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DESIGN AND FABRICATION OF A WIND SIMULATOR FOR RENEWABLE ENERGY TRAINING AND RESEARCH IN NIGERIA

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ABSTRACT

Every year, the laboratory offers a variety of teachings, demonstrations, and initiatives related to renewable energy. Different researchers match the needs of the students' work depending on the area of activity. However, little is achieved in Nigerian institutions regarding wind energy research and demonstration. The lack of laboratory facilities for the training of students in wind turbine technology could be one of the reasons. The proposed Framework is a scaled-down version of the available wind turbine power plant. The proposed device would make it possible to work with students at Nigeria Universities, to practice the wind turbine simulator in a working and configurable model. The simulator gives insight into the various components and implications of changes to the operating points of any wind turbine in light of the wind speed and the pitch angle. Students will learn concepts such as the I-V characteristics of a wind energy system, cut-off, cut-in velocity, and power output. It would also enable the user to control the wind speed externally. The proposed wind lab will also be worthwhile for conducting a wind resource evaluation at various sites. Wind resource assessment, like other technical projects, needs planning and coordination. The developed wind simulator lab is beneficial in real-time data monitoring to justify further site-specific investigations, to compare areas to identify relative developmental potential, to get representative data to estimate the performance and/or economic viability of selected wind turbines, and to monitor the potential for wind turbine use because of it cost-effectiveness.

Keywords: Wind Lab, Training, Wind Energy, Wind Turbine Model, Simulator

INTRODUCTION

As a result of technological advancement and industrialization, the use and price of fossil fuels have become increasingly high (Aidonojie et al., 2023, Chung et al., 2023, Restrepo, 2021). Also, this has caused an increase in the emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2), methane (CH_4), surface-level ozone (O_3), nitrogen oxides, and fluorinated gases, which contribute to global climate change (Ukhurebor et al., 2022). Hence, there is a need for cleaner renewable energy sources such as wind and solar energy (Hassan et al., 2023). With the increasing worldwide recognition of renewable energy technologies (RETs), alternative energy sources are expected to become the primary sources of global energy demand at some stage in the future. Some researchers (Ajewole et al., 2017; Martin et al., 2020 and Ter et al., 2025) in particular, used wind energy conversion technology (WEC) as the promise of the electricity resource, which can eventually replace the traditional energy resource in the longer term, even though it currently supplements the generation of fossils, as global supply decreases quickly (Clausen & Wood, 1999, (Martin, Jung, & Vanli, 2020). However, the truth remains that once demonstrated correctly in the region, electricity companies would not want to apply emerging technologies in the new territory (Clausen & Wood, 1999, (Martin, Jung, & Vanli, 2020).) RET education, research, and facilities must therefore be affordable for the growing desire for Nigerians to use renewable energy resources for the safe production of power (Clausen & Wood, 1999). To achieve this, Nigerian

Electricity Supply Industry is undergoing a complete overhaul by the government in an effort to enhance the country's electrical services. Rehabilitating government-owned electrical infrastructure in 1999 and putting the 2010 Power Sector Reform into effect marked the beginning of the reform. While some stakeholders have seen these reforms improve the industry, the general public have yet to witness the positive impact of the reforms (Babatunde *et al,* 2023). Majority of Nigerians are yet to witness the impact of electricity reform because the electricity sector is characterized by administrative shortcomings and infrastructural deficiencies. Due to this obvious fact the energy sector is undergoing a significant transition (from an energy production model to a consumption model). Energy-related laboratories and experimental facilities are becoming increasingly important in the modern world. For new and developing topics, engineering laboratories are crucial for giving graduates of universities appropriate training and education (Guo et al., 2022). This is a crucial component of any learning paradigm and promotes efficient knowledge transfer methods. A platform for study in real-world settings is provided by laboratory facilities, particularly in the applied sciences and engineering technology sectors (Ndunagu, Ukhurebor, & Adesina, 2023). It is important to note that industry trips are unable to give students practical experience or a platform for experimentation Chung et al., 2023. Consequently, mechanical frames, a software part for the proof and validation of wind energy converting systems in new wind regions, are designed as an economical experimental facility that will make up the proposed Wind Lab Simulator. A realistic wind speed profile on the simulator would be implemented with the hardware interface for a motor-driven wound rotor induction to check its performance under an almost-true-world scenario, and during the experiment, the simulator precisely replicates some functions of the real wind conversion systems. The simulator could therefore be considered suitable for use as a laboratory testbed for wind demonstration and validation. As stated earlier, the growing desire for renewable energy resources for safe power production, education, science, and RET growth must be affordable in some emerging African countries. The manufacture of a demonstration system, such as the proposed wind laboratory simulator, is a technological approach to validating wind energy resources on site. This training practice for wind turbine systems in Nigeria can be extremely expensive to accomplish using advanced wind turbine simulators. The use of the proposed RET simulation model can provide our students with acceptable, cost-effective trial and demonstration environments. so that the obstacle of high cost can be overcome by importing the technology. Albeit, this present study aims to design, fabricate, and evaluate an almost-true-world scenario of demonstration of a WEC device model on a laboratory scale. The model is designed to simulate wind turbine operations and, therefore, to provide WEC technology with cost-effective and environmental testing. An attempt will be made to produce an artificial wind generator for laboratory simulation purposes, conduct a performance assessment in a controlled environment on the fixed pitch wind turbine, deploy the fabricated system for students' practical and research demonstration of wind turbine cut-in speed, assessment of tip speed ratio (TSR) at different wind speeds, assessment of the performance coefficient of a typical wind turbine, and enhance student practical expertise in the energy analysis of different branches with an AC load-only wind turbine system and the power analysis of different branches with a DC load-only wind turbine system.

Literature Review

Africa faces the challenge of producing more capacity to fulfill current and potential demands with over half a billion people lacking access to energy on the continent (Abanihi et al., 2020). Many countries have a clean and secure potential to do this. For example, with clean energy options, the Continent is well positioned to remedy current power shortages with possible alternatives as shown in Table 1. Indeed, Africa's renewables are world's highest and the continent has sufficient potential for renewable energy to meet its future energy requirements (Kayizzi-Mugerwa et al., 2016). Africa is estimated to have 18 of the 35 most advanced countries with green energy reserves at the top, standardized by annual domestic energy consumption (Hafner et al., 2018). Likewise, in the developing world there are at least eight African countries most equipped with wind power (Kayizzi-Mugerwa et al., 2016), (Rajendran et al., 2023). While global wind power production remains underdeveloped compared to the development of other renewables like hydroelectricity, it grew by an average of approximately 30% annually from 1996 to 2008; wind production is one of the most rapidly growing energy resources worldwide in terms of both scope and technology (Hafner et al., 2018), (Kayizzi-Mugerwa et al., 2016). The increase reflects, in particular, technological developments and energy security issues over a decade that has seen some of the highest prices of oil in history (Ogiesoba-Eguakun et al., 2023). Climate change considerations have also played a role. The situation in Nigeria is no different from the situation in other countries in Africa. In fact, because of the lack of training and expertise in the use of these technologies, wind energy systems develop and deploy very slowly. The situation is changing; however, as renewable energy demand is growing.

Table 1: Developing Regions with the Highest Potential for Solar, Wind, Hydro and Geothermal Energy

Region	Total Renewable Energy	Solar	Wind	Hydro	Geothermal
Africa	18	24	8	11	9
East Asia/Pacific	4	5	3	6	4
Europe/Central Asia	3	0	6	5	14
Latin America/ Caribbean	7	5	8	9	3
Middle East	1	0	1	0	0
South Asia	0	0	1	1	0
All World Bank Regions*	33	34	27	32	30

Source: (Kayizzi-Mugerwa et al., 2016)*188 countries (close to world total of 193 countries per the World Almanac statistics 2012)

A number of mechanisms, like irrigation pumps, can be used to control or generate electricity with wind turbine mechanical energy. Wind turbines are key tools in the rural areas and are still limited in some parts of Nigeria. Wind turbines can accelerate Nigeria's electrification that includes both large-scale and small-scale systems that can for example form an integral part of a mini-grid, together with solar PV (Ecosense. 2014, Hafner et al., 2018). Wind speed depends highly on pressure gradients and landscape shape, hence highly favoured in deserts, coastlines and natural channels. Renewable energy education is growing in response to issues such as oil scarcity and global warming (Rajendran et al., 2023). Student interest in these topic areas is growing, and clean energy systems as well as greenhouse solutions for trained manpower are increasingly needed by the industry and government. A team at Edo State University Uzairue has taken up this challenge. The aim of this research is to develop a wind turbine technology to improve students' understanding of this technology.

MATERIALS AND METHODS

The Wind Energy Lab System is a scaled-down version of a real wind turbine power plant. This device allows students to work with a wind turbines model that works and is configurable. This technology will simulate and instruct the various components and the effects of modifying any wind turbine points, as described in wind speed and angle of pitch. The students will be able to learn concepts such as the IV features, a cut-off speed, the performance coefficient of a wind turbine, the Tip Speed Ratio (TSR) for wind speeds and power analysis in a variety of wind turbine-only power systems with AC load. The major components of the wind lab are: 1. Artificial wind blowing system (electric motor and fan blades) 2. Wind turbine generator unit (aerodynamic blades, gearbox mechanism, and alternator). 3. Variable frequency drive (VFD) board. 4. Signal control and display unit (wind speed, motor rpm, voltage, current, and power monitoring and control system). 5. Power backup unit (lithium-ion battery bank). 6. Remote monitoring and control unit (smart Android Bluetooth control app). 6. Tachometer with Sensor. 7. Anemometer. Design Concept: The design of the proposed simulator is mechanically powerful at a maximum output of 2000W at a rated wind speed of $1 m/s^2$-$12 m/s^2$ and along with ten test runs to determine the reliability of the wind turbine simulator. The analog real-life windspeed data flow to the facility via the input scheduler of this software component.

The scheduler includes the analog/digital converter and the giga-processor card (GP) of the RTDS measures the mechanical speed of the simulator from the rotor speed determined by the encoder. The torque output of the soft model is multiplied by the gear system ratio and converted into a voltage signal for the engine excitement interface. The conversion takes place at the engine drive with a full-scale analog torque to the rated torque engine. The drive is used to supply voltage signals to the motor that correspond with the momentary torques that are generated at different wind speeds. As the engine drives a super synchronous speed directly connected WRI machine, the expected electrical power is generated. A novel part of the proposed wind simulator is that it can be controlled from an android mobile phone, and all data from a phone itself can be read (The Isometric view in Figure 2). The PC/Screen and the mobile phone display in real time the entire system's functionality for real-time monitoring is designed to create the special mobile PC data acquisition interface: ambient and humidity temperatures, wind speed, wind direction, speed generator, generator output current, voltage/power, etc. the key deliverables of the proposed Wind Energy Lab system are as shown in Table 2.

Table 2: Key Deliverables and Description

Key Deliverables	Description
Novel Design	Compact design and fabrication of the Wind Lab having system software and mobile compatibility. Student's android phones can control and monitor the activities on the wind lab.
Usability	It can be used both indoors and outdoors
Specifications	A 300-Watt Wind energy training system with artificial wind generator, charge controller, inverter cum lithium-ion battery, AC/DC Loads.
Features	Provision to varying wind speed, ability to calculate and turn-in the power of the wind mass and, the controllability of the angle of attack of the wind flow on the rotor blades by the pitching mechanism. The speed of the wind simulator hub, the mechanical power and the mechanical torque developed by the hub can also be demonstrated. Production of real power with the corresponding reactive power consumption by the generator and the power factor of the generator can be evaluated.

Principle of Operation of the Wind Energy Training System

The Wind Lab simulator consists of hardware parts, which are linked to a software model, as is shown in Figure 1. The soft framework is built on the computer-assisted design platform of the digital simulator in real-time using a component model library block set (RTDS). The soft signal output activates a direct current engine, which is conditioned to operate in the torque control mode with an external analog voltage signal. The current electric power is generated by a wound rotor induction (WRI) system powered by a servomotor. The grid interface generator forms the hardware part of the simulator.

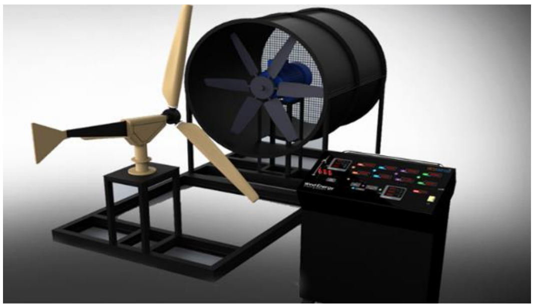

Figure 1: A Typical Wind Energy Training System (Ecosense, 2014, Ajirlo, 2021)

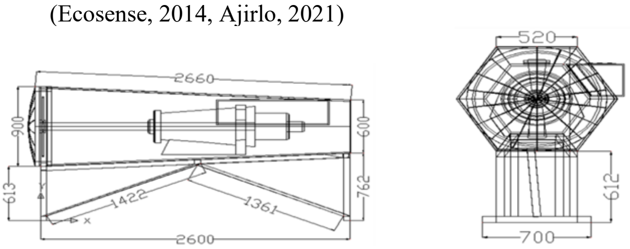

Figure 2: Isometric View of the Proposed Wind Lab

Construction Process

Machine construction involves several techniques which includes boring, keyway cutting, machining, drilling, slotting, oxyacetylene gas welding, electric welds, and grinding (Suleiman et al., 2022). The machine symbolic is depicted in Figure 1-2. Accessibility and ease of assembly were critical considerations throughout the modelling of the wind turbine laboratory fabrication. Components are diligently linked thoughtfully. The initial step is to weld each flange to its corresponding location as shown in Figure 3. 2.5mm Mild steel plates and 1.5mm angle bars were used to construct the tunnel and frames, respectively. The frames were welded together, with the vent wind tunnel sitting the frames with rollers as support and mobility. The concept of design and fabrication allows one to demonstrate a wind turbine with rotor blade pitching and a variable speed generator. The axial fan in the wind tunnel has a variable speed and provides the airflow required for the experiments. The generator is driven directly by a 3-blade rotor. A servo motor is used to change the angle of the rotor blades. Figure 6 and Figure 7 denote the variable-speed motor and the blades or blower were bought and constructed. The wind turbine was mounted on a frame (angle bar and mild steel pipe) with bolts and nuts to support the base as depicted in Figures 4 and 8 (Suleiman et al., 2022).

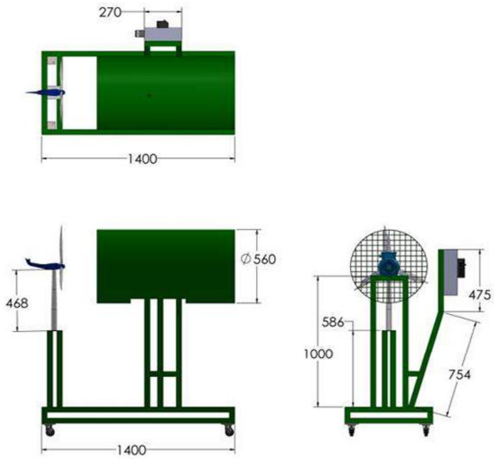

Figure 3: Side and Front View of the Open Wind Tunnel

Figure 4: Photograph of the Wind Turbine Simulator

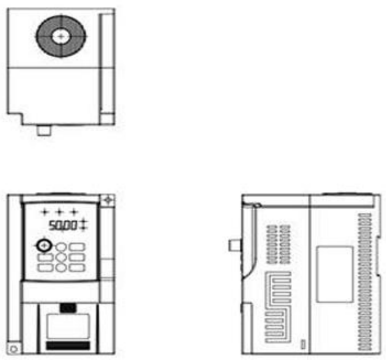
Figure 5: Diagram of the Variable Speed Motor

The Motor and Its Controller
This section controls the motor speed and wind speed. The power pack is connected to the motor controller through a box switch. Subsequently, attach the motor to the motor. By an input voltage of 220V alternate current and a voltage regulation range of 50 –220V, the peak power is 2000W. Various critical parameters must be met for the system to function accurately. Distinctively data such as wind velocity, speed, electrical power and temperature are measured through the instrumentation box and a weather station.

Power Developed for Wind Turbine Model
Figure 4 denotes how the power generated is compute by a typical wind turbine calculated by the following equations (Kojabadi & Chang, 2011).

$$P_{output(wind)} = \frac{1}{2}\rho A \bullet \upsilon^3 C_\rho \quad (1)$$

Where: ρ – Air density, kg/m^2 A – Area of blade coverage, determine through knowledge of blade length, m^2 v – Wind speed, m/sec - Power coefficient where, max = 0.59 and is known as Betz's coefficient.
Wind speed is the singular pertinent variable for determining wind power generation at the chosen locations for wind farms. Wind speed controls the RPM of the blades connected to the generator rotor and thereby the generator's electrical output. Wind speeds are more consistent at heights of some 100m above prevailing hilltops, which is one of the reasons for sighting wind turbines on tall towers along ridges and above cliffs. Research and studies are performed on the average wind profiles of the location to test the feasibility of a wind farm establishment. If determined suitable, this wind data is used to select the optimal size generator to optimize its power generation over the expected range of wind speeds and maximize its time spent generating rated power.

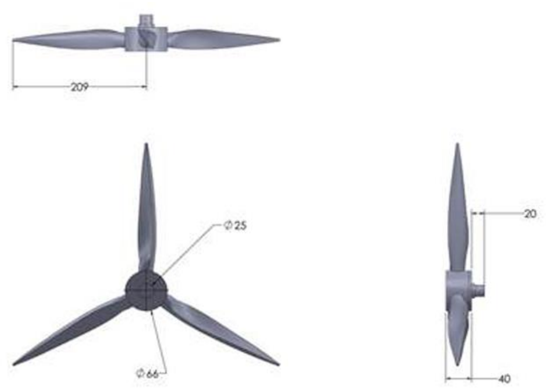

Figure 6: Diagram of the Blower

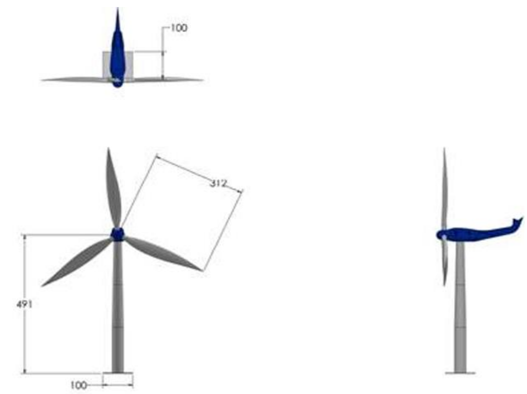

Figure 7: CAD Diagram of Wind Turbine

Customizable of Component features

Customizable features of the Wind Simulator system, as depicted in Figure 4, offers are: 1. Removable and changeable blade profiles. This allows different and innovative blade designs to be tested and performance analyzed. 2. Adjustable blade pitch angles: Enable experiments and investigations into the benefits of adjustable pitch angles. Provides a platform to test automated power optimizing algorithms and determine the effectiveness for implementation into full-scale turbines. 3. Simulating Real Wind Profiles from Set Locations: This system can load the wind profiles recorded through the laptop and simulate the wind environment when investigating new possible wind farm locations.

RESULTS AND DISCUSSION

In this section, results are presented that were obtained from measurements performed on the wind simulator, wind tunnel test, numerical simulation, and BEM analysis. The blade element momentum (BEM) theory developed by Glauert is used to compute the output power, which is the main objective of optimizing the fabricated wind turbine lab (Suleiman *et al.,* 2022). The most popular engineering model for calculating and analyzing the aerodynamic loading of propellers and wind turbine blades is BEM, which is a generalization of momentum theory combined with blade element theory (Spera, 1994). A blade is separated into a limited number of separate pieces in BEM, each of which has a defined chord and twist angle. The continuity, momentum, and angular momentum equations can then be applied to each component to get the local thrust and torque for the entire blade. After calculating the total aerodynamic torque (Q), the following formula is used (Burton, 2011, Suleiman et al., 2022):

$$C_\rho = \frac{Q\Omega}{0.5PAU_0^3} \quad (1)$$

Where ρ is the air density, A is the swept area of blades, U_0 is the wind velocity, and Ω is the angular velocity.

Model of the Blade Movement

An airplane wing functions similarly to a blade. A pocket of low-pressure air formed on the blade's downwind side when the wind blows. The rotor then rotates as the blade is drawn toward the low-pressure air pocket. We refer to this as lift. The wind's force against the blade's front side, known as drag, is substantially less than the lift force. The rotating shaft rotates a generator to provide power, and lift and drag work together to make the rotor spin like a propeller. The following equation determines the three-phase power produced by a balanced system:

$$P_{3phase} = 3 \bullet V_{phase} I_{phase} \quad (2)$$

The RPM and the number of poles in the generator determine the frequency using the following theoretical equation:

$$f(hz) = \frac{RPM \bullet P}{120} \quad (3)$$

P stands for the number of generator poles, while RPM stands for the generator rotations per minute. It is possible to use turbines independently or in conjunction with a utility power grid. A wind farm is often constructed with numerous turbines for utility-scale wind energy sources. From an operational perspective, the wind turbine control system's job is to extend the turbine's lifespan while also providing the maximum output power achievable within the turbine ratings. The extension of turbine lifetime is determined by reductions in the structural loading of the turbine.

For the development and efficient operation of large-scale wind turbines, control techniques have been developed and are currently a key focus of the wind business today Figure 9. Managing wind turbine blade pitch angles efficiently is a crucial process in the development of control systems.

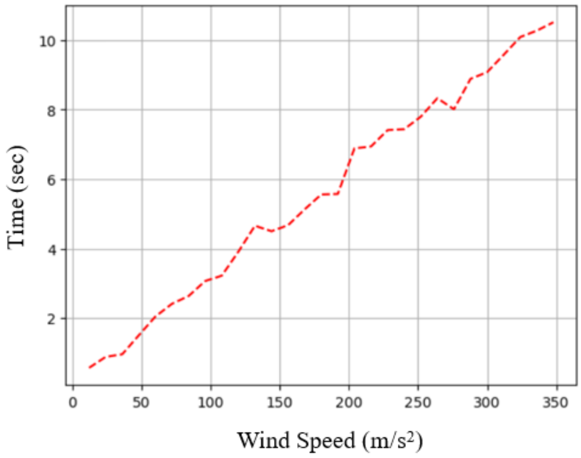

Figure 8: Trial test with the wind turbine trial. time used from the wind turbine simulator: 1 data point each second

System Familiarization

In a lab experiment, the wind turbine simulator operates at 2m/s under the specified circumstances. Utilizing the theoretical formulas, determine the following values at 5m/s:

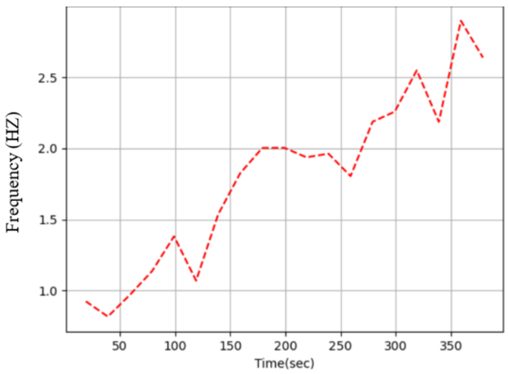

Figure 9: Chart of Frequency Vs Time-Frequency from practical values

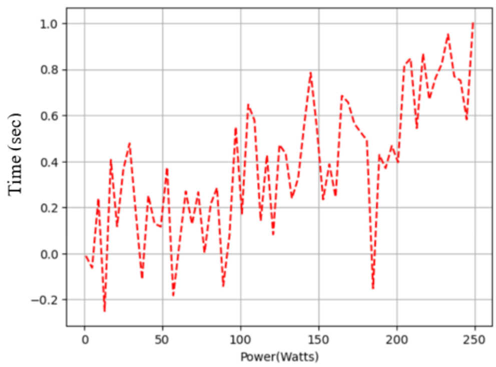

Figure 10: Power vs time- power generation curve

Total Power (W)

$$Power(P) = \sqrt{3}V_{line} \quad I_{phase} \quad (4)$$

Any phase can be chosen because the simulator's conditions are balanced:

$$Power(p) = \frac{V_a I_a + V_b I_b + V_c I_c}{\sqrt{3}} \quad (5)$$

$$P = \frac{6.19*0.0335+6.37*0.0333+6.31*0.0313}{\sqrt{3}}$$

P = 0.356W

Frequency

$$Frequency(f) = \frac{Generator \quad RPM(N)*Number of \quad poles(P)}{120} \quad (6)$$

$$Frequency(f) = \frac{1046\times4}{120}$$

F=34.86Hz

We contrasted the calculated theoretical values with the actual numbers that the chart provided. 34.88 Hz is the practical frequency; it is clear that the theoretical frequency calculation and the practical result that is returned are exactly the same. In a similar manner, the power calculations were validated Figure 10.

Power Model Developed at 155 RPM

The turbine's condition is set at 155 RPM with 4V excitation. Test at 0%, 50%, 70%, and 90% balanced load for 50 seconds. The total watt-hours of power generated over the course of 24 hours can be calculated using the power curve wind generating graph in Figure 12 and an average loading of 50%. For a particular wind speed, Figure 11 shows that power output rises as the pitch angle increases. In order to smooth the wind power production, a pitch control mechanism is essential.

In concise as depicted above the system is compact and the production of Wind Lab has system software and mobile compatibilities in comparison with its contemporaries. Android phones are available to students to control and monitor wind laboratory activities. It can be used both internally and externally. The ability to calculate and switch on wind mass power and the controllability of the attack angle of the wind flow on rotor blades by the pitching mechanism are provided for different wind speeds. The speed of the wind simulator hub, mechanical power and mechanical torque produced by the hub can also be demonstrated. The actual power production by the generator and the power factor of the generator can be evaluated with the corresponding reactive power consumption. The values generated are analyzed with Python, the histogram for wind speeds, and the probability density function using statistical methods like Weibull or Relyeigh, in order to optimize operations of the wind system.

CONCLUSION

The idea behind how wind turbines operate is simple. Two or three propeller-like blades orbit a rotor thanks to the energy of the wind. The main shaft, to which the rotor is linked, rotates a generator to produce power. In this study, a new blade profile is examined in order to enhance the performance of a wind turbine. This model's performance is improved with the usage of the individual blade control system and the open tunnel system. Consequently, a tiny horizontal axis wind turbine simulator is being designed and optimized in order to increase output power and enhance initial performance because this turbine lacks a pitch adjustment mechanism to change the blade angles of attack. This study provided a trial test for the design optimization of HDPE blades that were one meter long. Blade element momentum theory was used to calculate the blade's goal function. The testing results indicate that the nonlinear distributions are preferable in terms of output power; nevertheless, the blade is unable to start at the initial wind speed that was investigated in this study. The turbine starting was hastened by raising the starting performance contribution in the target function because of the larger chord and twist values at the blade root. The findings demonstrate that the turbine operates effectively for linear distributions in terms of output power and, more importantly, starting time.

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