Journal of Inventive Engineering and Technology (JIET)
ISSN: 2705-3865
Volume-4, Issue-1, pp-49-57
www.jiengtech.com
Research Paper Open Access

RELIABILITY LEVEL IN THE FUNCTIONAL EVALUATION OF ENERGY DENSITY FROM THE ACTIVITY RESPONSES OF AVERAGE WIND SPEED AND POWER DENSITY

C. I. Nwoye[1], C. C. Emekwisia[2], C. N. Nwambu[3] and O. R. Opetubo[4]

[1,2,3]Chemical Systems Research and Empirical Model Laboratory, Department of Metallurgical and Materials Engineering, Nnamdi Azikiwe University, Awka, Nigeria
[4]Department of Materials Science and Engineering, Clemson University, South Carolina, USA

Corresponding Author: cc.emekwisia@unizik.edu.ng

ABSTRACT : *This paper presents the reliability level in the functional evaluation of Energy Density (ED) from the activity responses of Average Wind Speed (AWS) and Power Density (PD). Results generated from the research showed that ED increases with increase in the quotient of PD and $AWS^{0.27}$. Evaluation of ED was carried out using a derived and validated empirical model. The response coefficient of the ED to combined influence of the AWS and PD was evaluated to ascertain the viability and reliability of the highlighted dependence. Regression generated results showed trend of data point distribution similar to those from actual and derived model. Evaluation of energy density per unit wind speed and per unit power density were calculated as 11.44, 10.01 and 10.1 $(kWh/m^2)(m/s)^{-1}$ and 0.74, 0.65 and 0.66 (kWh/W) as obtained from actual, predicted and regression results respectively. The correlations between energy density and wind speed & power density as evaluated from the actual, derived and regression results were all > 0.98. Standard errors incurred in predicting energy density as a function of wind speed & power density instead of going through conventional the experiment were < 0.15 and 0.03 respectively. The validity of the model; $\xi = \vartheta\, [ḫ\, Ɣ^{0.27}]^{-1}$ was rooted on the insignificant deviation of model-predicted values of energy density from the corresponding experimental values which was less than 7%. This translated into over 93% operational confidence, response and reliability level for the derived model as well as over 0.93 response coefficient of ED to the collective operational contributions of AWS and PD.*

KEYWORDS: Reliability level, Functional Evaluation of Energy Density, Average Wind Speed, Power Density

---

Date of Submission:10-10-2023 Date of acceptance: 16-10-2023

I. INTRODUCTION

Wind energy is one of the most abundantly available form renewable of energy all over world. The economical and ecological return presented by wind energy has prompted applicability of some electrical systems using the energy source. Following increased demand for wind energy, series of research and development projects have been put in place to enhance previous effort geared at produce electricity from wind [1].

In recent time, wind power technology has been growing widely. With the incorporation of Wind turbines together with the electrical grid, it is necessary for the system operators to know the behaviour of wind turbine under all the operating conditions. Some areas of interest in the power system such as calculation of wind speed, modelling, control and stability analysis of the wind system connected with electric grids are of importance in the modern power system [2]. The problem associated with the various effects of wind energy when integrated with the power system; on the stability of the system is gaining awareness due to increase in its penetration level [2].

Presently, renewable energy sources have gained more attention in power sectors as a result of the need to reduce the usage of fossil fuels to generate the electrical power [3]. Today, wind power has become the most established sources in generating the electricity amongst all the renewable sources due to its potential technical and economic prospects. Wind power generation has continued to increase globally. With the latest wind annual report of 2015, about 392 GW is installed all over the world. This supplies 4% of world's electricity demand [4]. It is expected that its increased usage will continue to grow approximately 24% per year globally. With the worldwide rise in electricity generation through wind turbines, the impact on the electric utility grids has also increased. At the end of 2015, six countries including China (145362 MW), Spain (23,025 MW), Germany (44,947 MW), USA (74,471 MW), India (25,088 MW) and UK (13,603 MW) had over 10,000 MW of the installed capacity [5].

India is now amongst the top five countries for wind power installed capacity worldwide. The total renewable energy installation connected with the electric grid in India attained almost 33,792 MW. At the beginning of 2015, wind power was about11% of total installed capacity of 260.8 GW and about 66.5% of total renewable energy capacity [5]

Research has shown [2] that with a boost in the penetration level of wind power, the pertinence in ensuring that wind power penetration does not have effect on security, power quality, stability & reliability of every network of power system under all operating conditions also increased. The effect of wind power generators is insignificant on stability of power system when implemented on a small scale. With a rise of the penetration level, the power system's dynamic performance may be influenced. In the power system sectors, variable-speed WTs which use DFIGs are gaining increased awareness amongst several wind generation technologies, as a result of low investment, great energy transfer capacity and adaptable control. It is essential that detailed design and full stability analysis is carried out before connecting the DFIG to the grid. Also for system modeling, simulation is most important.

Some scientists have modeled some aspects in wind energy production. Andreas et al. [6] presented an alternative approach to obtain third-order model for DFIG as well as introduced the possibility to develop a model of rotor circuit's voltage sources that can be useful for simulation of several generating methods, like variable-speed WECS. The essence of the work was to get a set of some simplified equations as compared to those commonly used.

Guanjun (2013) suggested that by the Weibull Probably Density Function (PDF), the wind velocity variation can be described accurately. Combined with the Weibull PDF, the arithmetic mean wind speed and the cubic root cube wind speed can be derived and calculated. Based on the obtained wind speed, wind power and energy can be calculated [7]. The researcher also posited that wind power is a function of air density, the area intercepting the wind and the wind speed. It is calculated as [7]:

$$P = 1/2 \varepsilon . S . \upsilon^3 \qquad (1)$$

where P is the output power in watts, ε is the air density (kg/m^3), S is the area (m^2), where wind is passing and v is the wind speed (m/s).

In this work, attempt will be made to derive a model which predicts the wind energy density based on the average wind speed and power density.

Table 1: Variation of energy density with average wind speed and power density [8]

(ɣ) (m/s)	ϑ (W/m^2)	(ξ) (kWh/m^2)
3.14	18.96	14.10
3.00	16.53	11.11
2.82	13.73	10.21
2.98	16.20	11.78
2.71	12.19	9.06
2.76	12.87	9.27
2.69	11.92	8.87
2.89	14.78	10.99
2.59	10.64	7.66
2.43	8.78	6.53
2.47	9.22	6.64
2.64	11.26	8.38

II. METHODOLOGY AND MODEL FORMULATION

A. Model formulation

Computational analysis (using C-NIKBRAN [9]) of results in Table 1 indicates that

$$\frac{\vartheta}{\xi} = ђ\,[\text{Ɣ}^{K}] \qquad (2)$$

Introducing the values of ђ and K into equation (2) reduces it to

$$\xi = \frac{\vartheta}{1.05\,(\text{Ɣ}^{0.27})} \qquad (3)$$

Where

(ϑ) = Power density (W/m^2)

(ɣ) = Average wind speed (m/s)

(ζ) = Energy density (kWh/m^2)

ђ = 1.05;equalizing constant

K = 0.27;equalizing constant

B. Boundary and Initial Conditions

The ranges of average wind speed, power density and energy density are 2.64 -3.14 (m/s), 11.26 -18.96 (W/m^2) and 8.38-14.1 (kWh/m^2) respectively.

III. RESULTS AND DISCUSSION

A. Model validation

Model validation was carried out using graphical, statistical, computational and deviational methods. The derived model was rooted in equation (2). Equation (2) agrees with Table 2 following the values of ϑ / ξ and ђ [Ɣ^{K}] and evaluated from Table 1.

Table 2: Variation of ϑ / ξ with ђ [Ɣ^{K}]

ϑ / ξ	ђ [Ɣ^{K}]
1.3447	1.4308
1.4878	1.4126
1.3448	1.3892
1.3752	1.4100
1.3455	1.3743
1.3883	1.3811
1.3439	1.3716
1.3449	1.3984
1.3890	1.3576

Graphical Analysis

Critical comparative analysis of Figs 1 and 2 shows close alignment of the curves and areas covered by model-predicted energy density (relative to wind speed and power density) and those from the actual results.

Comparison of derived model with standard model

The validity of the derived model was further verified through application of the regression model (ReG) in predicting the trend of the actual results. Critical comparative analysis of Figs. 1 and 2 shows very close alignment of curves and areas covered. These translated into significantly similar trend of data points distribution for actual, predicted and regression model (ReG) predicted results relative to wind speed and power density.

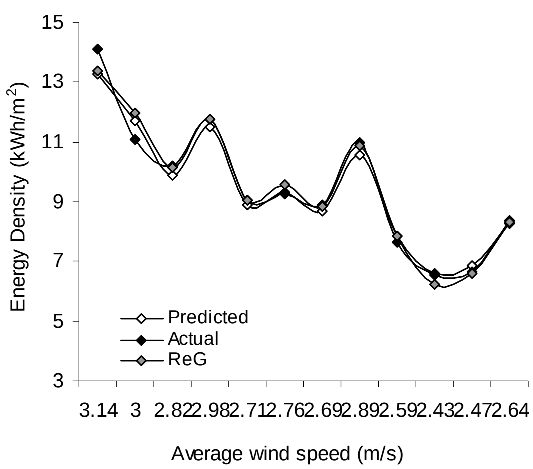

Fig. 1: Comparison of the energy densities (relative to wind speed) as obtained from actual, predicted and regression results.

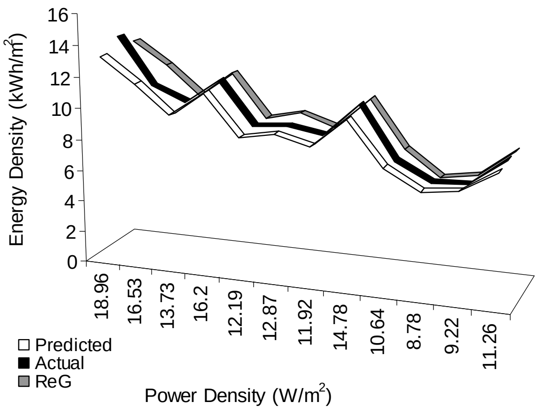

Fig. 2: Comparison of the energy densities (relative to power density) as obtained from actual, predicted and regression results.

Figs.1 and 2 strongly indicate that the degree of alignment of curves and dimension equality of areas covered is indicative of the proximate agreement between both actual, model-predicted and regression values of energy densities. This also indicates that the derived model is valid, reliable and exhumes a very high operation confidence.

Statistical Analysis

The correlations between energy density and wind speed, and power density as evaluated from actual, derived and regression results were all > 0.98. Furthermore, the standard error incurred in predicting energy density as a function of wind speed & power density instead of going through conventional the experiment were < 0.15 and 0.03 respectively

Computational Analysis

Energy density per unit wind speed

The energy density per unit wind speed

ξ_γ $(kWh/m^2)(m/s)^{-1}$ was calculated from the equation;

$$\xi_\gamma = \xi / \gamma \quad (4)$$

Re-written as

$$\xi_\gamma = \Delta\xi / \Delta\gamma \quad (5)$$

Equation (5) is detailed as

$$\xi_\gamma = \xi_2 - \xi_1 / \gamma_2 - \gamma_1 \quad (6)$$

Where

ξ_γ = Change in the energy densities ξ_2, ξ_1 at wind speed values γ_2, γ_1.

Considering the points (3.14, 14.1) & (2.64, 8.38), (3.14,13.2541) &(2.64,8.2509) and (3.14,13.3863) & (2.64,8.3386) as shown in Fig. 1, designating them as (γ_1, ξ_1) & (γ_2, ξ_2) for actual, predicted and regression results, and then substituting them into equation (6), gives the slopes: 11.44, 10.01 and 10.1$(kWh/m^2)(m/s)^{-1}$ respectively as their corresponding energy densities per unit wind speed.

***Energy density per unit power density ξ_ϑ* (kWh/W)**

Similarly, substituting into equation (6) points (18.96, 14.1) & (11.26, 8.38), (18.96, 13.2541) & (11.26,8.2509) as well as (18.96,13.3863) & (11.26,8.3386) culled from Fig. 2, as (ϑ_1, ξ_1) & (ϑ_2, ξ_2) for actual, predicted and regression results also gives the slopes: 0.74, 0.65 and 0.66 (kWh/W) respectively as their corresponding energy densities per unit power density. The proximity between values in each result set indicates significantly high validity level for the derived model.

Deviational Analysis

A comparative analysis of energy densities as obtained from actual and derived model reveal deviation of model-predicted values from those of the actual. This is believed to be due to the fact that some considered assumptions and experiment-oriented conditions which prevailed during the actual field work were not considered during the model formulation. This necessitated the introduction of correction factor, to bring the model-predicted values to those of the actual.

Deviation (Dv) (%) of the model-predicted energy density from that of the actual is given by

$$Dv = \left(\frac{\xi p - \xi a}{\xi a} \right) \times 100 \qquad (7)$$

Where

ξp = Model-predicted energy density

ξa = Energy density evaluated from actual results

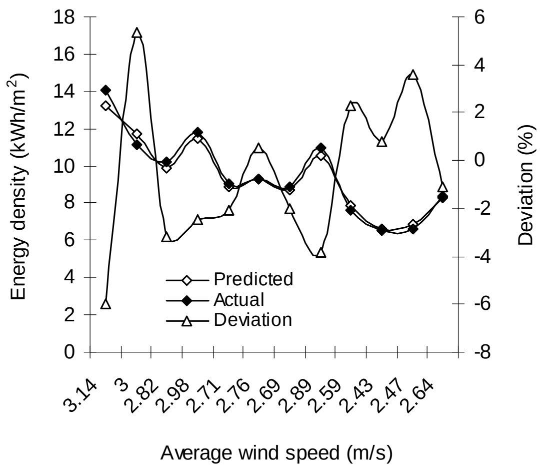

Fig. 3: Variation of model-predicted energy density (relative to average wind speed) with associated deviation from actual result

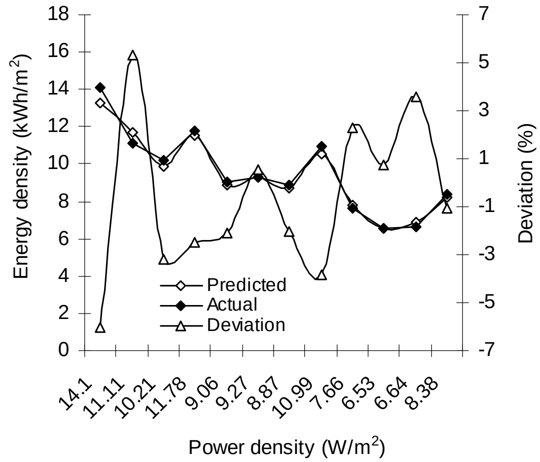

Fig. 4: Variation of model-predicted energy density (relative to power density) with associated deviation from actual result

Correction factor (Cr) is the negative of the deviation i.e.

$$Cr = -De \quad (8)$$

Therefore

$$Cr = -100\left(\frac{\xi p - \xi a}{\xi a}\right) \quad (9)$$

Introduction of the corresponding values of Cf from equation (9) into the model gives exactly the corresponding actual values.

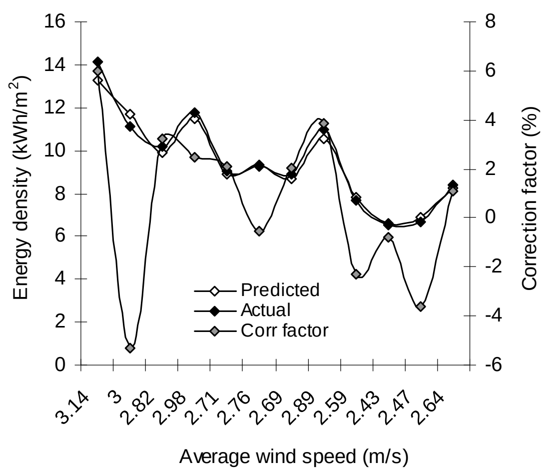

Fig. 5: Variation of model-predicted energy density (relative to average wind speed) with associated correction factor to actual result.

Figs. 3 and 4 show that the least and highest deviations of model-predicted results (from actual results) are 0.52 and - 6.0 %. These deviations correspond to model-predicted energy densities: 9.318 and 13.2541 KWh/m^2; wind speeds: 2.76 and 3.14 m/s and power densities: 12.87 and 18.96 W/m^2 respectively.

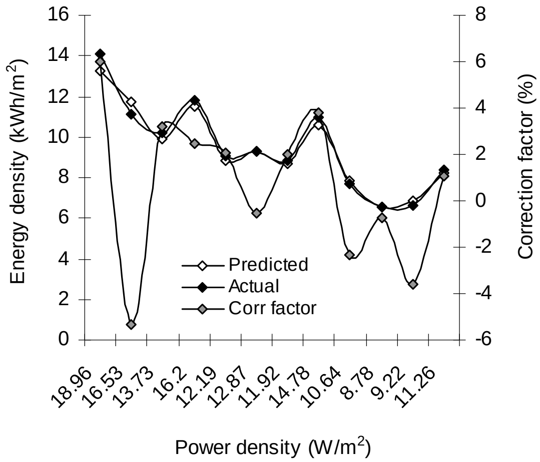

Fig. 6: Variation of model-predicted energy density (relative to power density) with associated correction factor to actual result.

Equations (8) and (9) show that correction factor is the negative of the deviation. It is strongly believed that the correction factor takes care of the assumptions made and experimental condition prevailing during the field works which were not considered during the model formulation.

Figs 5 and 6 indicate that the least and highest correction factor to the model-predicted energy density are - 0.52 and 6 %. These correction factors correspond to model-predicted energy densities: 9.318 and 13.2541 KWh/m^2; wind speeds: 2.76 and 3.14 m/s and power densities: 12.87 and 18.96 W/m^2 respectively.

It is important to state that the deviation of model predicted results from that of the actual is just the magnitude of the value. The associated sign preceding the value signifies that the deviation is deficit (negative sign) or surplus (positive sign).

IV. CONCLUSION

Following attempt to establish the reliability level in the functional evaluation of Energy Density (ED) from the activity responses of Average Wind Speed (AWS) and Power Density (PD) using a derived and validated empirical model, regression generated results showed trend of data point distribution similar to those from actual and derived model. Evaluation of energy density per unit wind speed and per unit power density were obtained as 11.44, 10.01 and 10.1 $(kWh/m^2)(m/s)^{-1}$ and 0.74, 0.65 and 0.66 (kWh/W) as obtained from actual, predicted and regression results respectively. The correlations between energy density and wind speed & power density as evaluated from actual, derived and regression results were all > 0.98. Standard errors incurred in predicting energy density as a function of wind speed & power density instead of going through conventional the experiment were < 0.15 and 0.03 respectively. The validity of the model; $\xi = \vartheta [ƀ\gamma^{0.27}]^{-1}$ was rooted on the insignificant deviation of model-predicted values of energy density from the corresponding experimental values which was less than 7%. This translated into over 93% operational confidence, response and reliability level for the derived model as well as over 0.93 response coefficient of ED to the collective operational contributions of AWS and PD.

REFERENCES

[1] G. Gupta, D. Kaushik, K. Mathur, R. Pal, and P. Bhatnagar (2016), "Power Generation through Wind Turbine in Locomotives & validation of performance parameters for a Bi-Directional Wind Turbine: Wells Turbine" International Journal of Engineering Technology, Management and Applied Sciences, Volume 4, Issue 4.

[2] G. Kaur, D. Pardeshi, B. S. Surjan (2016), "Literature review on Wind Power Generating System", International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering, Vol.4, Issue 6.

[3] Heier Siegfried (2006), "Grid integration of wind energy conversion systems". Chichester, Wiley, UK.

[4] Wind report by World Wind Energy Association (2015), http://www.wwindea.org/hyr2015/

[5] Global Wind Report Annual Market Update (2015), by Global Wind Energy Council (GWEC)- www.gwee.net

[6] A. Feijo, J. Cidrs, and C. Carrillo (2000), "Third order model for the doubly-fed induction machine," Elec. Power Syst. Res., 56, pp. 121-127.

[7] G. Ding, B. Fan, T. Long, H. Lan, Y. Liu, and J. Wang (2013), "Analysis of Technical Properties of Wind and Solar Photovoltaic Power", China, 1, pp. 39-44.

[8]B. T. Abur and G. A. Duruna (2016), "Wind Speed Distribution and Estimation of Wind Power in Benue State, Nigeria", Proceedings of the 8th Conference of Renewable and Alternative Energy Society of Nigeria (RAESON) Nsukka, April, 20-23, pp 90-95.

[9] Nwoye, C. I. (2008), Data Analytical Memory; C-NIKBRAN

