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Renewable Wind Energy Design Concepts and Considerations: An Alternative Power Supply for Remote Observatories

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Abstract— Observatories globally require a smooth, sustained and reliable power system for their operations, which are usually, round the clock. Observatories are usually very remote sometimes at locations that are hundreds of kilometers away from power grids. This results in huge burden of extending power grids across several distances to observatories. Power interruptions are common experiences with public grids and pose great threats with gravity that can interrupt scheduled observations. Hence, there is the need for observatories to drift from the conventional power system to renewable energy system. This paper presents the design concepts and considerations for setting up a wind turbine energy system for NASRDA Centre for Basic Space Science Observatory, as a case study of the deployment of such system for remote or non-habitable observatories.

Index Terms— Energy, Power, Rotor height, Wind Speed, Wind Turbine.

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1 Introduction

The increasing demand in energy over the world, as well as the growth in the prices of the fossil fuels resources and the exhaustion of its reserves in the long run have favoured the research for other alternative renewable energy sources [1]. Renewable energy technology offers the possibility of generating energy using natural and non-depleting sources like wind, biomass, hydropower, solar power, etc. These energy generation sources can help countries meet their sustainable development goals through provision of access to clean, secure, reliable and affordable energy [2]. Wind energy source is one of the renewable energy generation sources that guarantee reliable power by integrating wind turbine technology to harness the energy. Wind energy technology extracts the kinetic energy from the wind to realize mechanical energy that can be used to perform some specific tasks or even for driving generators that convert mechanical energy to electrical energy. The technology can be designed to run independently or as hybrid with some other renewable energy alternatives that might be situated at such areas.

The major benefit attributed to the wind turbine technology is the fact that it is pollution-free and does not involve combustion or nuclear reaction [3]. More so, renewable wind source is very available and free everywhere. The wind turbine makes use of the principle of energy conversion to generate power. The first large-sized wind electricity turbine can be traced to Charles F Brush in 1888 [4] and was used to generate about 12 kW. Afterwards, the technology has recorded slow trend in development and deployment globally until later part of the 19th century. Since the year 2000, the installation capacity of this technology has grown at an average of 24% per year [5] with the attended increase in the generated power.

2 WIND TURBINE TECHNOLOGY

2.1 Wind Turbine Sub-Systems

The basic components of a wind turbine comprise of the following sub-systems: the tower, the rotor sub-system, the gearbox sub-system, the generator and the control and protection sub-system.

The height of the tower for mounting the system is of paramount importance in deploying wind turbine in any location. This is because wind speed is a dependable factor for the effi-

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ciency of a wind turbine [6] and it has been observed that wind speed increases at higher altitude [7]. Therefore, it is considerate to use taller towers for deploying wind turbine in locations that record lesser wind speed.

The rotor subsystem comprises of the rotor blade, hub and the rotor shaft. The rotor is an airfoil shaped blade that converts the kinetic energy of the wind to mechanical energy. The rotor blades can range from two and above. The sweeping area of the rotor blades is one of the dependable factors that determine the amount of energy the turbine can generate [3], [6]. Observations have shown that two or three rotor blades offer more efficiency in the system performance [6]. These rotor blades are attached to the shaft at the front end.

The gearbox sub-system is attached to the back-end of the rotor shaft. The gearbox is used to alter the rotational velocity of the shaft to suit the generator [3], although smaller turbines (less than 10 KW) can use direct drive generator that does not require a gearbox [4].

The generator converts the mechanical energy of the gearbox to electrical energy. The generation of electricity at this subsystem is based on the movement of magnetic field around the stator windings of the generator. Wind turbines often make use of synchronous generator type than the asynchronous type because of the attributed less rotation speed requirement. Therefore, the turbine operates without gearbox even for bigger designs [4]. The energy generated can be fed to the electrical grid after passing through the transformer and voltage regulator systems.

The control and protection sub-system refers to the safety features that ensure that the turbine is not working at dangerous conditions. These may include the brake system that slows or stops the system from movement under excessive wind speed, the yaw system that repositions the system to face the wind direction, the nacelle that encloses the gearbox, generator, brake control systems, etc.

2.2 Classifications

Wind turbine can be classified based on the axis of rotation of the rotor shaft. It is said to be a Horizontal Axis Wind Turbine (HAWT) when the horizontal shaft and the generator are both located at the top of the tower otherwise, it is said to be a Vertical Axis Wind Turbine (VAWT) thereby having a vertical rotor shaft design [3]. It can also be classified as an Onshore wind turbine or Offshore wind turbines based on their location [2].

2.3 System Design and Model

The power produced by the wind turbine, P_{kin} is the net kinetic energy change across the wind turbine from initial air velocity of V_1 at the front-end of the rotor to the turbine exit air velocity of V_2 at the back-end of the rotor [3] as stated below:

$$P_{kin} = \frac{1}{2} \times m \times \left[V_1^2 - V_2^2\right] \tag{1}$$

Where m is the mass flow rate of the wind which is given by the product of the air density (ρ), the sweeping area of the rotor blade (A) and the air average velocity (V_a)

$$m = \rho \times A \times V_a \tag{2}$$

Where $V_a = \frac{1}{2} \times \left[V_1 + V_2\right]$

Substituting equation (2) into equation (1), and then solving through

$$\begin{aligned} P_{kin} &= \frac{1}{2} \times \rho \times A \times \frac{1}{2} \times \left[V_1 + V_2\right] \times \left[V_1^2 - V_2^2\right] \\ &= \frac{1}{4} \times \rho \times A \times \left[V_1^3 - V_2^3 - V_1 V_2^2 + V_1^2 V_2\right] \end{aligned} \tag{3}$$

To realize the maximum power from the rotor, equation (3) is differentiated w.r.t. V_2 as follows:

$$\frac{dP_{kin}}{dV_2} = \frac{1}{4} \times \rho \times A \times \left[-3V_2^2 - 2V_1 V_2 + V_1^2\right] \tag{4}$$

Equating the equation (4) to zero

$$\frac{1}{4} \times \rho \times A \times \left[-3V_2^2 - 2V_1 V_2 + V_1^2\right] = 0$$

Since density, ρ and area, A cannot be zero in reality, therefore, only the expression in the bracket is equated to zero:

$$\left[-3V_2^2 - 2V_1 V_2 + V_1^2\right] = 0$$
$$\left[V_1 - 3V_2\right]\left[V_2 + V_1\right] = 0$$

The solutions are:

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$$V_2 = -V_1 \qquad V2 = \frac{V_1}{3}$$

But velocity cannot be a negative value.

Therefore substituting $V_2 = V_1 / 3$ into equation (3), it will then result to:

$$P_{kin} = \frac{1}{4} \times \rho \times A \times \left(V_1^3\right) \times \frac{32}{27}$$

$$= \frac{16}{27} \times \frac{1}{2} \times \rho \times A \times V_1^3 \qquad (5)$$

Eqn. (5) is the theoretical maximum power that is extractable from the wind. The fraction 16/27 is referred to as the Bertz coefficient. This coefficient determines the maximum efficiency of any wind turbine design [3].

The following dependable factors can be deduced from eqn. (5):

- The generated power is a function of the wind velocity and it increases with the wind speed cubed
- The generated power is a function of the sweeping area of the rotor blade and it increases with the rotor diameter squared.
- The generated power is also a function of the density of the air at the site of the deployment.

The optimum range of the wind speed for turning the rotor blade is of paramount importance for every design. It has been observed that if the rotor turns too slow or very fast, there will be relatively no power generation [2]. Therefore, in considering the altitude to locate the optimum range for the wind speed, the following model based on [8] is employed:

If the wind velocity, V_{rif} at a certain height, h_{rif} is known, then, the velocity, V at any arbitrarily altitude, h can be deduced as follows:

$$V = V_{rif} \left(h/h_{rif}\right)^{\alpha} \qquad (6)$$

And

$$\alpha = 1/\ln\left(h/z_0\right) \qquad (7)$$

Where

z_0 = the morphology factor of the turbine's site (values of 0.01 to 0.001 for regions without building or trees and 0.0001 for offshore applications).

3 DEPLOYMENT

3.1 Site Characterization

The Centre for Basic Space Science (CBSS); a department under the National Space Research and Development Agency (NASRDA) was used as a case study for this work. The CBSS is situated at Nsukka, Enugu State with coordinate location of Lat: 6.8N and Long: 7.4E. It is relatively remote and has morphology factor of about 0.001. The department houses some installed space research equipments like the Nigeria Environmental Climatic Observing Programme (NECOP) station used for meteorological study, a 3m Radio Telescope and some Optical Telescopes like the motorized Meade and Comet Hunter used for Astronomical study, etc. The average power demand at this facility is about 20kW.

3.2 Method

The site was characterized using NECOP meteorological station, situated 3m above the ground to realize the relevant parameters via in situ measurement. The NECOP station generates nine variables covering several meteorological scenarios but for the purposed of this work, only the wind speed data for the year 2013 was extracted and used. The wind speed data considered were averaged values in every five (5) minutes for the first six months of the year.

The wind speed/altitude relationship model of equations (6) and (7) were used to generate the various corresponding wind speed values for the different rotor hub heights of 10m and 15m. These variables were used to generate the theoretical wind power values of equation (5). The work considered the performances when the rotor blade length is 50% of the rotor hub height as well as when it is 80% too for the two variable rotor hub heights. The model was simulated using MATLAB software and the performance results were shown in the subsequent section.

4 RESULTS

The performance results in Figures 1 through 6 shows that the

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theoretical power increases as the hub height increases. This can be attributed to the higher wind speed experienced at higher altitude. More so, the theoretical power increases with the increase in sweeping area of the rotor blade. The implication is that increasing the rotor blade length increases the sweeping area that consequently increases the generated power.

It was observed that the design model and parameters considered in the work were able to provide more than the 20KW power demand for the CBSS research facility used as the case study for the work.

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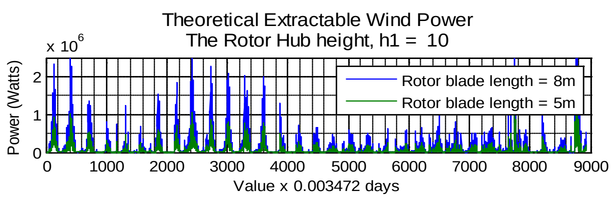

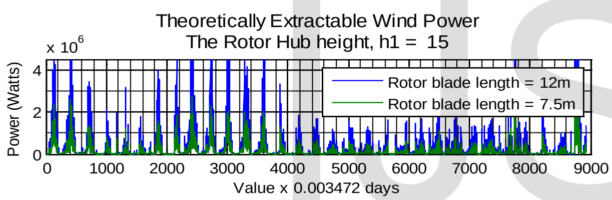

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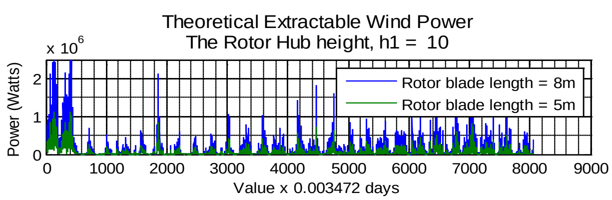

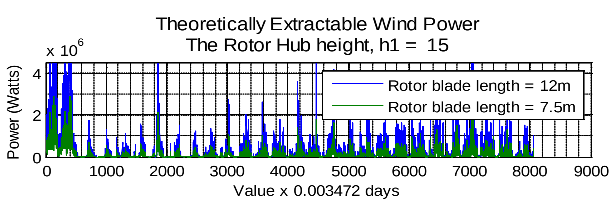

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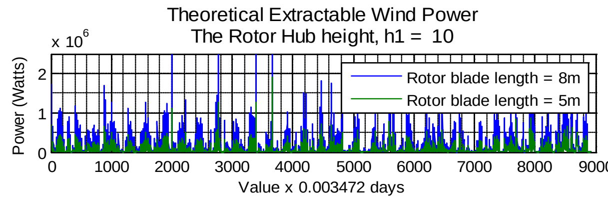

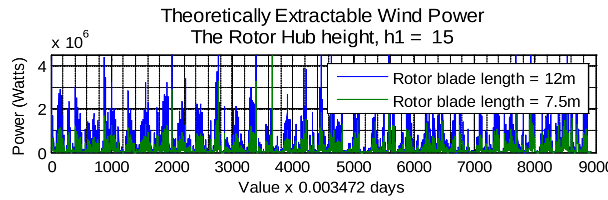

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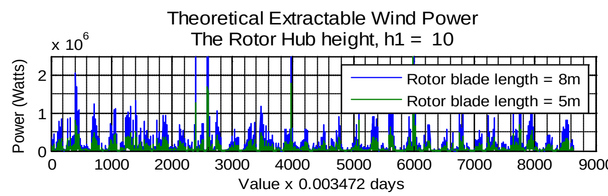

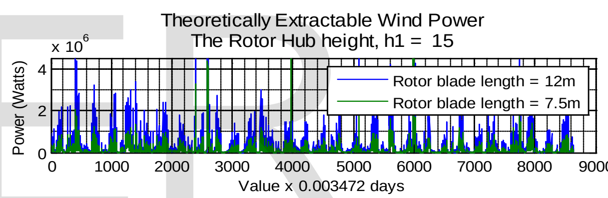

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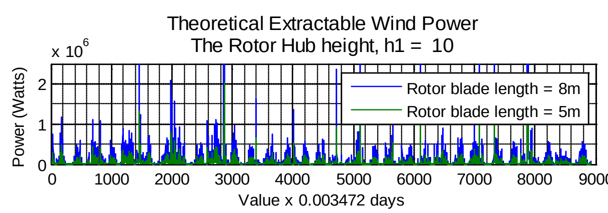

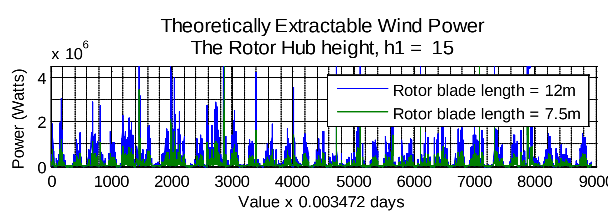

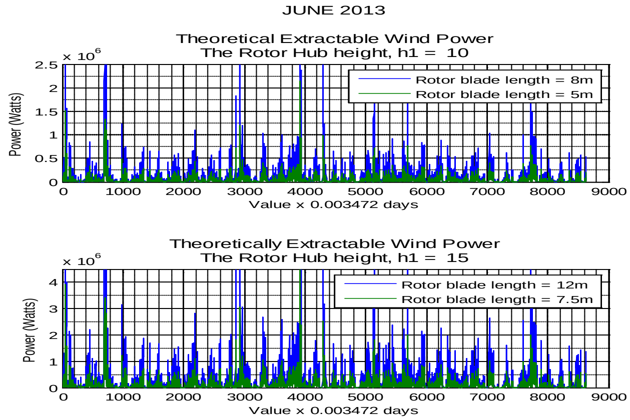

4 Conclusion

The work considered the theoretical design concepts for Wind Turbine energy generation at CBSS observatory. The variations show that wind power can be adapted to generate much above 20KW required at site characterized. The unsteady variations of the power plots is as a result of unsteady wind drives, hence the need to deploy a compensative design off grids power banks to cater for low wind drive periods. It has been shown that Wind Turbine technology can serve suitably well as a good energy alternative to research facilities located at remote and/or non-habitable regions in the globe. Importantly though, the engineers need to carry out site characterization and also know the power demand for such site. Site characterization is of enormous importance as it is always a tool to model the power output, design parameters and system configurations before the final deployment of the technology. The fact that the technology uses renewable wind energy and poses no pollution threat makes it a desirable energy migration option globally. Currently, Nigeria and the global world are focusing their attention to the use of clean energy sources.

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