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Research Article

Performance optimization of a horizontal axis wind turbine simulator under the effects of blade's pitch angle variation

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Abstract

The optimization of wind turbine performance is a critical issue for enhancing energy conversion efficiency. This study investigates the effects of blade pitch angles and Variable Frequency Drive settings on the performance of a wind turbine system using the Spectra Quest wind turbine simulator. Employing a Taguchi design of experiments with a full factorial approach, a total of 81 experimental tests are conducted to analyze the influence of three blade pitch angles (0°, 10°, and 20°) combined with three distinct Variable Frequency Drive settings (12, 15, and 18) on shaft rotational speed, power output, and vibration levels. Using Taguchi's response analysis and analysis of variance, this research identifies Variable Frequency Drive as the most influential factor on turbine performance metrics. Regression modelling further elucidates the complex relationships between the operational parameters and performance outcomes. The results reveal significant interactions between the input parameters and demonstrate that lower blade pitch angles in conjunction with higher Variable Frequency Drive settings maximize both shaft rotational speed (171 rpm) and power output (24.102 W), maintaining acceptable vibration levels. The best pitch angle input parameters are found to be β1=0o, β2=0o and β3=0o with a VFD setting of 18. A notable increase in air resistance at higher pitch angles corroborates the findings of previous studies, highlighting the need for optimal parameter settings to enhance turbine efficiency.

1. Introduction

The increasing reliance at renewable power sources marked a significant transition in worldwide strength strategies aimed toward mitigating weather change and lowering dependence on fossil fuels. Among numerous renewable technologies, wind energy has emerged as one of the maximum promising solutions due to its sustainability, low environmental impact, and potential for scalability. The international installed wind energy capability has grown drastically in recent years, accomplishing 837 GW throughout 31 nations in 2021 [1]. This expansion has caused considerable CO2 emission reductions, with projections signifying wind power should account for over 30% of the worldwide energy era via mid-century [2]. The industry has visible technological improvements, such as larger turbines and accelerated efficiencies [3]. By 2017, wind strength had turned out to be the second-largest form of power technology in Europe [4]. Despite demanding situations, projections endorse international wind power capacity may want to attain 5800 GW by 2050 [5].

The outcomes of blade pitch angles and rotor speeds on wind turbine performance have been considerably studied using simulations and experimental techniques [6]. Research showed that varying pitch angles and angular velocities significantly affect turbine overall performance parameters which include power output, torque, and performance [7]. For a horizontal-axis wind

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turbine, optimal pitch angles exist for maximum energy technology at given wind velocities [8]. In Darrieus-type turbines, a small negative valued fixed pitch angle could improve performance, although variable-pitch blades can enhance starting torque and efficiency at lower tip speed ratios [9][10]. Experimental studies on a horizontal wind turbine with NACA 6412 airfoils at low wind speeds revealed that an 8° pitch angle produced higher electrical power and total efficiency [11]. Multiple studies employed Taguchi-based design of experiments to analyze the effects of various parameters on turbine efficiency [12]. Wind speed and blade number also significantly impact turbine performance, with optimal results observed at higher wind speeds and 5-blade configurations [13]. The Taguchi method, sometimes combined with Grey Relational Analysis, proved effective for both parameter and tolerance design optimization [14]. Tittus and Diaz (2020) analyzed a turbine performance for different blade tip sizes and twist angles and found that drag and lift coefficients had less significance compared to other parameters [15]. Bossanyi (2003) proposed individual blade pitch control as a method for significant load reduction in pitch-regulated turbines [16]. Firman Aryanto et al. (2013) investigated the impact of wind speed and blade number variations on horizontal-axis wind turbine performance, concluding that the best efficiency was achieved with 5 blades at 4 m/s wind speed [13]. Labib, A.M., et al. (2020) examined the effect of blade angle variation on the aerodynamic performance of a horizontal axis wind turbine using computational simulation and experimental validation [17]. Gumilar, L. et al. (2020) revealed that increasing the pitch angle of a horizontal-axis wind turbine decreases the maximum power produced [18]. These findings highlighted the importance of optimizing blade pitch angles and rotor speeds to enhance wind turbine performance across various designs and operating conditions [19].

The value of this study lies in its systematic investigation of ways varying blade pitch angles and VFD settings have an impact on vital performance measures, particularly shaft rotational speed, energy output, and vibration levels. By addressing this subject matter, the interplay of these parameters and their implications for wind turbine design and operation may be explored. The primary objectives of this study are to: 1) analyze the outcomes of different blade pitch angles and VFD settings on the performance of a wind turbine system, 2) offer an in-depth statistical evaluation of the records through Taguchi's response evaluation and regression modelling techniques, and 3) optimize the operational parameters to maximize strength output at the same time as minimizing vibration problems.

This article is structured as follows: section 2 discusses the methods and materials employed, detailing the experimental design, data collection process, and analytical techniques used. Section 3 highlights the results and discussion including the experimental measurements and their analysis, Taguchi design response analysis, analysis of variance (ANOVA) from regression modelling and finally optimization using Grey Relational Analysis of best-fit responses with optimal parameter settings [20][21]. Finally, section 4 summarizes the conclusions with key contributions of this research work, suggests practical implications, and outlines directions for future research in the domain of wind energy optimization.

2. Methods and Materials

2.1 Experimental Set-Up

This section outlined the methodology employed in this research. The WTS model used in this research study was the Spectra Quest (SQ) type that used a Vibra Quest (VQ) simulation software and data acquisition system, shown in Fig.s 1 and 2. The SQ WTS weights 222.7 kg, has a centerline height of 2.369 m, a sweeping blade diameter of 3.3 m, and base measurements of 2.991 m × 2.438 m. On the rotational shaft, a tachometer and an accelerometer were installed to detect the vibration level and rotational speed in one direction of vibrational excitation, respectively.

Fig. 1. SQ WTS

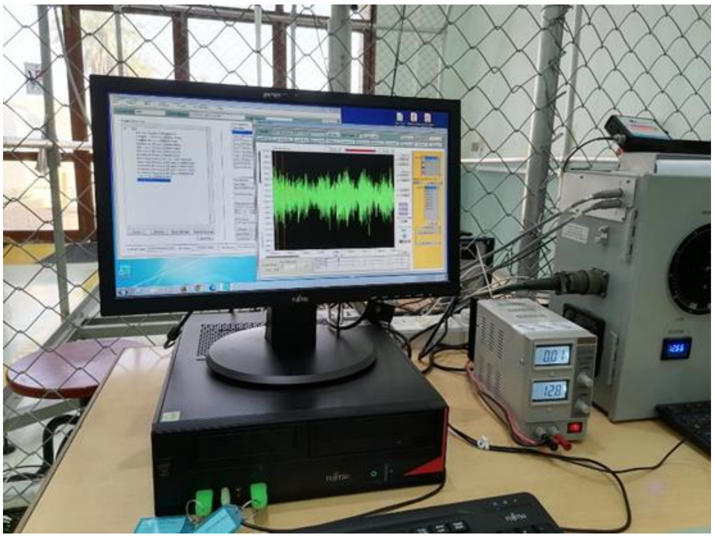


Fig. 2. VQ analysis software

2.2 Taguchi Design of Experiment

The analysis was predicated on four critical input parameters:

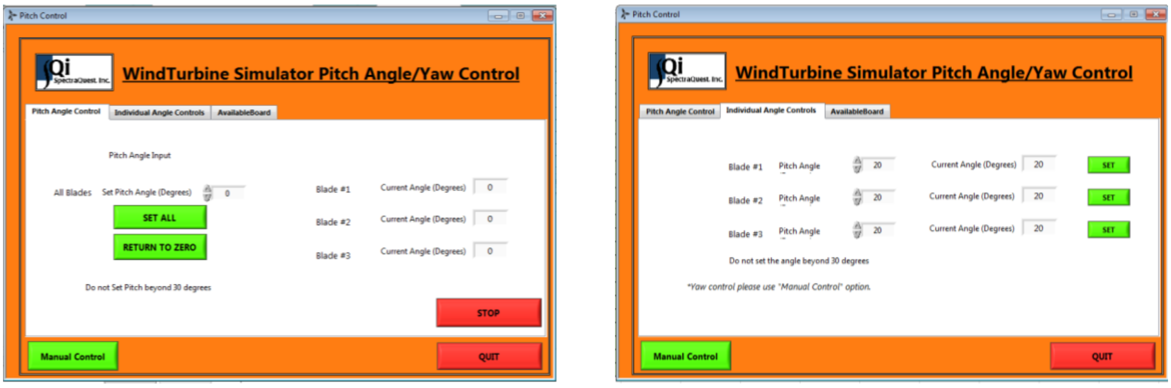
- The pitch angles of the three blades were varied systematically. Each pitch angle was selected from three distinct levels to examine the effects of adjustment.
- The variable frequency drive (VFD) controlled the rotational speed of the turbine shaft. Three different VFD settings were utilized to create varied operational conditions. The running conditions emphasized that the turbine would operate under varying shaft rotational speeds due to input parameters.

Studying pitch angles from 0° to 30° strikes a balance between capturing meaningful aerodynamic and structural behavior and avoiding overly complex or unrealistic scenarios. This range is particularly relevant for applications involving lift, drag, energy capture, and load control. This confirms practical visions for engineering design and analysis. The Taguchi design of experiments DoE with a full factorial approach was used to plan the experimental work. There are four input parameters, β1, β2, β3 and VFD. Taguchi design of experiments with a full factorial approach was used to plan the experimental works. The Experimental layout was based on L_{81} (3^4) orthogonal array. To design the Experimental layout based on this L_{81} (3^4) orthogonal array, three levels were required for each input parameter. The determining pitch angle variations were 0^o, 10^o and 20^o, which were selected within the pitch angle range, with equal increments in between. The four input parameters each had three levels are shown in Table 1. The responses were the shaft rotational speed, vibration level and power output.

The blade angles were changed using pitch control software, shown in Fig. 3. The initial setting was when β1=0^o, β2=0^o and β3=0^o. Both the initial and maximum settings of the angles are shown in Fig. 3. The Variable Frequency Drive (VFD) was set for three levelling values; 12, 15 and 18, as shown in Fig. 4.

Table 1. Experimental input parameters and their levels

Factor	Name	Levels		
β1	Blade 1 Pitch Angle	0^o	10^o	20^o
β2	Blade 2 Pitch Angle	0^o	10^o	20^o
β3	Blade 3 Pitch Angle	0^o	10^o	20^o
VFD	Variable Frequency Drive	12	15	18



(a) (b)

Fig. 3. Setting of blade angles (a) Initial setting and (b) maximum setting)

(a) (b) (c)

Fig. 4. VFD settings (a) 12, (b) 15 and (c) 18

2.3 Experimental testing of the WTS as per DoE

This involved a systematic change of the pitch angle of each blade, starting first with 0^{o} pitch angle for all three blades, setting the VFD to 12 and performing the experiment. The shaft rotational speed, vibration level and power output were measured and recorded using a mounted tachometer, accelerometer and a 3-phase field-controlled alternator, respectively. Then, the VFD setting was changed to 15 then 18, and the experiment was performed again for each VFD setting. After that, the pitch angles were changed as per the design of experiment and the experimental work was performed for 81 tests.

2.4 Results Analysis

The results of 81 experiments were analyzed to investigate the effects of changing pitch angles on the shaft rotational speed, vibration level and power output. The Vibra Quest software generated the vibration waveform reports in MS Excel format. At higher angles, the air resistance was expected to play a negative role on rotational speed and power output. Simultaneously and at certain combinations of pitch angles, the wind turbine was expected to undergo a balancing scenario at which the vibration level decreased within the same setting of VFD.

2.5 Regression Modelling:

The regression modelling for the three responses was performed using Minitab software to develop the best fit regression models, considering the R-squared values for each response.

2.5 Optimization

The multi-responses of this research work were optimized using Grey Relational Analysis. For the shaft rotational speed and power output, the higher-the-better criterion was used. While, for vibration level, the lower-the-better criterion was used. The normalization of the original sequence of each response was calculated as follows:

For higher-the-better criterion: $$Y_{ij} = \frac{X_{ij} - min(X_{ij})}{max(X_{ij}) - min(X_{ij})} \quad (1)$$

For lower-the-better criterion: $$Y_{ij} = \frac{max(X_{ij}) - X_{ij}}{max(X_{ij}) - min(X_{ij})} \quad (2)$$

where x_{ij} is the measured response, $min(x_{ij})$ is the minimum of x_{ij} and $max(x_{ij})$ is the maximum of x_{ij}, i is the response variables and j is the experiment number. The Deviation Sequence (distinguishing coefficient) Δ_{ij} was calculated as follows:

$$\Delta_{ij} = max(Y_{ij}) - Y_{ij} \quad (3)$$

where $max(Y_{ij})$ is the expected sequence, Y_{ij} is the comparability sequence and Δ_{ij} is the deviation sequence of $max(Y_{ij})$ and Y_{ij}. The grey relational coefficient ξ_{ij} was calculated as follows:

$$\xi_{ij} = \frac{min(\Delta_{ij}) + \zeta \times max(\Delta_{ij})}{\Delta_{ij} + \zeta \times max(\Delta_{ij})} \quad (4)$$

where ζ is the differentiating coefficient, $0 \leq \zeta \leq 1$, and 0.5 is the widely accepted value. The grey relational grade GRG (γ_j) for each experiment was computed as follows, for n number of responses:

$$\gamma_j = \frac{\sum_{i=1}^{n} \xi_{ij}}{n} \quad (5)$$

If larger γ_j is obtained, then the equivalent set of process parameters is nearer to the most favorable optimal setting.

3. Results and Discussion

The results of the experimental tests using the Spectra Quest Wind Turbine Simulator (SQ WTS) are presented in this section. This detailed the effects of varying the pitch angles of the blades under different settings of Variable Frequency Drive (VFD) on shaft rotational speed, power output, and vibration levels.

3.1 Experimental Overview

A total of 81 experiments were conducted based on the Taguchi design of experiments approach using a full factorial design with $L_{81}(3^4)$ orthogonal array. Each experiment was systematically designed to assess the impact of the three blade pitch angles' combinations (0°, 10°, and 20° for each of the three blades) and three Variable Frequency Drive (VFD) settings (12, 15, and 18). Table 2 shows the measured responses of the experimental work.

Table 2. Measured responses from experimental tests

Exp	Input Parameters				Measured responses		
	β1 (°)	β2 (°)	β3 (°)	VFD	Rot. Spd. (rpm)	Power Output (W)	Vibration Level (m/s²)
1	0	0	0	12	112	10.730	6.274
2	0	0	0	15	141	17.430	10.106
3	0	0	0	18	171	24.102	10.326
4	0	0	10	12	111	10.643	6.943
5	0	0	10	15	139	16.898	11.238

Table 2 (continued)

Exp	Input Parameters				Measured responses		
	β1 (°)	β2 (°)	β3 (°)	VFD	Rot. Spd. (rpm)	Power Output (W)	Vibration Level (m/s²)
6	0	0	10	18	168	23.868	10.849
7	0	0	20	12	107	10.237	7.486
8	0	0	20	15	134	16.014	10.239
9	0	0	20	18	157	21.164	10.411
10	0	10	0	12	110	10.701	7.400
11	0	10	0	15	139	17.290	11.402
12	0	10	0	18	167	23.868	10.760
13	0	10	10	12	109	10.382	7.352
14	0	10	10	15	137	16.558	11.181
15	0	10	10	18	164	22.610	10.354
16	0	10	20	12	106	9.688	8.013
17	0	10	20	15	131	15.015	9.925
18	0	10	20	18	153	20.498	10.859
19	0	20	0	12	107	10.411	8.005
20	0	20	0	15	135	16.218	11.316
21	0	20	0	18	159	22.192	10.966
22	0	20	10	12	107	10.121	7.308
23	0	20	10	15	132	15.844	10.204
24	0	20	10	18	155	20.905	10.396
25	0	20	20	12	103	9.380	8.424
26	0	20	20	15	126	14.652	8.952
27	0	20	20	18	143	17.955	11.675
28	10	0	0	12	110	10.701	7.712
29	10	0	0	15	139	17.325	12.348
30	10	0	0	18	166	23.907	10.925
31	10	0	10	12	108	10.614	7.795
32	10	0	10	15	136	16.660	12.325
33	10	0	10	18	162	23.028	11.423
34	10	0	20	12	105	10.295	6.774
35	10	0	20	15	133	15.576	7.052
36	10	0	20	18	155	21.090	10.072
37	10	10	0	12	109	10.701	10.528
38	10	10	0	15	137	16.762	7.474
39	10	10	0	18	163	23.400	12.156
40	10	10	10	12	108	10.498	10.750
41	10	10	10	15	135	16.422	7.739
42	10	10	10	18	159	22.306	11.469
43	10	10	20	12	105	10.092	10.872
44	10	10	20	15	129	15.180	8.217
45	10	10	20	18	150	20.424	9.910
46	10	20	0	12	106	10.353	11.462
47	10	20	0	15	132	15.980	8.174
48	10	20	0	18	153	20.831	10.679
49	10	20	10	12	105	10.237	11.416
50	10	20	10	15	130	15.312	8.378
51	10	20	10	18	152	22.572	10.309

Table 2 (continued)

Exp	Input Parameters				Measured responses		
	β1 (°)	β2 (°)	β3 (°)	VFD	Rot. Spd. (rpm)	Power Output (W)	Vibration Level (m/s^2)
52	10	20	20	12	103	9.240	7.490
53	10	20	20	15	128	14.080	7.599
54	10	20	20	18	143	17.710	10.287
55	20	0	0	12	108	10.440	6.916
56	20	0	0	15	137	16.558	10.124
57	20	0	0	18	162	22.534	9.982
58	20	0	10	12	107	10.237	7.081
59	20	0	10	15	134	15.444	9.469
60	20	0	10	18	157	20.905	9.675
61	20	0	20	12	104	9.660	8.354
62	20	0	20	15	128	14.652	8.630
63	20	0	20	18	146	18.720	11.268
64	20	10	0	12	106	10.034	7.744
65	20	10	0	15	133	15.378	9.940
66	20	10	0	18	156	20.646	10.647
67	20	10	10	12	105	9.520	7.942
68	20	10	10	15	130	14.916	9.354
69	20	10	10	18	152	20.128	10.513
70	20	10	20	12	101	9.184	8.862
71	20	10	20	15	124	13.760	8.772
72	20	10	20	18	140	17.535	12.254
73	20	20	0	12	103	9.296	8.976
74	20	20	0	15	127	14.718	8.951
75	20	20	0	18	147	19.152	10.863
76	20	20	10	12	102	9.100	8.739
77	20	20	10	15	125	13.952	8.912
78	20	20	10	18	142	17.920	12.414
79	20	20	20	12	99	8.505	9.561
80	20	20	20	15	119	12.524	8.593
81	20	20	20	18	133	15.411	10.496

3.2 Shaft Rotational Speed

The collected experimental results showed varied shaft rotational speeds based on different combinations of input parameters. Fig. 5 shows the graph of shaft rotational speed versus the VFD setting for each combination of blade pitch angles (legend β1+β2+β3). For each VFD setting, the rotational speed varied as a result of air resistance on the blade, mostly with higher pitch angles. From the initial blades' angle settings (input parameters) to the final blades' angle settings (input parameters), the rotational speed varied from 99 rpm to 112 rpm at VFD = 12. For VFD = 15, the rotational speed changed from 119 rpm to 141 rpm. While, for VFD = 18, the rotational speed altered from 133 rpm to 171 rpm. The maximum pitch angle settings (20°) marked a decrease in rotational speed. This confirmed the hypothesis that increased blade angle contributes to higher air resistance [22].

3.3 Power Output

The power output results reflected similarly the interdependencies of the blade angles and VFD settings, as shown in Fig. 6. This power output was proportionally related to the shaft rotational speed connected to the power alternator by the gearbox. For the angle adjustments of the first blades (input parameters) and the last blades (input parameters), if VFD = 12, the power output varied from 8.505 W to 10.730 W, if VFD = 15, the power output varied from 12.524 W to 17.430 W, and when VFD = 18, the power output varied from 15.411 W to 24.102 W. An inverse relationship was noted at the maximum blade angle settings (20°), which resulted in reduced power outputs due to increased drag [17].

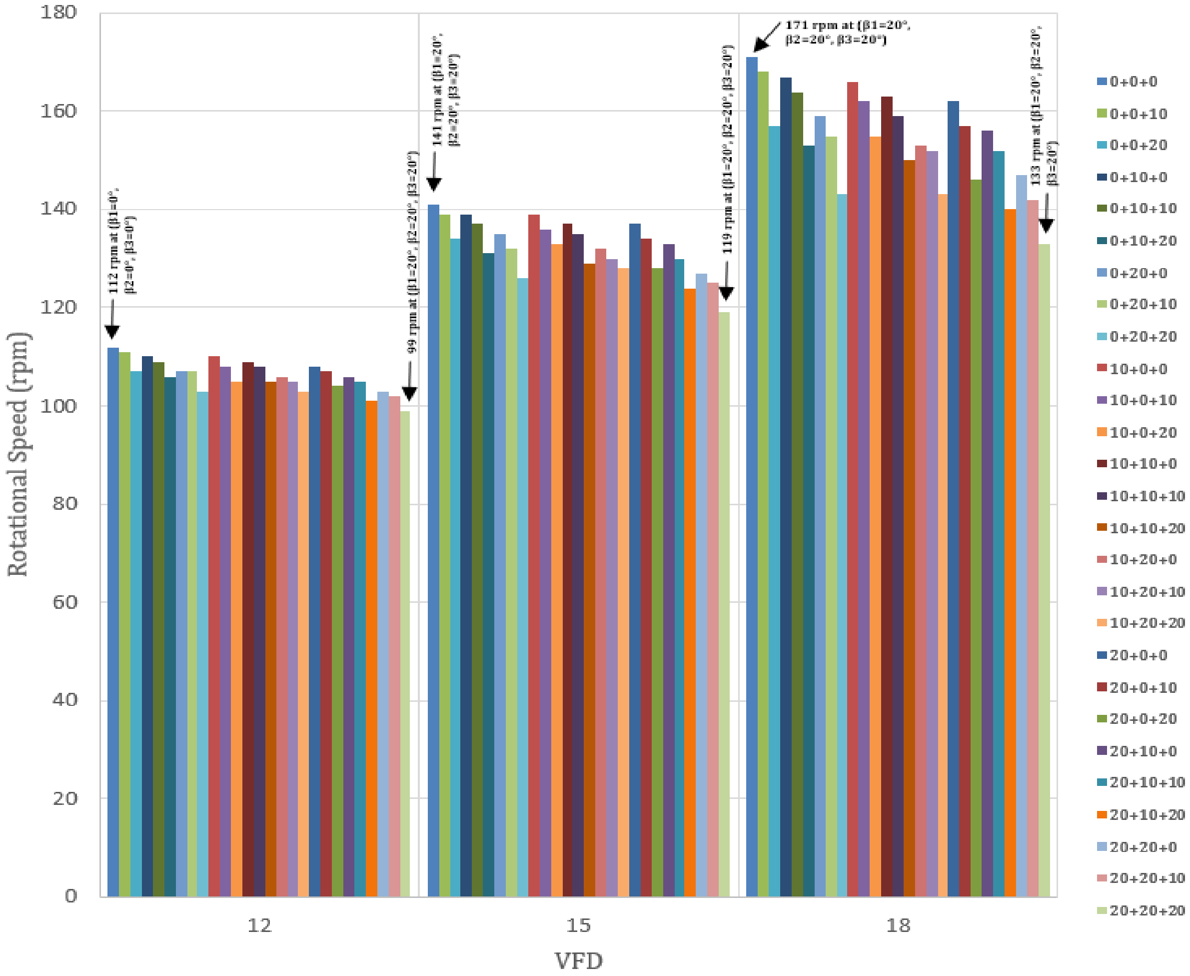


Fig. 5. Variation of shaft rotational speed against the VFD setting (legend β1+β2+β3)

3.4 Vibration Level

The measurements of the vibration levels, as illustrated in Fig. 7, revealed that combinations of higher pitch angles often led to increased vibration levels. However, some specific combinations of pitch angles and VFD settings led to a balancing effect. For example, in VFD = 12, the pitch angle combinations of (experiment 34) showed a vibration level of (6.77 m/s2) and (experiment 55) showed a vibration level of (6.92 m/s2). These two combinations showed lower vibration levels just above the initial reading of (experiment 1) which was (6.27 m/s2). The same for VFD = 15, the pitch angle combinations of (experiment 35), (experiment 38) and (experiment 53) showed much lower vibration levels of (7.05 m/s2), (7.47 m/s2) and (7.60 m/s2) respectively. This is compared to the initial reading of (experiment 1) which was (10.11 m/s2). For VFD=18, the pitch angle combinations of (experiment 60), (experiment 45) and (experiment 36) showed much lower vibration levels of (9.68 m/s2), (9.91 m/s2) and (10.07 m/s2) respectively. This is compared to the initial reading of (experiment 1) which was (10.33 m/s2). To some extent, the wind turbine system underwent balancing scenarios at these combinations of pitch angles [23].

3.5 Taguchi Response Analysis

Taguchi's response analysis focused on optimizing performance metrics through the design of experiments and the minimization of variability. The experimental investigations of blade angle variations on wind turbine systems were analyzed using Taguchi's response analysis, as responses for means and signal-to-noise ratios. The influence of selected input process parameters on various performance measures like the shaft rotational speed, power output and vibration level are detailed.

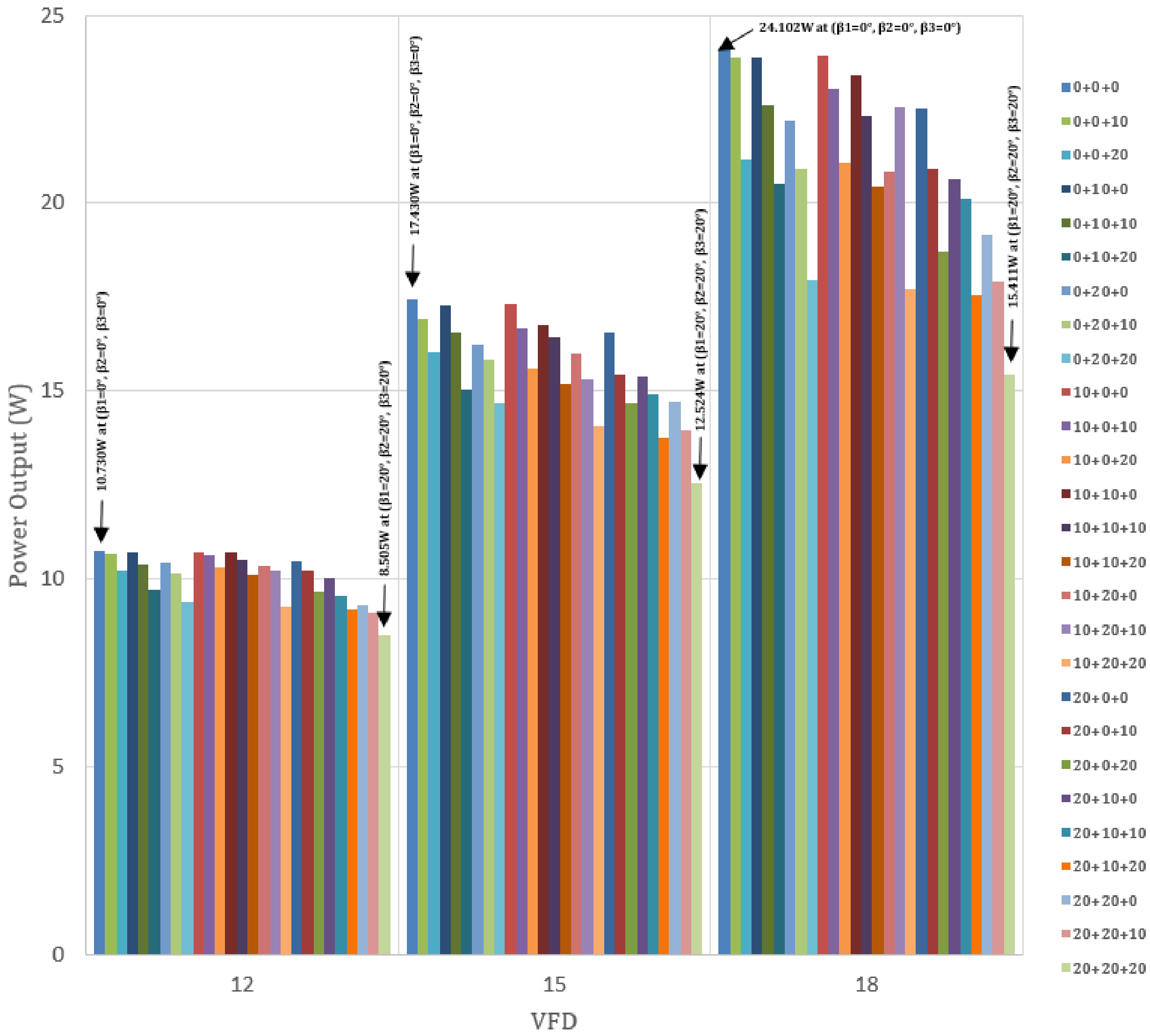


Fig. 6. Variation of power output against the VFD setting (legend β1+β2+β3)

3.5.1 Taguchi's Response Analysis for The Shaft Rotational Speed

In this case, the process parameters β1, β2, β3 and VFD were analyzed for their effects on the shaft rotational speed. In Table 3, the Mean and Signal to Noise Ratios values illustrated how changes in each factor impact the system's performance. Considering the higher-the-better criterion, the best possible set of process parameters observed from the analysis was β1-1, β2-1, β3-1 and VFD-3, which means (β1=0°, β2=0°, β3=0° and VFD=18). The response graphs for the rotational speed of both Means and Signal to Noise Ratios are shown in Fig. 8.

Table 3. Response table for the shaft rotational speed

Level	Means				Signal to Noise Ratios			
	β1	β2	β3	VFD	β1	β2	β3	VFD
1	134.2	134.7	134.6	106.1	42.44	42.47	42.46	40.51
2	131.9	131.8	132.3	132.2	42.30	42.29	42.32	42.42
3	126.9	126.5	126.1	154.6	41.97	41.95	41.92	43.77
Delta	7.3	8.2	8.5	48.5	0.47	0.52	0.54	3.26
Rank	4	3	2	1	4	3	2	1

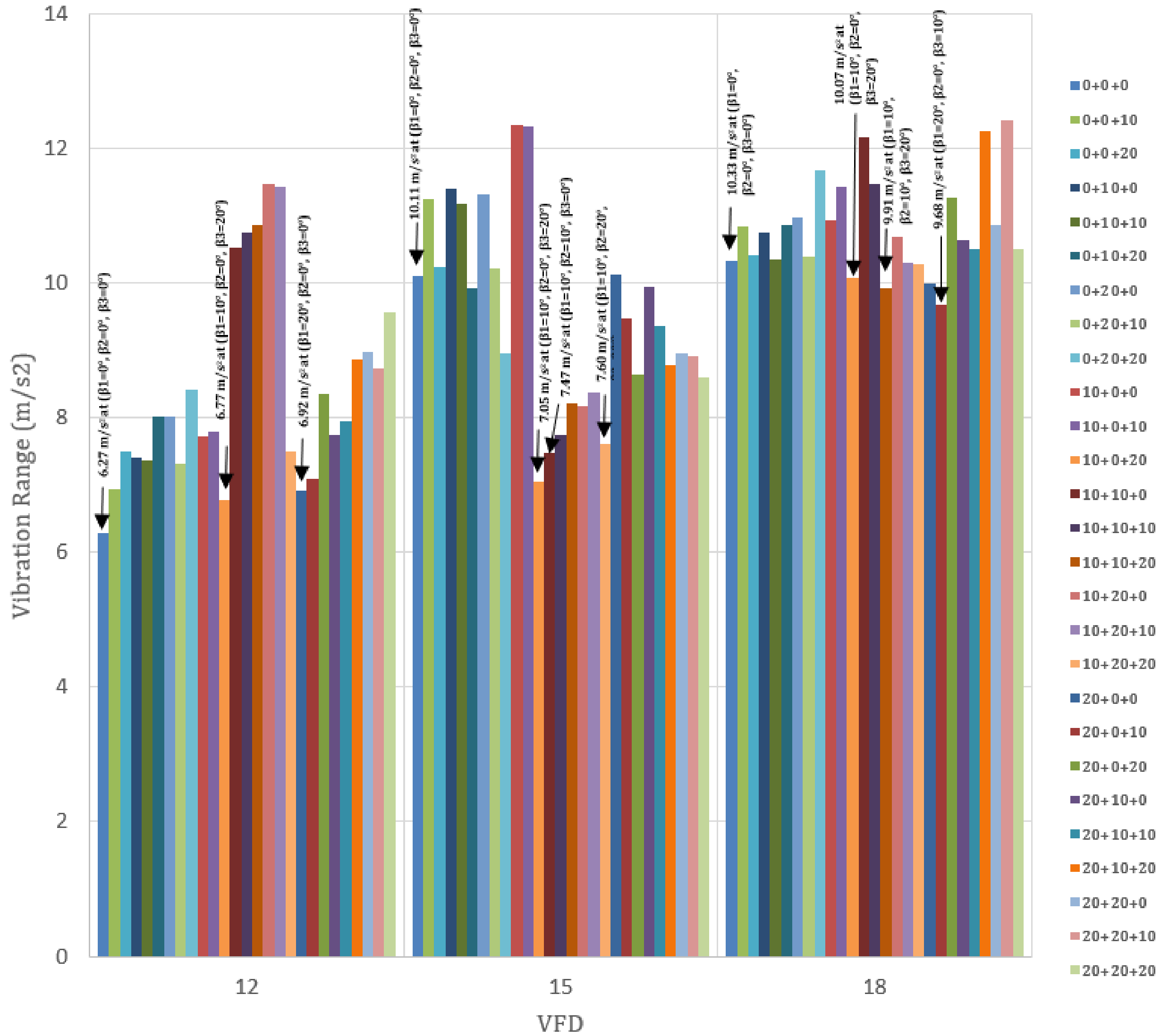
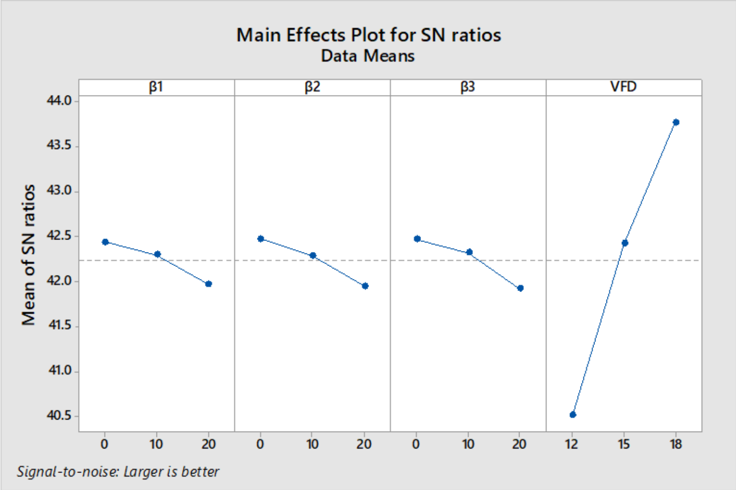


Fig. 7. Vibration levels across different settings (legend β1+β2+β3)

(a)



(b)

Fig. 8. Response graphs for the shaft rotational speed: (a) Means, 8b) Signal to Noise Ratios

3.5.2 Influence of Process Parameters on The Shaft Rotational Speed

Looking at the rankings in Table 4, VFD had the most significant impact on the rotational speed with the highest Delta values (48.5 for Means and 3.26 for S/N Ratios). This indicated that the shaft rotational speed was most sensitive to changes in the VFD settings. The pitch angles β3, β2, and β1 followed in descending order of influence, with β3 showing a slightly higher impact than β2 and β1.

3.5.3 Taguchi's Response Analysis for The Power Output

In this instance, the impact of the process parameters β1, β2, β3, and VFD on the power output was examined. Table 5 shows how variations in each factor affect the system's performance through the Mean and Signal to Noise Ratios values. The analysis revealed that the optimal set of process parameters, based on the higher-the-better criterion, was β1-1, β2-1, β3-1, and VFD-3, similar to the shaft rotational speed response with β1=0°, β2=0°, β3=0°, and VFD=18. Fig. 9 displays the response graphs for the rotating speed of Means and Signal to Noise Ratios.

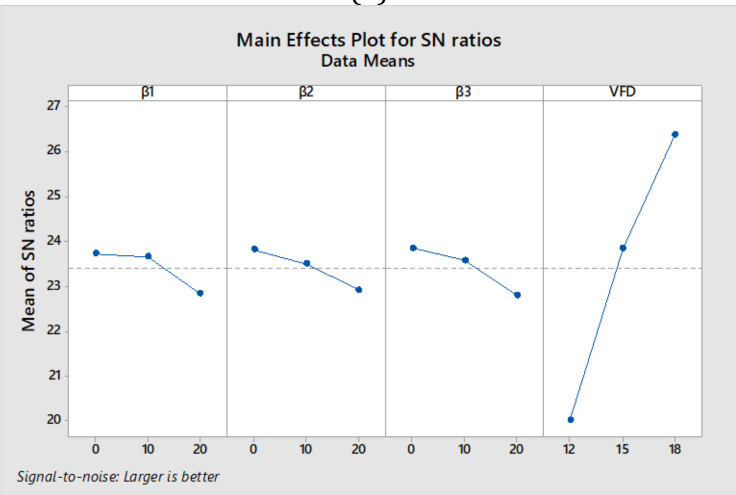
Table 4. Response table for the power output

Level	Means				Signal to Noise Ratios			
	β1	β2	β3	VFD	β1	β2	β3	VFD
1	16.12	16.28	16.36	10.04	23.72	23.81	23.85	20.02
2	15.97	15.69	15.84	15.60	23.66	23.49	23.57	23.83
3	14.48	14.61	14.38	20.94	22.84	22.91	22.80	26.37
Delta	1.65	1.66	1.98	10.90	0.89	0.90	1.05	6.35
Rank	4	3	2	1	4	3	2	1

3.5.4 Influence of Process Parameters on The Power Output

When examining the influence of each parameter on power output, VFD had the most substantial impact, with the highest Delta values of 10.90 for Means and 6.35 for S/N Ratios. This indicated that the power output was also highly sensitive to changes in the VFD setting. The pitch angles β3, β2, and β1 follow in descending order of influence. The rankings confirmed that VFD was the most critical factor in optimizing power output. The pitch angles had a comparatively smaller, but still significant, impact. The consistency in the optimal parameter settings for both power output and shaft rotational speed underscored the interconnected nature of these performance metrics within the system.

(a)



(b)

Fig. 9. Response graphs for power output: (a) Means, (b) Signal to Noise Ratios

3.5.5 Taguchi's Response Analysis for The Vibration Level

In the third case, the impact of process parameters β1, β2, β3, and VFD on the vibration level was examined. Table 5 displays how variations in each factor affect the system's performance in terms of Mean and Signal to Noise Ratio values. The analysis revealed that the optimal set of process parameters, based on the lower-the-better criterion, was β1-3, β2-1, β3-3, and VFD-1, (β1=20°, β2=0°, β3=20°, and VFD=12). Fig. 10 displays the response graphs for the rotating speed of Means and Signal to Noise Ratios.

Table 5. Response table for vibration level

Level	Means				Signal to Noise Ratios			
	β1	β2	β3	VFD	β1	β2	β3	VFD
1	9.569	9.326	9.709	8.377	-19.48	-19.22	-19.61	-18.34
2	9.679	9.718	9.686	9.504	-19.56	-19.64	-19.59	-19.46
3	9.446	9.650	9.298	10.812	-19.42	-19.60	-19.26	-20.66
Delta	0.234	0.392	0.411	2.435	0.14	0.42	0.34	2.32
Rank	4	3	2	1	4	2	3	1

(a)

(b)

Fig. 10. Response graphs for vibration level (a) Means, (b) Signal to Noise Ratios

3.5.6 Influence of Process Parameters on The Vibration Level

When assessing the impact of each parameter on vibration levels, the VFD setting had again the most significant influence. It indicated the highest Delta values of 2.435 for Means and 2.32 for S/N Ratios. The vibration level is highly sensitive to changes in VFD also. The pitch angle β3 showed a slightly higher impact on vibration levels compared to β2 and β1. This ranking emphasized that the blade pitch angles played a significant role, particularly β3.

3.6 Analysis of Variance for Measured Performance

The analysis of variance (ANOVA) for the measured performance in wind turbine showed the significance of the input parameters on the system's responses. ANOVA was used on the performance measures at 95% confidence level and was computed using Minitab statistical software. In this context, ANOVA revealed that VFD was the more dominant factor influencing system responses. Due to balancing scenarios at which the rotational speed was affected, the P-values of the blade pitch angles input parameters were higher than 0.05, but still they created influence as shown in Fig. 7. Table 6 shows this analysis.

3.7 Regression Modelling Results

In this section, a regression analysis was conducted to quantify the relationship between input parameters (predictors) and system responses. Two types of regression models were developed to determine the best model fit for wind turbine performance, namely; linear model and full quadratic model. Minitab software was used in the regression analysis. Table 7 shows the input variables of each model. The R-squared values of the developed models were compared to determine the best-fit model, as shown in Table 8.

Table 6. Analysis of variance (ANOVA) analysis

Response	Source	DF	Adj SS	Adj MS	F-Value	P-Value
Shaft rotational speed (rpm)	β1	2	743.4	371.7	44.15	0.000
	β2	2	929.0	464.5	55.17	0.000
	β3	2	1043.9	521.9	62.00	0.000
	VFD	2	31791.6	15895.8	1888.15	0.000
	Error	72	606.1	8.4		
	Total	80	35114.0			
Power output (W)	β1	2	44.92	22.460	35.51	0.000
	β2	2	38.31	19.155	30.28	0.000
	β3	2	56.79	28.396	44.89	0.000
	VFD	2	1605.03	802.515	1268.66	0.000
	Error	72	45.54	0.633		
	Total	80	1790.60			
Vibration level (m/s^2)	β1	2	0.737	0.3684	0.22	0.801
	β2	2	2.372	1.1858	0.72	0.492
	β3	2	2.885	1.4425	0.87	0.423
	VFD	2	80.220	40.1102	24.20	0.000
	Error	72	119.320	1.6572		
	Total	80	205.534			

Table 7. Regression models input parameters

Regression model	Input variables
Linear	Linear: β1, β2, β3 and VFD
Full quadratic (Linear + Squared + Interaction)	Linear: β1, β2, β3 and VFD Squared: $β1^2$, $β2^2$, $β3^2$ and VFD^2 Interaction: (β1×β2), (β2×β3), (β3×β1), (β1×VFD), (β2×VFD), (β3×VFD)

Table 8. R^2 values of various developed regression models

Regression model	R^2 values (%)		
	Rotational speed (rpm)	Power output (W)	Vibration level (m/s^2)
Linear	97.76	96.71	40.86
Full quadratic (Linear + Squared + Interaction)	99.72	99.33	44.89

From the developed regression models shown in Table 10, the full quadratic model showed the best fit. The regression equations for the responses are:

$$\text{Rotational Speed} = -56.71 + 0.854\,\beta1 + 0.957\,\beta2 + 1.144\,\beta3 + 16.330\,VFD - 0.01333\,\beta1^2 - 0.01167\,\beta2^2 - 0.01889\,\beta3^2 - 0.2037\,VFD^2 - 0.00361\,\beta1x\beta2 + 0.00139\,\beta2x\beta3 - 0.00111\,\beta3x\beta1 - 0.06019\,\beta1xVFD - 0.07407\,\beta2xVFD - 0.07963\,\beta3xVFD$$

$$\text{Power Output} = -20.59 + 0.3165\beta 1 + 0.2354\beta 2 + 0.3254\beta 3 + 2.722\,VFD - 0.00674\beta 1^2 - 0.00241\beta 2^2 - 0.00469\beta 3^2 - 0.0120\,VFD^2 - 0.001434\beta 1x\beta 2 - 0.000938\beta 2x\beta 3 - 0.000129\beta 3x\beta 1 - 0.01657\beta 1xVFD - 0.01644\beta 2xVFD - 0.02133\beta 3xVFD$$

$$\text{Vibration Level} = 3.03 + 0.088\beta 1 + 0.239\beta 2 + 0.025\beta 3 + 0.28\,VFD - 0.00172\beta 1^2 - 0.00230\beta 2^2 - 0.00183\beta 3^2 + 0.0101\,VFD^2 + 0.00073\beta 1x\beta 2 - 0.00052\beta 2x\beta 3 + 0.00089\beta 3x\beta 1 - 0.00505\beta 1xVFD - 0.01194\beta 2xVFD - 0.00082\beta 3xVFD$$

3.8 Performance Optimization

This section optimized the performance of the wind turbine system by balancing the system output responses. The optimization process utilized Grey Relational Analysis (GRA) in conjunction with a full factorial design in Minitab software. The optimization process resulted in defining the optimal settings of process parameters. The GRA focused on two primary criteria: maximizing the shaft rotational speed and power output (higher-the-better), and minimizing the vibration level (Lower-the-better). By applying these criteria, a Grey Relational Grade (GRG) was computed for each experimental test. Table 9 shows the calculated GRCs and GRG values, and ranking.

Table 9. Calculated GRCs and GRG values, and ranking

Exp.	Dependent Variables (Responses)			Grey Relation Coefficients			GRG	Rank
	Rot. Speed	Vibration Level	Power Output	Rot. Speed	Vibration Level	Power Output		
1	112	6.274	10.730	0.379	1.000	0.368	0.582	22
2	141	10.106	17.430	0.545	0.445	0.539	0.510	35
3	**171**	**10.326**	**24.102**	**1.000**	**0.431**	**1.000**	**0.810**	**1**
4	111	6.943	10.643	0.375	0.821	0.367	0.521	29
5	139	11.238	16.898	0.529	0.382	0.520	0.477	48
6	**168**	**10.849**	**23.868**	**0.923**	**0.402**	**0.971**	**0.765**	**2**
7	107	7.486	10.237	0.360	0.717	0.360	0.479	47
8	134	10.239	16.014	0.493	0.436	0.491	0.473	51
9	157	10.411	21.164	0.720	0.426	0.726	0.624	13
10	110	7.400	10.701	0.371	0.732	0.368	0.490	39
11	139	11.402	17.290	0.529	0.375	0.534	0.479	46
12	**167**	**10.760**	**23.868**	**0.900**	**0.406**	**0.971**	**0.759**	**3**
13	109	7.352	10.382	0.367	0.740	0.362	0.490	40
14	137	11.181	16.558	0.514	0.385	0.508	0.469	57
15	164	10.354	22.610	0.837	0.429	0.839	0.702	5
16	106	8.013	9.688	0.356	0.638	0.351	0.449	70
17	131	9.925	15.015	0.474	0.457	0.462	0.464	62
18	153	10.859	20.498	0.667	0.401	0.684	0.584	20
19	107	8.005	10.411	0.360	0.639	0.363	0.454	67
20	135	11.316	16.218	0.500	0.378	0.497	0.459	66
21	159	10.966	22.192	0.750	0.396	0.803	0.650	9
22	107	7.308	10.121	0.360	0.748	0.358	0.489	42
23	132	10.204	15.844	0.480	0.439	0.486	0.468	59
24	155	10.396	20.905	0.692	0.427	0.709	0.609	15
25	103	8.424	9.380	0.346	0.588	0.346	0.427	72
26	126	8.952	14.652	0.444	0.534	0.452	0.477	49
27	143	11.675	17.955	0.563	0.362	0.559	0.495	37
28	110	7.712	10.701	0.371	0.681	0.368	0.473	52
29	139	12.348	17.325	0.529	0.336	0.535	0.467	60
30	166	10.925	23.907	0.878	0.398	0.976	0.750	4
31	108	7.795	10.614	0.364	0.669	0.366	0.466	61

Table 9 (continued)

Exp	Dependent Variables (Responses)			Grey Relation Coefficients			GRG	Rank
	Rot. Speed	Vibration Level	Power Output	Rot. Speed	Vibration Level	Power Output		
32	136	12.325	16.660	0.507	0.337	0.512	0.452	68
33	162	11.423	23.028	0.800	0.374	0.879	0.684	8
34	105	6.774	10.295	0.353	0.860	0.361	0.525	28
35	133	7.052	15.576	0.486	0.798	0.478	0.587	19
36	155	10.072	21.090	0.692	0.447	0.721	0.620	14
37	109	10.528	10.701	0.367	0.419	0.368	0.385	76
38	137	7.474	16.762	0.514	0.719	0.515	0.583	21
39	163	12.156	23.400	0.818	0.343	0.917	0.693	7
40	108	10.750	10.498	0.364	0.407	0.364	0.378	78
41	135	7.739	16.422	0.500	0.677	0.504	0.560	24
42	159	11.469	22.306	0.750	0.371	0.813	0.645	10
43	105	10.872	10.092	0.353	0.400	0.358	0.370	79
44	129	8.217	15.180	0.462	0.612	0.466	0.513	33
45	150	9.910	20.424	0.632	0.458	0.680	0.590	18
46	106	11.462	10.353	0.356	0.372	0.362	0.363	80
47	132	8.174	15.980	0.480	0.618	0.490	0.529	27
48	153	10.679	20.831	0.667	0.411	0.705	0.594	17
49	105	11.416	10.237	0.353	0.374	0.360	0.362	81
50	130	8.378	15.312	0.468	0.593	0.470	0.510	34
51	152	10.309	22.572	0.655	0.432	0.836	0.641	11
52	103	7.490	9.240	0.346	0.716	0.344	0.469	58
53	128	7.599	14.080	0.456	0.699	0.438	0.531	26
54	143	10.287	17.710	0.563	0.433	0.550	0.515	32
55	108	6.916	10.440	0.364	0.827	0.363	0.518	31
56	137	10.124	16.558	0.514	0.444	0.508	0.489	41
57	162	9.982	22.534	0.800	0.453	0.833	0.695	6
58	107	7.081	10.237	0.360	0.792	0.360	0.504	36
59	134	9.469	15.444	0.493	0.490	0.474	0.486	43
60	157	9.675	20.905	0.720	0.474	0.709	0.635	12
61	104	8.354	9.660	0.350	0.596	0.351	0.432	71
62	128	8.630	14.652	0.456	0.566	0.452	0.491	38
63	146	11.268	18.720	0.590	0.381	0.592	0.521	30
64	106	7.744	10.034	0.356	0.676	0.357	0.463	63
65	133	9.940	15.378	0.486	0.456	0.472	0.471	55
66	156	10.647	20.646	0.706	0.412	0.693	0.604	16
67	105	7.942	9.520	0.353	0.648	0.348	0.450	69
68	130	9.354	14.916	0.468	0.499	0.459	0.475	50
69	152	10.513	20.128	0.655	0.420	0.662	0.579	23
70	101	8.862	9.184	0.340	0.543	0.343	0.409	74
71	124	8.772	13.760	0.434	0.551	0.430	0.472	54
72	140	12.254	17.535	0.537	0.339	0.543	0.473	53
73	103	8.976	9.296	0.346	0.532	0.345	0.408	75
74	127	8.951	14.718	0.450	0.534	0.454	0.479	45
75	147	10.863	19.152	0.600	0.401	0.612	0.538	25
76	102	8.739	9.100	0.343	0.555	0.342	0.413	73
77	125	8.912	13.952	0.439	0.538	0.434	0.470	56

Table 9 (continued)

Exp	Dependent Variables (Responses)			Grey Relation Coefficients			GRG	Rank
	Rot. Speed	Vibration Level	Power Output	Rot. Speed	Vibration Level	Power Output		
78	142	12.414	17.920	0.554	0.333	0.558	0.482	44
79	99	9.561	8.505	0.333	0.483	0.333	0.383	77
80	119	8.593	12.524	0.409	0.570	0.402	0.460	64
81	133	10.496	15.411	0.486	0.421	0.473	0.460	65

The GRG combined the GRCs into a single performance score. Test 3 showed the highest GRG (0.810), making it the top rank, which means $\beta 1=0^{o}$, $\beta 2=0^{o}$, $\beta 3=0^{o}$ and VFD=18. This indicated the best overall performance. With higher GRG achieved, test 3 was the best balance between power output and vibration control, making it a more optimal scenario. The optimal setting for system performance is shown in Table 10. The regression equation for GRG is:

$$GRG = \begin{aligned}[t] & 0.933 + 0.00757\,\beta 1 + 0.00034\,\beta 2 + 0.01168\,\beta 3 - 0.0928\,VFD - 0.000111\,\beta 1^2 + 0.000032\,\beta 2^2 \\ & - 0.000070\,\beta 3^2 + 0.00466\,VFD^2 + 0.000011\,\beta 1 x \beta 2 + 0.000079\,\beta 2 x \beta 3 + 0.000044\,\beta 3 x \beta 1 \\ & - 0.000566\,\beta 1 x VFD - 0.000361\,\beta 2 x VFD - 0.000941\,\beta 3 x VFD \end{aligned}$$

Table 10. Optimal setting for system performance analysis

	Optimal setting
Parameters and levels	$\beta 1=0^{o}$, $\beta 2=0^{o}$, $\beta 3=0^{o}$ and VFD=18
Shaft rotational speed (rpm)	171
Power output (W)	24.102
Vibration level (m/s^2)	10.326
Grey Relational Grade	0.810

4. Conclusion

This study conducted a comprehensive investigation into the impact of varying blade pitch angles and Variable Frequency Drive (VFD) settings on the performance characteristics of a wind turbine system. Using the Spectra Quest Wind Turbine Simulator (SQ WTS), a systematic experimental approach, grounded in Taguchi's method, was implemented to evaluate the influence of these variables on critical metrics, including shaft rotational speed, power output, and vibration levels. A total of 81 experiments were designed to capture the interactions between different pitch angles and VFD settings, revealing that these factors significantly influence the operational efficiency of wind turbines.

The results highlighted that an optimal combination of lower blade pitch angles (0°) and higher VFD settings (18) achieved the best performance, with a peak shaft rotational speed of 171 rpm and a maximum power output of 24.102 W, while maintaining vibration levels within acceptable limits. Conversely, increasing blade pitch angles introduced higher air resistance, negatively impacting rotational speed and power output. Some specific combinations of pitch angles, however, demonstrated a unique balancing effect, reducing vibration while maintaining satisfactory power levels, suggesting potential avenues for refining wind turbine design to optimize performance.

Furthermore, the main two regression models developed highlighted the critical role of VFD settings in enhancing system performance. This demonstrated that it is the most significant predictor for rotational speed and power output. Analysis of Variance (ANOVA) confirmed these findings, with VFD showing a dominant influence over system responses compared to blade pitch angles, which still contributed to performance variation. Mostly, in the balancing scenarios.

The optimization process employing Grey Relational Analysis (GRA) technique identified the optimal operating condition that maximized power output while minimizing vibration. This underscored the potential for future operational guidelines in wind turbine design and management. These insights not only contributed to the foundational knowledge of wind turbine performance dynamics, but also served as a basis for future research targeting improved efficiency and sustainability in wind energy technology.

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