.e., 0.5, 1, 1.5, 2, and 3. The reason behind selecting these values is to compare the effect of varying rotor aspect ratio on the VAWT's performance. Selecting this range of values was based on the recommendation of similar studies that examined the optimal rotor aspect ratio as in [8] and the application requirement.

Different values of blade pitch angles were selected to compare their effect on the VAWT's performance. The selected values of blade pitch angle were positive negative, and zero i.e., -2,-1, 0, 1, and 2. Selecting the range if these values was based on the previous discussion of the optimal blade pitch angle and the recommendations of similar studies that examined the blade pitch angle for wind turbine that would enhance power performance and start up capability of the turbine [13, 14].

Regarding the estimated values of the operational parameters, estimations have been made for the maximum power coefficient and rated wind speed based on recommendations of similar research studies. The estimation of maximum power coefficient Cp was 0.4 based on the previous discussion of the estimation of maximum power coefficient and the recommendation of similar studies that examined the performance of small SB-VAWT (e.g., [8]). The estimation of rated wind velocity was 6 m/s. The selected parameters i.e., rated power, maximum power coefficient, rated wind speed as well as the different values of solidity factor and rotor aspect ratios were used to calculate the height, width, and chord length of turbine's prototypes and the Reynolds numbers.

3.2. Analyzing method for the performance of the SB-VAWT

In order to analyze the aerodynamics and the performance of the SB-VAWT's, DMST model was employed. The selection of the DMST was based on the findings of previous studies that showed that the DMST was successful in predicting the performance of VAWT [21].The software that was used to run the analysis was QBlade v0.96.3. QBlade is prominent tool to examine the performance of wind turbine [26, 27, 28]. QBlade is commonly used to analyze the performance of VAWT using DMST model. The analysis involve plotting performance curves for the selected airfoil i.e., NACA4415 based on different solidity factor, rotor aspect ratio and blade pitch angle. The next two sections present theoretical modelling of the prototypes of the VAWT. Based on the calculated parameters of the small SB-VAWT of Darrieus-type, simulation software for wind turbine blade design was used to simulate the energy efficiency of the VAWT.

Table 1. A description of different design parameters of turbine's prototypes.

	Design Parameters	Value	Justification	References
1.	Number of blades	3	• VAWTs with three blades tend to run more smoothly. • Three blades would help the VAWT for self starting. • VAWTs with three blades would have stable power coefficient under low wind speed condition.	[8,9, 22]
2.	Rotor type/ Blade inclination	Straight	• VAWT with straight blades is easy to manufacture. • VAWT with straight blades has simple structure. • VAWT with straight blades is cheap to manufacture.	[8, 22].
3.	Airfoil (airfoil camber line)	NACA4415	• Asymmetrical profiles have better performance n than symmetric profile for on the VAWT's performance.	[22, 29]
4.	Solidity factor (NB .C/R)	In the first case: 0.2, 0.4, 06, and 08. In the second case: 0.2, 0.4, 06, 08 and 1.	• To compare the effect of varying solidity factor on the VAWT's performance.	[8]
5.	Rotor aspect ratio (H/D)	0.5, 1, 1.5, 2, and 3.	• To compare the effect of varying rotor aspect ratio on the VAWT's performance. •	[8]
6.	Blade pitch angle.	-2,-1, 0, 1, and 2.	• To compare the effect of varying blade pitch angle on the VAWT's performance.	[13, 15]

3.3. Theoretical modelling for the VAWT with of anticipated maximum power of 30 watt

For the case of power of 30 watt was selected based this selection and estimated maximum power coefficient of 0.4 the available power of the wind was calculated as 75 Watt. The area of the rotor was calculated as 0.57 m^2, based on the value of the estimated maximum power coefficient, the available power in the wind $P_{available}$, the initial estimation of rated wind velocity U_1, and the value of air density of 1.225 kg/m^3. Based on the calculated area of the rotor and five different cases with varying aspect ratio, the blade lengths and rotor diameters were calculated. After that, airfoil chord lengths were calculated based on the designed number of blades, five cases of varying rotor solidity, and selected value of rotor aspect ratio that was 1.5. After that, the free stream Reynolds numbers were calculated based kinematic air viscosity, the selected free stream velocity, and the five cases of varying rotor solidity. The free stream Reynolds numbers were calculated through the use of eq. 6. The range of free stream Reynolds numbers was between 9,600 and 50,000. The values free streams Reynolds number were used to calculate local Reynolds numbers through the use of equation 8. Based on several iterations of analysis using DMST model, the tip speed ratio for maximum power coefficients were found for each airfoil at four cases of varying rotor solidity. The results show that the range of the values of local Reynolds numbers was between 40,320 to 110,500 for NACA4415.Table 2 shows the calculated parameters of the small SB-VAWT of Darrieus-type.

Based on the calculated parameters of the small SB-VAWT of Darrieus-type, simulation software for wind turbine blade design was used to simulate the energy efficiency of the VAWT for the different cases as in the following chapter. Energy efficiency "expressed usually in terms of flow energy utilization factor and coefficient of power (C_P)" [30, p.1936]. The current study employed Q-Blade simulation software. Q-Blade employs (DMST) model for the simulation of VAWTs.

Table 2. The calculated parameters of the small SB-VAWT of Darrieus-type.

	Calculated Parameters	Based on the design values	Value	Used Equation
1.	Total power of the wind P_{tot}	• Rated power(P_{Rated}). • Estimated maximum power coefficient($C_{p(Max)}$).	$P_{avaliabler}$ =75 Watt	$P_{Tot} = \frac{P_{Rated}}{C_{p(Max)}}$............(3)
2.	The area of the rotor	• Estimated maximum power coefficient$C(_{p(Max)})$. • The total power in the wind (P_{Tot}), • The initial estimation of rated wind velocity(U_1), • Air density(ρ).	A=.057 m^2	$A = \frac{PWR_{Avaliableot}}{(1/2)\rho U^3}.C_p$…(4) Air density(ρ) =1.225 kg/m^3
3.	Blade length (H) and rotor diameter (D)	• The area of the rotor (A). • The Rotor aspect ratio (AR).	Case 1: H/D=0.5; H=0.53m; D=1.07 m Case 2: H/D=1; H=0.75; m; D=0.75m Case 3: H/D=1.5; H=0.92; m; D=0.61m Case 4: H/D=2; H=1.06; m; D=.53m Case 5: H/D=3; H=1.3; m; D=.43m	A=H*D...........(5) A=0.57 m^2 C=0.13
4.	Airfoil chord length (c)	• Number of blades (N_b). • Solidity factor (σ). • Rotor radius (R).	Case 1: $\sigma = 0.2$; c=0.025 Case 2: $\sigma = 0.4$; c=0.05 Case 3: $\sigma = 0.6$; c=0.08 Case 4: $\sigma = 0.8$; c=0.1 Case 5: $\sigma = 1$; c=0.13	$c = \frac{\sigma R}{N_b}$...............(2) (H/D)=1 R=.375
5.	Free stream Reynolds number ($Re_{\text{Free stream}}$)	• Kinematic viscosity of air (v). • The initial estimation of rated wind velocity(U_1). • Airfoil chord (c).	Case 1: $\sigma = 0.2$; c=0.025; $Re = 9{,}600$ Case 2: $\sigma = 0.4$; c=0.05; $Re = 19{,}206$ Case 3: $\sigma = 0.6$; c=0.08; $Re = 30{,}729$ Case 4: $\sigma = 0.8$; c=0.1; $Re = 38{,}412$ Case 5: $\sigma = 1$; c=0.13; $Re = 50{,}000$	$Re = \frac{Uc}{v}$...............(6) v = (1.562* 10^{-5} m^2/s) at temperature of 25 C
6.	Blade's Reynolds number(Re_{Blade}) for NACA4415	• Kinematic air • viscosity (m^2/s) • Relative velocity (U) • Airfoil chord (c)	Case 1: $\sigma = 0.2$; c=0.025; λ_c_{pmax}=4.20; $Re = 40320$ Case 2: $\sigma = 0.4$; c=0.05; λ_c_{pmax}=3.20; $Re = 61459$ Case 3: $\sigma = 0.6$; c=0.08; λ_c_{pmax}=2.61; $Re = 80{,}202$ Case 4: $\sigma = 0.8$; c=0.1; λ_c_{pmax}=2.41; $Re = 92{,}572$ Case 5: $\sigma = 1$; c=0.13; $\lambda_{cpmax} = 2.21$; $Re = 110500$	$Re = \frac{Uc}{v}\lambda_{cpmax}$.........(8)

4. Results and Discussion

The simulations of the energy efficiency of the VAWT for the small SB-VAWT of Darrieus-type based on different parameters were presented. The energy efficiencies of turbines were presented thorough the curves of coefficient of power (CP) and tip speed ratio (TSR) through the use of Q-Blade simulation software. Q-Blade employs (DMST) model for the simulation of VAWTs. In addition, the results of the experimental verification of the performance of the selected turbines were presented.

The analysis of the performance of the VAWT with anticipated maximum power of 30 watt involve checking the power performances of the proposed designs of small SB-VAWT of Darrieus-type with the NACA4415 airfoil through plotting the curves of power coefficients versus TSR at various values of aspect ratio, solidity factor, and blade pitch angle.

4.1. T VAWT's energy efficiency at varying rotor aspect ratios

The power performances of the proposed designs of small SB-VAWT of Darrieus-type with the NACA4415 airfoil was checked through finding the values of power coefficients at various values of aspect ratio. Figure 3 show that an increase in aspect ratio enhance the value of tip speed ratio at which the maximum power coefficient is achieved, as bigger the aspect ratio smaller the tip speed ratio. For NACA4415, the greater maximum power coefficient occurs at aspect ratio of 1.5 followed by the aspect ratio of 1. For NACA4415, an increase in rotor aspect ratio leads to greater maximum power coefficients, but that leads to fewer values of tip speed ratios in which the turbine would efficiently operate. For small SB-VAWT of Darrieus-type with NACA4415 airfoil, the value of maximum power coefficient increases by 90% when the aspect ratio increased from 0.5 to 3.

The findings related to the effect of aspect ratio on the performance of the SB-VAWT of Darrieus-type with the NACA4415 airfoil can be explained through the relation $\lambda = \Omega R/U$ that shows that the TSR is directly related to the radius of the rotor, and as we can see as the increase in the rotor aspect ratio cause a decrease in the rotor radius and that explain that the increase in aspect ratio enhance the value of TSR at which the maximum power coefficient is achieved.

The previous findings aligned with the finding of previous studies that show the optimum value for rotor aspect ratio was between 0.5 and 2 for the range of maximum power coefficient [8]. However, the findings did not align with the findings of other studies that showed that the value for rotor aspect ratio should be low e.g., 0.4 [4].

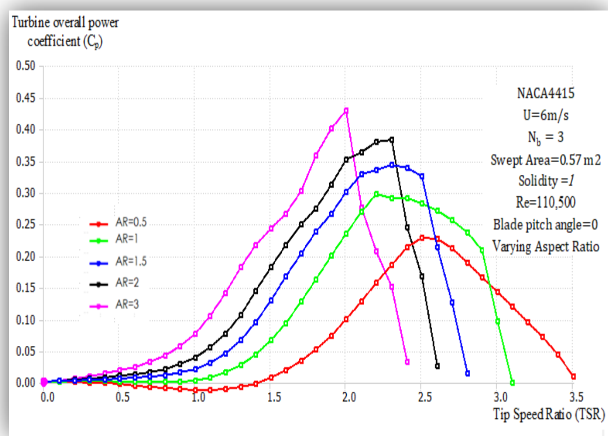

Fig. 3: Power coefficient versus TSR at different rotor aspect ratio at constant swept area for NACA4415 airfoil.

4.2. T VAWT's energy efficiency at varying rotor solidity factors

e The power performances of the proposed designs of small SB-VAWT of Darrieus-type with the NACA4415 airfoil was checked through finding the values of power coefficients at various values of solidity. it can be seen in figure 4that an increase in solidity enhance the value of tip speed ratio at which the maximum power coefficient is achieved, as bigger the solidity, smaller the tip speed ratio. The turbine's performance versus solidity varies based on the used airfoil. For small SB-VAWT of Darrieus-type with NACA4415 airfoil, the value of maximum power coefficient increases by nearly four times when the solidity factor increase from 0.2 to 1. The turbine's performance versus solidity varies based on the used airfoil.

The findings related to the effect of solidity factor on the performance of the SB-VAWT of Darrieus-type with the NACA4415 airfoil can be explained as through the influence of solidity factor of the Reynolds number, whereas the solidity factors increase the blade Reynolds number increase and as a consequence the power coefficient increase.

The previous findings in relation to the effect of solidity factor on the performance of the SB-VAWT of Darrieus-type with the NACA4415 airfoil aligned with the finding of previous studies that show the reduction of solidity would increase the range of the operating tip-speed ratio and the reduction of solidity would reduce the maximum power coefficient [23]. However, the findings did not align with the findings of other studies the recommended the optimum value for rotor solidity to be between 0.2 and 0.6 [8].

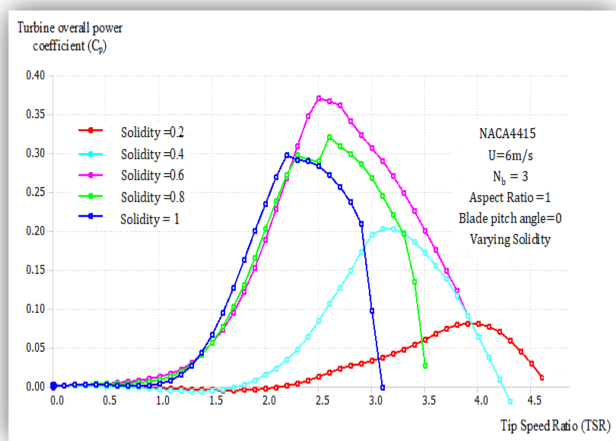

Fig. 4: Power coefficient versus TSR at different solidity at constant aspect ratio for NACA4415 airfoil.

4.3. VAWT's energy efficiency at varying blade pitch angles

The power performances of the proposed designs of small SB-VAWT of Darrieus-type with the NACA4415 airfoil were checked through finding the values of power coefficients at various values of blade pitch angle. it can be seen in figure 5 that a positive blade pitch angle would make the range of angular speed operation shorter while the a negative blade pitch angle would make the range of angular speed operations wider compared to the zero value of blade pitch angle. Furthermore, a negative blade pitch angle leads to greater maximum power coefficients to a zero blade pitch angle, while a positive blade pitch angle leads to smaller maximum power coefficients compared to a zero blade pitch angle. For small SB-VAWT of Darrieus-type with NACA4415 airfoil, the value of maximum power coefficient increased by 59% when blade pitch angle decreased from 2 to -2 degree.

The findings related to the effect of blade pitch angle on the performance of the SB-VAWT of Darrieus-type with the NACA4415 can be explained by stall phenomena, where Reference [13] pointed large and positive blade pitch angle would lead to a big fall in C_P due to stall on blades in the upwind area.

The findings related to the effect of blade pitch angle on the performance of the SB-VAWT aligned with the findings of previous research studies that show the advantages of using small and negative blade pitch angle [18, 24, 25].

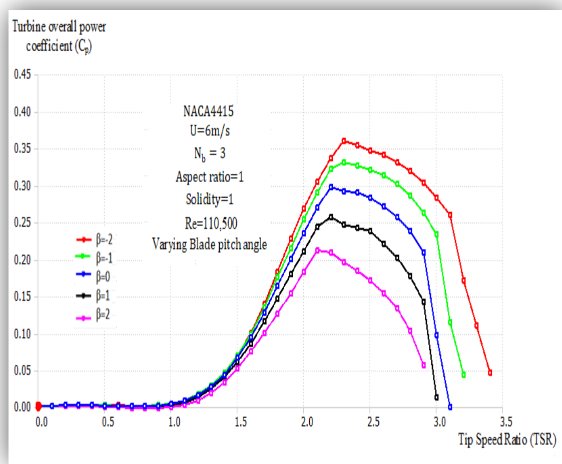

Fig. 5: Power coefficient versus TSR at different blade pitch angle at constant aspect ratio and solidity for NACA4415 airfoil.

5. Conclusions and Recommendations

5.1 Conclusions

The theoretical analysis shows that there is an optimum frequency of rotation for optimum performance for the turbine, where if the turbine's rotor rotates slowly, most of the wind would get through the turbine without hitting the blades and providing energy for the turbine. However, if the turbine's rotor rotates quickly, the wind would create tumultuous effect pushing the wind away from the turbine and that negatively affect the turbine's performance. However, the characteristics of the turbine play an integral role in its performance. Based on the small scale tests of the prototypes of the VAWT, the results showed that the SB-VAWTs of Darrieus-type with the NACA4415 and the selected characteristics have the capability of self starting. A careful selection of the VAWT's aspect ratio for the turbine need be considered, where a VAWT's aspect ratio affect the value of tip speed ratio at which the maximum power coefficient is achieved as well as the value of maximum power coefficients. An increase in aspect ratio enhances the value of Tip Speed Ratio (TSR) at which the maximum power coefficient is achieved; In addition, an increase in rotor aspect ratio leads to greater maximum power coefficient. Bigger the solidity, smaller the tip speed ratio at which the maximum power coefficient is achieved. The bigger the solidity means the bigger the chord. The bigger chord need a small tip speed ratio to develop torque and that would influence the self-starting capability of the turbine. An increase in solidity enhances the value of TSR at which the maximum power coefficient is achieved. Finally, the results shows that a small negative blade pitch angle leads to greater maximum power coefficients compared to a zero blade pitch angle.

5.2 Recommendations

Based on the findings of the current study, the study has the following recommendations for practice:

- To use the findings in relation to shape of airfoils, rotor aspect ratio, solidity, and blade pitch angle to guide the design of VAWT to harvest energy from wind.
- To fully test the prototypes of the VAWT and examine their potential in harvesting energy from wind.

Nomenclature

Symbols	Description	Unit
A	Projected frontal area of turbine	m^2
AR	Aspect Ratio	-
a	The induction factor that accounts for the deceleration in the wind as it passes through the turbine rotor	
c	Airfoil chord length	m
C_p	Turbine overall power coefficient	-
D	Rotor diameter	m
H	Blade height	m
N_b	Number of blades	
R	Rotor radius	m
Re	Reynolds number	-
U, U_l	Air stream velocity (Wind speed)	m/s
NACA	The National Advisory Committee for Aeronautics	-
PWR_{Avalia}	Available power in the wind	watt
$Re_{Free\ Stre}$	Free Stream Reynolds number	-
Re_{Local}	Local Reynolds number	-
SB	Straight Blade	-
U_{rel}	The velocity of the flow as compared to the turning rotor.	m/s
VAWT	Vertical Axis Wind Turbine	-
β	Blade pitch angle, the angle between the chord line and the direction of the blade speed.	Degree
μ	μ is the viscosity of the fluid	Pascal-seconds (Pa.s)
ρ	The fluid density in kilograms-per-cubic-meter typical value of ρ for air is ((1.225 kg/m3)	Kg/m^3
ϕ	The azimuth angle	Degree
v	kinematic viscosity, typical value of v for air is (1.562* 10^{-5}) at temperature of 25 C	m^2/s
Ω	Angular velocity of rotor	radians/sec
λ_{Cpmax}	Tip-speed ratio at maximum possible turbine overall power coefficient	-
λ (TSR)	Tip-speed ratio	-
σ	Solidity	-
ω	The angular velocity imparted to the wake	Rad/s

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