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Development Of Analytical Model For Characterizing A 2500 W Wind Turbine Power Plant Under Varying Climate Conditions In Nigeria

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***Abstract*—In this paper, development of analytical model for characterizing a 2500 W wind turbine power plant under varying climate conditions in Nigeria is presented. The annual average wind speed data from all the States in Nigeria were obtained from NASA portal. The lowest wind speed data was used as a reference wind speed which was then used to determine the number of a selected wind turbine that can deliver the required 2500 W power output. Eventually, the wind speed data from all the States in Nigeria were used to determine the number of wind turbines required producing the same specified output power. From the results obtained a simple analytical model was developed to determine the output of the wind turbine for any given wind speed. Also, the analytical model for computing the minimum number of the selected wind turbine that will deliver the specified output power of 2500 W was developed. The results show that , at the minimum wind speed data of 1.54 m/s about 123 of the selected 20.4526784 W wind turbine is needed to deliver the specified 2500 W power. At the upper wind speed data of 3.7 m/s about 8.8 or 9 of the selected 20.4526784 W wind turbine is needed to deliver the specified 2500 W power. The result is about 92.85 % reduction in the number of required wind turbines.**

Keywords— Wind Turbine, Analytical Model, Renewable Energy, Global Warming, Sizing Of Wind Turbine

1. Introduction

Today, renewable energy systems have been widely adopted across the globe due to the global quest for environmentally friendly energy systems [1,2,3,4]. Among the renewable energy sources, wind energy is one of the most promising option [5,6,7,8,9,10,11]. Particularly, unlike the solar energy which can only be available for some hours within the day, the wind energy can be available all through the day [12,13,14,15,16,17]. In this wise, wind energy systems can be integrated with the solar energy system to enhance the availability of the power supply [18,19,20,21,22,23].

Although the renewable energy systems are more environmentally friendly than the prevalent fossil fuel energy source [24,25,26,27,28], the initial investment cost of renewable energy systems are usually very high [29,30,31]. As such, researchers are most often focused on designing optimized renewable energy systems. In this paper, a 2500 W wind turbine power plant is presented. The wind turbine is sized based on the wind speed data of one of the States in Nigeria. Then, the wind speed data of the various States in Nigeria are used to develop an analytical model that gives the minimum number of the selected wind turbine which can deliver the same required daily energy demand. The idea presented in this paper will enable users of the 2500 W wind turbine plant to cut down on the initial investment cost if their location site has higher wind speed data than the reference wind speed used in the initial sizing of the wind turbine.

2. Methodology

2.1 Sizing of the Wind Turbine System

In order to characterize the wind turbine power output under varying climate conditions across Nigeria, first, the sizing of the wind turbine system is performed. The following assumptions have to be considered for the sizing of the wind turbine power output [32,33];

(i) The power output from a wind turbine is directly proportional to the area swept by the rotor .

(ii) The power output from a wind turbine is also proportional to the cube of the wind speed [32,33]. Therefore, if the wind turbine kinetic equation is given as,

$$K = \frac{1}{2}mv^2 \qquad (1)$$

But wind power (P) in Watt is also given as (Sarkar, 2012);

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

Where k = kinetic energy (Joules)

m = Mass in k/g
V = Wind speed (ms^{-2})
A = Swept Area (m^2)
ρ = Density of Air (kg/m^3)

The approach adopted in this paper is to size the wind turbine for a given power rating of 2.5 kW base on some chosen design values for charging of the battery. The wind data obtained from NASA portal for Nigeria showed that the lowest annual average wind speed occurred in Bayelsa State and it is 1.54 ms^{-1} . Specifically, the sizing of the turbine entails determination of power output of each wind turbine and the number of such wind turbines that will satisfy the required power. The power generated by each of the wind turbine is P_{wtb} and it is given as;

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

In order to determine the value of P_{wtb}, the following assumptions are made;

(i) V = Wind speed (ms^{-1}) which in this case is the lowest wind speed in the study area (V = 1.54 ms^{-1}).
(ii) A = swept area (m^2) . A value of = 7 m^2 is taken.
(iii) ρ = air density in kilograms per cubic meter = 1.6 kg/m³

Then,

$$P_{wtb} = P = \frac{1}{2}(\rho)(A)(V^3) = \frac{1}{2}(1.6)(7)(1.54) = 20.4526784 \text{ W}$$

The number of wind turbines that will produce the total expected power output of 2.5 kW or 2500 W is given as;

$$N_{wtb} = \frac{\text{Total Expected Power}}{P_{wtb}} \qquad (4)$$

Therefore,

$$N_{wtb} = \frac{2500}{20.4526784} = 122.2334 \approx 123$$

So far m it has been demonstrated that for the selected reference wind speed value about 123 wind turbines are needed where each of the wind turbines has 20 W power output , swept area size of 7 m^2 and with the turbines operating in a climatic condition that has average wind speed of 1.54 ms^{-1}. The power output of the turbine changes significantly with the wind speed. Notably, at higher wind speed than the selected reference wind speed of 1.54 ms^{-1} the wind turbine output will be higher than what is obtained at the reference wind speed. Therefore, considering Nigeria with different climatic conditions and average wind speed data in the 37 States, different numbers of wind turbines will be required to produce a given required power output.

2.2 Development of model for the Wind turbine power output under varying climate conditions

The actual power generated by each wind turbine is given as P_{wtb} = 20.4526784 W and the total number of wind turbines is denoted as N_{wtb} and then the actual total power generated by all the wind turbines (P_{atwtb}) is given as;

$$P_{atwtb} = N_{wtb} * P_{wtb} \qquad (5)$$

Then, with N_{wtb} = 125 and $P_{wtb} = 20.4526784\ W$ then P_{atwtb} becomes;

$P_{atwtb} = 20.4526784 * 123 = 2515.679$ W

Given that the required daily power demand is 2500 W and the actual total power produced by the wind turbines is P_{atwtb}, the percentage excess power produced by the wind turbines is given as;

$$PE_{wtb} = \frac{(P_{atwtb} - 2500)100}{2500}\% \qquad (6)$$

Given that for the selected case study with wind speed of 1.54 m/s and $P_{atwtb} = 2556.585$ W, then, the PE_{wtb} becomes;

$$PE_{wtb} = \frac{(2515.679 - 2500)100}{2500}\% = 1.5\%$$

In order to derive the required model for the wind turbine output power under varying climatic conditions, the annual average wind speed data for the 36 States in Nigeria along with that of Abuja are arranged in ascending order. The data also includes the monthly average wind speed data for Bayelsa State which has the lowest annual average wind speed. The 50 different wind speed, V values were used to compute P_{atwtb} and PE_{wtb} and then a graph of P_{atwtb} versus wind speed , V , PE_{wtb} versus wind speed , V and N_{wtb} versus wind speed , V were plotted. For each of the graphs a trend line model was fitted using Microsoft Excel 2010 version. The trend line models give the analytical models for assessing the wind turbine power output under varying climate conditions.

3. Result and Discussion

The results on the model for the Wind system output under varying climate conditions are given in Table 1. The graphs of the required peak power demand and the actual total power produced by the wind turbines versus wind speed, V are given in Figure 1. The wind speed values cover the range of values obtaining across Nigeria in Table 1 and Figure 1.

Table 1: The actual total power produced by the wind turbines (W) and the percentage actual total power produced with respect to the required power versus wind speed, V

Wind Speed (m/s)	Actual total power produced by the wind turbines (W)	Percentage Actual total power produced WRT The Required Daily Power (%)	Wind Speed (m/s)	Actual total power produced by the wind turbines (W)	Percentage Actual total power produced WRT The Required Daily Power (%)
1.5	**2515.7**	**0.6**	**2.6**	**11421.3**	**356.9**
1.6	**2665.6**	**6.6**	**2.6**	**11692.1**	**367.7**
1.6	**3038.3**	**21.5**	**2.6**	**11829.1**	**373.2**
1.7	**3324.7**	**33.0**	**2.6**	**11967.2**	**378.7**
1.8	**3884.7**	**55.4**	**2.6**	**11967.2**	**378.7**
1.8	**4017.1**	**60.7**	**2.6**	**12246.6**	**389.9**

1.9	**4504.2**	**80.2**	**2.6**	**12246.6**	**389.9**
1.9	**4576.9**	**83.1**	**2.6**	**12387.9**	**395.5**
1.9	**4724.5**	**89.0**	**2.6**	**12530.3**	**401.2**
1.9	**4799.5**	**92.0**	**2.8**	**14481.7**	**479.3**
1.9	**4875.2**	**95.0**	**2.8**	**15446.9**	**517.9**
2.0	**5266.1**	**110.6**	**2.9**	**16799.1**	**572.0**
2.0	**5266.1**	**110.6**	**2.9**	**16973.5**	**578.9**
2.1	**6198.5**	**147.9**	**2.9**	**17503.9**	**600.2**
2.1	**6379.0**	**155.2**	**3.1**	**20322.1**	**712.9**
2.1	**6379.0**	**155.2**	**3.1**	**21324.7**	**753.0**
2.2	**7536.2**	**201.4**	**3.2**	**23211.4**	**828.5**
2.2	**7638.5**	**205.5**	**3.3**	**24084.4**	**863.4**
2.3	**7845.9**	**213.8**	**3.4**	**25895.7**	**935.8**
2.3	**8271.8**	**230.9**	**3.5**	**28531.3**	**1041.3**
2.3	**8825.5**	**253.0**	**3.5**	**29279.9**	**1071.2**
2.4	**8939.2**	**257.6**	**3.7**	**34327.1**	**1273.1**
2.4	**9285.9**	**271.4**	**3.7**	**34607.7**	**1284.3**
2.4	**9883.5**	**295.3**	**3.7**	**34889.8**	**1295.6**
2.4	**9883.5**	**295.3**	**3.7**	**35173.4**	**1306.9**

The analytical expression for determining the actual total power produced by the wind turbines (P_{atwtb}) under different climatic conditions is given by the trend line expression;

$$P_{atwtb} = 700V^3 \qquad (7)$$

The graph in Figure 1 shows that the least wind speed value is 1.54 m/s with such wind speed the wind turbines were just able to produce 0.6% in excess of the required peak power of 2500 W.

Similarly, the upper wind speed value of 3.7 m/s produced about 1306.9 % power in excess of the required peak power. Essentially, with the design specifications, the actual power produced by the wind turbines anywhere across Nigeria will be in excess of the rated peak power capacity of 2500 W.

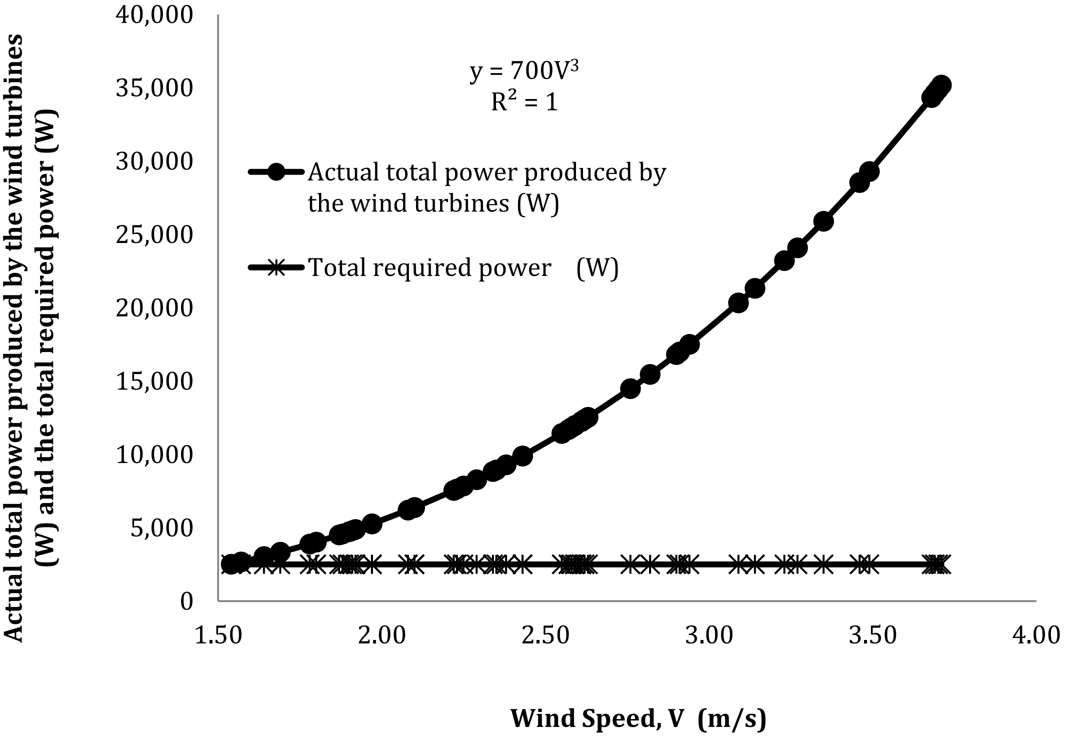

Figure 1: The actual total power produced by the wind turbines (W) and the total required power (W) versus wind speed, V (m/s).

The analytical expression for determining the percentage actual total power produced with respect to the required power (%) (PE_{wtb}) under different climatic conditions in Nigeria is given from Figure 2 as;

$$PE_{\text{wtb}}(\%) = 221.5V^2 - 562.4(V) + 357.4 \quad (8)$$

The results on the actual number of wind turbines versus wind speed, V are given in Table 2 and Figure 3. The results show that as the wind speed increases the number of the wind turbines required to deliver the given required power decreases. As such, at the lowest wind speed of 1.54 m/s about 123 wind turbines are required while at the upper wind speed of 3.7 m/s only about 9 wind turbines are needed to meet the same power demand. Eventually, from Table 2 and Figure 3, the analytical model for computing the minimum number of the selected wind turbine that will deliver the specified output power of 2500 W is given as;

$$\text{Nwtb} = 449.2(V^{-3}) \quad (9)$$

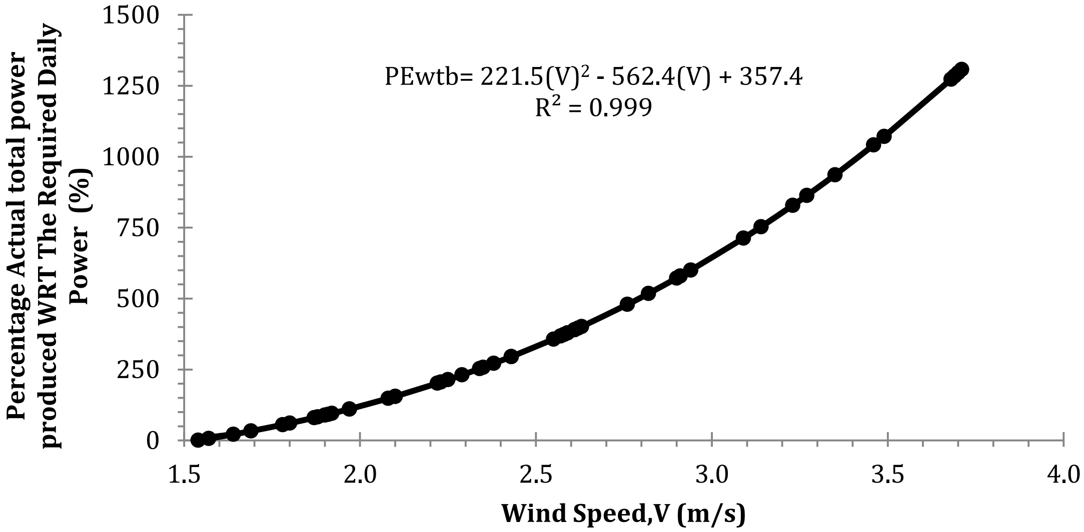

Figure 2: Percentage actual total power produced WRT the required power (%) versus wind speed, V (m/s).

Table 2: The actual number of wind turbines versus wind speed, V

Wind Speed (m/s)	Actual Number of Wind Turbine	Wind Speed (m/s)	Actual Number of Wind Turbine	Wind Speed (m/s)	Actual Number of Wind Turbine	Wind Speed (m/s)	Actual Number of Wind Turbine
1.5	123.0	2.1	49.9	2.6	26.5	3.1	15.2
1.6	116.1	2.1	48.5	2.6	26.2	3.1	14.5
1.6	101.8	2.1	48.5	2.6	25.9	3.2	13.3
1.7	93.1	2.2	41.1	2.6	25.9	3.3	12.8
1.8	79.7	2.2	40.5	2.6	25.3	3.4	11.9
1.8	77.0	2.3	39.4	2.6	25.3	3.5	10.8
1.9	68.7	2.3	37.4	2.6	25.0	3.5	10.6
1.9	67.6	2.3	35.1	2.6	24.7	3.7	9.0
1.9	65.5	2.4	34.6	2.8	21.4	3.7	8.9
1.9	64.5	2.4	33.3	2.8	20.0	3.7	8.9
1.9	63.5	2.4	31.3	2.9	18.4	3.7	8.8
2.0	58.8	2.4	31.3	2.9	18.2		
2.0	58.8	2.6	27.1	2.9	17.7		

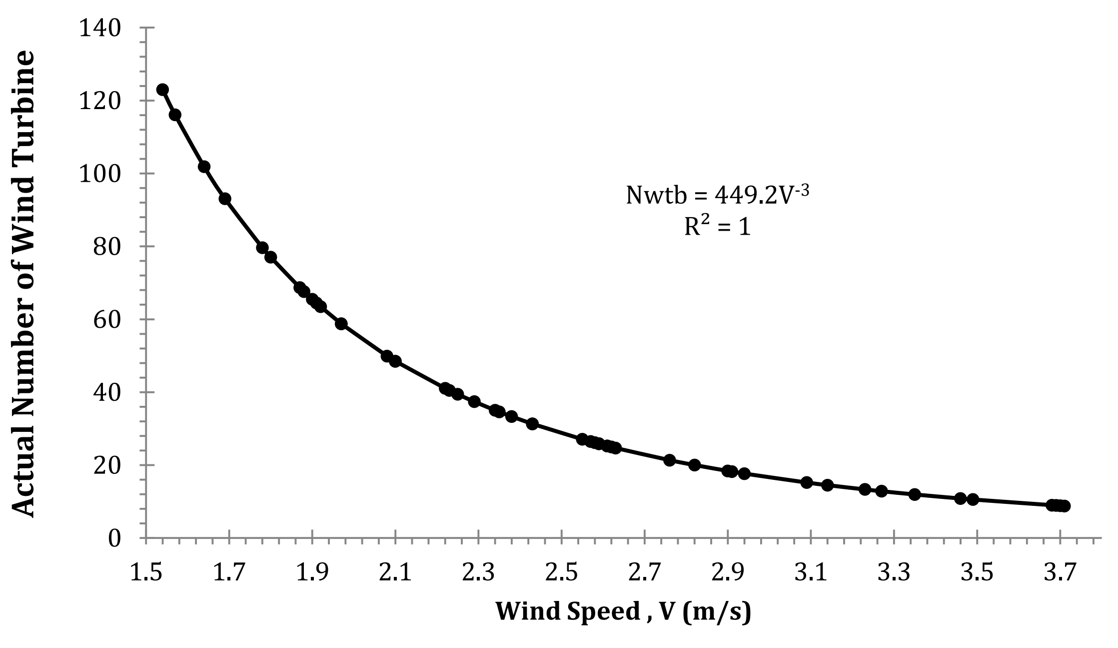

Figure 3: The actual number of wind turbines versus wind speed, V

4. Conclusion

In this paper, the sizing of a 2500 W wind turbine power is conducted using the minimum wind speed data obtained from NASA portal for Bayelsa State in Nigeria. Subsequently, the power output of the wind turbine was also determined for the wind speed data of the various States in Nigeria. The results showed that the power generated by the wind turbine is proportional to the cube of the wind speed. As such, as the wind speed increases, the number of wind turbines needed to meet the required power decreases. As such, the number of the selected wind turbine that can be used to generate the same given power demand is computed. Simple relational model was generated for computing the wind turbine power output as a function of the wind speed, Also, another relational model was developed for computing the number of wind turbines that can generate the same required power. This second model will enable users to determine the minimum number of the wind turbine that can generate the required power based on the prevailing wind speed in the area.

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