Journal Renewable Energy & Mechanics (REM)
DOI: 10.25299/rem.2024.vol7(02).18240
Received 2024-07-20; Revised: 2024-08-24; Accepted 2024-09-29

Vol. 07 No.02 2024
E-ISSN: 2614-8315
P-ISSN: 2714-621X

Optimization of Turbine Blade Pitch Angle of a Home-built Wind Turbine for Maximum Power Output

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ABSTRACT

Wind energy greatly reduces the world's dependence on fossil fuels (oil and natural gas), and is environmentally friendly. One of the most cost-effective alternatives of energy sources is wind power. This study used a horizontal axis wind turbine to investigate the optimal blade pitch angle that can give maximum electrical output. A proportional integral derivative pitch controller was used to establish blade pitch angles. Wind speeds of 3, 4, 5 and 6 m/s were run at every pitch angle respectively, and a maximum electrical power output was 1124.7W at a blade pitch angle of 16.8^0 when a wind speed of 6 m/s was used. Every wind speed was run for 100 seconds. A simulation, using Visual Basic 6 software, was done at the respective blade pitch angles, and a wind speed of 6 m/s. The electricity produced was recorded. The simulated electrical power produced yielded a relationship that predicted the electrical power output with a coefficient of determination (R^2) of 0.9752; this shows a very close agreement with actual electric output values.

Keywords: *Blade Pitch Angle, Electrical Power Wind Turbine, Simulation, Software, Optimal.*

INTRODUCTION

Wind, like sunlight, moonlight, and rain, is an essential component of our daily lives. Life on Earth depends heavily on the wind. In 2018, the global community was urged by the global crisis summit to look for new and renewable energy sources to replace traditional energy sources. Petrusevska (2022) distinguished and categorized wind energy as a form of renewable energy. In 2010, global wind turbine installation reached 30%, with a total capacity of 160 GW, led by the United States with 39 GW, followed by Germany and China with 26 GW (Dimitrov, 2010). Wind power is an environmentally benign and sustainable energy source (Ming *et al.*, 2016). It significantly reduces the world's reliance on oil and natural gas while not damaging the environment (Zhang *et al.*, 2015). This study looked into the optimal wind turbine pitch angle for maximum electrical power generation. The design parameters were selected and adjusted for Kenya's specific environmental circumstances.

The way the air responds to varying pressures across the globe is known as wind. Wind is the flow of air that equalizes these differing pressures. This phenomena is explained by the second law of thermodynamics, which states that every system strives for the largest entropy possible (Bergman, 2011; Eastop and McConkey, 1994).

Air pressure is often higher at the equator than it is at the poles. The warmer temperatures in the tropical areas are the primary cause of this. Different wind speeds can be caused by a variety of factors, such as the sun, clouds, temperature, humidity, and topography. These criteria dictate that winds in the northern hemisphere should originate from the south. But the wind from the south blows east because of coriolis force (Liu *et al.*, 2019). According to Burton *et al.* (2011), the Coriolis force is the inertia acting on moving objects within a rotating frame of reference relative to an inertial frame.

Small horizontal-axis wind turbines (SHAWTs) must be installed in areas with limited wind resources. According to Culotta *et al.* (2015)), SHAWTs are defined as those that produce a voltage of less than 1000V AC or 1500V DC and have a swept area of less than 200m^2. A cut-in wind speed of 4 m/s is another characteristic of SHAWTs (Clarke and Eng, 2018; El Zein, 2019). According to Davis *et al.* (2023), at a height of 10 meters above the earth, the average wind speed over 50% of the planet is 6.04 meters per second. Buildings, trees, and mountains all stand at this height and obstruct the wind's ability to flow freely. Due to these characteristics, the wind speed is reduced and turbulence increases, rising two to three times the height of the obstruction and two to ten times the frontal contact section (Martón *et al.*, 2021; Martón Lluch *et al.*, 2019).

A home-based wind turbine can be used in homes to generate power for domestic use. Wind energy is a clean source of fuel, which means it does not produce environmental emissions of greenhouse gases (Kalyani *et al.*, 2015). Wind energy is sustainable and reliable. This means as long as the sun rises and heats the earth surface and the earth will rotate, the movement of heating the earth surface and the earth rotation generate wind (Kazimierczuk, 2019; Mukulo *et al.*, 2014; Takase *et al.,* 2021). Wind energy is cost effective; materials used to fabricate a domestic wind turbine were readily and cheaply available thus making power cheaper by four to six cents per kilowatt-hour as compared to the electricity from the grid (Council, 2017; Kanyako and Baker, 2021; Karki and Billinton, 2004). Over the past few years, there has been a 35% annual average growth in the use of wind energy worldwide. The main wind energy investors are from Europe, China, the United States, Germany, and India. The demand for solutions to combat global warming, combined with technological advancements and economies of scale, has made wind energy the most likely alternative to replace nuclear and fossil fuels (Long *et al.*, 2023; Ming *et al.*, 2016; Saidur *et al.*, 2010). This study has contributed knowledge in the field of renewable energy; especially wind energy.

MATERIALS AND METHODS

2.1 Introduction

In this study, power was produced using an existing model of a horizontal axis micro wind turbine. The turbine's specifications are displayed in Table 2.1 below:

Table: 2.1: Wind turbine specifications.

Item	Value	Item	Value
Rated power at 5m/s	500 W	Generator type	Plda50.pma
Blade diameter	1 m	Power rating	0.5 kW
Hub height	10 m	Voltage rating	14/28 V
Swept area of blade	0.785 m^2	Ampere rating	1.79/3,57 A
Rotor speed	20-500 rpm	Torque	< 0.15 Nm
Tower type	Tubular	Power efficiency	> 65%

Location of study

The project was done in Kinangop area of Nyandarua County in Kenya. The average speed of wind in this location is 6.2 m/s according to Porté-Agel *et al.* (2011). However, at the time of this study, the average wind speed was 6.3 m/s in the south-west direction. The area did not have tall buildings that would obstruct wind flow. The sky was clear and with an average temperature of 22^{0}C. Geographical coordinates for Kinangop are 37^0 40” E, 36^0 42” N.

Materials and Equipment

They included a small horizontal wind turbine, anemometer, ohm-meter, voltmeter, ammeter, alternator, and tower.

The experimental set-up was as given in figure 2.1

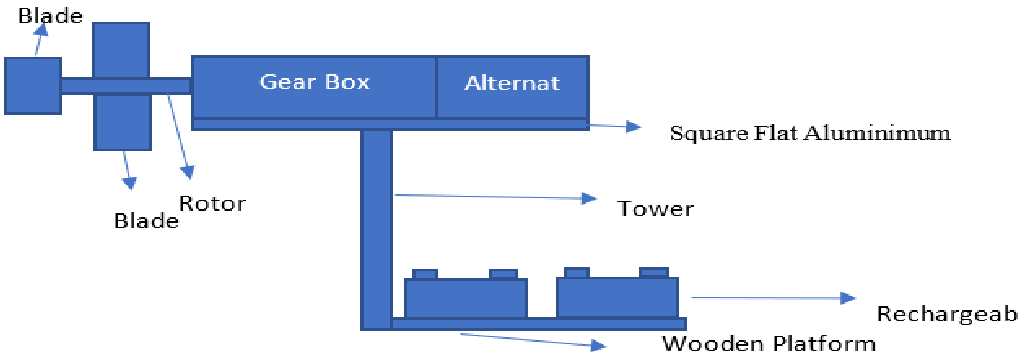

Figure 2.1: Wind turbine assembly

Description:

The blades were casted with fiberglass and mounted into a mound the shape of a wind turbine. After 3 hours the mound was removed. Sharp edges were removed and the blade was measured 2m and cut to the right length. Three holes were drilled on the blade and bolted to the shaft. The shaft was connected to the hub that was carrying the 3 blades. The alternator was then mounted to the housing and supported by the base plate. The housing was then screwed firmly the turbine tail (aluminium square plate) on the other end. The platform was then mounted to the tower. Using anemometer, the wind turbine was correctly positioned in the direction of the wind. The tower was installed into the ground firmly. Steel nails were used to secure the tower into the ground.

METHODS

2.4.1 To establish various blade pitch angles of a wind turbine

The following procedure was done:

i. The pitch angle controller software was based on proportional integral derivative (PID). The software was mounted onto the wind turbine set-up.

ii. An in-coming lowest wind speed of 3 m/s (herein called cut-in, c_{in}) was input into the software.

iii. An out-going maximum wind speed of 7 m/s (herein called cut-out, c_{out}) was input.

iv. The 3 m/s wind speed was run against the blades for 100 seconds.

v. A mathematical algorithm done by Kumar and Chatterjee

(2016) in the software established the probable pitch angles.

2.4.2 To determine the optimal pitch angle for maximum electric power output.

The procedure was:

i. The lowest pitch angle of 0.0^0 was set in the software to enable the blades to tilt at that angle when the wind blows.
ii. Wind speeds of 3, 4, 5, and 6 m/s were blown respectively against the blades for 100 seconds.
iii. The electrical power produced in every wind speed at a pitch angle of 0.0^0 was recorded.
iv. Steps i, ii, and iii were done for pitch angles of 5.6^0, 11.2^0, 16.8^0, 22.4^0, 28.0^0, 33.6^0, 39.2^0, 44.8^0, 50.4^0, 56.0^0, 61.6^0, 67.2^0, 72.8^0, 78.4^0, 84.0^0, and 89.6^0.

2.4.3 To simulate the blade pitch angle and electrical power output.

The steps undertaken are as outlined:

i. Visual Basic 6 software was attached to the horizontal axis wind turbine (HAWT) to control and simulate blade pitch angle.
ii. The HAWT was run using a wind speed of 6 m/s for 100 seconds at every blade pitch angle to produce electric power.
iii. The measured data were presented in real time.

Note: Additionally, a recording data system based on Microsoft Office Excel linked with Visual Basic 6 was installed in the monitoring system.

RESULTS AND DISCUSSION

3.1 Establishment of various blade pitch angles.

The PID controller gave the following blade pitch angles: 0.0^0, 5.6^0, 11.2^0, 16.8^0, 22.4^0, 28.0^0, 33.6^0, 39.2^0, 44.8^0, 50.4^0, 56.0^0, 61.6^0, 67.2^0, 72.8^0, 78.4^0, 84.0^0, and 89.6^0.

Turbulent movement of wind coupled with a fluctuation in the speed of wind impede the efficient working of a wind turbine, and may cause its failure with catastrophic consequences (Ouyang *et al.*, 2017). Determining the angle of incidence between the blade and the wind flow allows one to adjust the force of the wind on the rotor, which is why it's crucial to run a wind turbine with variable speed (Menezes *et al.*, 2018). Proportional integral derivative (PID) control is one of the suggested strategies for regulating a wind turbine's blade pitch angle. It works by using a mathematical algorithm of the system with feedback from the controlled variable to determine the error between the desired and measured values (Kumar and Chatterjee, 2016). Noton (2014) found out that the weights of the integral time, the time of the derivative, and the proportional constant affect how the PID controller is adjusted (gains). The goal of adjusting optimum gains is to achieve the intended control response. Nonetheless, it's crucial to remember that the ideal reaction in a variable-speed wind turbine varies depending on how much the wind speed varies. Researchers Chavero-Navarrete *et al.* (2019) and Sruthi *et al.* (2017) have noted that this property causes a PID controller to become unstable when wind speed fluctuates significantly.

The maximum power point tracking (MPPT) system, which employs the optimal torque, is applied by the mathematical method, which is based on an indirect power control (IPC) model (Merabet *et al.*, 2011). In this instance, the generator's torque is regulated to achieve an optimal torque (OT) reference curve, which is based on the highest power output at a specific wind speed (Abdullah *et al.*, 2012; Ganjefar *et al.*, 2014; Nasiri *et al.*, 2014). The research conducted by Bianchini *et al.* (2015), Molina and Mercado (2011), Neammanee *et al.* (2010), Schinas *et al.* (2007), and Muljadi and Butterfield (2001) is consistent with the IPC model.

A fuzzy logic controller is an additional technique for managing the pitch angle to lessen the impact of wind speed on a wind turbine (Xiao *et al.*, 2015). The intended pitch angle is then controlled by the fuzzy logic controller (FLC), which first determines the previously computed gains for the error, whether they are large, positive, or negative (Baburajan, 2018; Civelek *et al.*, 2016). The gain values are ascertained when the controller employs artificial neural networks (ANNs) (Kang *et al.*, 2014). In a separate finding, Taher *et al.* (2013) demonstrated that in "differential evolution," the PID gain values can be adjusted using an optimization technique in response to changes in operating points. Behera *et al.* (2016) and Hodzic and Tai (2016) discovered that a "particle swarm" optimization approach can be used to modify the proportional and integral gains of a proportional integral derivative controller. In a study by Ebrahim *et al.* (2018), the PID parameters were the moth's location in a Three Dimensional (3D) search space, and the moths were changed throughout the "flame-moth" optimization method. (Chavero-Navarrete *et al.*, 2019) computed the gains of a PID controller using an optimization approach based on the teaching-learning paradigm of a classroom.

Since the controller is modified for each of these wind speed ranges, all of the aforementioned observations were made with the goal of enhancing the response of the control signal for various wind speed ranges. The pitch angle's mechanical rotating speed is these methods' main drawback (Ouyang *et al.*, 2017). For this investigation, however, the PID controller described by Kumar and Chatterjee (2016) proved to be adequate.

3.2 Optimal blade pitch angle for maximum electric power output

Table 3.1: Rotational speed vs Pitch angle

Pitch angle (^{0})	Wind speed (m/s)				Pitch angle (^{0})	Wind speed (m/s)			
	3	4	5	6		3	4	5	6
0.0	0	0	0	0	50.4	0	38	63	93
5.6	0	92	142	202	56.0	0	18	47	81
11.2	0	124	182	252	61.6	0	2	27	57
16.8	20	135	202	282	67.2	0	0	18	39
22.4	0	117	162	218	72.8	0	0	2	6
28.0	0	106	146	195	78.4	0	0	0	1
33.6	0	96	117	145	84.0	0	0	0	0
39.2	0	81	99	123	89.6	0	0	0	0
44.8	0	45	78	117					

The corresponding graph given by Excel is as shown in figure 3.1

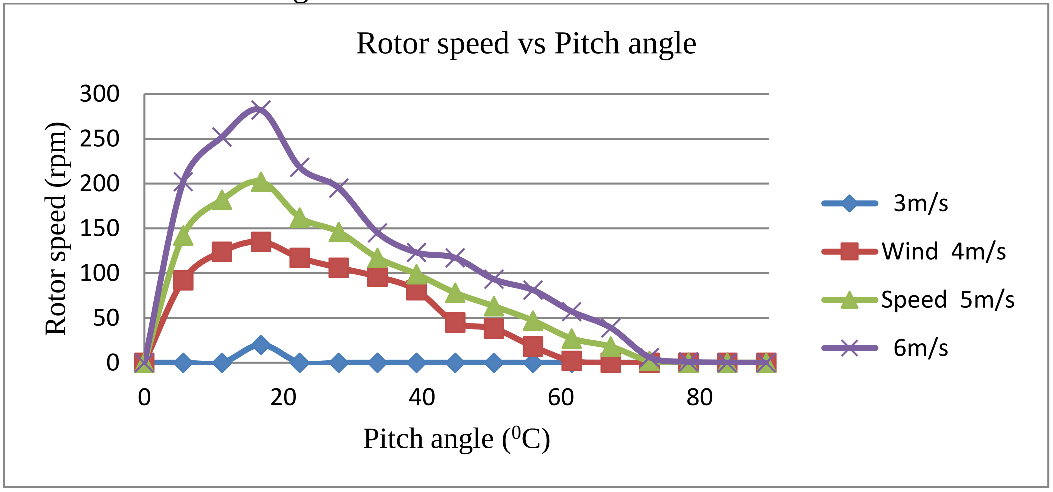

Figure 3.1: Rotor speed vs Pitch angle

Table 3.2 shows the data collected on electricity generated for 100 seconds.

Table 3.2: Pitch angle vs Electric power output

Pitch angle (^{0})	Electric power (W)	Pitch angle (^{0})	Electric power (W)
0.0	0.00	50.4	415.38
5.6	850.77	56.0	353.28
11.2	1008.09	61.6	233.22
16.8	1124.70	67.2	214.59
22.4	961.86	72.8	61.41
28.0	862.50	78.4	0.00
33.6	685.86	84.0	0.00
39.2	536.13	89.6	0.00
44.8	500.94		

Figure 3.2 shows a graphical representation of the data in Table 3.2

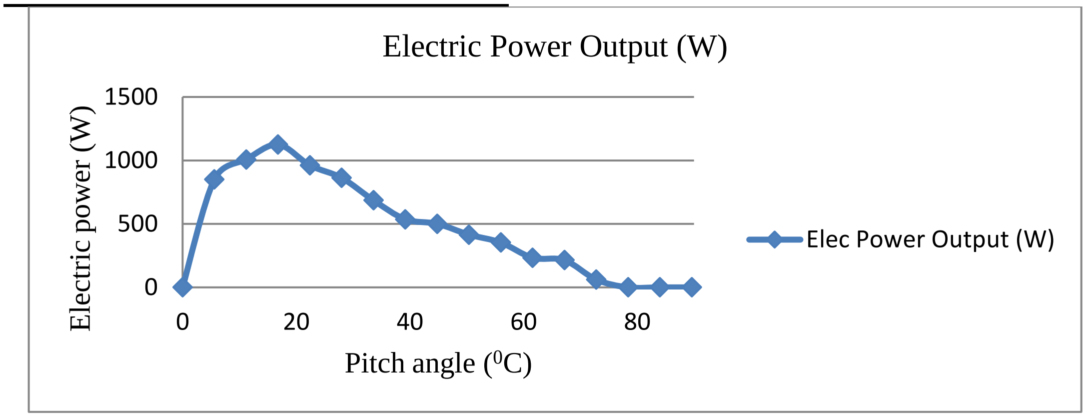

Figure 3.2: Electric power output vs Pitch angle

Another way of identifying the optimal pitch angle is to analyse the power conversion efficiency recorded by the power conversion unit (an alternator in this study) in the wind turbine assembly. Table 3.3 shows the data.

Table 3.3: Power conversion efficiency

Pitch angle (^{0})	Power Conversion efficiency (%)	Pitch angle (^{0})	Power Conversion efficiency (%)
0.0	0	50.4	14
5.6	24	56.0	12
11.2	27	61.6	10
16.8	31	67.2	7
22.4	28	72.8	6
28.0	25	78.4	4
33.6	21	84.0	0
39.2	19	89.6	0
44.8	15		

A graphical presentation of the data above is shown in figure 3.3

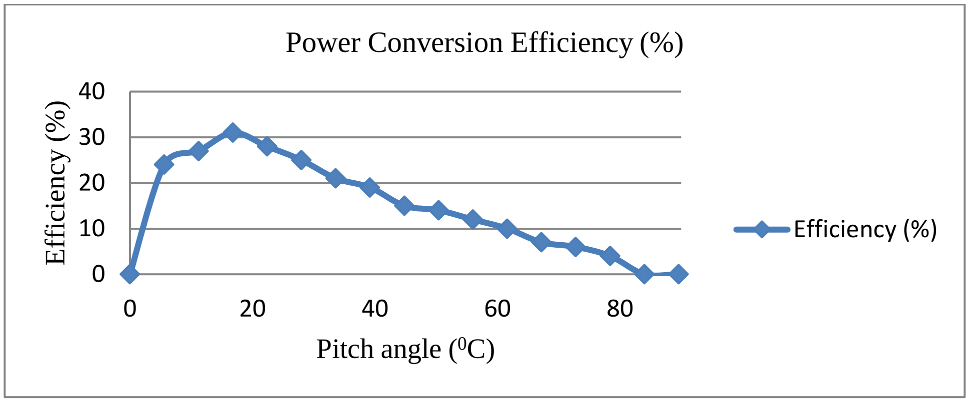

Figure 3.3: Power conversion efficiency vs Pitch angle.

The principle of working of a wind turbine is to capture kinetic energy from the wind, convert it into mechanical energy, and lastly avail it to the point of utilization. the theory behind this is outlined in the work done by Sudhamshu *et al.* (2016).

Table 3.2 shows the data that was recorded during this study. It involved the rotor rotational speed (ω) with wind speed (v) and pitch angle (β). The corresponding graph given by Excel is as shown in figure 3.1

The rotor speed rose gradually as the pitch angle increased in all wind speed scenarios, peaking at a pitch angle of 16.8^0. After that, the rotor speed decreased to zero rpm for pitch angles of 22.4^0, 61.6^0, and 72.8^0 at wind speeds of 3 m/s, 4 m/s, 5 m/s, and 6 m/s, respectively. At 16.8^0 of the pitch angle, the swept area of blades in contact with the wind had the lowest drag force and produced the most torque (Merabet *et al.*, 2011).

After achieving the highest rotor speed at a pitch angle of 16.8^0, the rotor speed declines steadily to zero. This behaviour is explained by the Weibull curve as articulated by Pedrosa *et al.* (2020), Kohout (2022), and Elmahdy (2015); that as the blade pitch angle increases above 16.8^0, the wind imparts a decreasing torque to the blades and hence the fall in rotor speed.

The site of this research (Kinangop area) has an average wind speed of 6 m/s. consequently, a further analysis is based on this wind speed. Table 4.2 shows the data collected on electricity generated for 100 seconds. The duration of 100 seconds was chosen as an average value because the steady wind speed varies between 90 seconds to 110 seconds (Biegel *et al.*, 2011).

Table 3.3 shows the data that was collected with regard to the variation of the blade pitch angle versus the electric power generated. Figure 3.2 shows a graphical representation of the data in Table 3.3

The wind power equation (3.1) as given by Eisa (2019) is as follows:

$$P = \frac{1}{2} c_p \rho A V^3 \qquad (3.1)$$

where:

P = Wind power (W), c_p = Coefficient of power, ρ = Density of air (kg/m^3)

A = Swept area of the rotor (m^2), V = Wind speed (m/s)

The rotor speed increases with increasing wind speed. This suggests that when wind speed increases, so does the output of electric power. This is due to the fact that wind power is directly correlated with the cube of wind speed (Chavero-Navarrete *et al.,* 2021; Eisa, 2019; Zou *et al.*, 2020). It was observed that the highest electric power output of 1124.7W was attained when the blade pitch angle was 16.8^0.

Another way of identifying the optimal pitch angle is to analyse the power conversion efficiency recorded by the power conversion unit (an alternator in this study) in the wind turbine assembly. Table 3.3 shows the data whose graphical presentation is shown in Figure 3.3

A blade pitch angle of 16.8^0 resulted in a high power conversion efficiency of 31%. Giordano *et al.* (2020) found out that the wind turbine's performance is determined by the speed at which wind enters its rotor. However, since wind speed is recorded at the turbine's back, where a lower value is present, this amount is rarely obtainable. The ratio of the electrical power generated by a wind turbine to the aerodynamic power of the wind at the rotor's entrance is known as the turbine's efficiency. The efficiency can also be estimated as the ratio between electrical energy and wind energies in a certain time interval (Carullo *et al.,* 2021; El-Ahmar *et al.*, 2017). This low power conversion efficiency is attributed to the losses incurred in the transmission system from the rotor to the alternator (Chavero-Navarrete *et al.*, 2021).

3.3 Simulation of the blade pitch angle and electrical power output

Table 3.4: Actual vs Simulated power output

Pitch angle (^{0})	Electric power (W)	Simulated power (W)	Pitch angle (^{0})	Electric power (W)	Simulated power (W)
0.0	0.00	0.00	50.4	415.38	461.78
5.6	850.77	621.63	56.0	353.28	318.12
11.2	1008.09	809.95	61.6	233.22	187.01
16.8	1124.70	914.74	62.7	214.59	80.48
22.4	961.86	947.99	72.8	61.41	10.53
28.0	862.50	921.73	78.4	0.00	0.00
33.6	685.86	847.97	84.0	0.00	0.00
39.2	536.13	738.71	89.6	0.00	0.00
44.8	500.94	605.98			

Figure 3.4 is a graphical representation of the data in Table 3.4.

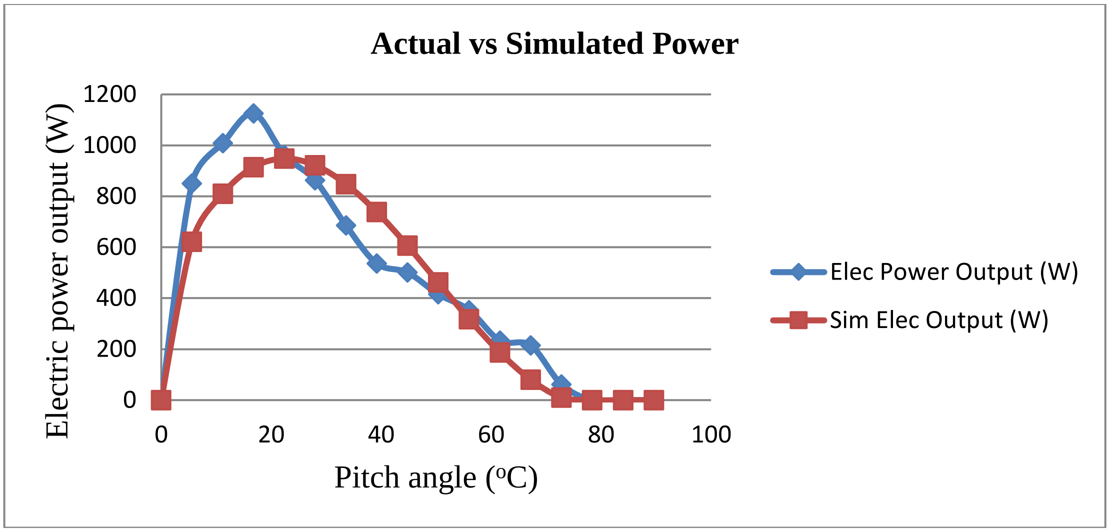

Figure 3.4: Actual vs Simulated power output

Simulation is the imitation of a situation or a process. Wind turbine simulation was done to establish the relationship between the wind speed, pitch angle and the electric power output. A wind speed of 6 m/s was used. This wind speed was chosen because the site in which the study was conducted has an average velocity of 6 m/s (Burton *et al.*, 2011). All the blade pitch angles were subjected to this wind speed. Figure 3.4 is a graphical representation of the data in Table 3.4.

The simulated values relate to the actual values by equation (3.2) with a coefficient of determination (R^2) of 0.9752.

$$y = 0.0127x^3 - 1.969x^2 + 73.84x + 140.63 \qquad (3.2)$$

where: y = power output (W), x = blade pitch angle (^{0}C)

The variation in the actual response values that a prediction model with specified independent parameters can explain is measured by R^2 (Eterkin and Firat, 2015; Hossain *et al.*, 2007; Mukhopadhyay *et al.*, 2013a). In this instance, the R^2 value was 0.9752, indicating that the model can account for 97.52 percent of the variation in the sample. According to Niladevi *et al.* (2009) and Sen (2008), an excellent statistical model has an R^2 between 0.75 and 1.0; the results of this investigation show that the model fits the data well. Therefore equation 4.1 may be used to predict the power output of a horizontal axis wind turbine at the various blade pitch angles with a constant wind speed of 6 m/s.

An aeroelastic simulation tool for horizontal axis wind turbines is made with Visual Basic 6. It can endure a range of aerodynamic loads that could be harmful to the wind turbine's mechanical parts, structures, and output of power (Ahlstrom, 2005). The performance of Visual Basic 6 is quite similar to the computational fluid dynamics (CFD) simulations performed by Nguyen *et al.* (2021) to ascertain the impact of various blade pitch angles on the forecast of power production of a horizontal axis wind turbine at diverse loadings.

When producing wind electricity, a thorough dependability and cost-evaluation method is crucial. It should be noted that the Visual Basic 6 Simulator was developed using both analytical methods (Abouzahr and Ramakumar, 1991; Giorsetto and Utsurogi, 1983; Wang *et al.*, 1984) and Monte Carlo simulation (Billinton and Bai, 2004; Karki and Billinton, 2004) for evaluating the suitability of power generation systems. These simulation techniques identify the wind variation's chronology and how it affects a power system (Abouzahr and Ramakumar, 1991). Additionally, Billinton *et al.* (1996) provided an approach that used a time-series auto regressive and moving average (ARMA) model to mimic the hourly wind speed. Karki and Hu (2005) also provided experimental backing for this idea.

CONCLUSION

A proportional integral derivative (PID) controller was applied on a horizontal axis wind turbine (HAWT) to help in varying the blade pitch angles. A cut-in and cut-out wind speed of 3 m/s and 6 m/s were input in the software. The following blade pitch angles were established: 0.0^0, 5.6^0, 11.2^0, 16.8^0, 22.4^0, 28.0^0, 33.6^0, 39.2^0, 44.8^0, 50.4^0, 56.0^0, 61.6^0, 67.2^0, 72.8^0, 78.4^0, 84.0^0, and 89.6^0.

An optimal blade pitch angle for generating maximum electrical power was 16.8^0. A wind speed of 6 m/s yielded 1127.4W at this angle. The highest power conversion efficiency of 31% was also recorded at this blade pitch angle.

Visual Basic 6 Simulator was used to determine a relationship between blade pitch angles and the electric power production. A constant wind speed of 6 m/s was used. An equation for predicting electric power output with an R^2 value of 0.9752 was established.

ACKNOWLEDGEMENT

We appreciate the services accorded to us by the Kinangop Meteorological Station management and fraternity during the time of the research.

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