



# Optimizing Small Wind Turbine Blades: A BEMT Approach

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**Abstract** – This paper explores the optimization of small wind turbine blades, focusing on the design and utilization of theoretical algorithms such as computational fluid dynamics (CFD), blade elementary method (BEM) theory, and the vortex wake system (VWS). Among these methods, BEM theory has proven to be the most effective in optimizing horizontal-axis wind turbine (HAWT) blades and is commonly employed in modeling and constructing small wind turbine blades. The study centers on designing and optimizing aerofoils to enhance rotor blade pitch angles and determining the optimal number of blades for maximizing power output at various wind speeds using BEMT. Using a NACA-4412 type aerofoil as the starting point, the paper investigates different pitch angles, blade radii, and chord lengths for Designs 1, 2, and 3. Results indicate that at an 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. The predictions suggest rated outputs of 7.5 W, 20 W, and 40 W for Designs 1, 2, and 3, respectively. The study reveals that Design 3, with a blade radius of 1m, a chord length of 0.1m, and a pitch angle ranging from 12° near the rotor hub to 2° at the blade radius tip, achieved a significant power output of 39.5 W at a wind speed of 4.2 km/h. The findings contribute valuable insights into optimizing wind turbine blade design for enhanced energy efficiency.

**Keywords:** Aerofoil design, Blade optimization, BEM theory, Small wind turbines, Pitch angle, Wind turbine performance.

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## I. Introduction

In the pursuit of maximizing the efficiency of small wind turbines, researchers have delved into the intricate realm of aerodynamic design and theoretical modeling. This paper navigates the landscape of theoretical algorithms, including computational fluid dynamics (CFD), blade elementary method (BEM) theory, and the vortex wake system (VWS), to optimize horizontal-axis wind turbine (HAWT) blades. Among these methods, BEM theory emerges as the most effective, becoming a cornerstone in the modeling and construction of small wind turbine blades. The primary focus lies in the meticulous design and optimization of aerofoils, specifically to improve rotor blade pitch angles and ascertain the ideal number of blades for optimal power output across various wind speeds using BEMT.

The primary objective of a Small Wind Turbine (SWT) is consistently to optimize the power extracted from the

wind. Equally crucial is the imperative to safeguard the turbine under all circumstances.

Consequently, effective power management emerges as a pivotal aspect of wind turbine utilization. To avert potential damage during exceptionally high wind speeds, the aerodynamic forces acting on the rotor can be actively controlled to diminish the captured power, thereby ensuring the protection and integrity of the turbine [1]. Modern, high-capacity wind turbines, particularly those integrated into electricity utilities and the electricity grid, commonly employ blades with a cross-sectional design reminiscent of aerofoils employed for lift in aircraft wings. As the rotation of the rotor accelerates, a relative rotational wind is induced in the blade's rotation plane. This, combined with the actual incident wind, determines the "apparent wind direction" [2]. Additional research performed by other authors



utilizing BEMT to design and optimize wind turbine blades will be highlighted below.

[3] carried out the study on designing of small horizontal axis wind turbine (HAWT) blades using blade element momentum theory.

Three blades were considered, and the blade pitch angle was kept constant. MATLAB software was used for parameter calculations, while Q-blade software was used for airfoils analysis and power simulation. Four-digit airfoils of NACA 4412 and SG6043 were considered. The highest power coefficients were obtained at  $3.0 \times 10^5$  for all TSR values, with the highest power coefficient and output at TSR 6. The design blades were able to harvest wind powers of 79.3 W and 80.10 W at 4 m/s.

[4] in their work discussed the process of selecting and designing the aerofoil and blades for small-scale horizontal-axis wind turbines (SHAWTs) using blade element momentum theory. Four model turbine rotors, including E216, SG6043, NACA63415, and NACA0012, this analysis demonstrated the exceptional performance of the model rotor with E216 airfoil when compared to the other three models. [5] in their study planned to design a 2 kW small scale horizontal axis wind turbine for rural applications. Aerodynamic analysis on 10 airfoils was performed using QBlade software, revealing SD7080 as the most suitable for high power production in low wind speed applications. [6] Investigated the design method for small horizontal-axis wind turbine blades using BEM theory. They used MATLAB and Xfoil programs to analyze the impact of rotor solidity values and blade number on performance. The blades were developed using 3D printing additive manufacturing and tested at wind speeds ranging from 2 to 8 m/s. The results showed that a rotor solidity of 0.055-0.085 improved the performance. [7] Used Blade-Element Momentum (BEM) theory in MATLAB software to design and optimize a 400 Watt small wind turbine blade. The analysis covered the parameters like Reynolds Number, Airfoil, Lift Coefficient, Lift to Drag Ratio, and Angle of attack. The study aimed to extend knowledge of the SG airfoil family and optimize suitable airfoils for small horizontal axis wind turbine blades. The study also investigated the optimum distribution of chord length and twist angle along the blade's 700mm length at 8 m/s wind speed. [8] In their research used XFOIL to develop and test three high-performance airfoils (EYO7-8, EYO8-8, and EYO9-8) for small wind turbine applications. The airfoils were used to design 3-bladed 6mm diameter wind turbine rotors. The results showed that the new airfoils compared favorably with existing low Reynolds number airfoils and were suitable for small wind turbine blade design. The performance

improvement was attributed to design optimization using an optimal thickness-to-camber ratio. [9] Designed a small horizontal axis wind turbine blades using Schmitz formulas and BEMT. The SG6043 airfoil was used and the blade was divided into equal length elements. MATLAB code calculated chord length and twist angle, and Blade element momentum theory characterizes the rotor's performance. The Wilson-Walker method was also used for the correction.

[10] Presented a novel optimization approach for hydrokinetic turbine swept blades, with the objective of designing blades that minimize axial load and cavitations. The approach, using blade element momentum theory, exhibited a minimal computing burden and straightforward implementation. The approach demonstrated an 18% improvement in turbine torque and power coefficient. Nevertheless, Prandtl's tip loss was not influenced by the sweep effect. [11] Devised a system to manage dynamic stall in a 5MW wind turbine using BEM theory. The design used ten S809 Airfoil cross-sections and was suitable with automated wind turbine power production. The approach demonstrated sophisticated capabilities for future assessments and may be used to independent aerodynamic optimization and aerostructure improvements.

The objective of this work is to explore and optimize the design of small wind turbine blades, employing theoretical algorithms such as computational fluid dynamics (CFD) and blade elementary method (BEM) theory. Specifically, the study focuses on the meticulous design and enhancement of aerofoils to improve rotor blade pitch angles, as well as determining the optimal number of blades for maximizing power output at varying wind speeds using BEMT. The chosen NACA-4412 aerofoil serves as the departure point for the investigation. Through systematic exploration of different pitch angles, blade radii, and chord lengths, the research aims to provide valuable insights into the complex interplay of design parameters and their impact on the overall energy efficiency of small wind turbines.

## II. Methodology

The angle between the chord line of the aerofoil and the direction of the apparent wind is termed the angle of attack. Analogous to aircraft wings, the lift generated by the incident wind force increases as the angle of attack rises from  $0^\circ$  to approximately  $15^\circ$ . Beyond this point, where the smooth laminar flow transitions to turbulent, the lift force diminishes rapidly, accompanied by an increase in drag, leading to a stall.

In the context of a rotating blade, the tangential velocity of sections along the length increases toward the tip for a given rotation speed. Consequently, the blade pitch (angle relative to the rotational plane) must be twisted to maintain an optimal angle of attack along the blade's length. For fixed blade rotors, optimizing the pitch angle and twist as a function of radius is essential for a chosen wind operation speed.

Higher pitch angles are typically selected for lower wind speeds. The optimization of the number of blades and rotor speed is crucial to maximize energy extraction from the available wind resource. While rotors with multiple blades have the potential to capture more wind energy, there exists a practical limit to the number of blades due to the turbulence generated by each spinning blade. This turbulence diminishes the energy extractable by the subsequent blade from the wind. Additionally, the same turbulence effect imposes constraints on permissible rotor speeds, as a high-speed rotor doesn't allow sufficient time for the air flow to settle after a blade's passage before the arrival of the next blade. Conversely, there is a lower limit to both the number of blades and rotor speed. Insufficient blades or a slow-turning rotor allow much of the wind to pass through the gap between blades without harnessing its energy effectively. In this scenario, fewer blades necessitate a faster rotor speed to optimize wind energy extraction [2].

Figure 1 showcases an optimized blade plane design emphasizing power transfer efficiency and key physical mechanisms pertinent to this study. Figure 2 (a & b) illustrates the dynamic operational conditions associated with these designs.

In the realm of modern, high-capacity wind turbines utilized in electricity grids, the blades typically adopt a cross-sectional shape akin to aircraft wing aerofoils. For small wind turbines, the state-of-the-art blade design, depicted in Figure (2a), adheres to specifications such as blade radius ( $r$ ), chord length ( $C_p$ ) along the radius, tip dimension, and twist as a function of ratio. The latter, varied intentionally, aims to enhance power transfer efficiency per unit length along the blade radius [12].

As the rotor gains rotational speed, the resulting relative rotational wind in the blade's rotation plane, combined with the incident wind, determines the "apparent wind direction".

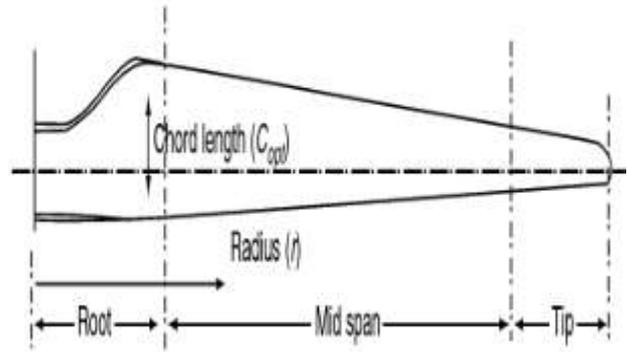


Figure 1. Chord and Radius of a blade illustrated with a typical blade plane [12]

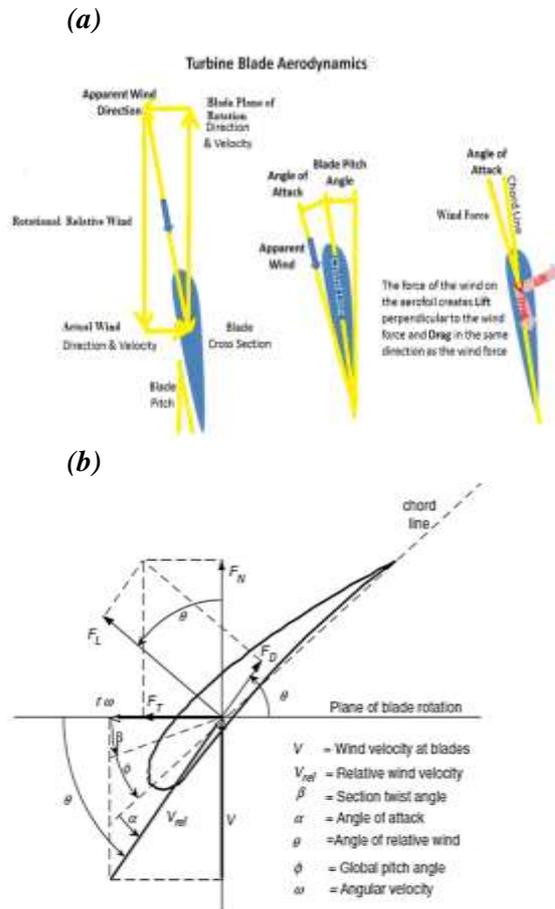


Figure 2 (a & b). Twist Angle vs. Pitch Angle of a Wind turbine blade [ 2 & 13]

The Tip Speed Ratio (TSR) is a concept used by wind turbine designers to optimize the blade configuration for a specific shaft speed required by an electrical generator, with the aim of obtaining the utmost energy from the wind.

The tip speed ratio is defined by [12] in his (2012) publication.

$$\lambda = \frac{\Omega r}{V_w}$$

Where;

- $\lambda$  = Tip speed ratio
- $\Omega$  = Rotational velocity (rad/s)
- $r$  = Radius
- $V_w$  = Windspeed

A well-designed standard 3-bladed rotor would typically have a tip speed ratio ranging from 6 to 7.

The tangential velocity (S) of any blade section situated at a distance 'r' from the center of rotation (the root of the blade) is expressed as  $S = r\Omega$ , where  $\Omega$  denotes the angular velocity of rotation in radians. Notably, for a given wind speed, the apparent wind differs at the root and tip of the blade due to variations in rotational relative wind speed. Pitch control serves as an effective means during high wind speeds to uphold power output akin to the rated power of the generator. This is particularly pertinent due to the prevalence of gusts, causing instantaneous power fluctuations around the rated average value [13]. It underscores the significance of considering relative wind speed and attack angle under dynamic conditions for optimal pitch control in wind turbine operation.

### $\Pi = \Theta + \alpha$

In a general observation, the relative wind speed consistently equals the pitch angle of the blades relative to the rotation plane, in addition to the angle of attack on the blade. Moreover, as the blade speed increases, there is a corresponding increase in the relative wind direction angle, leading to a reduction in the attack angle. Elevating the pitch angle from one blade design to another results in an increase in the attack angle, intensifying thrust on the blade due to momentum and energy transfer.

For a more in-depth understanding of the precise physics, theory, and relationships governing Horizontal Axis Wind Turbines (HAWTs), [13] article provides comprehensive details. Therefore, deriving the relative wind directions of HAWT blades under dynamic conditions can be challenging, prompting a simpler focus on the pitch angle of the blade (aerofoil). Using this parameter as a reference proves more manageable and serves as a basis for deriving subsequent parameters, such as power transfer and will be considered for this study.

### III. Optimization using BEMT

The NACA 4412 aerofoil, renowned for its high cl/cd ratio, is a widely accepted choice due to its compliance with National Advisory Committee for Aeronautics (NACA) standards, particularly suitable for small-scale wind turbines like Horizontal Axis Wind Turbines (HAWT) [14]. The optimization of power output in these turbines, particularly at low wind speeds, involves a crucial step: varying the pitch angle to manipulate power coefficients [15].

This study hones in on the design and optimization of the NACA aerofoil profile type, aiming to enhance the performance of small HAWTs across various low wind speeds using the Blade Element Momentum Theory (BEMT). Initially formulated by Glauert in 1935, the BEM theory integrates blade aerodynamics and momentum theory, as established by [16].

The paper employs BEMT with specific formulas to calculate parameters crucial in wind turbine blade design, incorporating angular momentum to define axial force and torque for each negligible dr blade field [17]. This approach is instrumental in refining the understanding of wind turbine dynamics and optimizing their performance under varying wind conditions.

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

Denoted as:

a= "axial induction factor"

a' = factor of rotational induction

$\Phi$  = blade section angle of airflow

Lift coefficient (CL) equals drag coefficient (Cd).

The following torque will be applied to the blade's dr-wide portion:

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

The lift coefficient (CL) and drag coefficient (CD) change depending on the angle of attack and the type of aerofoil. These are essential for calculating the torque and forces based on the formulas provided.

The geometry-dependent parameters, such as the CL and the turbine diameter, are crucial in determining the turbine's output. Next, let's take a look at the tangential induction and the axial factors:

$$a = \frac{1}{\frac{4r \sin^3 \phi}{\sigma (C_L \cos \phi + C_D \sin \phi)} + 1} \tag{3}$$

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

[18] Introduced an approximate formula for the Prandtl tip-loss function. The Prandtl tip loss correction factor is denoted as (F).

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

Here is a description of the local solidity:

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

Subsequently, in the event that the factor of axial induction exceeds 0.4, Equation (3) will no longer yield acceptable outcomes; an alternative equation, as suggested by [18], may be employed instead:

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

[19, 20, Highlighted the imperative need to explore alternative methods for accurately estimating aerofoil behavior at high negative and positive angles of attack. In addressing this, the system based on the Viterna formulas is employed to extrapolate data from the aerofoil to the high stall/lift growth regime. Specifically, the drag-and-lift coefficients are determined within the range of  $\alpha_{\text{stall}} < \alpha < 90^\circ$ , showcasing the application of the Viterna formulas in extending the understanding of aerofoil characteristics into the challenging high-angle-of-attack conditions.

$$C_D = B_1 \sin^2 \alpha + B_2 \cos \alpha \quad (8)$$

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

Where:

$$B_1 = C_{D_{\text{max}}} = 1.11 + 0.018AR \quad (\alpha = 90^\circ) \quad (10)$$

Therefore, this paper's design departure points were:

1. Lift coefficient (CL) = 1.060 for Designs 1, 2, and 3.
2. The pitch angles (Qp) for Designs 1, 2, and 3 were 6°, 10°, and 12°.
3. Design 1, 2, and 3 had drag coefficients (CD) of 0.0160, 0.0160, and 0.0160 each.

## IV. Results and Discussion

Figure 3 illustrates the blade geometry, showcasing variations in chord length and blade radius for Designs 1, 2, and 3 without optimization. Chord length, defined as the width of the wind turbine blade at a specific point along its length, holds significance in blade design. The relationship is established, as articulated by [12], that an increase in chord length directly correlates with an augmentation in power generation. In this context, the values for blade radius were set at 0.85 m, 0.95 m, and 1 m for Designs 1, 2, and 3, respectively, with corresponding maximum chord lengths of 0.06 m, 0.08 m, and 0.1 m. Figure 3 provides a visual representation of the unoptimized blade geometry, offering insights into the initial parameters considered before the optimization process. It is noted that a similar study highlights the implementation prediction that the 7-blade prototype has given exceptional results in the coastal region of South Africa [21].

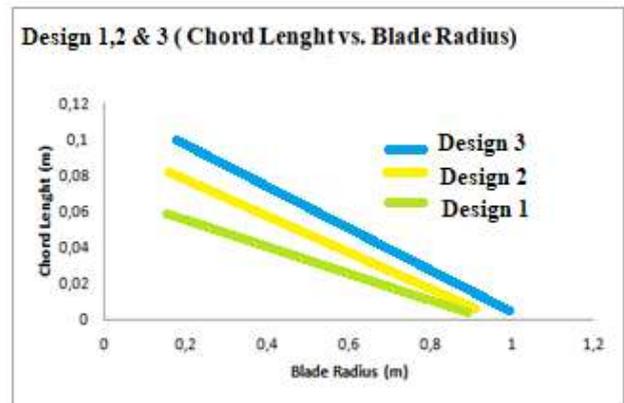


Figure 3: Chord Distribution for Designs 1,2&3

Figures 4, 5, and 6 illustrate the optimized chord radius and pitch angle distribution for Designs 1, 2, and 3, respectively. In Figure 4, corresponding to Design 1, the twist distribution of the blade reveals a design with 1.1° at the tip, gradually increasing to 6.1° at the root. For Design 2, portrayed in Figure 5, the twist distribution demonstrates a design with 1.2° at the tip, escalating to 9.9° at the root. Design 3, depicted in Figure 6, show cases a twist distribution design ranging from 1.5° at the tip to 11.9° at the root.

These figures provide a visual representation of the optimized parameters, offering insights into the nuanced variations in chord radius and pitch angle across the different designs.

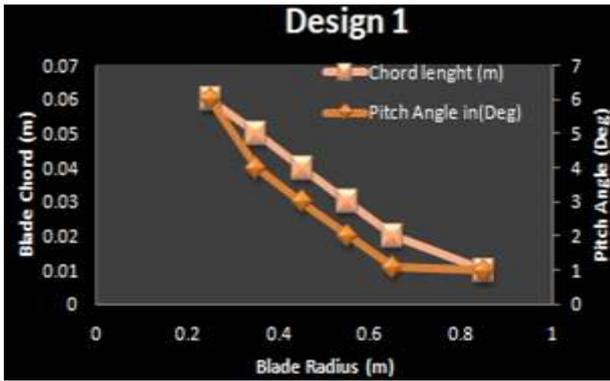


Figure 4. Radius of Chord and Twist Angle Distribution for Design 1

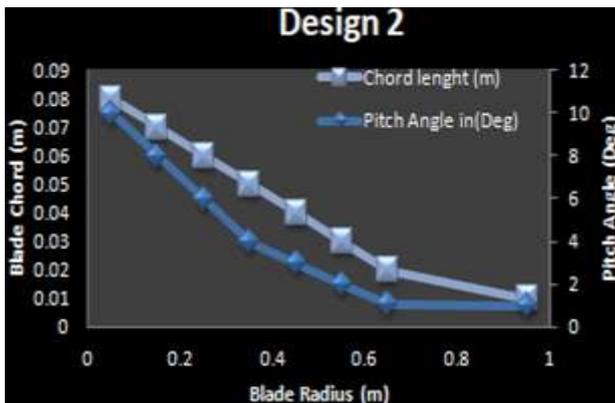


Figure 5. Radius of Chord and Twist Angle Distribution for Design 2

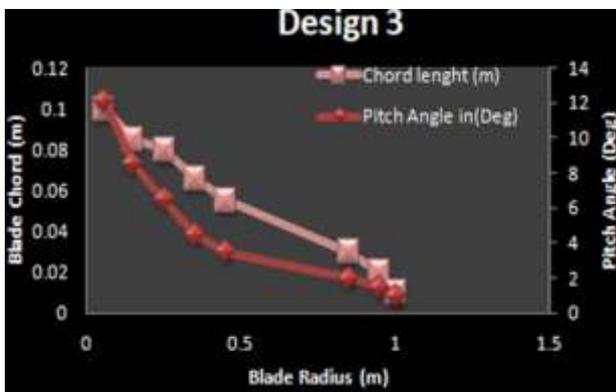


Figure 6. Radius of Chord and Twist Angle Distribution for Design 3

Figure 7 presents Designs 1, 2, and 3 at varying pitch angles of 6°, 10°, and 12°, respectively. The rationale behind this selection lies in the anticipation that an increase in the number of blades would enhance power delivery, particularly at low wind speeds. The visual representation in Figure 7 allows for a clear observation of how different pitch angles contribute to the overall design of the wind turbine blades, providing valuable insights into the optimized configurations for improved performance, especially in lower wind speed conditions.

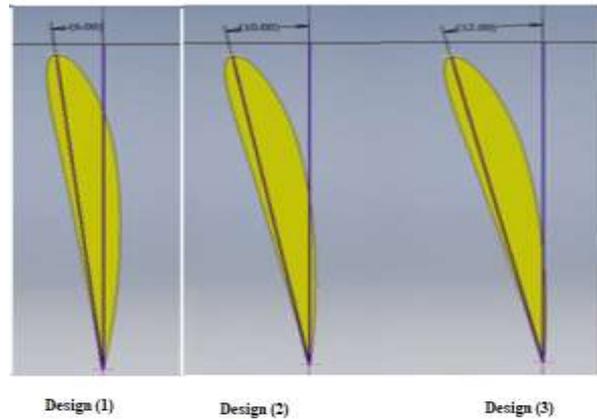


Figure 7: Twist angles chosen with respect to the hub plane for subsequent Designs 1, 2 & 3

The wind turbine system, featuring 3, 5, and 7 blades, was established, installed, and commissioned in Soweto, Johannesburg, South Africa, as illustrated in Figure 8. Experimental data were diligently gathered during this phase. Subsequent to this, advanced rotor systems with higher blade counts were conceptualized based on the earlier discussed theoretical considerations. These designs were then fabricated by an independent international supplier and subsequently assembled and put into operation in Soweto. The Wind Generator System underwent setup, installation, and commissioning in Soweto, accompanied by the collection of experimental data. Simultaneously, the Seven-Blade Wind Generator System was established, installed, commissioned, and subjected to experimental data collection in the same location. To differentiate between the various blade configurations, this paper refers to them as Prototype 1 (3 blades), Prototype 2 (5 blades), and Prototype 3 (7 blades), corresponding to the three distinct designs implemented.

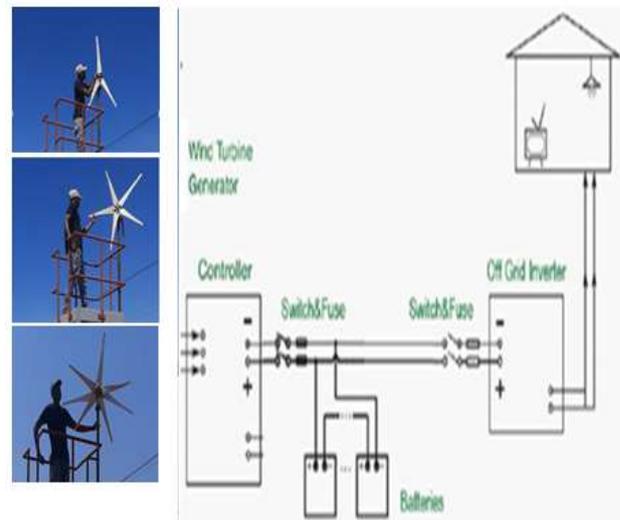


Figure 8. Prototype 1, 2 and 3, Setup, Installation and Commissioning

Table 1 summarizes all the experimental data, ranging from the number of blades to the angles of attack. It also enables a straightforward comparison among the results obtained for the three types of blades. This tabular representation provides a comprehensive overview, facilitating a quick and precise analysis of the relative performances. The inclusion of these key parameters in a unified visual format allows for a comprehensive understanding of the experimental observations. Table 1 shows that prototype 3 (7 blades) achieved the highest output power of 39.5 W, with maximum performance achieved at various low wind speed of 2.3 m/s.

Table1. Blade Design Comparative Overview

Chosen Design Criteria	Design 1	Design 2	Design 3
Blade Aerofoil Type/ Mid-Spin Aerofoil/ Tip Aerofoil/ Root Aerofoil	NACA-4412	NACA-4412	NACA-4412
Blade Quality	UV - protected Nylon fibre	UV - protected Nylon fibre	UV - protected Nylon fibre
Diameter hub (m)	0,156	0.156	0,156
Blade Number	3	5	7
Blade radius chosen (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 ( $Q_p$ ) (degree) near hub, grading/twisting towards zero along the length of the blade	6°	10°	12°
Targeted/Estimated Angle of Attack 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 ( $\epsilon = CL/CD$ )	66.3	66.3	66.3
The drag coefficient (CD)	0,0160	0,0160	0,0160
Predicted/Simulated using Q-blade software power output at various low wind speed	<b>7.5 W@ 2.3 m/s Average low wind speed</b>	<b>20W@ 2.3 m/s Average low wind speed</b>	<b>40W@ 2.3 m/s Average low wind speed</b>

## V. CONCLUSION

This paper has successfully focused on the intricate design and optimization of wind turbine blades, with a particular emphasis on key parameters such as aerofoil type, number of blades, and pitch angles along the blade radius.

1. The study affirms the suitability of NACA-4412 aerofoils, showcasing their advantageous specifications, including a low cut-in speed, broad chord area/length at small radius positions, and tapering towards the blade tip for maximizing torque and energy capture.
2. The flexibility of extending the blade radius and adjusting pitch angles along the radius contributed to the adaptability of these aerofoils. Moreover, the results underscore the positive impact of increasing pitch angles, particularly from the standard 6° to 10° and 12° near the hub, coupled with optimized attack angles for Designs 1, 2, and 3.
3. The findings reveal that Design 3, featuring a 7-rotor-blade with a maximum pitch angle of 12°, achieved the highest power output of 39.5 W, with peak performance achieved at various low wind speeds 2.3 m/s. Design 2 and Design 1 also demonstrated notable power outputs of 12.5 W and 8.2 W, respectively, at the same wind speed.
4. Importantly, the study confirms the efficacy of the Blade Elementary Method (BEM) theory as the most optimal approach for optimizing Horizontal Axis Wind Turbine (HAWT) blades, solidifying its standing as the predominant method for modeling and constructing small wind turbine blades.

## Declaration

- A South Africa patent with the following subject: “a Rotor of a Wind Turbine, a Wind Turbine arrangement, and an energy generating system” was filed in the SA patent register as Provisional Patent, SA 2017/01408, and Complete SA Patent, SA 2018/03431, by Unisa DITTC office under the name of L. W. Snyman in 2017 and 2018 respectively, after the necessary disclosures were made.
- The authors declare that this article has not been published before and is not in the process of being published in any other journal.
- The authors confirmed that the paper was free of plagiarism.

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