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Full Length Research Paper

Development and Testing of a Horizontal Axis Wind Turbine Simulator

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ABSTRACT: With the recent increase in fossil fuel prices and the quest for cleaner renewable energy sources, wind turbines have emerged as an alternative power generation technology. Greenhouse gases emitted into the atmosphere, such as carbon dioxide (CO_2), contribute to global climate change. The most desirable goals of research in the design of small-scale wind turbine simulator are increased efficiency, decreased starting time, and ease of manufacture of rotor blades. This article analyses the design and potential power generation of a horizontal-axis wind turbine simulator. A multi-objective technique is used to evaluate a laboratory-scale horizontal axis wind turbine simulator in terms of output power and starting time for four different combinations of linear/nonlinear chord length and twist angle distributions along one-meter plastic blades. The power coefficient and beginning time are calculated using the blade element momentum theory. This simulator is critical, primarily to support wind energy harnessing in developing countries, as simplified distributions could make wind turbine blade manufacture easier. The wind turbine simulator is developed and built utilizing materials that are readily available in the area. The blade shape is modeled by an airfoil. The actual power is then measured at various wind speeds, and the power coefficient is calculated.

Keywords: Wind turbine, Blade, Twist angle, Airfoil, multi-objective design

INTRODUCTION

Every year, the laboratory hosts a range of renewable energy teachings, demonstrations, and activities. Various academic promoters match the needs of the students' work according on the activity area. However, little progress has been made in Nigerian wind energy research and demonstration. The lack of laboratory equipment to instruct students in Wind Turbine Technology could be the explanation.

The Wind Energy Training Framework (Wind Lab) is a scaled-down version of the actual power plant for wind turbines (Wind Lab). The proposed gadget was created to allow students to practice with a working and configurable wind turbine simulator model. The simulator provides insight into the different components and ramifications of changing the operating points of any wind turbine as defined in terms of wind speed and pitch angle. Students will study about the I-V characteristics, cut-off, cut-in speed, and output power of a wind energy system. It also allows the user to externally regulate the wind speed.

The planned Wind Lab is beneficial for assessing wind resources across multiple sites. Wind resource evaluation is similar to other technical initiatives that necessitate planning and organization. The Wind Lab would be useful for determining whether sufficient wind resources exist in the area to justify further site-specific investigations, comparing measurements to distinguish relative development potential, obtaining representative data for estimating the performance and economic viability of selected wind turbines, and screening for potential wind turbine installation sites.

With the expanding global acceptance of renewable energy technologies (RETs), so-called alternative energies are likely to become the dominant sources of global energy demand at some point in the future. Some researchers, in particular (Ajewole et al., 2017; Martin et al., 2020), have proposed Wind Energy Conversion (WEC) technology as a good electric power resource that, while currently supplementing the generation of fossil-based electricity, can eventually replace it in the long run as the latter's global availability declines rapidly (Clausen and Wood, 1999; Martin et al., 2020).

However, until this has been properly proven by demonstration inside the zone, power utility firms will be unwilling to employ any of the emerging technologies in the new territory (Ajewole et al., 2017; Martin et al., 2020). As a result, facilities for teaching, research, and development on RETs must be inexpensive to meet the growing demand of several emerging African countries to use renewable energy resources for secure electricity generation (Ajewole et al., 2017).

The planned Wind Lab simulator will be made up of mechanical frames and a software component designed to provide a cost-effective experimental facility for demonstrating and verifying wind energy conversion devices in new wind zones. A real-life wind speed profile would be implemented on the simulator using the hardware interface of a motor-driven wound rotor induction generator to examine its performance under a near-real-world scenario, and the simulator would precisely replicate some operating characteristics of natural wind energy conversion systems during the experiment. As a result, the simulator may be deemed suitable for wind demonstration and validation at a laboratory level testbed.

Major components of the wind lab

Some of the significant components of a wind turbine simulator include:

Artificial wind blowing system (electric motor and fan blades).
Wind turbine generator unit (aerodynamic blades, gearbox mechanism, and alternator).
VFD (variable frequency drive) board.
Signal control and display unit (wind speed, motor rpm, voltage, current, and power monitoring and control system).
Power backup unit (lithium-ion battery bank).
Remote monitoring and control unit (intelligent android Bluetooth control app).
Tachometer with Sensor.
Anemometer

The growing ambition of several emerging African countries to use renewable energy resources for secure electricity generation, education, science, and RET development infrastructure must be affordable. Fabrication of a demonstration system, such as the Wind Lab Simulator, is one technological technique of verifying Wind Energy resources in a site. It may be very expensive in many underdeveloped countries to carry out this practice of training students in Wind Energy systems in Nigeria using extremely advanced wind turbine simulators. The proposed RET device simulation model can provide acceptable and low-cost testing and demonstration environments for our students, thus bypassing the barrier of high costs associated with importing technology.

Objective

This research was aimed at the following purposes;

(a) This study aims to design, fabricate, and evaluate a near-real-world demonstration of a WEC device model on a laboratory scale. The model is designed to simulate wind turbine operations, thus providing cost-friendly testing and environmental proofing for WEC technology.
(b) To design and fabricate an artificial wind generator for laboratory simulation purposes.
(c) To perform a performance evaluation of the fixed pitch wind turbine in a controlled environment.

Wind resources assessment

With more than half a billion people lacking access to energy on the continent, Africa faces the challenge of producing more capacity to fulfil current and potential demands. The potential remains for many countries to do so cleanly and safely. The continent is well-positioned with clean energy options to fix current power shortages, which are feasible alternatives (Table 1). Indeed, Africa's reserves of renewable energy resources are the highest globally, and the continent has enough renewable energy potential to meet its future energy needs (Kayizzi-Mugerwa et al., 2016). Africa is home to 18 of the top 35 developed countries with the highest-ranking green energy reserves, normalized by annual domestic energy usage (Hafner et al., 2018). Likewise, at least 8 African countries are among the most endowed in wind energy capacity in the developing world (Kayizzi-Mugerwa et al., 2016).

Although global wind-based electricity generation is still underdeveloped compared to the development of other renewable energies such as hydro, between 1996 and 2008, it expanded at an annual average pace of about 30 percent; rendering wind one of the world's fastest-growing energy resources in terms of both scope and technical advances (Hafner et al., 2018; Kayizzi-Mugerwa et al., 2016). In a decade that saw some of the highest oil prices reported globally, the rise mainly reflects technology and energy security developments. Considerations on climate change have played a part as well. In Nigeria, the situation is not different as experienced in other African countries.

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 the world total of 193 countries per the World Almanac statistics 2012)

The development and deployment of Wind Energy systems are prolonged due to the lack of training and expertise in using such technology. However, the situation is changing as there has been increased demand for renewable energy use.

Wind turbine mechanical energy may be used to control several mechanisms, such as irrigation pumps or to generate electricity. Although wind turbines can be critical tools for rural areas and are still limitedly used in some parts of Nigeria, we are talking about wind turbines because of their ability to speed up Nigeria's electrification. This means both large-scale schemes and small-scale systems, which, along with solar PV, can be an integral part of a mini-grid (Ecosense, 2014; Hafner et al., 2018). Wind potential is less distributed across the Nigerian space than solar potential. The main factor determining the geography of wind potential is wind speed, which is highly dependent on pressure gradients and the shape of the landscape. Hence the presence of deserts, coastlines, and natural channels all play in favour of high wind speeds. While these may serve as limitations, the potentials still exist to harness the potential of Wind Energy Systems in Nigeria.

Renewable energy education is increasingly developing in response to oil scarcity and global warming. There is an increasing level of student interest in these subjects and a growing need from industry and government to build clean energy systems and greenhouse solutions for trained staff. A staff team at Federal Polytechnic Auchi has taken up this challenge. This research aims to develop Wind Turbine Technology to enhance students' understanding of such technology. Access to reliable and affordable energy has become a fundamental human right (Hughes, 2018). The lack thereof in the developing nations implies that a large portion of the population in such countries cannot be provided with the necessities. Consequently, such countries score quite low on the Human Development Index (HDI), which strongly correlates with the per capita energy use of that country (United Nations Development Programme, 2019). Realising such a global dilemma, the United Nations General Assembly in 2015 laid down the famous Sustainable Development Goals. One of the main goals is to achieve access to clean energy in developing nations by 2030 (United Nations General Assembly, 2015).

Wind turbine simulator

The Wind Energy Lab System is a scaled-down version of an actual power plant for horizontal wind turbines. The horizontal-axis wind turbine has the main rotor shaft running horizontally. Key advantages of this arrangement are that the generator and gearbox can be placed at the tower to support it and that the turbine needs to be pointed into the wind. This device enables students to work with a functioning and configurable wind turbine model. The technology will simulate and provide insight into the individual components and implications of modifying wind turbine operating points as described in wind speed and pitch angle. Students will learn concepts such as I-V features, cut-off, cut-in rate, the coefficient of performance of wind turbine, the Tip Speed Ratio (TSR) at different wind speeds, power analysis at various branches of wind turbine energy system with AC load only and the power analysis to varying components of wind turbine energy system with DC load only. The simulator, by design, has a maximum mechanical power output of 500 W at a rated wind speed of 12 m / s. The analogue real-life wind speed data feeds into the facility using this software component's input scheduler. An analogue/digital converter is included in the scheduler. The Giga-processor (GP) card of the RTDS measures the simulator's mechanical speed from the rotor speed determined by the encoder. The soft model's torque output is multiplied by the gear system ratio and converted to a voltage signal for the interface motor excitation. The conversion is performed with the analogue full-scale torque limit set to the rated engine torque in the engine drive. Through the drive, voltage signals corresponding to the instantaneous torques generated at various wind speeds are thus fed into the motor. As the motor drives the directly connected three-phase WRI machine at a super-synchronous speed, the expected electric power is produced. A novel part of the proposed Wind Simulator (Figures 1 and 2) is that it can be controlled by an android mobile phone, and all data is read from the phone itself. We plan to construct a special mobile phone PC data acquisition interface: ambient temperature and humidity, wind speed, wind direction, speed generator, generator output current, voltage, power and other details are displayed on the PC/Screen and mobile phone in real-time, the whole system's working status for real-time

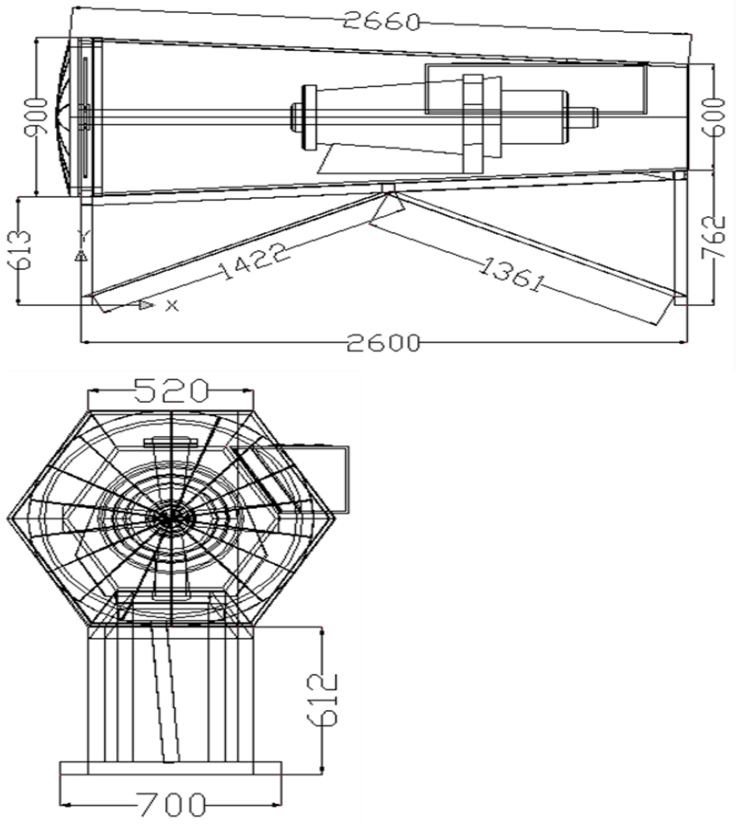

Figure 1: Isometric View of the Proposed Wind Lab.

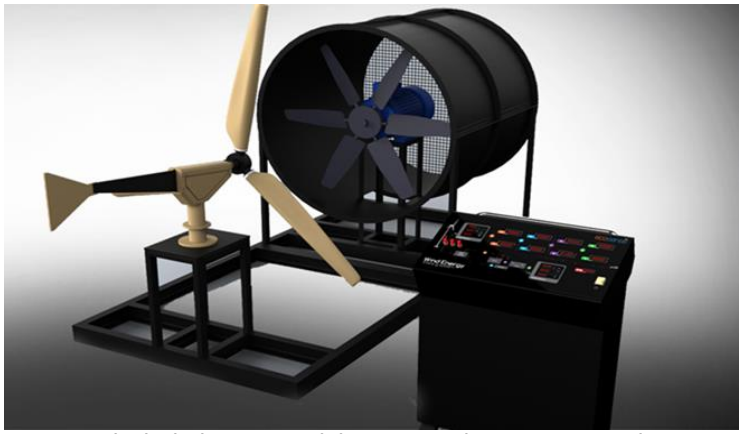

Figure 2: A typical wind energy training system (Ecosense, 2014).

monitoring.

METHODOLOGY

Conceptualization and design of wind turbine simulator

A typical wind turbine operates on a simple principle: the energy in the wind turns two or three propeller-like blades around a rotor. The rotor is connected to the main shaft, rotating within a stator surrounded by copper wire loops. Electromagnetic induction is created, and electricity is generated. Horizontal axis turbines sit high atop towers to take advantage of the more robust and less turbulent wind at 100 feet (30 meters) or above ground. A blade acts much like an airplane wing. When the wind blows, a pocket of low-pressure air forms on the downwind side of the

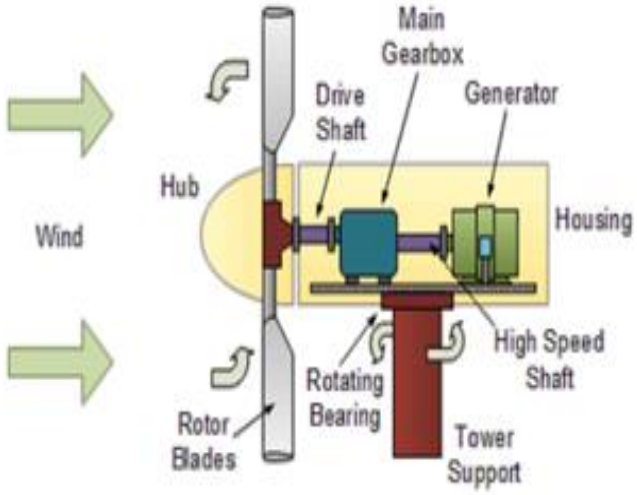

Figure 3: Inside view of a wind turbine
Source:http://www.alternative-energy-tutorials.com/wind-energy/wind-turbine-design.html

edge. The low-pressure air pocket then pulls the blade toward it, causing the rotor to turn. This is called a lift. The force of the lift is much stronger than the wind's force against the front side of the blade, which is called drag. The combination of lift and drag causes the rotor to spin like a propeller, and the turning shaft rotates a generator to make electricity. The energy recovery process through wind power includes extensive theoretical principles and practical aspects. Therefore, we designed a wind simulator that captures the reality of the field experience and that of the simulated environment in our concept. Undoubtedly, students interested in renewable energy and physical sciences need to acquaint themselves with the performance of wind energy technology. They need training on how the technology works both at a laboratory, theoretical and field scales. The performance of wind turbines depends on mechanical and electrical components and efficient plant control. The influence of the effective parameters under all relevant operating conditions must be known. For this purpose, the dependence of the rotor power on wind speed, rotor speed and rotor blade angle is taken into account in corresponding characteristic diagrams. The inside view of a typical wind turbine as used in the wind lap is shown in (Figure 3). The experimental unit is a locally fabricated open wind tunnel (Figures 1 and 4), in which streamlines, flow and turbulence are initiated using a 3-phase electric motor (with gear reduction). The open tunnel serves as the wind source during a lab simulation. The wind from the tunnel spins a wind turbine mounted opposite the tunnel (Figure 5). As shown in (Figures 4 and 5), the wind tunnel can be used to conduct experiments with different profile shapes and drag bodies. As a result, it is possible to measure, for example, how the angle of incidence affects the pressure distribution on the profile. Lift and drag forces resulting from this determine the conversion of the wind's kinetic energy into mechanical energy on the rotor shaft see the orientation of the wind turbine (Figure 4).

Fabrication process

Machine fabrication includes a variety of techniques such as lathe machining, drilling, boring; keyway cutting; slotting; oxyacetylene gas welding; grinding, and electric welds. The machine's schematic is shown in (Figures 1-3). Accessibility and ease of assembly were critical considerations throughout this model wind lab creation. Parts are carefully connected thoughtfully. The first step is to weld each flange to its corresponding location (Figure 6). 2.5 mm Mild steel plates and 1.5 mm angle bars were used to fabricate the tunnel and frames, respectively. The Frames were welded together, with the open wind tunnel sitting the frames with rollers as support and mobility. This design and fabrication concept 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. The variable-speed motor as shown in (Figure 7) and the blades or blower (Figure 8) were

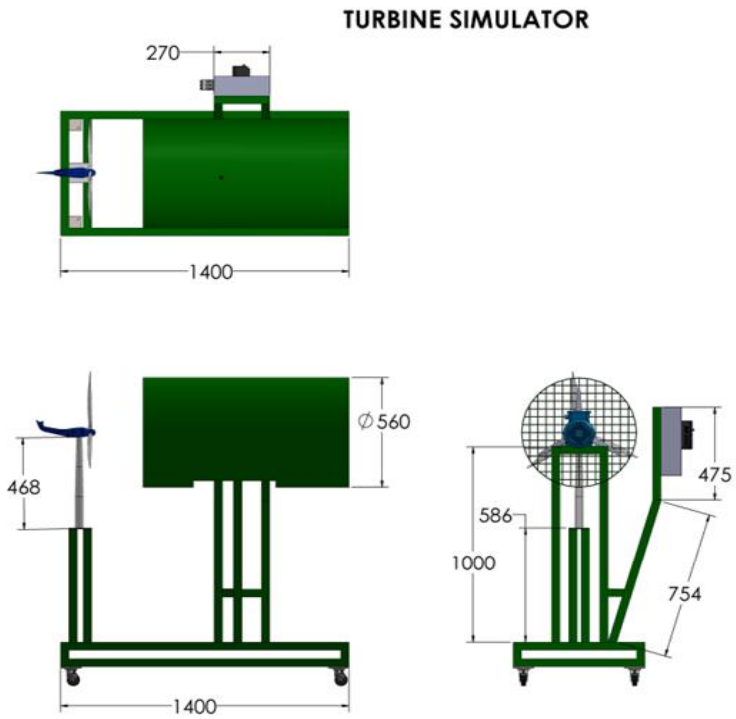

Figure 4: Side and front view of the open wind tunnel.

Figure 5: Photograph of the wind turbine simulator.

purchased off the shelf and fabricated. The wind turbine was mounted on a frame (angle bar and mild steel pipe) with bolts and nuts to support the base as shown in (Figures 5 and 9).

Control/Instrumentation Box

The instrumentation box controls the lab's motor speed and wind speed. The power supply is connected to the

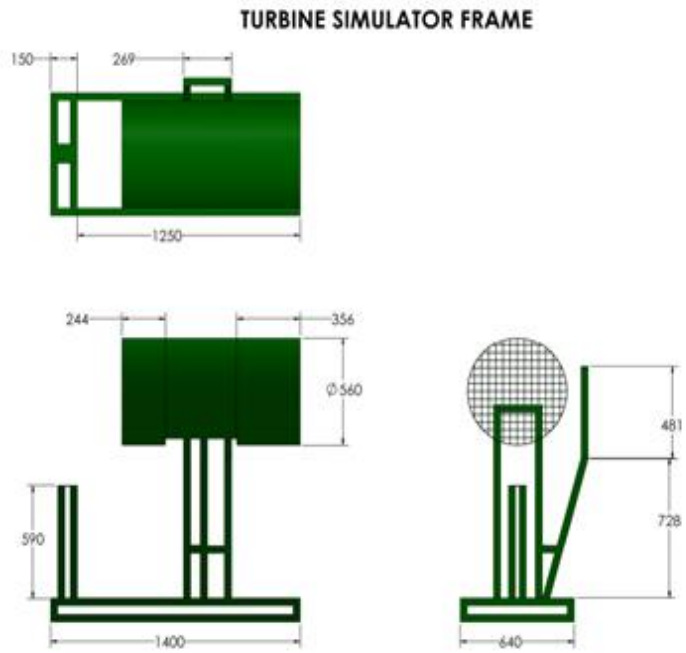

Figure 6: CAD diagram of the wind simulator frames.

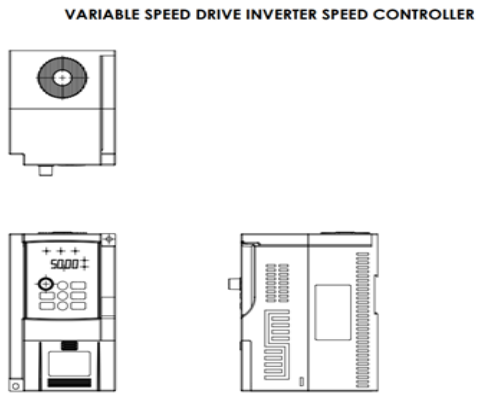

Figure 7: CAD diagram of the variable speed motor.

motor controller through a box switch. Afterwards, attach the motor to the motor controller. With an input voltage of 220V AC and a voltage regulation range of 50-220V, the maximum power is 2000W. Several critical parameters must be met for the system to function correctly. Typical data such as wind velocity, speed, electrical power and temperature are measured through the instrumentation box and a weather station.

Power developed

Figure 5 shows how to compute the power generated by a typical wind turbine using the calculations [1] below:

$$P_{avail} = \frac{1}{2}\,\rho . Av3\ Cp \qquad (1)$$

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 Cp - Power coefficient where Cp, max = 0.59.

One key variable for determining wind power generation is the wind speed at the locations chosen 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

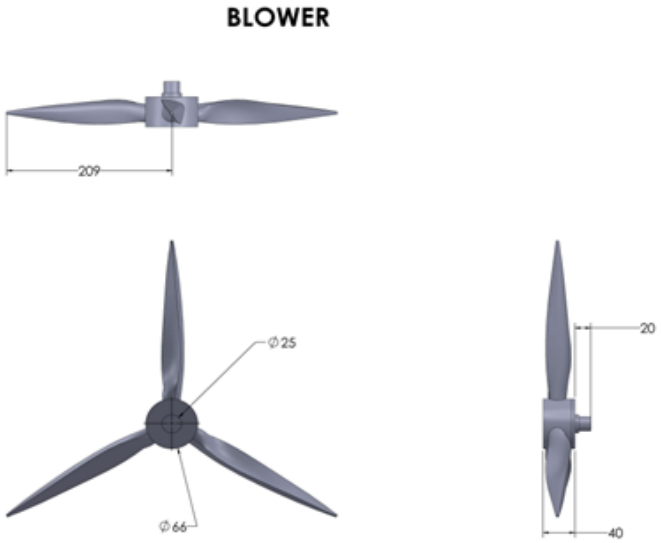

Figure 8: CAD Diagram of the Blower

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.

Customizable features

Customizable features that the Wind Simulator system, as shown in (Figure 5), 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

Analysis of findings from the initial test

The first goal of optimizing the fabricated wind turbine lab, the output power, is calculated using the blade element momentum (BEM) theory formulated by Glauert (1935). BEM is a generalization of the momentum theory coupled with the blade element theory; it is the most widely used engineering model for computation and analysis of the aerodynamic loading of propellers and wind turbine blades (Spera, 1994). In BEM, a blade is divided into a finite number of independent sections whose chord and twist angles are known. Then, the local thrust and torque for the whole blade can be determined by applying the continuity, momentum and angular momentum equations to each element. Once the total aerodynamic torque (Q) is computed, CP is calculated as (Burton et al., 2011):

$$C_p = \frac{Q\Omega}{0.5\rho A U_0^3} \quad (2)$$

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.

Blade movement

A blade acts much like an airplane wing. When the wind blows, a pocket of low-pressure air forms on the downwind side of the blade. The low-pressure air pocket then pulls the blade toward it, causing the rotor to turn. This is called lift. The force of the lift is much stronger than the wind's force against the front side of the blade, which is called drag. The combination of lift and drag causes the rotor to spin like a propeller, and the turning shaft rotates a generator to make electricity. The 3-phase power generated from a balanced system is calculated by:

$$P_{3\,phase} = 3\,.V_{phase}I_{phase} \quad (3)$$

The theoretical equation for the calculation of the frequency depends on the RPM and the number

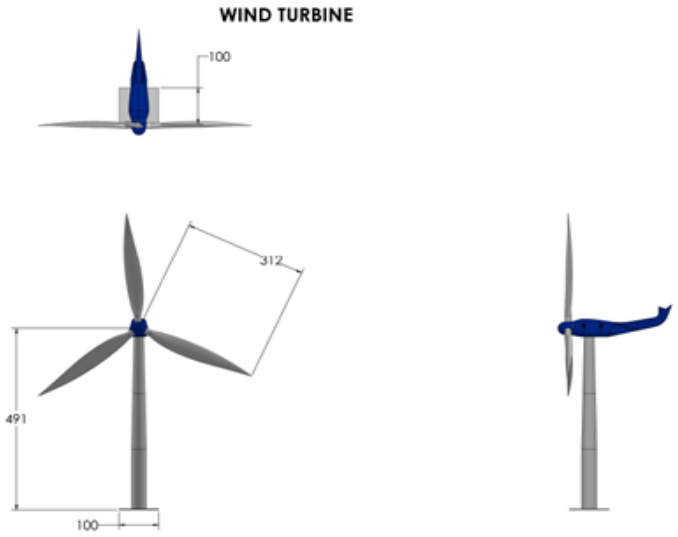

Figure 9: The CAD diagram of the wind turbine.

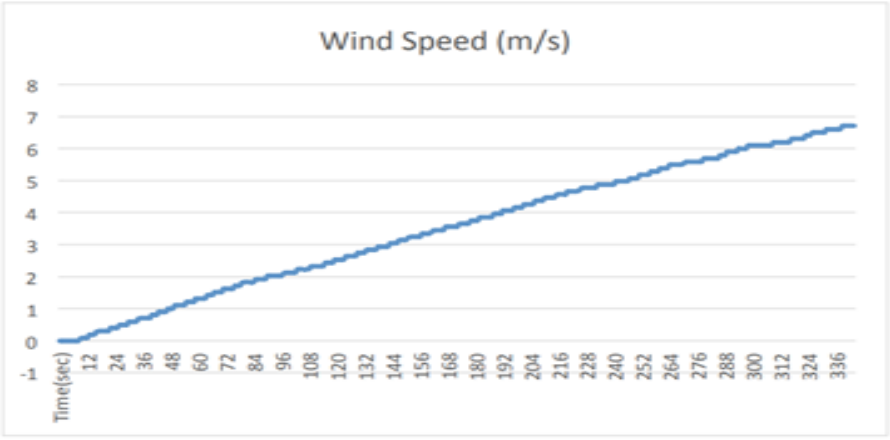

Figure 10: Trial test with the wind turbine trial. time used from the wind turbine simulator: 1 data point each second.

of poles within the generator:

$$f(hz) = \frac{RPM.P}{120} \quad (4)$$

RPM represents the generator revolutions per minute, and P denotes the number of generator poles. Turbines can be used as stand-alone applications, or they can be connected to a utility power grid. For utility-scale wind energy sources, many turbines are usually built together to form a wind farm. From an operational point of view, the task of the wind turbine control system is to simultaneously deliver the best possible output power up to the turbine ratings and prolong the turbine lifetime. Reductions in the turbine structural loading govern the prolongation of turbine lifetime. For this reason, control methods have been devised and are currently a focal point of today's wind industry for the development and effective management of large-scale wind turbines (Figure 10). A key mechanism in the control systems development is effectively managing wind turbine blade pitch angles.

System familiarization

A laboratory trial test with the wind turbine simulator under the described conditions engages at 2m/s.
At 5 m/s, use the theoretical equations to calculate the following quantities:

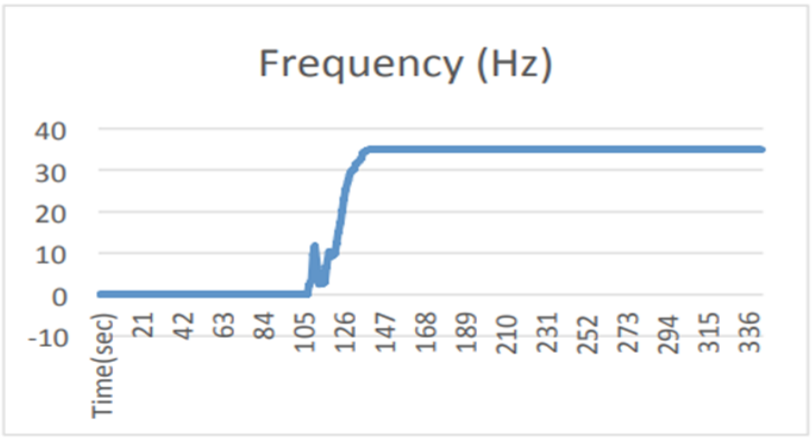

Figure 11: Chart of Frequency Vs Time-Frequency from practical values.

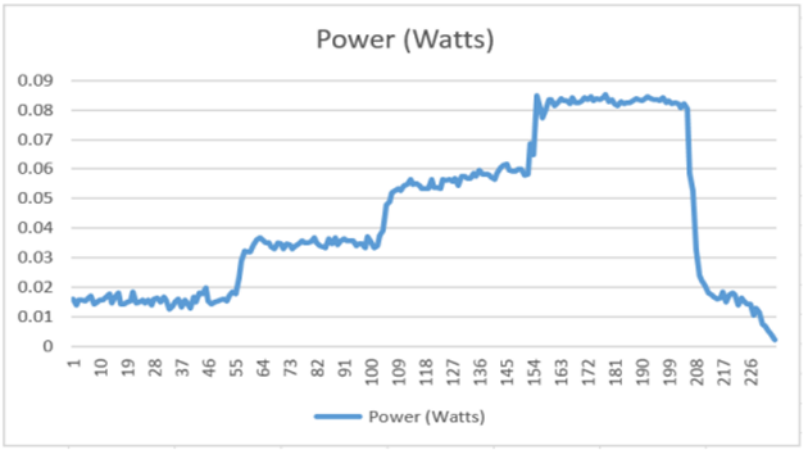

Figure 12: Power vs time- power generation curve.

a. Total Power (W)

$$\text{Power (P)} = \sqrt{3}\, V_{\text{Line}}\, I_{\text{phase}} \quad (5)$$

Balanced conditions from the simulator; therefore, any phase can be used:

$$\text{Power (P)} = \frac{V_a I_a + V_b I_b + V_c I_c}{\sqrt{3}} \quad (6)$$

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

P = 0.356 W

b. Frequency

$$\text{Frequency } (f) = \frac{Generator\ RPM\ (N) * Number\ of\ Poles\ (P)}{120}$$

$$F = \frac{1046 * 4}{120}$$

$$F = 34.86Hz$$

We compared the theoretical values calculated to the practical values returned from the chart.

Practical frequency equals 34.88Hz; as evident, the theoretical frequency calculation perfectly matches the practical value returned. Validation of the power calculations was performed along the same lines (Figure 11).

Power developed at 150 RPM

The condition is set at 150 RPM on the turbine at 4V excitation. Trial for 50 seconds at 0%, 50%, 70% and 90% balanced load. Based on the power curve wind generation graph in (Figure 12) and an average loading of 50%, the total watt-hours of power generated for the 24 hours can be determined. Figure 12 demonstrates that power output increases as the pitch angle are increased for a given wind speed. Hence, a pitch control system is crucial in

smoothing the wind power output.

Conclusion

Wind turbines work on a straightforward concept. The wind's energy propels two or three propeller-like blades around a rotor. The rotor is attached to the main shaft, which generates power by spinning a generator. In this project, the performance of a vertical axis wind turbine is improved by examining a new blade profile. The open tunnel system and the individual blade control system are used to increase the performance of this model. Because this turbine does not have a pitch adjustment mechanism to modify the blade angles of attack, the design and optimization of a small horizontal axis wind turbine simulator is being done to boost output power and improve beginning performance. A trial test for the design optimization of one-meter-long HDPE blades was given in this research. The objective function of the blade was computed using blade element momentum theory. The nonlinear distributions are desirable from an output power standpoint, according to the testing results; nevertheless, the blade cannot start at the initial wind speed examined here. Due to the higher chord and twist values at the blade root, the turbine starting was accelerated by increasing the contribution of starting performance in the goal function. The results show that the turbine performs well in terms of output power and, more critically, starting time for linear distributions.

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