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A Comprehensive Review on Performance Evaluation of a Mini Wind Turbine for Electricity Generation

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ABSTRACT

Wind energy as a clean source of renewable energy is available in large amount in some part of the world. This can be used to solve the challenges of epileptic power issues if well harnessed appropriately. This paper reviewed the principles of operations, mathematical expressions as well as functionality of wind turbines including their various types. These are Vertical Axis Wind Turbine (VAWT) and Horizontal Axis Wind Turbine (HAWT) and the merits and demerits of each including factors to consider in sitting a wind farm and various modeling techniques in analyzing wind energy that will aid the overall harnessing of wind energy for power generation. Wind speed trend as well as metrological data was also reviewed. Aerodynamic modeling and the different designs of turbines with varying principles of energy extraction and the Blade Element Momentum (BEM) model including the top loss, variable and constant wind speed turbine is also extensively reviewed.

INTRODUCTION

Wind energy is the process by which electrical energy is generated using wind as the natural resource. Wind turbines are energy conversion devices that convert kinetic energy from wind into electrical energy. The principle behind the functionality of wind turbines involves the rotation of blades to turn the rotor by the wind speed. The rotating part (rotor) is attached to the shaft of a generator thus generating electricity when it turns or rotates (Kunduru Akhil, 2010). Wind power density is the measure of wind energy in a particular place at a particular time. It is the average power that can be found per square of the turbine swept area with S.I unit of watt per square meter. This indicates how much energy is available on the site. There are basically two classes of wind turbines (vertical and horizontal axis wind turbines). The smallest type of wind is used for battery charging for generation of about 2kW back-up power. Power used at home and industries can be obtained from larger wind turbines. Wind power is classified majorly into three types:

- Wind turbines that can generate more than 100kW (Utility-Scale wind turbines).
- Wind turbines that can generate 100kW or lower (Distributed wind turbines)
- Wind turbines installed in water bodies (Offshore wind turbines).

Collections of different wind turbines installed in an area to generate electricity are called a wind farm. About 2500 wind farms existed in Denmark in 1900s. These wind farms produced enormous amount of energy which was approximately 30MW. The bigger turbines were situated on 24m-79ft, they had four blades which ranged between 23m-75ft in diameter. The US had about 72 generators that were wind driven in 1908. Americans had about 100,000 wind mills used majorly for pumping water during World War I (Alan, 1986). Wind generators for electricity became common in farms around 1930s. This was prevalent in US farms due to lack of proper distribution systems. Generators were placed on fabricated high-tensile steel lattice towers due to the low cost of steal at that time. The first horizontal axis wind generator was built in Yalta USSR in 1931. It was rated at 100kW and mounted on a 30-meter tower connected to a 6.3kVA distribution system. Its performance coefficient was reported to be 0.32 which is not very far from the coefficient of performance (0.59) of recent wind turbines (Alan, 1986). In the autumn of 1941, the first wind turbines rated in megawatts was connected to the grid in Vermont. The Smith-Putnam wind turbine encountered a critical damage after operating for only 1100 hours. Shortage of materials during the Second World War prevented it from being repaired. The first wind turbine to be connected to the grid in UK was designed and manufactured in 1951 by John Brown and company. However, with the emergence of fossil fuel, these great advancements in wind turbine technology were overlooked thus relegating wind turbine systems to much smaller sizes. But there was massive development of micro-turbines in the 1970s due to the anti-nuclear protest that happened in Denmark in early 1970s. Some activist in Germany, turbine designers in Spain and others with interest in US pushed for policies that favored the wind turbine industry in the early 1990s. Some wind turbine companies were established in China and later in India. By 2012 Vestas (Danish wind Turbine Company) was the biggest wind turbine company in the world. The rotation of wind turbines can be vertical or horizontal. But the commonest type is the horizontal axis wind turbine (American wind energy association 2009).

Literature Review

Wind Speed Trend in Nigeria

Wind speed in Nigeria is not constant. It varies with location, which means that the wind speeds obtainable in different states in Nigeria are different. In Nigeria, wind speed is classified into four different regimes: 1.0 – 2.0 m/s (e.g. Oshogbo, Minna and Yola), 2.1 – 3.0 m/s (e.g. Lagos, Makurdi and Port Harcourt), 3.1 – 4.0 m/s (e.g. Enugu, Kana, Maiduguri) and > 4.1 m/s (e.g. Jos Nguru, Sokoto) (wind speed pattern in Nigeria 2018). From the studies conducted by Fadare in 2008, it was predicted that the average wind speed per annum in Nigeria is 4.7 m/s (Oyewole *et al* 2018). Fig 2.1 is the map of Nigeria showing the meteorological locations for the study

Fig2.1. *Map of Nigeria showing Wind Speed Pattern in Nigeria (Oyewole et al 2018)*

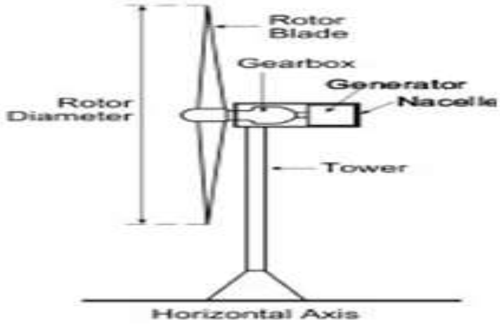
A probability density distribution conducted across five cities (Ikeja, Port Harcourt, Ilorin Jos and Kano) in Nigeria in the year 2018 is tabulated as shown in Table 2.1(Oyewole *et al* 2018)

Table2.1. *Wind speed Variations in Nigeria(Source: Oyewole et al 2018)*

MONTH	IKEJA		PORT HARCOURT		JOS		KANO		ILORIN	
	Mean speed (m/s)	STD m/s	Mean speed (m/s)	STD m/s	Mean speed (m/s)	STD m/s	Mean speed (m/s)	STD m/s	Mean speed (m/s)	STD m/s
Jan	10.9	1.5	4.9	2.8	13.8	5.3	12.2	4.1	4.2	1.5
Feb	10.4	1.4	5.8	3.4	14.7	5	12.4	4.4	4.5	1.1
Mar	11.9	1.4	5.8	2.8	14.8	4.4	12.1	3.9	5.2	1.1
April	11.7	1.7	5.8	2.9	14	3.9	11.5	3.4	5.4	1.6
May	9.8	1.2	5.6	2.9	12.2	4.4	11.2	3.2	5.2	1.2
June	10.6	4.9	5.6	2.9	12.5	3.9	11.6	3.5	4.8	1
July	12	3.3	6.2	3.5	12.1	3.8	11.2	3.5	4.9	1.2

Types of Wind Turbine

There are two categories of wind turbines. These include horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). Wind turbines that rotate about the vertical axis are called vertical axis wind turbine while horizontal axis turbine spins around the horizontal axis (Kunduru Akhil et al, 2010).



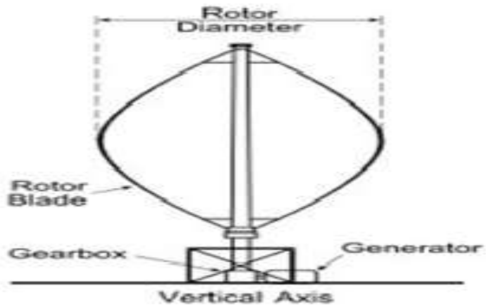


Fig2.2. *Horizontal and vertical-axis wind turbine configuration (Source: Jasmine Martinez, 2017)*

Horizontal Axis Wind Turbines

These are wind turbines which rotate parallel to stream wind and ground (Dafrose and Bajaro 2011). The generator and rotor shaft are fixed on the roof top and it is directed into the wind. Wind vanes and sometimes wind sensors fixed with servomotor are implored to detect the wind direction. Majority of horizontal wind turbines are built with gear box to trap good speed that can drive the electric generator. (Morten, 2016).The horizontal axis axil is attached by bearings at the top of the tower were the blades are also attached and it is enclosed in a nacelle. The nacelle is where the gearbox and generator are located. Horizontal axis wind turbines utilize airfoil design to generate the spinning of the blades. The concept of wind foil of HAWT blade is that the wind travels over the top of the blade rather than under it, thus creating less pressure on top of the blade generating lift and creating rotational movement (Lucas et al 2013)

HAWTs are built mostly with three or two blades, but more blades can be used which depends on the choice of the designer. Fig 2.3 is a vertical axis wind turbine.

Fig2.3. *Front view of a typical horizontal axis wind turbine (Source: Renogensolar.com)*

Types of Horizontal Axis Wind Turbine (HAWT)

Two kinds of HAWT that existare the upwind turbine and the downwind turbine.

Upwind Turbine

This is a kind of HAWT that the rotors face the wind. It also circumvents the shadow of the wind behind the tower. For this reason, it is used in most wind turbine designs. The major drawbacks are that the rotor is immovable and it is placed far from the tower. The strength of the rotor depends on the mechanism; the preferable mechanism is the yaw mechanism (Danish wind industry association 2003). The blades are allowed to bend during high wind which can reduce area covered by the blades. The blades of the turbine have to be strong to avoid being tossed around by the wind. The blades are properly situated in the tower and have to point towards the wind to maximize energy capture.

Downwind Turbine

This is a category of wind whose rotor is placed at the bottom part of the tower. It can be installed without a yaw mechanism which is one of its merits. The disadvantage is that the power it generates fluctuates (Danish wind industry association 2013). Downwind turbines are built such that that no additional mechanism is needed to align them to the wind direction. Wind farms usually make use of turbines having three blades for power generation. Three bladed turbines ensure high reliability because of their low torque ripple. The blades are most times painted white in order to make it visible in the day to aircrafts. The length ranges between 20 to 80 meters (66 to 262ft). Wind turbine sizes have greatly increased over the years. In recent years, there are wind turbines with huge power capacity which are installed off shore. Steel towers with tubular shapes are used. The height is always between 70m to 120m. The blades spin at an angular velocity of 10rpm to 22rpm (300 ft/s) (Tony et al 2001). Higher tip speeds cause more noise and erosion. The generator speed is enhanced with the help of the gear box. However, some of the turbines implore other drive mechanisms. Some downwind turbines run at steady speed; however variable speed operation is better because it ensures that more energy is collected by using solid-state power converters interfaced with the transmission system. Protection is usually included in turbine design to avert damage at high speeds by using proper break systems. (Rajveer Mittal *et al* 2010). The major components of most horizontal axis wind turbine are displayed in the fig 2.4.

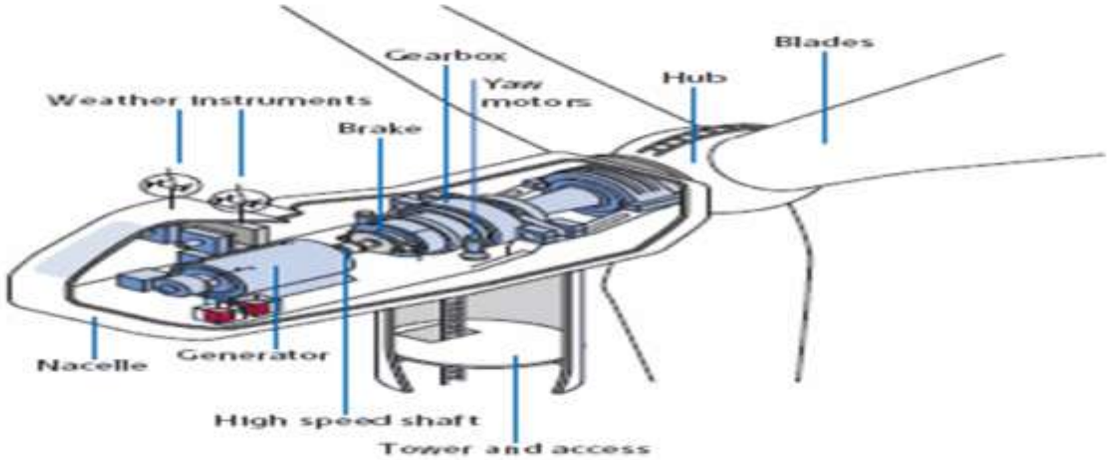


Fig2.4. *Components of horizontal axis wind turbine (Source: Jasmin Martinez, 2017)*

Vertical Axis Wind Turbines

Wind turbine whose rotor is arranged vertically is called vertical axis wind turbine (VAWT). Its merit is that it must not face the wind direction before it can generate optimal power. This is a great advantage if the turbine were to be installed in an area that has unpredictable wind direction (Robert Whittlesey et al 2017). Another advantage it has is that it does not rotate uncontrollably and this is a good characteristic when the turbine is installed on a roof top. Sometimes the generator and the gear box are installed down the tower base. A direct drive is from the rotor to the generator on the ground. This is to ensure easy maintenance when fault or a major breakdown occurs. But less energy is produced by these designs which has been the major demerit it has. The key demerit is that it has low speed of rotation which can make the toque outrageous and also heighten the cost of the drive system. Another disadvantage is that it has low efficiency (Hugh, 2007). It also has a demerit of not being able to start on its own except with the help of an external force. There is also difficulty to design for high altitudes. However, VAWT can also use blades that directly face the wind. Research has shown that a three bladed turbine with air foil blades performs better and it's more efficient at lower speeds than the equivalent flat blade design (Lucas et al 2013). Fig 2.5 shows an example of VAWT.

Fig2.5. *Example of a vertical axis wind turbine (Source: www.goole.com)*

Mounting a turbine on the roof top generally makes the building to redirect wind flow across the roof which could double the wind velocity reaching the turbine. When the height of the tower mounted on the roof top is approximately half the building height, then the turbine can capture optimum wind at lowest turbulence (Marco Casini 2016).

Darrieus Wind Turbine

Georges Darrieus was a French man who invented Darrieus turbine. The reliability of the turbine is low because it generates high torque ripples and causes cylindrical stress on the tower, but its efficiency is good. Another challenge it has is that an external source of power is required to start running due to its low starting torque. To reduce the torque ripples, three or more blades are used making the rotor more solid. The ratio of blade area to rotor area is called solidity (Gurmit, 2014). It also has a problem of changing its angle of attack as the turbine spins, so each blade generates its maximum torque at two points on its cycle. This leads to a sinusoidal power cycle that complicates design (Jonny et al 2010) Fig 2.6 shows a type of Dirrieus wind turbine

Fig2.6. *A helical Darriues wind turbine*

Giromill

This is a kind of Darrieus turbine that has straight blades instead of curved blades. For cyclo-turbine the pitch varies which reduces the pulsating torque and it can start on its own. The variable pitch method has some advantages which lessen the blade bending moment and enhance operational efficiency during turbulent wind speed (S.C. Bhatia 2014).The operation of a Giromill VAWT is not different from that of a common Darrieus turbine. The wind hits the blades and its velocity is split into lift and drag component as shown in figure 2.7.

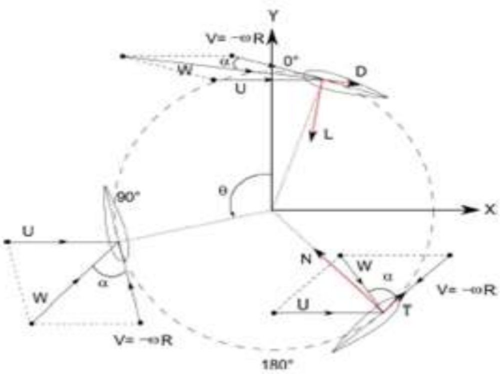


Fig2.7. *Forces that act on wind turbines (Source: Jonny et al 2010)*

The resultant vector sum of these two components of the velocity makes the turbine rotate. The swept area of Giromill wind turbine is given by the length of the blades multiplied for the rotor diameter. The aerodynamics of the Giromill is like the one of the common Darrieus turbine, the wind force is splits into lift and drag force and it make the turbine rotate (Jonny et al 2010). Fig 2.8 shows what a giromill looks like

Fig2.8. *An aerial view of the giromill*

Savonius Wind Turbine

This category of wind turbine is applied in anemometer. It has high reliability but its efficiency is quite low. They do not need external devices or mechanisms to initiate their start and are usually installed on roof tops and vans (Walter 2009). Fig 2.9 shows a typical structure of the Savonius wind turbine

Fig2.9. *The Savonius wind turbine*

Twisted Savonius

Twisted turbines are improved savonius with longer scoops to ensure smooth torque. It is most times installed on roof tops and it is best used in ships. Parallel turbine is another type of vertical axis wind turbine. This kind of turbine has been used for years. In the 1980s, a unit producing 10KW was built by Bruce Brill (an Israeli citizen). Fig 2.10 is a typical example of a twisted Savonius wind turbine (Mohammad et al 2019)

Fig2.10. *A twisted Savonius wind turbine(Source: Wikipedia)*

Wind Farm

A wind farm simply means collection of wind turbines installed together in a particular area for the purpose of generating electricity. The essence of wind farms is to harness enormous amount of energy from the wind. There some economic, operational and maintenance reasons why wind farms are preferable. Before any wind project can be executed, some legal fees and environmental preparations has to be done, because of this reason, opting for a wind farm is best because the legal fees don't depend on how large the wind project is (Sanne Akerboom et al 2018). This has prompted the installation of mega wind farms with some having as much as 150 wind turbines (EERE, 2007) with output power in hundreds of Megawatts (Ackermann, 2005)

Siting of Wind Farms

Wind turbines could be installed onshore or offshore which depends on the design and quantity of energy needed. Onshore wind farms are installed on land usually on mountainous or hilly scape in other to tap wind energy. Fig 2.11 shows the picture of an onshore wind farm.

Fig2.11. *Onshore wind farm (Source: Jasmin Martinez 2017)*

Offshore wind farms are installed at least 10km away from the sea shore. They have easy access to sea wind and has less environmental impact. However, they have the disadvantage of high cost of raising foundations, power cable installation and high maintenance cost (Sanne Akerboom et all 2018). Fig 2.12 shows a typical offshore wind farm

Fig2.12. *Offshore wind farm (Source: www.google.com)*

Theoretical Review

Designs of wind turbines are done using some modeling techniques that are simulated on computers to analyze the wind energy present in a particular location (Hewitt et al, 2017). Wind energy is converted into electrical energy using wind turbines. A conventional horizontal axis turbine has three major components, the rotor, generator and the structural support. The components that comprise the rotor include blades and these amounts to about 20% of the total cost of the wind turbine. The parts that constitute the generator comprise the drive systems, the gear box and other components for converting the wind speed into electricity. This amount to about 34% of the turbine cost. The tower or the frame work and the yaw mechanism amount to about 15% of the total wind turbine cost. Fig 3.1 shows the parts of a wind turbine generator

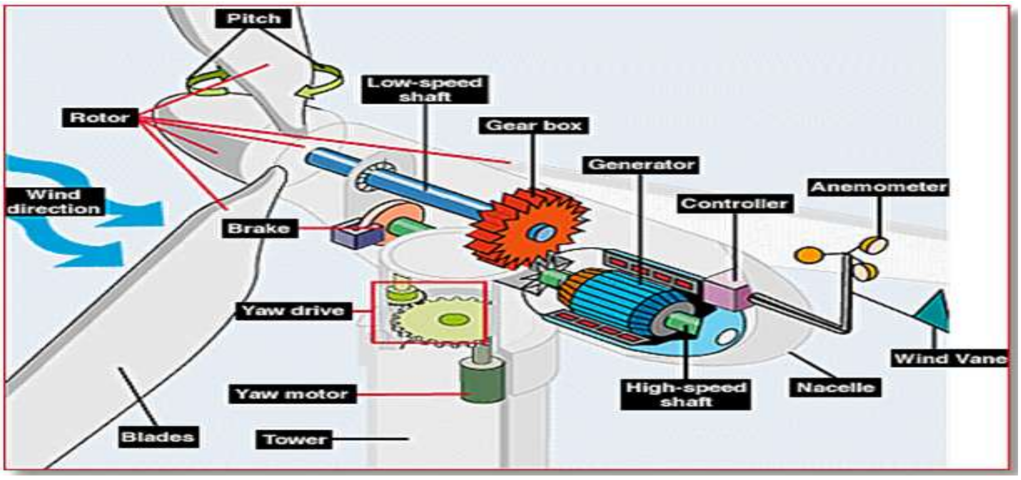


Fig3.1. *Parts of a wind turbine generator.(Source: www.goole.com)*

Efficiency of Wind Turbine System

Not all the wind energy fed into the turbine is converted into power. Some of the wind tapped by the blades is lost at the output end of the wind turbine. The term used to describe efficiency of wind turbines is called performance Coefficient (Cp) and it is highlighted in Betz's law. A physical limit exists to explain the quantity of energy that can be extracted, which is independent of design. The energy extraction is maintained in a flow process through the reduction of kinetic energy and subsequent velocity of the wind. The magnitude of energy harnessed is a function of the reduction in air speed over the turbine. 100% extraction would imply zero final velocity and therefore zero flow. The zero flow scenario cannot be achieved hence all the wind kinetic energy may not be utilized (Peter and Richard 2012). This law postulates that maximum wind energy which can be transformed into electrical power is 0.593 (16/27) of the total energy tapped by the blades. Let us call the blade area A (m2) and the wind speed V (m/s), Then maximum power P(W) that can be generated is given in equation 3.1

$$P = 0.5 \times Cp \times \rho \times v^3 \times A3.1$$

Where, ρ = density of air (Kg/m3), P= mechanical power in the air (Watts),Cp= Performance Coefficient of the turbine, V= wind velocity (m/s), A= Area of the rotor blades (m3).

The power the wind energy can produce is a cubic function of the wind speed. This implies that if the speed of the wind is increased by two, there would be a corresponding change in power amounting to eight times the initial turbine power. Therefore, turbines must be designed to withstand high speed velocity in order to avoid physical damage. The highest efficiency of wind turbines is measured at wind speeds between 10m/s to 15m/s. When the wind speed exceeds these values, care must be taken to put it under control so as to obtain the desired output power. Also the forces on the blades should be controlled to avert blade damage (Ackermann et al, 2005).

High wind energy does not occur often and as such has minute effect on the general performance of the turbine. However, if this high wind is not controlled, it can increase both turbine maintenance and production cost. [Harrison et al, 2000]. For every wind turbine, there is always a particular control system peculiar with it. There are different ways to control aerodynamic forces on the rotor and therefore reduce the power during high winds so as to avert damage (Ackermann, 2005).Due to the fact that wind energy is free (no cost of fuel), wind -to-rotor efficiency impacts on the price and cost of power. Further inefficiencies, which include losses due to gearbox, converter and generator losses, can contribute to power reduction in the wind turbine. Components are protected from wear and tear, by keeping extracted power fairly higher than the operational speed, thereby causing a reduction in the turbine efficiency. Wear and tear cause decrease in wind turbine efficiency times. However in Denmark, 3128 wind turbines which are 10year and above were analyzed and it was revealed that there was no reduction in 50% of the turbines while there was 1.2% decrease in the other half per year. (Sanne, 2013). It is worthy of note that design of horizontal turbine are more efficient than vertical turbine.

Aerodynamics Modeling

There are different designs of turbines with varying principles of energy extraction. The aerodynamics design of any type of turbine is dependent on the topology. There is always a maximum power which any particular topology can deliver. Some topologies are highly preferable to others. The procedures used to harness power have great effects on this. Turbines are categorized broadly as: lift-based or drag-based. The lift base has higher efficiency than the drag base. What differentiates these classes of turbine is the magnitude of the force involve in their energy extraction. The equation that governs power extraction in a wind turbine is given as shown in 2.2

$$P = F \times v3.2$$

Where, P = the power (W),F = the force vector(N), v = wind the velocity(m/s)

The wind interaction with the blades causes the generation of the force. The primary focus of the wind turbine aerodynamics is the distribution and magnitude of this force. The drag is the most common force of aerodynamics. The drag force moves in a parallel direction to the wind. The parts of the turbine are movable, which may alter air flow (wind) on its parts. A cycling wind on a calm day may be seen as a typical relative wind. For power to be extracted, the turbine parts must be in the force's direction. The drag force reduces the wind speed. The relative wind speed affects the maximum power that the drag force extracts. The lifting surfaces of lift-base wind turbine are always moving perpendicularly to the flow. Here, there is no decrease in the relative speed but the rotor speed increases with it. This explains why drag base forces appear smaller than the power limit of these machines

There are different sizes of wind turbine. Wind turbines have wide range of conditions when in operation. These variations make it stressful when comparing different classes of wind turbines. This problem of comparison is handled using non-dimentionalism for various qualities. Comparison between turbines can be made by non dimensionalism without giving considerations to size and wind conditions. One of the qualities of non dimensionalization is that it has the ability of producing several dimensional results. The most important parameter in the aerodynamics of wind turbines is the power coefficient. Some turbine in practice can exhibit more than a unity power coefficient. Here, it cannot inferred that the first law of thermodynamics has been violated because it is not an efficiency term considering the actual definition of efficiency.

Blade Element Momentum (Bem) Model

BEM model was originally proposed by Glauert by combining blade element theory and blade momentum theory. The blade element theory discretizes the blade into several elements and ignores the mutual influence between two adjacent elements. The aerodynamic loads on each element depend on its local airfoil characteristics, i.e. its lift and drag coefficients. The sum of these loads yields the total loads on the blade. The blade momentum theory introduces axial induction factor and angular induction factor to respectively calculate the induced velocity in the axial and tangential directions. The induced velocity affects the angle of attack of the blade and therefore influences the aerodynamic loads calculated by the blade element theory. Combining blade element theory and blade momentum theory provides a solution to obtain the performance parameters of each blade element through an iterative procedure (Linet al 2016)

Tip Loss

One of the main limitations of the original BEM model is that it ignores the effects of vortices shedding from the blade tip on the induced velocity. Practically, these effects play a significant role in the induced velocity distribution along the blade, especially the region near the blade tip. In order to compensate for this deficiency in the BEM model, several tip loss correction factors have been proposed. Prandtl proposed a tip loss correction factor through modeling the wake of the wind turbine as vortex sheets. Prandtl's tip loss correction is simple and efficient and also improves the accuracy in the predictions of induced velocity distribution. Based on the Navier- Stokes solutions, Xu and Sankar proposed a correction of Prandtl model, showing good agreement with the experimental data of NREL (Lin et al 2016)

Variable Speed and Constant Speed Wind Turbines

What differentiates variable speed wind turbine from constant speed wind turbine is whether the rotating part (i.e. the rotor) is meant to operate at steady speed or designed to operate at varying speed. Wind turbines usually operated at constant speed in the early 1970s. This implies that their rotors were fixed irrespective of the wind speed. Simple generators are used in constant speed and their speed is made constant by the electrical network frequency. A power electronic frequency converter is required for variable speed wind turbines. Although it is costly to afford the power electronics needed to vary the speed of wind turbines, it is still paramount to vary the speed of wind turbines because it ensures high efficiency (Balas et al, 2006). This is confirmed by having a plot of the coefficient of performance Cp against the tip speed ratio λ. The tip speed ratio λ, is the ratio of wind speed available for power generation to wind speed into the turbine. Its expression is written in equation 2.3 below.

$$\lambda = \frac{v_{TIP}}{v_{WIND}} = \frac{w \times R}{v} 3.3$$

Where, w =angular velocity of blades (rad/s), R= radius of the rotor (m),V= The speed of wind (m/s).

The optimum value of the coefficient of performance Cp is 0.59. This means that only a fraction of the wind power amounting to 0.59 is harnessed by the wind turbine. The power that reaches the turbine results from the continual change in kinetic energy of air when it is passing through the rotor. Betz was the first person in 1919 to discover the value of maximum coefficient of performance (0.593) and it relates to all types of turbines. The highest value Cp is only reached for a specific λ. w is always constant when the turbine has a fixed speed. The turbine efficiency is usually lowered for other wind speeds because operating at other speeds is an alteration the original design (Kathryn 2004). The variable speed wind turbine is aimed at making the tip speed ratio λ constant for the particular value that tallies with the coefficient of performance. This is achieved by using blade velocity suitable for wind speed changes. This gives variable speed wind turbines the special characteristics of being to run at the maximum obtainable efficiency irrespective of the velocity of the wind. This and the raised energy capture resulting from variable speed operation of wind turbines provide high benefits and ensures that the power electronics (frequency converters) needed is less expensive (Balas et al, 2006). Hence the wind industry must always build the variable wind turbines to ensure efficiency and optimal power availability.

Conclusion

This work involves comprehensive review on performance evaluation of mini wind turbine for electricity generation. Review of the principle of operation of wind turbine as well as the conversion of wind energy into electrical energy was considered in detail with their relevant mathematical expressions. Two basic types of wind turbines such as the Horizontal Axis Wind Turbine (HAWT) and the Vertical Axis Wind Turbine (VAWT) were also considered. wind speed trend in Nigeria including the country's meteorological data as obtained from NIMET with the population density distribution across the country were reviewed. Also considered in this paper is the wind farm concept including factors to consider in sitting wind farm and various modeling techniques as reviewed by various researchers in analyzing wind energy, efficiency of wind turbine system as well as the application of aerodynamic modeling principles and designs for wind energy extraction. Finally the blade element momentum (BEM) model including its tip loss, variable and constant wind speed of the turbine and design considerations in the determination of coefficient of performance of wind turbine were also critically considered and reviewed.

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