Small Wind Turbine Blade Optimization using Blade Elementary Method Theory (BEMT)

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Abstract:- Theoretical algorithms, such as computational fluid dynamics (CFD), blade elementary method (BEM) theory, and the vortex wake system (VWS) have been implemented in the design of aerodynamic wind turbines. On these theoretical methods, the (BEM) theory proved to be the best method in optimising HAWT blades and is thus the most commonly used approach in modelling and constructing small wind turbine blades. This paper will primarily focused on designing and optimizing the type of aerofoil required for improving the pitch angle of the rotor blades, and for determining the number of blades necessary to optimise the power output at various wind speed using BEMT. A NACA-4412 type aerofoil was chosen as the departure point for the blade design. Various pitch angles of 6°, 10° and 12° were chosen at an optimum angle of attack of 5°, 7° and 9°. A blade radius of 0.8-1.0 m and chord length of 0.08-0.1 m were subsequently chosen for Designs 1, 2 and 3 respectively at various low wind speeds. At average wind speed of 0 - 2.3 m/s (8.28 km/h), 3-blade, 5-blade and 7-blade sets were designed and optimized for performance. During the design of the wind turbine blades, it was predicted that at various wind speeds, the rated output would be 7.5 W, 20 W and 40 W respectively Design 1, 2 and 3. The results for Design 1, with a blade radius of 0.85 m, a chord length of 0.06 m near the rotor hub, with a pitch angle of 6° at the rotor hub and a tapering off to about 1° at the blade radius tip of the blade, produced a maximum output power of 8.2 W at 4.2 km/h wind speed, and Design 2, with a blade radius of 0.95 m, a chord length of 0.08m near the rotor hub, with a pitch angle of 10° near the rotor hub and a tapering off to 1° at the blade radius tip of the blade, yielded a maximum output power of 12,5 W at 4.2 km/h wind speed and lastly Design 3, with a blade radius of 1m, a chord length of 0.1m near the rotor hub, with a pitch angle of 12° near the rotor hub and tapering off to 2° at the blade radius tip of the blade, generated a very useful power output of 39.5 W during testing. The maximum power output was achieved at an average wind speed of 1.17 m/s (4.2 km/h).

Keywords:- *Small Wind Turbine's, Design, BEM Theory, Yielded Power.*

I. INTRODUCTION

The main goal of a SWT is always to maximise the power captured from the wind. It is also vital to ensure that the protection of the turbine is not compromised in any circumstances. Thus, a power management is a very significant aspect of a wind turbine use.

In order to prevent damage to the wind turbine at very high wind speeds, the aerodynamic forces on the rotor can be managed to reduce the captured power and protect the turbine (Bhadra et al., 2010).

A. Optimizing the efficiency of Horizontal Axis Wind Turbine (HAWT)

Figure 1, illustrate a typical blade plane design that will optimize power transfer, as well as the various physical mechanisms at play. Only those issues relevant to this study will be briefly reviewed here.

Modern, high-capacity wind turbines, such as those used by the electricity utilities in the electricity grid, typically have blades with a cross section similar to the aerofoils used to provide lift in aircraft wings (Lawson, 2014).

The typical blade design for state-of-the-art blades for small wind turbines is shown in Figure 1. The main specifications are the radius (*r*) of the blade, the width of the blade or "chord length" along the radius (C*p*), the tip dimension of the blade, and the twist of the blade as a function of ratio. The latter is varied in order to increase the power transfer per unit length along the radius of the blade (Schubel, 2012).

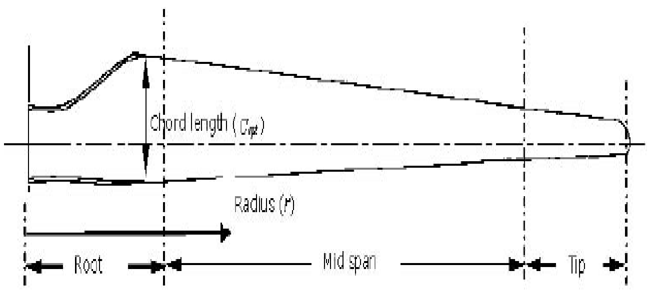

Fig 1: A typical blade plane illustrating Chord and Radius of a blade (Schubel & Crossley, 2012).

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Figure 2, (a) and (b) illustrate the typical dynamics at play during operational conditions.

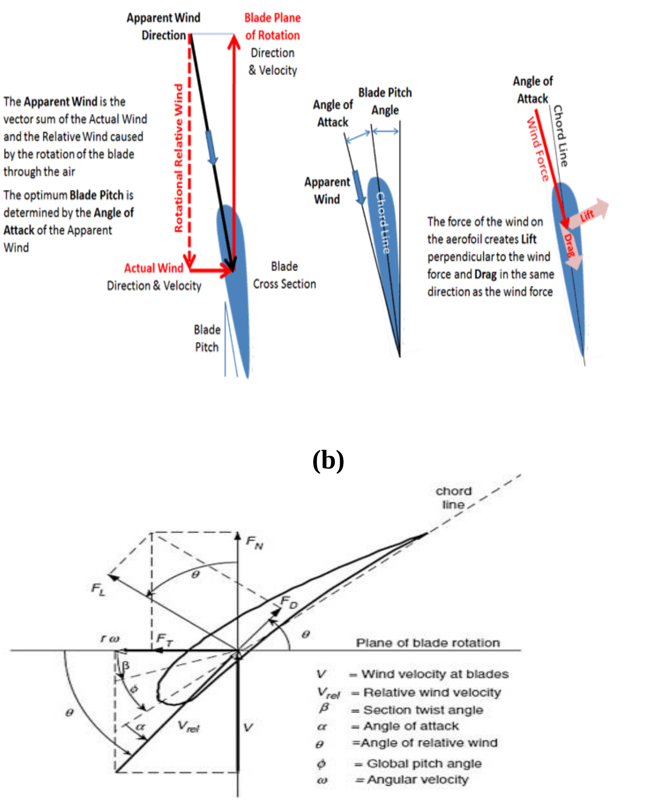

Fig 2: Angle of Attack vs. Pitch Angle of a Wind turbine blade (Lawson, 2014 and Sudhamshu et al, 2016).

As the rotor rotation picks up speed, a relative rotational wind is generated in the rotation plane of the blade. This component of the wind together with the actual incident wind causes an “apparent wind direction” (Lawson, 2014).

The direction of the apparent wind, relative to the chord line of the aerofoil, is known as the angle of attack. Similar to the action of aircraft wings, the lift resulting from the incident wind force increases as the angle of attack increases from 0° to a maximum of about 15°, at which point the smooth laminar flow of the air over the blade ceases, and the air flow over the blade separates from the aerofoil and becomes turbulent. Above this point, the lift force deteriorates rapidly while drag increases and leads to a stall (Lawson, 2014).

For a given speed of rotation, the tangential velocity of sections of the blade increases along the length of the blade towards the tip, so that the pitch of the blade (angle of the blade relative to the rotational plane) must be twisted to maintain the same optimum angle of attack at all sections along the length of the blade (Lawson, 2014).

However, as the wind speed changes, the twist will no longer be optimum. To retain the optimum angle of attack as wind speed increases, a fixed pitch blade must increase its rotational speed accordingly; otherwise, for fixed speed rotors, variable pitch blades must be used, as illustrated in Figure 2, (a) (Lawson, 2014).

For fixed blade rotors, the blade pitch angle and variation in (twist) pitch angle as a function of radius must hence normally be optimised for a chosen suggested wind operation speed of the turbine. Higher pitch angles are normally chosen for lower wind speed conditions (Lawson, 2014).

The number of blades in the turbine rotor and its rotational speed must be optimised to extract the maximum energy from the available wind (Lawson, 2014).

Although rotors with multiple blades should capture more wind energy, there is a practical limit to the number of blades which can be used because each blade of a spinning rotor leaves turbulence in its wake and this reduces the amount of energy which the following blade can extract from the wind. The same turbulence effect also limits the possible rotor speeds because a high-speed rotor does not provide enough time for the air flow to settle after the passage of a blade before the next blade comes along (Lawson, 2014).

There is also a lower limit to both the number of blades and the rotor speed. With too few rotor blades, or a slow turning rotor, most of the wind will pass undisturbed through the gap between the blades, thus reducing the potential for capturing the wind energy. The fewer the number of blades, the faster the wind turbine rotor needs to turn to extract maximum power from the wind (Lawson, 2014).

The notion of the Tip Speed Ratio (TSR) is a concept used by wind turbine designers to optimise a blade set to the shaft speed required by a particular electricity generator, while extracting the maximum energy from the wind (Lawson, 2014).

The tip speed ratio is given by Schubel, (2012):

$$\lambda = \frac{\Omega r}{V_w} \quad (1)$$

Where;

λ = Tip speed ratio
Ω = Rotational velocity (rad/s)
r = Radius
V_w = Windspeed

A well-designed typical 3-bladed rotor would have a tip speed ratio of around 6 to 7 (Lawson, 2014).

The tangential velocity S of any blade section at a distance ‘r’ from the centre of rotation (the root of the blade) is given by S = r Ω where Ω is the angular velocity of rotation in radians. For a given wind speed, the apparent wind will be different at the root of the blade from the apparent wind at the tip of the blade because the rotational relative wind speed is different (Lawson, 2014).

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The pitch control can be used at high wind speeds to maintain the power output that is similar to the rated power of the generator. Attributed to the prevalence of gusts, the instantaneous power varies across the rated average value of the power (Sudhamshu et al., 2016).

Figure 2, (b) illustrates the relationships between the pitch angle, the relative wind speed and the attack angle under dynamic conditions.

$$\Pi = \Theta + \alpha \quad (2)$$

In general, it can be seen that the relative wind speed is always equal to the pitch angle of the blades and relative to the rotation plane plus the angle of attack on the blade. Furthermore, as the blade speed increases, the relative wind direction angle increases, and the attack angle is reduced accordingly. As pitch angle is increased from blade-to-blade design, the attack angle correspondingly increases, and increases thrust on the blade as a result of momentum and energy transfer.

Further details about the exact physics, theory and relationships of HAWTs can be obtained from the article by Sudhamshu et al. (2016).

It is very difficult to derive the relative wind directions of HAWT blades under dynamic conditions, and is therefore much easier to use and focus on the pitch angle of the blade (aerofoil) and to use this parameter as a reference to derive all subsequent parameters, such as power transfer.

II. THE DESIGN ROUTE AND OPTIMAZATION USING BEMT

The NACA 4412 aerofoil is widely used as it has a high cl/cd ratio. This type of aerofoil complies with the National Advisory Committee for Aeronautics (NACA) requirement and is the acceptable type of aerofoil used for small-scale wind turbines such as HAWT. (Musyafa, 2014).

In order to achieve the optimum power output, the pitch angle was varied to manipulate power coefficients so that it could produce power at low wind speeds; thus choosing the pitch angle was a critical step (Djalal, 2017).

This study is sought to focus on design and optimization of NACA aerofoil profile type in order to increase the performance of small HAWT at various low wind speed using BEMT.

The existing theory of BEM, originally formulated by Glauert (1935), incorporates the theory of the blade part that is based on the aerodynamic performance of the aerofoil and the theory of momentum (Manwell et al., 2002).

In this paper, BEMT with formulas was used to calculate certain parameter used in designing wind turbine blades. Through the implementation of angular momentum, axial force and torque can be defined as formulae (1) and (2) for each negligible *dr* blade field. Then the normal load of the *dr* width part of the blade is as follows: (Ahmed et al., 2018).

$$dN = \frac{\rho}{2}\frac{V_0^2(1-a)^2}{\sin^2\phi}N_b(C_L\cos\phi + C_D\sin\phi)cdr \quad (1)$$

Where:
a = axial induction factor
a' = rotational induction factor
Φ = blade section airflow angle
CL = lift coefficient and Cd = drag coefficient
The torque on the *dr* width part of the blade will be as follows:

$$dT = \frac{\rho}{2}\frac{V_0(1-a)}{\sin\phi}.\frac{\omega_r(1+a')}{\cos\phi}N_b(C_L\sin\phi - C_D\cos\phi)crdr \quad (2)$$

Then, the lift coefficient (CL) and the drag coefficient (CD) vary according to the type of the angle of attack and aerial foil. These are critical in determining the torque and forces according to formulas (1) and (2) above.

The geometry dependant parameters, such as the CL and the turbine diameter, is repeated to determine the output of the turbine. Then, the tangential induction and the axial factors are as follows:

$$a = \frac{1}{\frac{4F\sin^2\varphi}{\sigma(C_L\cos\phi + C_D\sin\phi)}+1} \quad (3)$$

$$a' = \frac{1}{\frac{4\sin\varphi\cos\phi}{\sigma(C_L\sin\phi - C_D\cos\phi)}+1} \quad (4)$$

Glauert (1935) introduced an approximate formula for the Prandtl tip-loss function, where the Prandtl tip loss correction factor is known as *(F)*:

$$F = \frac{2}{\pi}ar\cos\left[\exp\left(\frac{N_b(r-R)}{2r\sin\varphi}\right)\right] \quad (5)$$

In which there is a local solidity described as follows

$$\sigma = \frac{cN_b}{2\pi r} \quad (6)$$

Then, if the factor of axial induction is greater than 0.4, Equation (3) will not give satisfactory results, and a different equation, proposed by Buhl (2005), can be used:

$$a = \frac{18F - 20 - 3\sqrt{C_N\left(50 - 36F\right) + 12F\left(3F - 4\right)}}{36F - 50} \quad \text{for } a > 0.4 \tag{7}$$

Hassanzadeh et al. (2016) reported that other methods must be used to estimate aero-foil activity at high negative and positive angles of attack. The system based on the Viterna formulas is used to generalise data from the aerofoil to the high stall/ lift growth regime.

The drag-and-lift coefficients are determined as follows in the case of $\alpha_{stall} < \alpha < 90°$.

$$C_D = B_1 \sin^2 \alpha + B_2 \cos \alpha \tag{8}$$

$$C_L = A_1 \sin 2\alpha + A_2 \frac{\cos^2 \alpha}{\sin \alpha} \tag{9}$$

Where:

$$B_1 = C_{D\max} = 1.11 + 0.018AR \quad \left(\alpha = 90°\right) \tag{10}$$

In this paper the departure points for each design were as follows:

1. The lift coefficient (CL) = 1.060, 1.060, and 1.060 for Designs 1, 2 and 3 respectively.
2. The pitch angles (Qp) = 6°, 10° and 12° for Designs 1, 2 and 3 respectively.
3. The drag coefficient (CD) = 0.0160, 0.0160 and 0.0160 for Designs 1, 2 and 3 respectively.

Figures 3, 4 and 5 depicts the blade geometry in between variations of chord length and blade radius for Designs 1, 2 and 3 without optimisation.

Figures 6, 7 and 8 depicts chord radius and pitch angle distribution for Designs 1, 2 and 3 respectively when optimised.

It can be seen in Figure 6 for Design 1 that twist distribution of the blade was designed for 1.1° at the tip to 6.1° at the root. For Design 2, as depicted in Figure 7, it can be seen that the twist distribution of the blade was designed for 1.2° at the tip to 9.9° at the root.

Design 3, as depicted in Figure 8, it can be seen that the twist distribution of the blade was designed for 1.5° at the tip to 11.9° at the root.

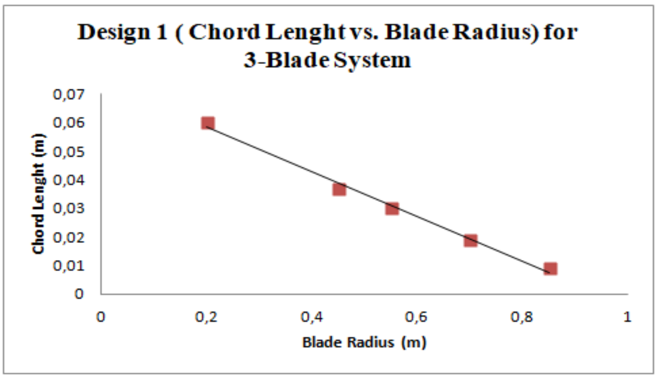

Fig 3: Chord Distribution (Chord Length (vs) Blade Radius) for Design 1 (author's image).

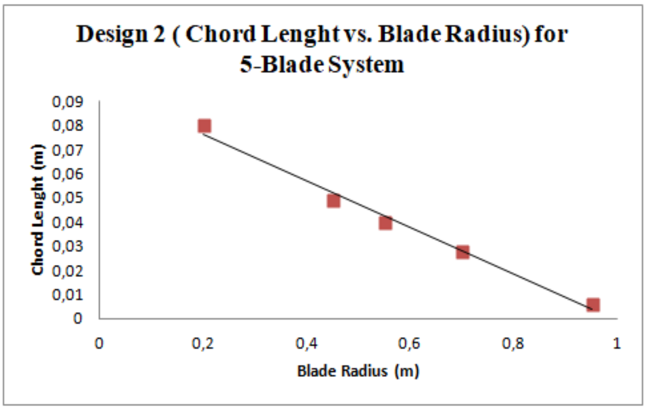

Fig 4: Chord Distribution (Chord Length (vs) Blade Radius) for Design 2 (author's image).

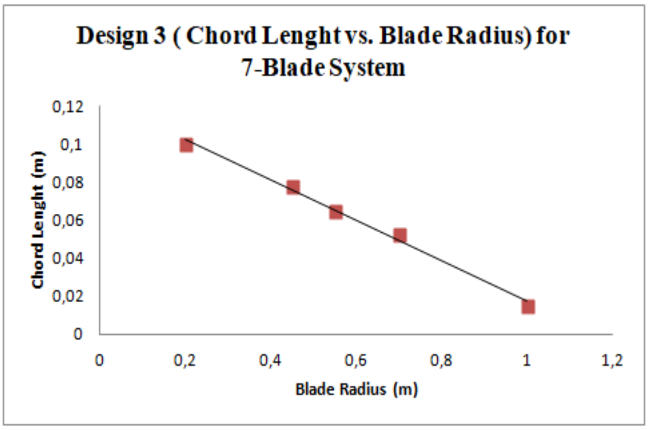

Fig 5: Chord Distribution (Chord Length (vs) Blade Radius) for Design 3 (author's image).

Chord length, or the width of the wind turbine blade at a given distance along the length of the blade, is an important factor in blade design because by increasing the chord length, the amount of power generated was consequently increased (Schubel, 2012). The values of blade radius for Designs 1, 2 and 3 were 0.85 m, 0.95 m, and 1 m, and the maximum chord lengths of 0.06 m, 0.08 m, and 0.1 m for subsequent Designs 1, 2 and 3 respectively.

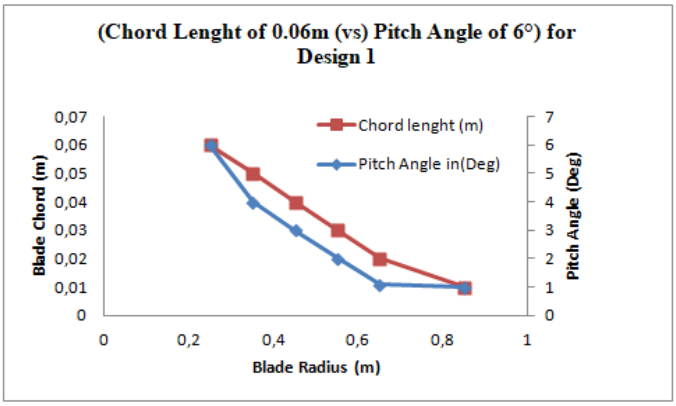

Fig 6: Chord radius and Twist/Pitch Angle Distribution for Design 1 (author's image).

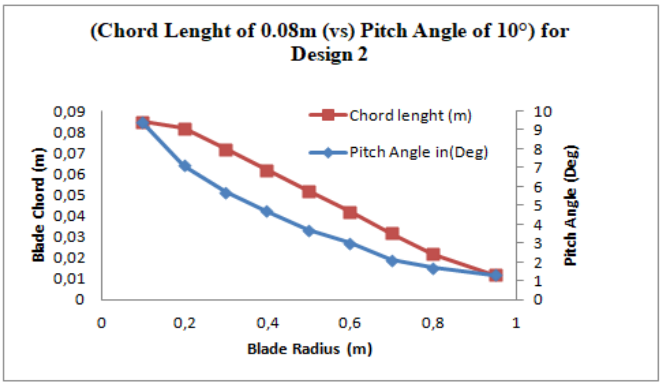

Fig 7: Chord radius and Twist/Pitch Angle Distribution for Design 2 (author's image).

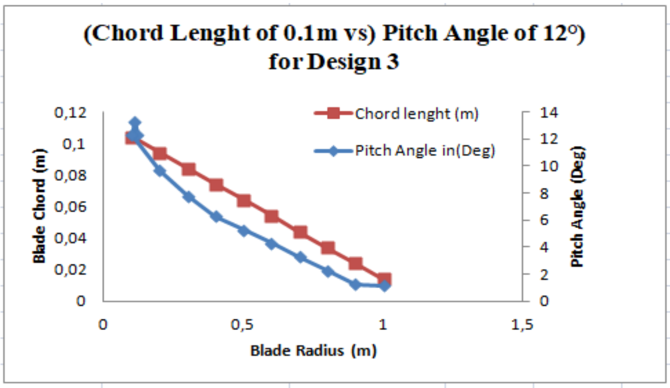

Fig 8: Chord radius and Twist/Pitch Angle Distribution for Design 3 (author's image).

Figure 9, depicts Design's 1, 2 and 3 at variation angles of 6°, 10° and 12° respectively. The rational for this choice was that when the blades are increased, there would be more power delivery at low wind speeds.

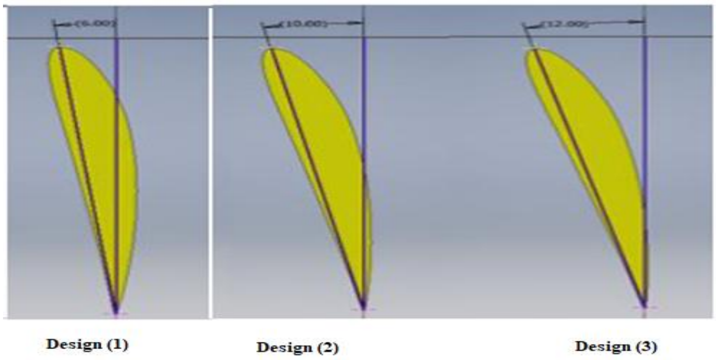

Fig 9: Chosen maximum pitch angle for the blades set at 6°, 10°& 12° at optimum attack angles of 5°, 7°& 9° with respect to the hub plane for subsequent Designs 1, 2 & 3 (author's image).

Table 1: Comparisons of overall blade designs.

Chosen Design Criteria	Design 1	Design 2	Design 3
Blade Aerofoil Type	NACA-4412	NACA-4412	NACA-4412
Mid-Spin Aerofoil	NACA-4412	NACA-4412	NACA-4412
Tip Aerofoil	NACA-4412	NACA-4412	NACA-4412
Root Aerofoil	NACA-4412	NACA-4412	NACA-4412
The hub diameter (m)	0,156	0.156	0,156
Number of blades	3	5	7
Chosen blade radius (m)	0,85	0,95	1
Chord Length at Hub grading to the tip of the blade (m)	0.06	0.08	0.10
Pitch angle (Qp) (degree) near hub, grading/twisting towards zero along the length of the blade	6°	10°	12°
Targeted/Estimated Angle of Attack (□□ (degree) at a low wind speed of 2.3m/sec	5°	7°	9°
The estimated lift coefficient (CL)	1,060	1,060	1,060
Estimated lift to drag ratio (ε = CL/CD)	66.3	66.3	66.3
The drag coefficient (CD)	0,0160	0,0160	0,0160
Predicted power output at various low wind speed	**7.5 W@ 2.3 m/s Average low wind speed**	**20W@ 2.3 m/s Average low wind speed**	**40W@ 2.3 m/s Average low wind speed**

III. CONCLUSIONS

The paper was primarily focused on designing and optimizing of wind turbine blades. This entailed choosing the aerofoil type, number of blades and the optimal pitch angle along the blade radius, in order to optimise the power output at various low wind speed. The main conclusions derived from the study are as follows:

1. NACA-4412 aerofoils proved to be sufficient as their specifications included a low cut-in speed at about 3-4 m/sec with a broad chord area/length at small radius positions and tapering towards the tip of the blade to small areas and width, maximising torque and energy capture. The blade radius could easily be extended to implement different radii, and in addition the pitch angle along the radius could easily be changed to different dimensions.
2. Furthermore, the results clearly confirm that increasing the pitch angle from the standard 6° used for NACA 4412 specifications to 10° and 12° near the hub, tapering/ twisting lower angles of the tip of the blade, and optimising the attack angle for Designs 1, 2 and 3, to 5°, 7° and 9° respectively along the section of the blade radius definitely increased the power delivery of the rotor.
3. The results showed that a Design 3 with a 7- rotor-blade with maximum pitch angle of 12° produced the maximum output power of 39.5 W. The maximum power output was achieved at 1.17 m/s (4.2 km/h) average wind speed.

Design 2, with a 5- rotor blade design and pitch angle of 10°, produced the maximum power output of 12.5 W at 4.2 km/h wind speed, and lastly Design 1 with a 3 – rotor-blade and a pitch angle of 6°, produced a maximum power output of 8.2 W at 4.2 km/h average wind speed.

4. Lastly, the (BEM) theory proved to be the best method in optimising HAWT blades and is thus the most commonly used approach that can be used in modelling and constructing small wind turbine blades.

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