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Response Surface Optimization of Power Voltage in Pilot Scale Wind Turbine Model

Abstract: - Wind turbines are of great significance due to their utilization of renewable energy sources, thereby reducing dependency on fossil fuels. The primary objective of this research paper is to optimize the output voltage by varying the pitch angle and the number of blades, utilizing a central composite response surface design. Through the analysis conducted, it was observed that the output voltage exhibits an increasing trend as the number of blades is increased within the range of 2 to 6. Furthermore, the output voltage demonstrates an initial increase with an increase in blade pitch angle from 0 to 45 degrees, followed by a subsequent decrease. The highest attainable output voltage, reaching 2630 mV, was achieved when the pitch angle and number of blades were at 29□ and 6, respectively. The findings of this study has potential for scaling up the operations to industrial wind turbine power plants.

Keywords: Wind turbine, Blade pitch angle, Number of blades, Output voltage, Response surface design.

INTRODUCTION:

A facility that manufactures wind turbines or their parts is known as a wind turbine plant. These facilities are typically situated where wind turbines can produce the most electricity, such as coastal or mountainous regions with strong wind potential [1,2]. The fabrication processes at wind turbine factories often include numerous steps, including the fabrication of wind turbine parts such blades, towers, generators, and control systems. These parts are then put together to create entire wind turbines, which are tested and put into service before being delivered to the locations where they will be installed [3,4]. The growth of renewable energy sources and the lowering of greenhouse gas emissions depend on the construction and operation of wind turbine facilities [5]. Wind turbine facilities are essential in the transition to a more sustainable energy system since wind energy is regarded as a clean and sustainable source of energy. However, the development of wind power facilities may also have certain negative effects on the ecosystem, including the possibility of bird and bat accidents with the turbines, noise pollution, and visual effects on the surrounding area. It is crucial to carefully assess suitable locations for wind turbine plants and to put in place the necessary mitigation strategies to reduce any negative effects [6–8]. The following are some of the parameters that impact power wattage in a wind turbine plant [9,10]: (i) wind speed, (ii) Wind direction, (iii) Air density, (iv) Temperature, (v) Turbine blade length and design, (vi) Maintenance and (vii) Environmental aspects.

The usage of renewable energy as a substitute for fossil fuels has grown steadily during the past 20 years. This has broadened the scope of renewable energy research and development initiatives. Wind energy has emerged as a potential prospect among the various forms of renewable energy systems, with a global installed capacity of approximately 842 GW as of 2022, representing a 9% increase over 2021 [11]. Wind energy has shown to be an environmentally benign and commercialized form of energy among the numerous alternative energy sources. Because of its availability, wind energy is an excellent way to generate energy because it is renewable. Wind turbines are machines that convert the kinetic energy in the wind into mechanical energy and then into electricity [12]. Wind turbine efficiency is much greater than that of other renewable energy extraction systems. Small-scale wind turbines have the potential to be a source of electricity generation. As a result, small-scale wind turbines must be cost-effective. Small-scale wind turbines can be connected to the electric grid via a power supplier or can operate independently (off-grid). As a result, tiny wind electric systems are an excellent solution for rural areas that are not already wired for electricity [13]. Commercial wind turbines are large wind turbines constructed in areas with favourable wind conditions.

Small wind turbines have a power coefficient of around 0.25 and are generally installed anywhere regardless of wind conditions. Based on power and rotor radius, these turbines are classed as micro (1 kW and >1.5m), midrange (5 kW and > 2.5m), and mini (20+ kW, > 5m) [14]. Many parameters, such as aerodynamic behaviour, generator characteristics, blade strength, rigidity, and noise levels, are important in the design of wind turbine blades. The primary goals of small wind turbine design are to maximize energy extraction and improve starting characteristics at low wind speeds; rotor aerodynamics is critical in reducing energy generation costs. However, the total energy produced is affected by both the power output and the probability distribution of the wind [15].

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Response surface methodology (RSM) is used to plan experiments, analyze results, and improve procedures. RSM is a combination of mathematical and statistical approaches to model and analyze the relationships between independent and dependent variables [16,17]. RSM aims to identify the ideal conditions for a process or product by systematically changing the inputs and analyzing its impact on the response variable(s), In RSM, the relation between the independent variables and the response variable(s) is described using mathematical models. These models can be used to forecast the ideal values of the independent variables that will produce the intended response [18,19]. Experiment design, data analysis, model construction, and optimization are among the phases of the RSM approach. It makes use of methods including response surface regression and optimization, as well as factorial design, central composite design, and Box-Behnken design. RSM finds its applications in numerous industries, including engineering, manufacturing, agriculture, and environmental science. It can be used to generate new products, enhance existing ones, and optimize processes [20,21].

A probabilistic power flow analysis method based on the stochastic response surface method was proposed by Ren et al. (2016) [22]. It is simple to represent the stochastic continuous input variables with various correlations that follow normal distributions, such as loads, or non-normal distributions, such as solar generation and wind power. By contrasting the probabilistic power flow analysis achieved using the suggested technique, the point estimate method, and the Monte Carlo simulation method, the correctness, efficacy, and adaptability of the proposed method are shown. The impact of profile adjustments on a NACA-0015 aerofoil used in vertical axis wind turbines is studied by Ismail and Vijayaraghavan (2015) [23]. In this study, RSA (Response Surface Approximation) was used to fully automate the optimization and maximize the average torque generated by the wind turbine blade. It was demonstrated that the improved aerofoil's optimal shape enhances the wind turbine blade's aerodynamics. In a wind tunnel experiment, Li et al. (2015) evaluated the aerodynamic forces based on various numbers of blades [24]. The test airfoil's blade symmetry is NACA 0021, and it has two to five blades. The upstream region of the azimuth angle of = 0 to 180 degrees determines most of the power that is absorbed from the wind by the turbine.

From the analysis of the literature, it was found that the pilot-scale wind turbine power plant has not been investigated by varying the number of blades and pitch angle with voltage as an output variable using response surface methodology. Hence, the present study aims to maximize output voltage by varying the number of blades and pitch angle.

MATERIALS AND METHODS:

Materials:

Pilot scale wind generator (1.2 W (maximum), 5.4 V, 500 mA), fan (115 W, 230 V), USB data monitor (10 W with USB cable and PC with installed clean energy trainer software) and connecting wires are used for the current study. The mentioned facilities are available in the renewable energy lab of Electrical Engineering Section.

Methods:

Experimental studies on pilot scale wind turbine model:

The rotor blades are fixed on the pilot scale wind turbine model so that they are unbent. Fan is switched on and the turbine model is placed at 50 cm. The clear energy trainer software is started, and wind generator module is selected with manual operating mode. The pitch angle is changed by rotating the blades. Finally, the output voltage is recorded. Each experiment was repeated thrice and the mean value between the values was taken as an output voltage.

Response surface analysis of output voltage in pilot scale wind turbine model:

The factors affecting the output voltage in wind turbine model are wind speed, wind direction, turbine blade length and design, and environmental factors like temperature, relative humidity, etc [10]. In the present study, pitch angle of blade (A), and number of blades (B) were considered for maximizing output voltage in wind turbine model.

The study chose central composite design (CCD) since it necessitates fewer tests. CCD requires $2^f + 2f + CP$ experiments, where f is the number of factors and CP is the number of centre points [25]. The number of experiments needed by CCD for 2 factors and 3 centre points is 11. RSM varies all the variables at once, in contrast to factorial design, which only varies one factor at a time, allowing for the investigation of interaction effects between the factors.

CCD with three levels is displayed in Figure 1 for two input factors. Low and high values are represented in the figure by -1 and +1, respectively. Zero is the midpoint between low and high values. The set of variables and their weights utilized in the pilot scale wind turbine model are displayed in Table 1. On the basis of the literature, the factors and levels were chosen. The CCD matrix created from Figure 1 is shown in Table 2.

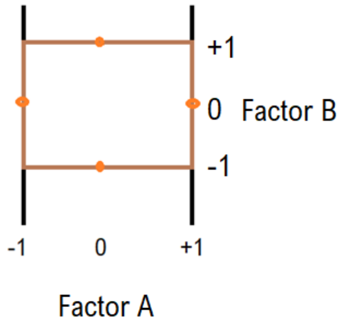

Figure 1. Central composite face centred response surface design for two factors

Equation 1 provides the general quadratic equation that connects dependent and independent components.

$$Y = \alpha_0 + \alpha_1 A + \alpha_2 B + \alpha_3 AB + \alpha_4 A^2 + \alpha_5 B^2 \quad (1)$$

where Y is the response (output voltage), A is pitch angle, and B is number of blades, α_0 is intercept, α_1 and α_2 are linear coefficients for pitch angle and number of blades, respectively, α_3 is interaction coefficient between pitch angle and number of blades, and α_4, and α_5 are quadratic coefficients for pitch angle and number of blades, respectively.

CCD analysis for the model was carried out using Design-Expert® 11.1.2.0 (64-bit). The least-squares principle, which asserts that the sum of the square of residuals is zero, was used to calculate coefficients. If Equation 1 is expressed as a matrix for 11 experiments, Equation 2 is obtained as shown below.

$$AX = B \quad (2)$$

Here, A stands for the input value matrix, X for the coefficient matrix, and B for the output value matrix. Equation 3 was used to calculate the coefficient matrix X.

$$X = (A^T A)^{-1}. (A^T B) \quad (3)$$

The 3-D surface plots were created after the coefficients had been determined to investigate the interaction effects between the input and the response factors. Analysis of variance (ANOVA) was used to determine how the experimental and predicted values varied from each other. To evaluate the goodness of fit, R^2, adjusted R^2, coefficient of variation, and sufficient precision were calculated. The local optima values with desirability function values between 0 and 1 were then returned.

RESULTS AND DISCUSSION:

Table 1. Factors and levels used for optimization of output voltage in pilot scale wind turbine model

Factor	Symbol	Unit	Level		
			Low (-1)	Centre (0)	High (+1)
Pitch angle	A	°	0	45	90
Number of blades	B	-	2	4	6

Table 1 shows the factors and levels used for optimization of output voltage in pilot scale wind turbine model. The factors affecting the output voltage in wind turbine are wind speed, wind direction, pitch angle, number of blades, turbine blade length and design, and environmental factors like temperature, relative humidity, etc [10]. Due to limitations in scale down of commercial wind turbine to its pilot scale and challenges in measuring wind speed, wind direction, turbine blade length and design, pitch angle and number of blades are selected as important variables to examine its influence on output voltage. The levels for factors like pitch angle (0, 45 and 90°) and number of blades (2, 4 and 6) were chosen based on criteria on experimental wind turbine model. The coded values of (-1, 0 and +1) were calculated based on the Equation (4).

$$x_c = \frac{x_a - \bar{x}}{\Delta x} \quad (4)$$

where x_a is actual value, $\bar{x}$ is average value and Δx is difference between levels.

Table 2. CCD matrix for optimization of output voltage in pilot scale wind turbine model

		Factor 1	Factor 2	Response 1
Std	Run	A:Pitch angle	B:Number of blades	Output voltage
		°	-	mV
7	1	45	4	1756
2	2	90	2	1.97
1	3	0	2	1132
8	4	0	4	1808
11	5	90	6	1532
10	6	90	4	744
3	7	45	6	2583
5	8	0	6	2548
6	9	45	2	1067
9	10	45	4	1742
4	11	45	4	1769

According to the CCD as shown in Figure 1, the combination of 8 sets are (-1,0), (-1,+1), (+1,0), (+1,-1), (0,-1), (-1,-1), (0,+1), and (+1,+1) with 3 centre points of (0,0). Table 2 shows the matrix of the CCD with 11 experiments including independent and dependent variables. The experimental data was fitted in linear, two factor interactive (2FI), quadratic and cubic models as shown in Table 3. The statistical significance of the developed model could be analysed by ANOVA as shown in Table 3 and by determination coefficient as shown in Table 4.

Table 3. ANOVA based model selection for optimization of output voltage in pilot scale wind turbine model

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Mean vs Total	2.530E+07	1	2.530E+07			
Linear vs Mean	5.036E+06	2	2.518E+06	30.36	0.0002	
2FI vs Linear	3250.71	1	3250.71	0.0345	0.8580	
Quadratic vs 2FI	**6.580E+05**	**2**	**3.290E+05**	**778.40**	**< 0.0001**	**Suggested**
Cubic vs Quadratic	642.99	2	321.50	0.6560	0.5803	Aliased
Residual	1470.34	3	490.11			
Total	3.100E+07	11	2.818E+06			

According to the ANOVA, F-value should be highest with p-value less than 0.05. As per this criteria, linear model has p-value < 0.05 but F-value is lesser than quadratic model. Then, p-value of 2FI is greater than 0.05. Finally, quadratic model has p-value < 0.05 but F-value is highest at 778.40, which is better than cubic model (Table 3).

Table 4. Model summary statistics for optimization of output voltage in pilot scale wind turbine model

Source	**Std. Dev.**	**R^2**	**Adjusted R^2**	**Predicted R^2**	**PRESS**	
Linear	287.96	0.8836	0.8545	0.7680	1.322E+06	
2FI	307.09	0.8842	0.8345	0.5652	2.478E+06	
Quadratic	**20.56**	**0.9996**	**0.9993**	**0.9974**	**14922.95**	**Suggested**
Cubic	22.14	0.9997	0.9991	0.9752	1.412E+05	Aliased

According to the model summary statistics, determination coefficient (R^2) should be highest of more than 0.99. As per this criteria, linear, 2FI, quadratic and cubic models have R^2 of 0.8836, 0.8842, 0.9996 and 0.9997, respectively. Hence, from ANOVA and model summary statistics, it was concluded that the quadratic model is good fit.

Table 5. ANOVA for optimization of output voltage in pilot scale wind turbine model

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	5.697E+06	5	1.139E+06	2695.70	< 0.0001	Significant
A-Pitch angle	1.717E+06	1	1.717E+06	4063.20	< 0.0001	
B-Number of blades	3.318E+06	1	3.318E+06	7850.82	< 0.0001	
AB	3250.71	1	3250.71	7.69	0.0392	
A²	6.376E+05	1	6.376E+05	1508.56	< 0.0001	
B²	5670.64	1	5670.64	13.42	0.0146	
Residual	2113.34	5	422.67			
Lack of Fit	1748.67	3	582.89	3.20	0.2473	Not significant
Pure Error	364.67	2	182.33			
Cor Total	5.699E+06	10				

The output voltage optimization created models are shown in Table 5 for the pilot scale wind turbine model. It demonstrated the models' significance with a low p-value (0.001) and a high F-value for output voltage of 2695.70. For output voltage, which demonstrates the best goodness of fit between experimental and expected values, R^2, adjusted R^2, predicted R^2, coefficient of variation, and sufficient precision were found to be 0.9996, 0.9993, 0.9974, 1.36%, and 168.43, respectively. Equation (5) provides a quadratic model that links independent and dependent variables as follows:

$$Y = 556.71 + 9.14A + 262.96B + 0.32AB - 0.25A^2 + 11.83B^2 \quad (5)$$

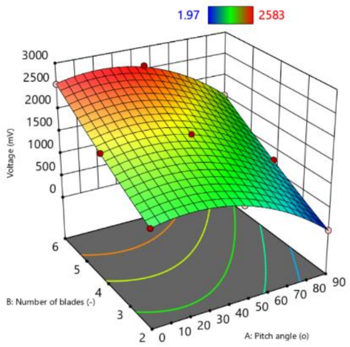

Figure 2. 3-D surface showing the effect of pitch angle and number of blades for optimization of output voltage in pilot scale wind turbine model

Three-dimensional surface plots are used to study the interaction effects between pitch angle and number of blades on output voltage. From the Figure 2, it was shown that at an initial pitch angle and number of blades of 0° and 2, respectively, the output voltage was 1132 mV. When pitch angle and number of blades increased to 45° and 4, respectively, the output voltage was increased to 1156 mV. When pitch angle and number of blades were further increased to 90° and 6, respectively, the output voltage was further increased to 1532 mV.

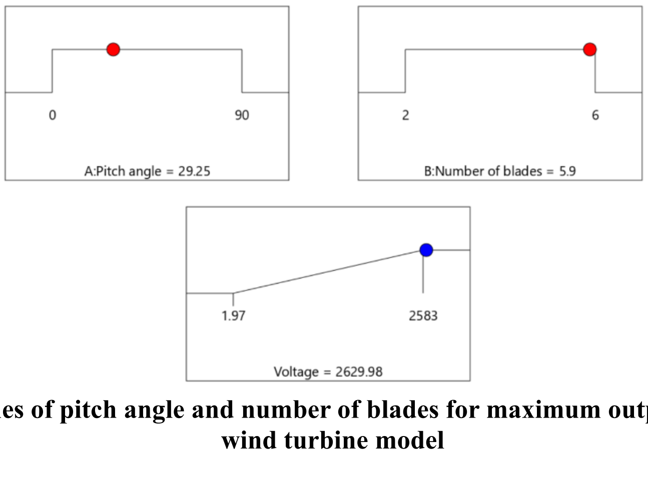

Figure 3. Optimal values of pitch angle and number of blades for maximum output voltage in pilot scale wind turbine model

From experiments, the maximum optimum voltage of 2630 mV was achieved at pitch angle and number of blades of 29° and 6, respectively (Figure 3). The experiments were repeated under optimal conditions in triplicate and the output voltage was found to be within the coefficient of variation of ±5% for validation.

CONCLUSION:

The present work aimed to maximize output voltage by varying number of blades and pitch angle. The optimal values show that the maximum output voltage of 2630 mV was achieved at pitch angle and number of blades of 29° and 6, respectively. The results showed the best goodness of fit between experimental and predicted values. Thus, the present study could be used to scale up of industrial wind turbine power plant.

CONFLICT OF INTERESTS

The authors declare no conflict of interests.

REFERENCES:

[1] Rediske, G., Burin, H. P., Rigo, P. D., Rosa, C. B., Michels, L., & Siluk, J. C. M. (2021). Wind power plant site selection: A systematic review. Renewable and Sustainable Energy Reviews, 148, 111293.
[2] Caneppele, S., Riccardi, M., & Standridge, P. (2013). Green energy and black economy: Mafia investments in the wind power sector in Italy. Crime, law and social change, 59, 319-339.
[3] Chaudhuri, A., Datta, R., Kumar, M. P., Davim, J. P., & Pramanik, S. (2022). Energy conversion strategies for wind energy system: Electrical, mechanical and material aspects. Materials, 15(3), 1232.
[4] Mittal, R., Sandhu, K. S., & Jain, D. K. (2010). An overview of some important issues related to wind energy conversion system (WECS). International Journal of Environmental science and development, 1(4), 351.
[5] Jaber, S. (2013). Environmental impacts of wind energy. Journal of Clean Energy Technologies, 1(3), 251-254.
[6] Wiedmann, T. O., Suh, S., Feng, K., Lenzen, M., Acquaye, A., Scott, K., & Barrett, J. R. (2011). Application of hybrid life cycle approaches to emerging energy technologies–the case of wind power in the UK. Environmental science & technology, 45(13), 5900-5907.
[7] Bergström, L., Kautsky, L., Malm, T., Rosenberg, R., Wahlberg, M., Capetillo, N. Å., & Wilhelmsson, D. (2014). Effects of offshore wind farms on marine wildlife—a generalized impact assessment. Environmental Research Letters, 9(3), 034012.
[8] Pasqualetti, M. J. (2011). Opposing wind energy landscapes: a search for common cause. Annals of the Association of American Geographers, 101(4), 907-917.
[9] Knudsen, T., Bak, T., & Svenstrup, M. (2015). Survey of wind farm control—power and fatigue optimization. Wind Energy, 18(8), 1333-1351.
[10] Atwa, Y. M., & El-Saadany, E. F. (2010). Optimal allocation of ESS in distribution systems with a high penetration of wind energy. IEEE Transactions on Power Systems, 25(4), 1815-1822.
[11] Prabhu, S. V., Wilson, V. H., Anand, K. T., Jose, S., Sivamani, S., Gomadurai, C., & Kifetew, M. (2022). Water Absorption Behavior of Teff (Eragrostis tef) Straw Fiber-Reinforced Epoxy Composite: RSM-Based Statistical Modeling and Kinetic Analysis. Advances in Polymer Technology, 2022.
[12] Govindarajan, D. K., Viswalingam, N., Meganathan, Y., Devaraj, B. S., Sivamani, S., & Sivarajasekar, N. (2022, November). Response surface methodology optimization for extraction of pectin from waste rinds of Citrus medica. In AIP Conference Proceedings (Vol. 2446, No. 1, p. 020013). AIP Publishing LLC.
[13] Sivarajasekar, N., Pradeepika, T., Sivapriya, S., Gayathri, V., & Sivamani, S. (2020, November). Optimization of copper (II) biosorption onto waste Gossypium hirsutum seed microwave-biochar using RSM. In AIP Conference Proceedings (Vol. 2270, No. 1, p. 020007). AIP Publishing LLC.
[14] Pachiyappan, J., Nirmala, G., Sivamani, S., Govindasamy, R., Thiruvengadam, M., Derkho, M., ... & Gribkova, V. (2022). Biogenic Synthesis, Characterization, and Photocatalytic Evaluation of Pristine and Graphene-Loaded Zn50Mg50O Nanocomposites for Organic Dyes Removal. Nanomaterials, 12(16), 2809.
[15] Udayakumar, M., Sivaganesan, S., & Sivamani, S. (2022). Process optimization of KOH catalyzed biodiesel production from crude sunflower-mahua oil. Biofuels, 13(8), 1031-1039.
[16] Global Wind Energy Council, GWEC-2023_interactive.pdf
[17] C. Balakrishna Moorthy & M.K. Deshmukh, "A new approach to optimize placement of wind turbines using particle swarm optimization ", International Journal of Sustainable Energy, Taylor and Francis publications, Vol.34, No.6, page 396-405, 2015.
[18] C.Balakrishna Moorthy & M.K. Deshmukh "Wind Resource Assessment using Computer Simulation Tool: A Case study", Energy Procedia, Vol.100, pp. 141-148, 2016.
[19] Karthikeyan, N., Kalidasa Murugavel, K., Arun Kumar, S., & Rajakumar, S. (2015). Review of aerodynamic developments on small horizontal axis wind turbine blade. Renewable and Sustainable Energy Reviews, 42, 801–822.
[20] Wood, D., (2011) Small Wind turbines, Analysis, Design, and Applications. Green Energy and Technology, Springer.

[21] Selvaraju, S., Naveen Prasad, B. P. S., & Cuento, A. (2023). Box-Wilson design and analysis for extraction of gelatin from black kingfish skin. Research and Innovation in Food Science and Technology.
[22] Ren, Z., Li, W., Billinton, R., & Yan, W. (2015). Probabilistic power flow analysis based on the stochastic response surface method. IEEE Transactions on Power Systems, 31(3), 2307-2315.
[23] Ismail, M. F., & Vijayaraghavan, K. (2015). The effects of aerofoil profile modification on a vertical axis wind turbine performance. Energy, 80, 20-31.
[24] Li, Q., Maeda, T., Kamada, Y., Murata, J., Furukawa, K., & Yamamoto, M. (2015). Effect of number of blades on aerodynamic forces on a straight-bladed Vertical Axis Wind Turbine. Energy, 90, 784-795.
[25] Sivamani, S., Prasad, B. N., Nithya, K., Sivarajasekar, N., & Hosseini-Bandegharaei, A. (2022). Back-propagation neural network: Box–Behnken design modelling for optimization of copper adsorption on orange zest biochar. International Journal of Environmental Science and Technology, 19(5), 4321-4336.