HARRAN ÜNİVERSİTESİ MÜHENDİSLİK DERGİSİ

HARRAN UNIVERSITY JOURNAL of ENGINEERING

e-ISSN: 2528-8733 (ONLINE)

Numerıcal Analysıs of Horızontal Axıs Wınd Turbıne (HAWT) Operatıon Varıables and theır Influence on Performance Cycle

Yatay Eksenli Rüzgâr Türbini (HAWT) Çalışma Değişkenlerinin Sayısal Analizi ve Performans Döngüsüne Etkisi

Yazar(lar) (Author(s)): Aniekan Essienubong IKPE[1], Enefiok Okon USUNGURUA[2], Victor Okon DAVID[3]

[1] ORCID ID: 0000-0001-9069-9676
[2] ORCID ID: 0000-0002-4162-6240
[3] ORCID ID: 0000-0001-7545-4267

Bu makaleye şu şekilde atıfta bulunabilirsiniz (To cite to this article): Ikpe A.E., Usungurua E.O., David V.O., "Numerıcal Analysıs of Horızontal Axıs Wınd Turbıne (HAWT) Operatıon Varıables and theır Influence on Performance Cycle", ***Harran Üniversitesi Mühendislik Dergisi***, 8(1): 27-41 (2023).

DOI: 10.46578/humder.1193367

HRU Muh Der, 8(1): 27-41 (2023)

Harran Üniversitesi
Mühendislik Dergisi

Araştırma Makalesi

Numerical Analysis of Horizontal Axis Wind Turbine (HAWT) Operation Variables and their Influence on Performance Cycle

Aniekan Essienubong IKPE[1,*], Enefiok Okon USUNGURUA[2], Victor Okon DAVID[3]

[123]*Akwa Ibom State Polytechnic Faculty of Engineering, Department of Mechanical Engineering, , Ikot Osurua, Ikot Ekpene, Nigeria.*

Makale Bilgisi

Başvuru: 23/10/2022
Yayın:28/04/2029

Keywords

Wind turbine
Renewable energy
Operation variables
Numerical analysis

Anahtar Kelimeler

Rüzgar türbini
Yenilenebilir enerji
Operasyon değişkenleri
Sayısal analiz

Abstract

Wind is one of the dependable sources of renewable energy due to its availability. The commonly used type is Horizontal Wind Turbine also known as Horizontal Axis Wind Turbine (HAWT), thus, understanding the imperative factors influencing the functionality of HAWT provides insight into its optimal design. This study therefore x-rayed the numerical analysis of HAWT to determine the various operation variables and their influence on the performance cycle. Research Likert questionnaire and 28 identified operation variables with weighty factors that have influence on HAWT were developed and distributed to 130 trained, knowledgeable and experienced wind turbine engineers/operators with 100 respondents outcome. A 28 x 100 data matrix were collated. With 28 variables identified, 18 iterations were computed. Ten (10) clusters (F_1 to F_2) were optimised, with each cluster consisting of computed influential variable(s) as input data and rated factors (output) computed as maximum value for each variable, being ranked by 13 judges in Sequential Merit Order (SMO) based on their influence on HAWT. Kendall's Coefficient of Concordance and Principal Component Analysis (PCA) statistical models were employed, respondents' scores transposed into data matrix and fed into StatistiXL software. A value of W = 0.56 (middling) obtained as the level of consistency. The level of coherence/agreement of data using chi-square model had F_{cal} =196.56, F_{tab} = 41.34 (χ^2_{cal} at $\chi^2_{0.05, 28}$). Therefore, null hypothesis H_0 rejected; alternative hypothesis H_1 accepted, which implies strong agreement with the data at 95% confidence level. The performance of HAWT was observed to depend highly on Cluster 3 (components that are prone to failure). Therefore, adequate consideration during the design phase should be given to factors listed under this category in order to guarantee optimum performance of the HAWT.

Yatay Eksenli Rüzgar Türbini (HAWT) Çalışma Değişkenlerinin Sayısal Analizi ve Performans Döngüsüne Etkisi

Öz

Rüzgar, kullanılabilirliği nedeniyle güvenilir yenilenebilir enerji kaynaklarından biridir. Yaygın olarak kullanılan tür, Yatay Eksenli Rüzgar Türbini (HAWT) olarak da bilinen Yatay Rüzgar Türbini'dir, bu nedenle HAWT'nin işlevselliğini etkileyen zorunlu faktörlerin anlaşılması, optimum tasarımına ilişkin fikir sağlar. Bu nedenle bu çalışma, çeşitli çalışma değişkenlerini ve bunların performans döngüsü üzerindeki etkilerini belirlemek için HAWT'nin sayısal analizini x-ışınlarına tabi tuttu. Araştırma Likert anketi ve HAWT üzerinde etkisi olan önemli faktörlere sahip 28 tanımlanmış işletme değişkeni geliştirildi ve 130 eğitimli, bilgili ve deneyimli rüzgar türbini mühendisine/operatörüne dağıtıldı ve 100 katılımcı çıktı. 28 x 100 veri matrisi harmanlanmıştır. Tanımlanan 28 değişkenle 18 yineleme hesaplandı. On (10) küme (F1'den F2'ye) optimize edildi; her küme, girdi verileri olarak hesaplanan etkili değişken (ler) den ve her bir değişken için maksimum değer olarak hesaplanan derecelendirilmiş faktörlerden (çıktı) oluşuyor ve 13 yargıç tarafından Sıralı Liyakat Sırasına göre sıralanıyor. (SMO), HAWT üzerindeki etkilerine göre. Kendall'ın Uyum Katsayısı ve Temel Bileşen Analizi (PCA) istatistiksel modelleri kullanıldı, yanıt verenlerin puanları veri matrisine aktarıldı ve StatistiXL yazılımına beslendi. Tutarlılık düzeyi olarak W=0.56 (ortalama) değeri elde edilmiştir. Ki-kare modeli kullanılarak verilerin tutarlılık/uyum düzeyi Fcal =196.56, Ftab = 41.34 (χ2'de χ2cal 0.05, 28) idi. Bu nedenle, sıfır hipotezi H0 reddedildi; alternatif hipotez H1 kabul edildi, bu da %95 güven düzeyinde verilerle güçlü bir anlaşma anlamına geliyor. HAWT'nin performansının büyük ölçüde Küme 3'e (arıza eğilimli bileşenler) bağlı olduğu gözlemlendi. Bu nedenle, HAWT'nin optimum performansını garanti etmek için tasarım aşamasında bu kategori altında listelenen faktörlere yeterince dikkat edilmelidir.

*İletişim yazarı, e-mail: aniekan.ikpe@eng.uniben.edu

1. INTRODUCTION (GİRİŞ)

Horizontal Wind Turbines or Horizontal Axis Wind Turbines (HAWT) are wind mills also known as wind axis machines used for wind power generation in which the axis of rotation of rotor is parallel to the ground and also parallel to wind direction [1]. A wind turbine is a rotating mechanical device that converts kinetic energy of fast moving winds into electrical energy. The central shaft is connected to the wind turbine generator which converts the rotary motion of the output shaft into electrical power [2,3]. All living things in one way or the other depend on energy for survival, and modern civilization will continue to thrive only if existing sources of energy can be developed to meet the growing world's demand [4,5]. Among the various sources of energy, the energy generated from wind turbine is renewable and contributes to 20-40% of the overall energy usage in advanced countries [6]. However, cheap and abundant supply of electric power has always been one of the major factors in the development of any country [7,8], and this can be harnessed from wind energy.

Bloch et al. [9] reported that modern life is so much dependent upon electric power that the per capita consumption of electricity is often an index of the economic development, prosperity and standard of living of a nation. This fact is evident in Appendix I [10], which presents the per capita consumption of electricity of various countries in the world. It can be deduced from Appendix I, that per capita consumption of electricity in Nigeria is only 117 KWh per year which is much below even the average per capita consumption of the world which is 20,993 KWh per year. It is therefore, quite clear that if the country is to become self-dependent and economically stable, more and more emphasis should be laid on the continuous, improved and increased rate of growth of dependable sources of electric power and distribution.

Though energy from the standpoint of natural sources and quantity availability to address practical needs maybe categorized as "main" or "major" sources which include fossil fuels (coal, oil, and natural gas), atomic or nuclear fuels (heavy isotopes of uranium and thorium and, in prospect light elements etc.) and water (supplied by rivers and waterfalls etc.), the energy derived directly from natural sources (the energy content of fossil fuels, hydro-power, wind, geo-thermal and nuclear) is termed 'primary energy' whereas the energy generated by man using suitable plants or stations to convert the primary energy is considered 'secondary energy', for example, electric energy, steam power, hot water power and so on [11].

However, with considerations on the human time scale and not geological time scale, the energy sources can equally be classified into two groups namely: renewable energy sources and non-renewable energy sources. While renewable energy sources are those energy sources that are naturally replenishing but flow-limited, that is, sources that are virtually inexhaustible in duration but limited in the amount of energy available per unit of time with major examples including biomass (wood and wood waste, municipal solid waste, landfill gas and biogas and biofuels), hydro-power, geothermal, wind as well as solar.

Non-renewable energy sources take into cognizance natural resources which when consumed, do not replenish at the same pace or speed at which it is used up [12]. These sources usually take millions of years to develop and typical examples include fuels such as oil, coal and natural gas which humans regularly tap to produce energy. Nuclear energy drawn from nuclear atoms also fall in this category. Appendix II illustrates a comparative energy mix derived from various energy sources in the U.S.A and Nigeria, and analyses the milestone covered as far renewable energy and greener energy are concerned. It further strengthens the reliability and dependability of the sectors regarding economic growth and presents the level at which each has been harnessed. A quick comparison has revealed clearly that apart from a stint in hydro-power, the country has lagged behind in terms of proper utilization of renewable energy (greener energy) resources and as such cannot address effectively the problem of energy availability and supply [13].

The rate of energy consumption is on the increase due to increasing population and industrialization, causing rural-urban migration [14,15]. However, the rural areas which depend more on agriculture struggle to afford cheap energy for improving the methods of production, processing, preservation and other numerous farming operations [16]. Moreover, residents in most rural areas cannot afford the high cost of fossil fuels, and therefore resort at alternatives that are detrimental to the environment. For example, an estimated 62% of Nigerians rely on wood fuel in their entire energy needs, resulting in massive deforestation [17,18]. These problems can be offset by employing HAWT with optimum performance cycle, to harness wind energy for consumption in rural areas. Modern wind turbine generator systems are constructed mainly as systems with a horizontal axis of rotation, a wind wheel consisting of three blades, a high-speed asynchronous generator (also known as induction generator) and a gear box [19].

This research seeks to address the operatıon varıables as well as theır influence on performance cycle and channels its efforts towards x-raying the possibilities of improving the level of harnessing renewable energy generally, but with a concentration on wind mill power machines in particular, especially within Nigeria energy sector. The main shaft is connected to the rotor and at the other end, to a planetary gearbox. The gearbox scales up the rotational speed to meet the requirements of the generator. The high-speed shaft connects the gearbox to the generator; it spins the generator to create electricity. The operation and performance of HAWT is affected by a number of factors which may be environmental, mechanical, operational, design and so on.

Studies have shown that wind turbine rotor blades are subjected to high fatigue cycle and vibrational frequency that can expose the blades to failure during rotation if proper monitoring and control devices are not installed [20], and also subjected to a wide range of loads such as flapping, tension and compression, twisting etc, all induced by the rotational movement and variable aerodynamic loads. The rotor shaft is subjected to loading conditions such as torsion, bending, and sometimes axial loading [21,22]. Resonances from the gear mesh stiffness fluctuations and nonlinearity may occur due to tooth separation [23]. Higher number of applied planet gears may result in higher mesh load factor while planets with low numbers of teeth may pose challenges during assembling [24].

This research attempts to numerical analysis the factors as well as the operation parameters of HAWT and their influence on its overall performance. It seeks to decipher the baseline design considerations for a reduced failure of components with an optimal efficiency in power output. Therefore, the importance of this research cannot be overemphasized following the epileptic and undependable power supply in Nigeria, the value contributed by wind energy to the nation's economy when properly harnessed and added to national grid, the employment created as well as credits in terms of technological advancement in renewable energy, which reduces the high dependability on power from fossil fuels and consequently prevent the negative footprint left on our environment.

2. MATERIALS AND METHODS (MATERYAL VE METOT)

In order to achieve a well-structured analysis, it was imperative to further categorize this section into two sub-sections to handle materials and methods separately as presented thus;

2.1. Materials

The materials used to carry out the research were questionnaires (Appendix III) and StatistiXL statistical analysis software.

2.2. Methods

The following outlines are the research methods employed in the analysis of some operating variables in this study based on their influence on horizontal axis wind turbine performance.

- The use of questionnaire to determine significant wind turbine operating variables.
- Analysis of questionnaire using Kendall's Coefficient of Concordance and Principal Component Analysis (PCA) statistical models to determine wind turbine operating variables with possible weight factors that have influence on wind turbine.
- After identifying 28 variables as possible weighty factors that have influence on the horizontal axis wind turbine operation, and subsequent administration of these variables in Likert Questionnaires (LQ) form to (130) respondents, a 28×100 data matrix were collated. With 28 variables identified as possible weighty factors that have influence on wind turbine, 18 iterations were computed to determine crucial clusters that are most influential on the wind turbine operation. Ten (10) clusters (F1 to F10) were optimised from the 18 iterations, with each cluster consisting of computed influential variable(s) (input) on the wind turbine operation and rated factors (output) computed as maximum value for each variable. In other words, the twenty-eight scale items were referred to thirteen (13) judges who are well-informed on the subject matter to rank them in Sequential Merit

Order (SMO) based on their influence on horizontal axis wind turbine operation. Accordingly, the ranking is presented in Table 1.

Table 1. *Ranking of scale items*

S/N	Variables	Rj
1	Wind speed	20
2	Hub height	39
3	Yaw control	109
4	Pitch angle	119
5	Tip speed ratio	131
6	Rotor speed	131
7	Blade length	131
8	Wind power	133
9	Blade material	134
10	Pitch control	136
11	Rotor angular velocity	142
12	Environmental benefit	173
13	Operating speed	174
14	Shaft torque	176
15	Wind direction	210
16	Rotor diameter	229
17	Power coefficient	229
18	Climatic condition	243
19	Output power	252
20	Operational simplicity	260
21	Air density	261
22	Power control	261
23	Cost efficiency	263
24	Operational cost	267
25	Axial induction factor	278
26	Maintenance cost	290
27	System reliability	305
28	Shaft diameter	335

Source: Field data

The questionnaire used in the study was designed from the data obtained from the relevant literature. Twenty-eight (28) variables were identified and used to design questionnaires with five point Likert's attitudinal scale that was administered to one hundred and thirty (130) respondents with deep knowledge about wind turbine operations. Respondents' responses were transposed into metric variables. Also, the research hypothesis was tested using same 28 variables and administered to 13 highly experienced engineers who understand the working principles of a wind turbine for rating. Suitable statistical models were used for the analysis of this research and these include;

- Kendall's Coefficient of Concordance (COC)
- The Principal Component Analysis

Having transposed the respondents' scores into data matrix and fed into StatistiXL software, it successfully facilitated the computation of the scree plot, eigenvalues and eigenvectors, factor loadings, and descriptive statistics. The mathematical theory that governs the software statistical analysis is sketched hereunder which considered the following:

- Let $N =$ number of scale items to be ranked and let $k =$ the number of judges assigning ranks.
- Input the observed rank into $K \times N$ matrix.
- For each entity obtain R_j, which is the total scores of each of the scale item.

- Obtain the mean of the various R_j's, where j refers to the variable response or stimulus from the judges on scale item i.
- Obtain the deviation of every R_j from the calculated mean of R_j.
- Obtain the square of the deviation of each of the scale items.
- The Kendall Coefficient of Concordance (W), which measures the degree of agreement between the judges is obtained from Equation 1 meanwhile Equation 2 calculates the sum of variance from the obtained data set.

$$W = \frac{S}{\frac{1}{12}K^2(N^3 - N)} \tag{1}$$

$$S = \sum(R_j - \frac{\sum R_j}{N})^2 \tag{2}$$

where S is the sum of variance (from the calculation, $S = 173980.9643$), $K = 13$ (the number of judges), $N = 28$ (the number of factors being ranked).
Inputting the above values into Equation 1;

$$W = \frac{173980.9643}{\frac{13^2}{12}(28^3 - 28)} = \frac{173980.9643}{308763} = 0.56$$

The Kendall's Coefficient of Concordance $W = 0.56$ which is at the threshold of substantial
The test hypotheses which are null hypothesis and alternative hypothesis are respectively represented as H_0 and H_1 and presented thus:
H_0: the ranking of the 13 judges are not coherent (null hypothesis)
H_1: the ranking of the 13 judges are in agreement (alternative hypothesis)
This is further evaluated following Equation 3 as shown:

$$\chi^2{}_{cal} = K(N - 1)W \tag{3}$$

where $k = 13$ judges, $W = 0.56$ and $N = 28$, it follows that;

$$\chi^2{}_{cal} = 13(28 - 1)0.56 \rightarrow \chi^2{}_{cal} = 196.56$$

At 5% level of significance, the chi-square (χ^2) table value is obtained at $\chi^2{}_{0.05,\ 28}$ as presented in Equation 4.

$$\chi^2{}_{0.05,\ 28} = 41.34 \tag{4}$$

Decision rule states: if $F_{cal.} > F_{tab.}$ reject H_0 whereas if $F_{cal.} < F_{tab.}$ accept H_0. Here, F represents chi-square factor and the subscripts cal. and tab respectively represent calculated and tabulated factors. From the comparison analysis above, null hypothesis, H_0 is rejected while the alternative hypothesis, H_1 is accepted. This implies that the ranking of the judges are in agreement. For the abridged theory of the application of PCA, let X_{ij} and Y_{ij} represent a pair of variables in the data matrix. Define column mean is given as:

$$\overline{X}_{.j} = \sum_{i=j}^{N} \frac{X_{ij}}{n_j} \tag{5}$$

and

$$\overline{Y}_{.j} = \sum_{i=j}^{N} \frac{Y_{ij}}{n_j} \tag{6}$$

Then

$$x = X_{ij} - \overline{X}_{.j} \tag{7}$$

and

$$y = Y_{ij} - \overline{Y}_{.j} \tag{8}$$

where i and j refer to the state of the matrix, then x and y refer to the respective mean deviation or deviation from the mean. Hence, the Correlation coefficient (CC), r_{ij} is given by Equation 9.

$$r_{ij} = \frac{\sum xy}{\sqrt{(\sum x^2).(\sum y^2)}} \quad (9)$$

$$x = X_{ij} - \overline{X}_{.j} \quad (10)$$

$$y = Y_{ij} - \overline{Y}_{.j}, \quad (11)$$

$$\overline{X}_{.j} = \sum_{i=j}^{N} \frac{X_{ij}}{n_j} \quad (12)$$

$$\overline{Y}_{.j} = \sum_{i=j}^{N} \frac{Y_{ij}}{n_j} \quad (13)$$

When r_{ij} is computed for every pair from the whole lot of pairs;

$$^{n}C_2 = \frac{n!}{(n-2)!2!} \quad (14)$$

One of the approaches adopted for model validation was to ensure that the validity of the result would be the correctness of the data obtained from the source and to personally administer the questionnaire to only knowledgeable and informed respondents. The rating of 13 judges who ranked the 28 variables relating to assessment performance of the wind turbine showed that the index of consistency in ranking is $W = 0.56$ which is considered middling. The χ^2 test statistical tool used to test the adequacy of W made us reject the null hypothesis of discordance among the judges at a (p-value of 0.05). This suggests that if the experiment was replicated 100 times, it is only in less than five occasions that the result obtained would differ.
Chi-square (χ^2) statistical tool was equally used to appraise how consistent the judges were in ranking the scale items. Since ${\chi^2}_{cal} = 196.56$ was greater than ${\chi^2}_{tab} = 41.34$, the null hypothesis (H_0) was not accepted, and therefore confirms that the judges ranking of the 28 scale items were consistent. The conclusion therefore is that the judges used the same criteria to do the ranking. The chi-square (χ^2) statistical tool has therefore validated the result obtained from the ranking by the judges.

This section examines the analysis of data to achieve the aim of the research using the models employed as analytical tools. Foremost is the PCA tool application of factorial study for modelling of wind turbine. The 28 variables identified through wide literature survey were used to craft questionnaires using 5-point Likert's attitudinal scale whose dimensions included: strongly agree, agree, undecided, disagree, and strongly disagree. The questionnaires were administered to respondents who have working experience in wind turbine plant. Statistical software (StatistiXL) was used to extract factors whose associated eigenvalues (λ) exceeded unity. These factors were given creative identifications and subsequently interpreted.

The Principal Component Analysis is one of the methods of factor Analysis that was employed in this study. Out of the 130 set of the questionnaire administered to knowledgeable respondents, 100 were retrieved. This is about seventy-nine percent (79%) success. Respondents' scores were then collated as data matrix as shown in Appendix III. The data were fed into StatistiXL software that gave the following output:

- Scree Plot
- Eigen Value and Eigen Vectors (EV)
- Factor Plot (Factor Loadings)
- Descriptive Statistics Results (DSR)
- Case Wise Factor Scores (CWFS)

3. RESULTS AND DISCUSSIONS (BULGULAR VE TARTIŞMA)

The plots of the extracted twenty eight factors were generated using StatistiXL software shown in Figure 1. Figure 1 is a line plot illustrates the eigenvalues of factors or principal components in this analysis. In this case, the scree plot was used to determine the number of principal factors to be retained in the Principal

Component Analysis (PCA). It is obvious from the scree plot that at eigenvalue of 1 corresponding to component number 7, the curvity tends to flatten out, suggesting that seven factors extracted are adequate.

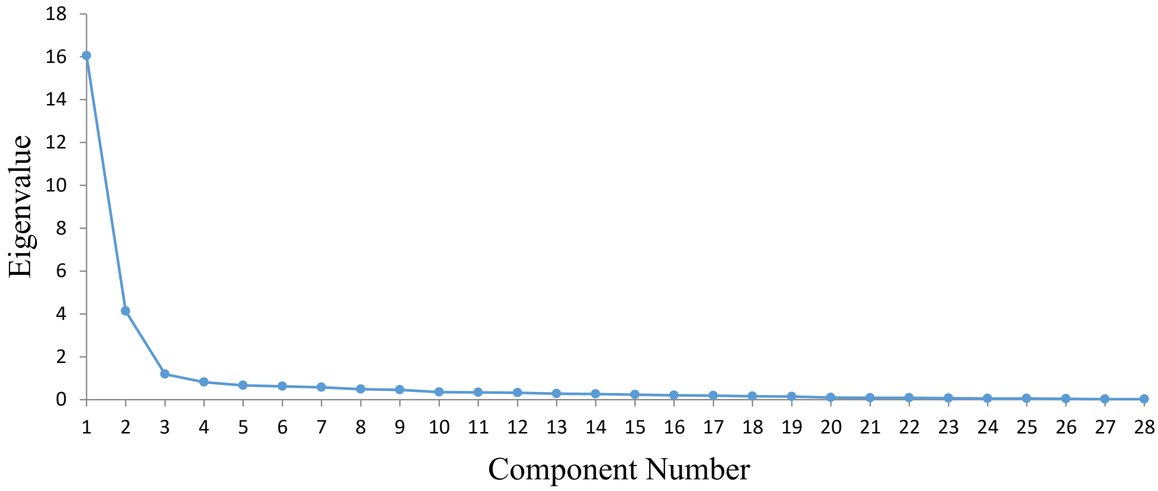

Figure 1. *Scree Plot of the operation variable factors*

3.1. Varimax Factor Loading (Factor Plots)

The factors were extracted by statistiXL software, having fed the collated data matrix into it. Factors are extracted at the eigenvalues greater than 1. The Varimax factor loading for various variables are presented in Table 2.

Table 2. *Varimax factor loading for various operation variables*

S/N	Variables	F1	F2	F3	F4	F5	F6	F7	F8	F 9	F 10
1	Environmental benefit	0.665	-0.047	0.312	0.091	0.136	0.078	0.035	0.028	0.027	0.019
2	Pitch control	0.718	0.044	0.358	0.122	0.123	0.200	-0.007	0.270	0.105	0.083
3	Yaw control	0.886	0.050	0.117	0.164	-0.004	0.105	0.144	0.042	0.028	-0.018
4	Shaft diameter	0.917	0.083	0.170	-0.019	-0.014	0.101	-0.065	-0.003	0.025	-0.033
5	Rotor speed	0.727	0.102	0.172	0.107	0.139	0.037	0.113	0.104	0.143	-0.043
6	Cost efficiency	0.629	0.025	0.285	0.163	0.106	0.077	0.215	0.113	-0.013	-0.047
7	Power control	0.795	0.069	0.231	-0.044	0.354	0.119	0.101	0.195	0.056	0.061
8	Pitch angle	0.750	0.107	0.273	0.222	0.063	0.128	0.038	0.033	0.051	0.018
9	System reliability	0.599	-0.022	0.618	-0.017	0.304	0.053	0.054	0.043	0.050	-0.061
10	Operational cost	0.883	0.067	0.177	0.104	0.029	0.051	0.140	-0.033	-0.023	-0.024
11	Rotor angular velocity	0.517	0.217	0.375	0.124	0.602	0.199	0.046	0.177	0.011	-0.033
12	Maintenance cost	0.326	0.113	0.892	0.148	0.039	0.105	0.103	0.096	0.014	0.017
13	Operational simplicity	0.650	0.109	0.234	0.181	0.114	-0.001	0.062	0.151	0.010	-0.075
14	Blade length	0.541	0.184	0.266	0.711	0.068	0.095	0.171	0.053	0.012	0.004
15	Blade material	0.507	0.256	0.300	0.250	0.059	0.127	0.636	0.113	0.092	-0.061
16	Axial induction factor	0.511	0.188	0.403	0.119	0.164	0.645	0.119	0.107	0.093	0.056
17	Climate condition	0.867	0.089	0.134	0.171	0.067	0.064	0.076	0.094	0.001	0.035
18	Operating speed	0.714	0.145	0.169	0.139	0.114	0.051	0.212	0.097	0.116	-0.032
19	Hub height	0.580	0.215	0.323	0.074	0.182	0.121	0.127	0.613	0.034	-0.044
20	Rotor diameter	0.779	-0.012	0.240	0.168	0.179	0.072	0.148	0.231	0.112	0.080
21	Power coefficient	0.460	0.161	0.480	0.174	0.193	0.278	0.122	0.095	0.016	0.021

22	Wind power	0.638	0.218	0.273	0.227	0.272	0.078	0.134	0.086	0.064	-0.055
23	Tip speed ratio	0.181	0.920	0.105	0.038	-0.049	0.001	0.101	-0.020	0.031	-0.009
24	Shaft torque	0.034	0.845	0.022	0.014	0.112	0.064	-0.005	0.070	0.040	0.046
25	Wind speed	0.079	0.775	0.104	0.016	0.033	0.091	0.084	0.045	0.092	0.050
26	Wind direction	-0.012	0.932	0.027	0.109	0.083	0.013	0.013	0.071	0.079	0.068
27	Air density	0.129	0.626	0.041	0.013	0.017	0.061	0.058	0.026	0.749	0.105
28	Out power	0.003	0.672	0.006	0.000	-0.017	0.040	-0.042	-0.021	0.115	0.725

After the identification of 28 variables as possible weighty factors that have influence on wind turbine, and the subsequent administration of these variables in Likert questionnaires form to respondents, a 28 × 100 data matrix were collated. With 18 iterations, ten (10) factors F1 to F10 were extracted. Convincingly, judging from the clusters 1 to 10, cluster 1 was considered as principal factors and therefore categorized as operational variables (Table 3); cluster 2 was classified as wind forces (Table 4); cluster 3 was labelled components prone to Failure (Table 5); cluster 4, 5, 6, 7, 8, 9 and 10 are lone factors in their domain and were group together to obtain miscellany. In Table 3, 14 variables were clustered and they are discussed as follows: operating speed has a factor loading of 0.918 thus making it the most intrinsic factor. Judging from the least scale item under this category which is cost efficiency with factor loading 0.629, all the variables have effect on the general performance on the wind turbine.

Table 3. *Cluster 1-operational variables*

S/N	Variable	Factor 1
1	Axial induction factor (AIF)	0.665
2	Pitch control	0.718
3	Yaw control	0.886
4	Operating speed	0.918
5	Rotor speed	0.727
6	Cost efficiency	0.629
7	Power control	0.795
8	Blade pitch angle (BPA)	0.750
9	Operational cost	0.883
10	Shaft diameter	0.650
11	Rotor angular velocity (RAV)	0.867
12	Operational simplicity	0.714
13	Rotor diameter	0.779
14	Wind power	0.683

The next cluster as presented in Table 4 is cluster 2 which is considered wind forces. 4 variables are under this assemblage with tip speed ratio as the most influential factor loading of 0.920. Shaft torque, wind speed, and wind direction which fall under this category are also very important variables as any attempt to undermine any of these variables may gradually or drastically affect the performance of the turbine efficiency as no principal factor can stand on its own without the support of others.

Table 4. *Cluster 2-wind forces*

S/N	Variable	Factor 2
1.	Tip speed ratio (TSR)	0.920
2.	Shaft torque	0.845
3.	Wind speed	0.775
4.	Wind direction	0.932

In Table 5, five (5) variables are clustered with rotor blade being the factor that is mostly prone to failure (0.892) due to the yaw, pitch and roll motions it undergoes and aerodynamic loads (AL) acting on the blade in the wind field domain [25]. This is followed by rotor shaft (0.618) due to the deflections, bending and the effect of centrifugal forces during rotation and then gear(0.480) due to high contact forces between the meshing gear teeth as well as gear mesh stiffness. The next variable that is prone to failure after gear is the shoe brake (0.392) due to damaged rotor disc, overheating brake pads, uneven wear on brake lining, loss of hydraulic brake fluid and so on. The last factor in this category that is also prone to failure is the bearing (0.256) due to lack of lubrication or over lubrication, contamination of lubricating fluid, internal clearance, misalignment, housing wear, extreme temperature and so on. The last seven Factors (F4, F5, F6, F7, F8, F9, and F10) as presented in Table 6 are secluded in their group with each having a factor loading of 0.711, 0.602, 0.645, 0.636, 0.613, 0.749, and 0.725 respectively. These lone factors can be clustered to obtain miscellany.

Table 5. *Cluster 3-components prone to failure*

S/N	Variables	Factor 3
1.	Shaft	0.618
2.	Rotor blade	0.892
3.	Gear	0.480
4.	Break	0.392
5.	Bearings	0.256

Table 6. *Cluster* 4, 5, 6, 7, 8, 9 & 10-*lone factor*

S/N	Clusters	Variables	Factor
1.	Cluster 4	Blade strength	4 0.665
2.	Cluster 5	Climate condition	5 0.602
3.	Cluster 6	Economic benefits	6 0.645
4.	Cluster 7	Blade materials	7 0.636
5.	Cluster 8	Height of the hub	8 0.613
6.	Cluster 9	Air density	9 0.749
7.	Cluster 10	Output power	10 0.725

The wind turbine components are jointly but exclusively explained as follows: blade length has a significant influence on the wind turbine operation as it determines the swept area of the turbine. Climate condition which also falls in this category has to do with variety in atmospheric temperature, (air density and humidity) at a particular time. This affect the wind flow as it also varies at different times. Hub height (HH) is also another variable that has great influence on wind turbine operations because the higher the hub above the ground, the more wind captured by the blade. Every other variable in this cluster have their own contributions to the overall performance of the wind turbine as negligence on one might affect the functionality of the turbine. Kendall's Coefficient of Concordance (KCOC) obtained is 0.56 which was considered as middling, suggesting that there was agreement among the judges that ranked the variables. Consequently, a null hypothesis claiming that the ranking of the range of factors by thirteen(13) judges is discordant which was rejected at a p-value of 0.05, thus suggesting that the computed index of consistent ranking (coefficient of concordance $W = 0.56$) is middling inter correlation. The ranking of the scale items imply that wind turbine operators should pay more attention to the issue raised according to their severity.

This will offer a veritable framework for achieving productivity from the wind turbine. The questionnaire couched in 5-point Rensis Likert's Attitudinal Scale (RLAS) was successful in extracting the responses from the 100 respondent's score into data matrix. The PCA deployed was successful in achieving parsimony by clustering a plethora of twenty-eight (28) variables into ten (10) collections.

4. CONCLUSIONS (SONUÇLAR)

Horizontal Axis Wind Turbine (HAWT) is one of the sources of renewable energy. Renewable energy (greener energy) is cheap, dependable and environmentally friendly, as such, intensive research and technological advancement should be geared towards achieving this. However, to design, install and operate HAWT, several operational variables and their influence on its safety and performance was critically analysed and taken into account. From the results and discussions presented, the conclusions drawn therefore are as follows; the scree plot illustrated an eigenvalue of 1 corresponding to component number 7 with a curvity that tends to flatten out, suggesting that seven (7) extracted factors were adequate. From cluster 1 (operation variables) considered the principal factors with 14 components had operating speed of 0.918 as the most intrinsic factor and cost efficiency of 0.692 as the least scale item. Nevertheless, all other parameters have effect on the general performance of HAWT. In cluster 2 (wind force) having 4 components had tip speed ratio as the most influential factor (0.920) whereas cluster 3 termed components that are prone to failure with 5 components recorded as major influence, starting from rotor blade (0.892) to the shaft (0.618) due to the deflections, bending and the effect of centrifugal forces during rotation and the gear (0.480) due to contact force between meshing gear teeth as well as the gear mesh stiffness. The shoe brake (0.392) due to damaged rotor disc, overheating brake pads, uneven wear on brake lining, loss of hydraulic brake fluid and the bearing (0.256) due to lack of lubrication or over lubrication, contamination of lubricating fluid, internal clearance, misalignment, housing wear, extreme temperature and so on. For cluster 4, 5, 6, 7, 8, 9 and 10 categorized as lone factors with 7 components had an average factor range of 0.602 - 0.749. Furthermore, the Kendall's coefficient of concordance $W = 0.56$, the index of consistency is middling and the model validation from chi-square ${\chi^2}_{cal} = 196.56 > {\chi^2}_{tab} = 41.34$ validating the alternative hypothesis that there exist a coherence in the data matrix generated. In all, HAWT should be designed as analysed in this study (baseline considerations), installed and functionally operated in order to contribute to the national grid, economic development, technological advancement and improved per capita consumption of electricity of the country since it is an index for measuring a nation's standard of living. Finally, adequate attention particularly during the design process should be given to items under Cluster 3 (components that are prone to failure) as the performance of HAWT depends highly upon the durability, reliability and longevity of factors listen under this category.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest associated with the publication of this paper.

REFERENCES (KAYNAKLAR)

[1] P. C. Sharma, Power Plant Engineering, 7th Edition. Sanjeev Kumar Kataria Publishers, Delhi, 2003.

[2] A. E. Ikpe, E. M. Etuk, A. U. Adoh, Modelling and Analysis of 2-Stage Planetary Gear Train for Modular Horizontal Wind Turbine Application. Journal of Applied Research on Industrial Engineering, 6:4 (2019) 268-282.

[3] E. M. Etuk, A. E. Ikpe, A. U. Adoh, Design and Analysis of Displacement Models for Modular Horizontal Wind Turbine Blade Structure. Nigerian Journal of Technology, 39:1 (2020) 121-130.

[4] J. Rayner, Basic Engineering Thermodynamics, 5th Edition. Dorling Kindersley, New Delhi, 2008.

[5] T. D. Eastop, A. McConkey, Applied Thermodynamics for Engineering Technologists. Dorling Kindersley, New Delhi, 2011.

[6] A. E. Ikpe, E. M. Etuk, U. Aruwa, Evaluation of the Performance of a Locally Fabricated Biomass Stove using Some Nigerian Woods. Nigerian Research Journal of Engineering and Environmental Sciences, 4:2 (2019), 776-788.

[7] C. A. S. Hall, K. Klitgaard, Energy and the Wealth of Nations: An Introduction to Biophysical Economics, 2nd Edition, Springer, New York City, 2018.

[8] R. Vedavalli, Energy for Development; Twenty-First Century Challenges of Reform and Liberalization in Developing Countries. Wimbledon Publishing Company, London, 2007.

[9] R. Bloch, N. Makarem, M. Yunusa, N. Papachristodoulou, M. Crighton, Economic Development in Urban Nigeria. Urbanisation Research Nigeria (URN), London, 2015.

[10] M. Su, L. Wang, Per Capita Renewable Energy Consumption in 116 Countries: The Effects of Urbanisation, Industrialization, GDP, Aging and Trade Openness. Energy, 2:B (2022) 38-43.

[11] S. Matthew, G. S. Philip, Comprehensive Renewable Energy, 2nd Edition, Prentice Hall, London, 2012.

[12] L. T. C. Montoya, M. Rezkallah, Wind Power Planning and Modelling. In: Hybrid Renewable Energy Systems and Microgrids, Gold Coast, Australia, 2021.

[13] J. O. Okeniyi, I. F. Moses, T. O. Okeniyi, Wind Characteristics and Energy Potential Assessment in Akure South West Nigeria: Economic and Policy Implications. International Journal of Ambient Energy, 36:6 (2013) 282-300.

[14] D. E. Bloom, J. D. Sachs, Geography, Demography and Economic Growth in Africa. Harvard Institute for International Development, Harvard, 2018.

[15] M. A. Hyams, Metropolitan Sustainability. Elsevier, Amsterdam, 2012.

[16] S. O. Oyedepo, Energy and Sustainable Development in Nigeria: The Way Forward. Energy, Sustainability and Society, 2:15 (2012) 41-49.

[17] M. Ladan, Policy, Legislature and Regulatory challenges in Promoting efficient and renewable energy for sustainable development and Climate change mitigation in Nigeria*.* 2nd Scientific conference of Assellau, University of Nairobi, Kenya, 2009.

[18] Y. Y. Babanyara, U. F. Saleh, Urbanisation and the Choice of Fuel Wood as a Source of Energy in Nigeria. Journal of Human Ecology, 31:1 (2010) 19-26.

[19] B. Boukhezzar, H. Siguerdidjane, Nonlinear Control of Variable Speed Wind Turbines without wind speed measurement. Proceedings of the 44th IEEE Conference on Decision and Control, Seville, Spain, December 12-15, 2005.

[20] E. M. Etuk, E. O. Ikpe, A. E. Ikpe, Computation of Aerodynamic Load(s) Induced Stresses on Horizontal Axis Wind Turbine Rotor Blade with Distinct Configurations. Journal of Science Part A: Engineering and Innovation, 8:3 (2021) 327-338.

[21] P. Hogg, Wind Turbine Blade Materials: SUPERGEN Wind Phase 1 Final Assemble. University of Loughborough, Engineering and Physical Science Research Council, 2010.

[22] E. E. Mike, I. A. Essienubong, Resultant Deflections from Static Analysis of Sun Gear Rotor Shaft Materials to Determine Their Performance in 2-Stage Planetary Gear Operations. International Journal of Engineering Science and Application, 4:2 (2020), 73-91.

[23] C. G. Cooley, R. G. Parker A Review of Planetary and Epicyclic Gear Dynamics and Vibrations Research. Transactions of the ASME, Applied Mechanics Reviews, 66 (2014) 1-15.

[24] B. Hohn, K. Stahl, P. Gwinner, Light-weight Design for Planetary Gear Transmissions. Gear Technology*, 6* (2013) 96-103.

[25] A. E. Ikpe, E. M. Etuk, A. E. Ndon, Modal Analysis of Horizontal Axis Wind Turbine Rotor Blade with Distinct Configurations under Aerodynamic Loading Cycle. Journal of Science Part A: Engineering and Innovation*,* 8:1 (2021) 81-93.

NOMENCLATURE

AIF	Axial Induction Factor
AL	Aerodynamic Loads
BPA	Blade Pitch Angle
CC	Correlation Coefficient
COC	Coefficient of Concordance
CWFS	Case Wise Factor Scores CWFS
DSR	Descriptive Statistics Results
EV	Eigen Value and Eigen Vectors
F	Factors
HAWT	Horizontal Axis Wind Turbine
HH	Hub Height
KCOC	Kendall's Coefficient of Concordance
KWh	Kilowatt hour
LK	Likert Questionnaires
PCA	Principal Component Analysis
SMO	Sequential Merit Order
RAV	Rotor Angular Velocity
RLAS	Rensis Likert's Attitudinal Scale
S	Sum of Variance
TSR	Tip Speed Ratio
H_0	Null hypothesis
H_1	Alternative hypothesis
χ^2	Chi-square
%	Percent
N	Number of scale items to be ranked
K	Number of judges assigning ranks
R_j	Total scores of each of the scale item
j	Variable response
i	Scale item
W	Kendall Coefficient of Concordance
cal.	Calculated factors
tab.	Tabulated factors
X_{ij} and Y_{ij}	A pair of variables in the data matrix
x and y	Mean deviation
λ	Eigenvalues

APPENDICES

Appendix I

Table 7. *Per capita consumption of electricity of various countries in the world*

Country	Per Capita Consumption (Kwh/Year)
Norway	11524
Australia	8000
Canada	6320
U.S.A.	5860
Sweden	5549
U.K.	3172
Japan	1240
India	380
Nigeria	117

Source: USA Monthly Energy Review; April 2022, Preliminary Data

Appendix II

Table 8. *Energy from different sources (energy mix) in USA and Nigeria in 2022*

Energy Sources	% Contribution	
	USA	Nigeria
Biomass	5.0	0.3
Hydropower	2.3	15.2
Wind	3.4	0.3
Solar	1.5	2.6
Geothermal	0.2	-
Petroleum	36.0	0.7
Natural Gas	32.2	77.3
Coal	10.8	3.6
Nuclear	8.4	-

Source: USA Monthly Energy Review; April 2022, Preliminary Data

Appendix III: Questionnaire

Dear Respondent,

The following scale items have been carefully selected from a number of possible variables relating to **HORIZONTAL AXIS WIND TURBINE (HAWT) OPERATION VARIABLES AND THEIR INFLUENCE ON ITS' PERFORMANCE**. You are kindly requested to carefully study these variables and rank them in descending order of importance (the most important is ranked 1 and the least important 28)

It is pertinent to inform you that objectivity in your response is crucial to the reliability of the result of this research project and we appeal that you be as factual as possible in your ordering of the scale items. We wish to assure you that any /information provided by you will be treated with utmost confidentiality and anonymity and would be used for academic purposes only.

Tale 9. *Research questionnaire*

S/N	FACTOR	FACTOR EXPLICATION	RANK
1	Environmental benefit	This refer to the benefits of wind as a source of energy compared to fossil fuel	
2	Pitch control	This is responsible for setting the wind turbine blade at the best angle to the wind to turn the rotor	
3	Yaw control	This is the angle of rotation of the nacelle around the vertical axis ensuring that wind turbines face directly into the wind.	
4	Shaft diameter	Main shaft arc in feet and inches (meters)	
5	Rotor speed	Speed at which the rotor rotate	
6	Cost efficiency	The act of saving money by making wind turbine perform in a better way	
7	Power control	Power control is the intelligent selection of transmitter power output in a system to achieve good performance within the system	
8	Pitch angle	Angle of inclination from the horizontal or vertical with respect to some reference point.	
9	System reliability	The ability of the wind turbine system or component to perform its required functions under stated conditions for a specified period of time	
10	Operational cost	Expenses which are related to the operation of wind turbine.	
11	Rotor angular velocity	The rate of change of angular position of a rotor	
12	Maintenance cost	Cost incurred to keep the turbine in a good working condition	
13	Operational simplicity	This is the ease with which the wind turbine will be used and operate.	
14	Blade length	Length of the wind turbine blade.	
15	Blade material	Material from which wind turbine blade is made from.	
16	Axial induction factor	The fractional decrease in wind velocity between the free stream and the energy extraction device	
17	Climate condition	Variety in the atmospheric condition at a particular time.	
18	Operating speed	The speed at or below which the turbine can operate.	
19	Hub height	The wind turbine hub height is the rotor height above the ground.	
20	Rotor diameter	The main rotor arc in feet and inches (meters)	
21	Power coefficient	The ratio of electrical power produce by the wind turbine divided by the wind power into the turbine	
22	Wind power	Wind power is the use of air flow through wind turbines to mechanically power generators for electric power.	
23	Tip speed ratio	The ratio between the tangential speed of the tip of a blade and the actual speed of the wind.	
24	Shaft torque	Property of a shaft that describe how much the shaft is prone to twisting.	
25	Wind speed	The rate at which air is moving in a particular area.	
26	Wind direction	A course along which wind moves.	
27	Air density	The degree of compactness of air. (result of air temperature, humidity and pressure.	
28	Output power	Total maximum output power that the system provides.	