International Journal of Engineering Research Updates

Journal homepage: https://orionjournals.com/ijeru/

ISSN: 2783-0187 (Online)

(Research Article)

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Optimization of wind turbine design parameters for power output in southern Nigerian states using response surface methodology

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International Journal of Engineering Research Updates, 2023, 05(02), 001–008

Publication history: Received on 03 November 2023; revised on 26 December 2023; accepted on 29 December 2023

Article DOI: https://doi.org/10.53430/ijeru.2023.5.2.0032

Abstract

Weather Risk Optimization of Vertical Wind Turbines when situated in Southern Nigeria was achieved using Response Surface Methodology. Wind speed at heights of 10m and 50m between the years of 1990 and 2020 was acquired for four sampled southern states of Imo, Delta, Edo, and Bayelsa states from the Nigerian Meteorological Agency. Parametric profiling in various locations in the country aided the selection of locations with low wind speeds in the region. Delta has the lowest wind speed of 1.81m/s. The model for determining the power output in the region shows 98% R squared value. Analysis shows that if offshore wind turbines must be sited in southern Nigeria, hub height will be 1125m and 827m for obtaining wind speeds of 10m/s and 5m/s respectively. The optimization plot shows a wind turbine of 114. 5m blade length, wind speed of 10 m/s, and hub height of 1125m can produce wind power of 8MW.

Keywords: Optimization; Power Output; Response Surface Methodology; Southern Nigeria; Wind Turbine

1. Introduction

The use of wind energy to generate electricity is becoming more and more important in most countries. Current interest in renewable energy resources, such as wind power, is mainly due to double support. On the one hand, it is driven by economic and political aspects, such as the upward trend in fossil fuel prices and insecurity of supply. On the other, there are social and environmental aspects, resulting from the ever-increasing social awareness about the harmful impacts of the emission of greenhouse gases responsible for global climate change. (Javier et al, 2012). The major environmental challenges that wind turbines experience are natural catastrophes another weather risks. The natural catastrophes that wind turbines have experienced or can experience is firestorms, dust storms, floods, hurricanes, tornadoes, volcanic eruptions, earthquakes, tsunamis, and other storms. The mentioned disasters have been experienced in wind turbine farms in the past mostly in developed countries in Asia, Europe, and America. In Nigeria a moderate gust which resulted to a spike in the northeastern wind speed data has been observed severally. (Nse-Esiaga e al, 2014). Cases of extremely low wind speed which does not have the capacity of effectively turning a wind turbine blade at moderate hub height have been experienced in the southern region of Nigeria. Aside from the low wind speed experienced in the southern region, this region is known to have a relatively high rainfall when compared with the northern region. Rain increases drag, slows the rotational speed of the wind turbine, and reduces the power for the same wind speed. As the rainfall rate increases, the drag increases as well, lowering the ideal coefficient of performance. (AI et al, 2011). The design of experiments has been applied in several fields of design, manufacturing, material science, and other aspect of engineering and social sciences. Response surface methodology which is a method of DOE can be used in optimizing the design parameters of wind turbines concerning weather risk affecting it.

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Among the several risks that inhibit the effective functioning of a wind turbine is weather risk. Southern Nigeria has been predicted to have low wind turbine potentials due to its low wind speed and high precipitation while the northeastern region has shown huge potential due to the high wind speed and low precipitation in this region. The tendency of an occurrence of a wild wind that can increase the degree of blade deflection of a wind turbine was observed in northern Nigeria in the Sahel region. This deflection can lead to blade failure and extreme rainfall with a low wind speed would reduce the rotational speed of a wind turbine blade. A proper optimization of the wind turbines variables, acknowledging the regional weather risk factors of southern Nigeria would help in designing, and siting functional wind turbines in locations in southern Nigeria that have low wind prospects. This research involves the use of 30 years of historical weather data acquired from a professional agency for the purpose of modeling, optimization, and simulation of wind turbines. The research focused on the weather risk optimization of the southern region of Nigeria. The hub height, blade length, and pitch angle were the major variables. Precipitation and wind speed were the factors chosen to determine the configuration of an enhanced wind turbine.

Researchers have predicted the potential of wind energy in Nigerian energy generation. O.I. (Okoro et al, 2007). Said in his work, the prospect of wind power in Nigeria, that there is high wind energy potential in Sokoto and a city near Jos. He analyzed the wind speed of six states in Nigeria from the year 2000 to 2003. Okoro suggests that wind energy generation should be utilized in rural electrification to aid irrigation and other agricultural activities.

The assessment of wind power for Enugu was done using the Weibull distribution, the result showing that a hub height of 10 m contains a mean wind speed, scale factor, shape parameter, and skew of 2.5 ± 0.3 m/s, 4.31 m/s, 2.21 and −0.46, respectively (Odo et al, 2012). Ajayi observed a research gap in the assessment of the wind energy profile in south-west, and conducted a study that depicted that a large-scale production of power could be emanated in Lagos and Oyo State with a mean wind speed of 2.9 to 5.8 m/s. In contrast, others could employ a small-scale production (Ajayi, et al., 2014). Annual mean wind speeds ranging from 3.09 to 4.15 m/s were depicted (Paul et al, 2012).

An optimized sizing of new WECs for mobile applications was proposed to ease the effects, and 1% of wind turbine output was lost when placed at 100 m (Okundamiya et al, 2013).

The south-west region was evaluated using the Weibull distribution on 37 years of wind data, the least annual mean power was achieved using DeWind 48 as 4.21 kW/a in Abeokuta, whereas the highest results occurred by employing DeWind D7-1.5 MW to 430.10 kW/a in Lagos (Adaramola et al, 2012). It was observed that Maiduguri and Bauchi depicted the best results, at peak values of 6.10 m/s and 7.04 m/s and their respectful mean power densities were 173.70 W/m2 and 299.88 W/m2, while Potiskum had an annual mean wind speed of 4.80 m/s and power density of 103.14 W/m2 (Ohunakin et al, 2013). It was deduced that global warming gives rise to wind speed while afforestation has a significant negative effect on future wind speed throughout the country (Matthew et al, 2017). The wind energy resources were visualized in six areas of south-south Nigeria for a hybrid system by applying the Weibull distribution function with values of wind speed estimated to be from 3.21 to 4.19 m/s at 10 m height (Diemuodeke et al, 2019). Okeniyi explored the Weibull as well as the Rayleigh distribution to verify the wind speed resources in Akure for an 11-year data period. When a hybrid system of wind and solar energy was examined, the yearly energy production was 283,027 per kWh, but when connected with diesel it was more cost-effective compared to standalone wind/solar hybridization (Salisu et al, 2019). Analysis of wind energy resources for the south-south region of Nigeria was explored for the water pumping system, the mean power density and annual energy varied in different locations as 6.28 ≤ APD ≤ 102.90 W/m2 and 422 ≤ AE ≤ 747 kWh/m2 per year, respectively (Abam et al, 2017). To simulate a hybrid system, the wind energy resources were examined in the six regional parts of Nigeria using the Weibull distribution function, and the wind speed was found to be in the range 3.74–11.04 m/s (Ukoba, et al., 2020). The resulting wind speed was found to be 0.9 to 13.1 m/s, having a mean absolute percentage error of 8.9% in the form of a map that could be employed to assess wind energy resources in any part of Nigeria (Fadare et al, 2010). The spontaneous change in wind speed would affect the wind energy generation (Allison, et al., 2020). Wind speed hugely determines the amount of power and electricity produced by a turbine; higher wind speeds would have higher power generated because stronger winds turn the blade faster. (European Wind Energy Association, 2013).

Nigeria being a fast-developing country with a population of over 180 million people has a growing energy demand. The population of Nigeria is expected to rise to 400 million in the year 2050 (Oyekola et al, 2019). The daily peak electricity generation is recorded as 4000-5000 MW compared to the total installed capacity of power plants which is estimated at 12522MW across various generating stations. The daily peak electricity generation is recorded as 4000-5000 MW compared to the total installed capacity of power plants which is estimated at 12522MW across various generating stations (such as Kanji, Afam, Ibom, Alaoji, Okpai, Olorunsogo, Egbin, Geregu, Sapele, among others). From, the two major sources of energy generation in the country: (i) thermal power turbine stations (such as Sapele station at 1020

MW; Egbin at 1320 MW capacity; among others) located in the south region close to the natural gas supply sources, and (ii) hydropower stations (Kanji, 800 MW; Shiroro, 600 MW; and the Jebba, 540 MW) which are located in the Northern region of Nigeria. More also, Furthermore, the comparison of the peak electric power demand forecast on April 2015 is 12.80 MW with the current peak power demand forecast (17,520 MW) dated the 14th of October 2016 shows a tremendous increase in the nation's electricity demands at an approximation of 36.8% due to spontaneous economic recovery; high population growth; commercial and industrial demands for a higher share of electricity from the distribution companies and urbanization. (Okeniyi et al, 2015). Wind energy with all its prospects as duly predicted by researchers has not been embraced by society and energy policymakers. (Akinbami, 2001). The increasing demand for a clean and sustainable energy-generating system would raise the quest for a renewable energy plant further than it is today. It is very paramount to know the sustainability of wind energy systems increasing change in climate in Nigeria.

2. Materials and method

The major parts of a wind turbine are the hub, rotor, nacelle, generator, and foundation. The hub height is a term used to describe the height of a turbine tower. The rotor spins the blade. These come in different configurations and possess different characteristics.

National Aeronautics and Space Administration (NASA) satellite called QuikSCAT carries the Sea winds instrument, a scatterometer. Although designed for measurements over the ocean, Sea winds can also collect data over land and ice. In a continuous 1,800-kilometer-wide band, Sea Winds makes approximately 400,000 measurements covering 90% of Earth's surface every day. QuikSCAT is a joint mission with NASA and the National Space Development Agency of Japan (NASDA).

Nigeria Meteorological Agency (NiMet) acquired data using field observers prior to 2004. In 2004 they adopted a technology called Automatic Weather Observing System (AWOS). This system has the capacity to measure weather data. However, NiMet acquires data from other agencies that make use of weather satellites. Acquiring data from multiple sources helps in data validation, however, a correlation analysis is necessary to determine the similarities data acquired.

An official request for southern Nigerian wind speed data for 30 years (1990-2020) was made through Enugu NiMet office which is situated at the Akanu Ibiam International Airport. A letter of attestation and admission letter were requested by the agency to identify me as a student of Enugu State University of Science and Technology for the acquisition is subsidized for research students. This request was processed, cost and sent to my mail in few days.

The two sets of wind speed and rain fall data acquired from NiMet and NASA were compared and found to have 96% correlation. Wind speeds at hub height 10m and 50m were also compared and the power output was found to be directly proportional to their heights and show similarities in wind trends. The data of locations in each southern state were compared statistically to determine the locations with the lowest wind speed and the highest precipitation in the south.

2.1 Experimental Design

The design of experiments of wind turbine hub height, blade length, and pitch angle, in the determination of the relationships between the operational (factors) and performance (responses) parameters of wind turbines when installed in Nigeria and the optimal settings in this study started within RSM experimental design, model fitting, optimization. The experimental design was developed based on, the number of variables available, the availability of resources, data collection sources, and time. Effects of the operational parameters of the wind turbine was the height of a hub/tower (Hh), blade length (BL) and pitch angle (PA); MINITAB (version 19) was used to create and randomize a thirty-four (20) two-coded levels (+1 and -1) half factorial design layout, with "+1" and "-1" indicating the high and low levels of the factors, respectively, and "0" indicating the factors' midpoint. Two level fractional factorial design (2^{k-q}) was employed because of its economic viability, desirable properties, orthogonality, and it permits marginally small experimental runs to be analysed for high factorial points. Experimental study variable number (K = 6), for independent variables including hub/tower (Hh), blade length (BL) and pitch angle (PA) was used for the design. The coded symbols of these factors are x_1, $x_{2,}$ and x_3 respectively. The number of experimental runs was determined from the following relation.

$$n = 2^{k-q} + n_c \ldots\ldots\ldots(1)$$

Where $n_c$the number of centre points, k is the number of factors in the design, q is the number of fractions and the number of experimental runs is n Table 1 is generated factorial design layout for this study.

Table 1 Randomized Design Layout for the Study

Experimental Runs		Coded Values		
StdOrder	RunOrder	X_1	X_2	X_3
1	1	-1	-1	-1
2	2	1	-1	-1
3	3	-1	1	-1
4	4	1	1	-1
5	5	-1	-1	1
6	6	1	-1	1
7	7	-1	1	1
8	8	1	1	1
9	9	-1	-1	-1
10	10	1	-1	-1
11	11	-1	1	-1
12	12	1	1	-1
13	13	-1	-1	1
14	14	1	-1	1
15	15	-1	1	1
16	16	1	1	1
17	17	-1	-1	1
18	18	1	-1	1
19	19	-1	1	1
20	20	1	1	1

Table 2 is a table of the expected limits of the factors in a coded and actual symbol all in millimeters as presented below with blade length and wind speed coded and actual.

Table 2 Limits of the process parameters

S/N	Factor Description	Factor Symbols		Factor Values	
		Coded	Actual	High (+1)	Low (-1)
1	Blade length (mm)	x1	BL	120	20
2	Wind speed (m/s)	x2	Ws	10	5

Experimental design of wind turbine for the optimization of power output using Minitab 18 started with the wind speeds of the southern Nigeria acquired from NiMet. The southern states with the least wind speed were selected statistically from all the southern state of Nigeria. The locations with the least wind speed in each state are being represented, these encoded locations wind speed A, wind speed B, wind speed C and wind speed D represents the wind speed of a location of Imo, Delta, Edo and Bayelsa respectively. These locations have the lowest onshore wind in speed at 50m. The least mean monthly wind speed experienced is 1.81m/s which occurred in 1996 in Delta state. Table 3 is the design of experiment of wind speed and blade length of 13 runs. Table 4 is the table of factors and response; the response is power output. The wind power was determined using equation 2.

Table 3 Design of experiment of two factors

No of runs	Blade length (m)	Wind speed (m/s)
1	15.50253	6.5
2	65	6.5
3	100	9
4	114.4975	6.5
5	65	6.5
6	30	4
7	65	2.964466
8	65	6.5
9	30	9
10	65	6.5
11	65	10.03553
12	65	6.5
13	100	4

Table 4 Design of experiment of two factors and response

No of runs	Blade length (m)	Wind speed (m/s)	Power (W)
1	15.50253	6.5	51013.63
2	65	6.5	896825.8
3	100	9	5634674
4	114.4975	6.5	2782743
5	65	6.5	896825.8
6	30	4	44520.88
7	65	2.964466	85076.08
8	65	6.5	896825.8
9	30	9	507120.7
10	65	6.5	896825.8
11	65	10.03553	3300574
12	65	6.5	896825.8
13	100	4	494676.5

2.2 Wind Power Equation

Wind power equation with P = Power output, kilowatts, Cp = Maximum power coefficient, ranging from 0.25 to 0.45, dimension less (theoretical maximum = 0.59),Cp 0.4 was recommended by literature.

ρ = Air density, kg/m^3 (1.23 kg/m^3), A = Rotor swept area,

$$\text{m}^2 \text{ or } A = \pi r^2 \text{............ (2)}$$

V = Wind speed, mph

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

3. Results and discussion

Figure 1 is a plot of wind speed in (m/s) versus blade length in (m). The plot shows that when the wind speed and blade length increased the wind power output also increased, when the blade length the power output also increased. Therefore, the wind power output is directly proportional to wind speed and blade length.

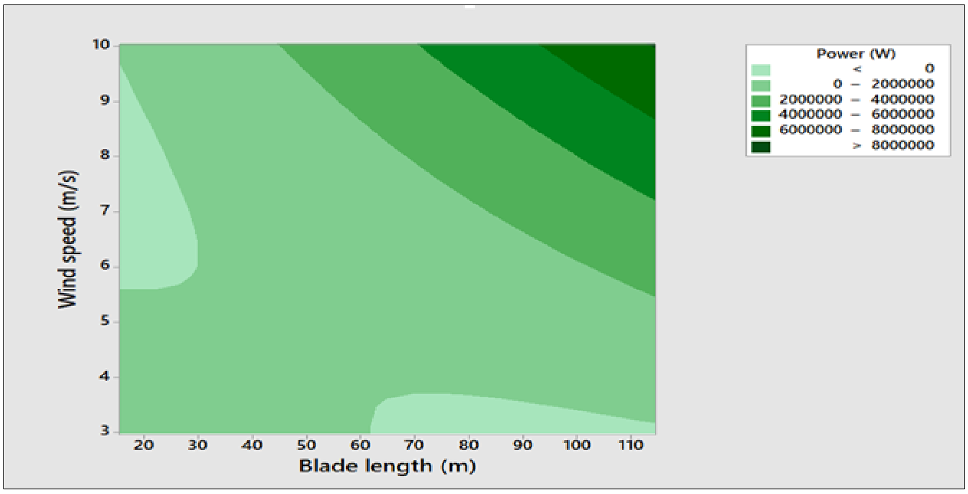

Figure 1 Wind speed versus Blade length

Empirical Modeling of Process Parameters for wind power output for wind turbine factors in wind speed and blade length for development of a model for wind turbine power generation. The power model was designed augment for the wind power equation 3. The model shows 98.32% R-square value that is it say that the model fits the observed data above 95 percent.

Power (W) = 4934536 - 83804 Blade length - 1249005 Wind speed
+ 235.8 Blade length*Blade length + 68296 Wind speed*Wind speed
+ 13364 Blade length*Wind speed

Table 5 Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
276001	98.32%	97.11%	88.03%

Optimization Plot of wind turbine power output shows that for 10m/s wind speed to be acquired, a blade length of 114 m would be required. And using an extrapolation with the wind speed of the state that has the lowest wind speed in the southern region while comparing the exact year it was being experienced at hub height of 10m and the corresponding wind speed, to determine the hub height of a wind velocity of 10.03m/s, shows the hub height will be 1125m and 827m for obtaining a wind speed of 5m/s. The optimization plot shows that a single wind turbine of 114. 5m blade length, wind speed of 10 m/s and a hub height of 1125m hub height can produce a wind power of 8MW.

Figure 3 is an impact factor plot of blade length and wind speed. The plot show that wind speed has greater impact in wind turbine power output than the blade length. The wind speed has 12.4 effect while blade length has an effect of 12 on power output. The product of the wind speed and blade length shows an effect of 8. Doubling the wind speed would have more effect on power output than doubling the blade length. This plot shows that wind speed is the major in basic wind turbine analysis.

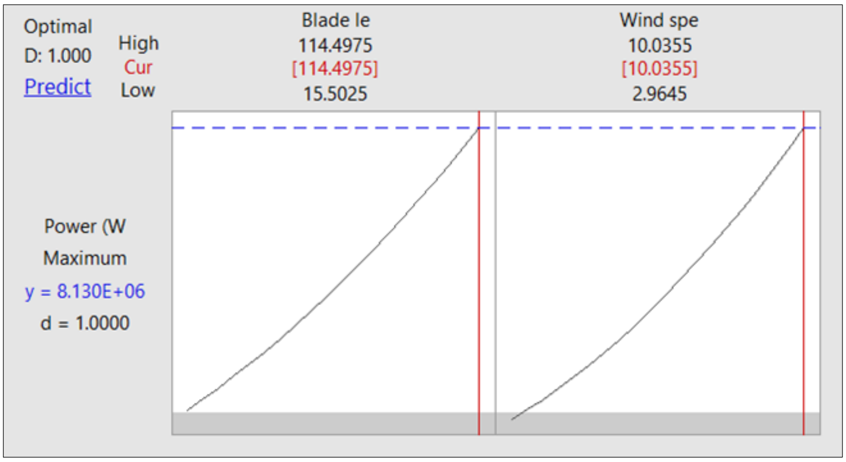

Figure 2 Optimization Plot of Power

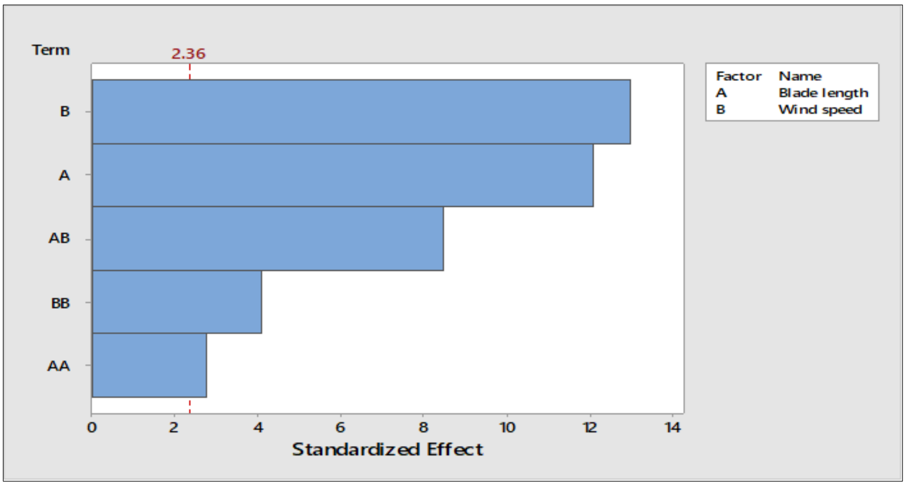

Figure 3 Impact of factors power output

4. Conclusion

This study confirmed the possibility of generating wind power in locations like Edo, Delta, Imo and Bayelsa which are the states with the least wind speed in the southern region of Nigeria. The least wind speed observed in the year 2006 in Delta state is 1.81m and was being used as a benchmark for the modeling. The analysis shows that the required hub heights of wind velocities of 5m/s and 10.03m/s will be 827m and 1125m respectively. The optimization plot shows that a single wind turbine of 114. 5m blade length, wind speed of 10 m/s, and a hub height of 1125m hub height can produce a wind power of 8MW. Wind speed was found to have a higher effect on wind power generation than the blade length. The model also proved the effect of doubling the wind speed in a wind turbine is higher than the effect of doubling the wind turbine blade length.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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