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Simulation of an Offshore Wind Turbine Using QBlade and MATLAB

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ABSTRACT

There is an energy crisis throughout the world. Renewable energy sources can play a significant role in mitigating energy crisis. So, it is necessary to have comprehensive ideas of renewable energy sources to design and optimize renewable energy systems effectively. For a country like Bangladesh with limited land and a long, uninterrupted coastline, offshore wind turbines could provide a highly advantageous solution to meet its power needs. In this study wind resource analysis for offshore location has been performed using Python. Based on wind data, a wind turbine is designed, and numerical analysis have been performed using QBlade and MATLAB Simulink. The Blade Element Momentum (BEM) theory has been employed to analyze different aerodynamic characteristics such as power coefficient (C_p), thrust coefficient (C_t), etc. The results are plotted against tip speed ratio (TSR) and tabulated in tabular form. The aerodynamic power output of the model turbine is found as 738 kw and 629 kw respectively from QBlade and MATLAB Simulink simulation.

Keywords: Offshore Wind Turbine; Numerical simulation; QBlade, MATLAB Simulink

1. Introduction

The growing demand for renewable energy sources has strengthened the research and development of offshore wind energy systems. Offshore wind turbines (OWTs), with their capacity to harness wind resources far from shore, present a promising opportunity for sustainable energy production. Table 1 shows the global offshore energy capacity from 2016 to 2023.

Table 1 Global offshore wind capacity from 2016-2023 [1].

Year	Capacity (GW)
2016	14.36
2017	18.84
2018	23.59
2019	28.29
2020	34.37
2021	54.26
2022	61.97
2023	72.66

The expected capacity of a single offshore wind turbine production is to be 17 MW while a single onshore wind turbine is to be 5.5 MW by 2035. Bangladesh is an overpopulated country with huge energy demand. The power sector of this country is mainly dependent on non-renewable energy sources. Figure 1 represents electricity generation in Bangladesh from different non-renewable energy sources in 2021-2022. From the figure it is seen that most of the electricity is generated using natural gas (55.1%) which is alarming. Besides, significant portion of electricity is generated using furnace oil and coal.

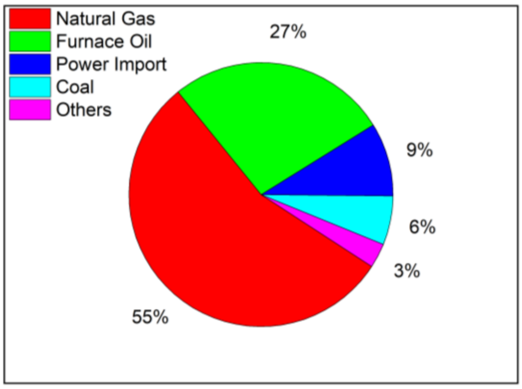


Fig. 1 Illustration of electricity generation sources of Bangladesh in 2021-2022 [2].

Marine Renewable Energy is a potential candidate to accomplish the energy demand of Bangladesh. By 2030, the Sustainable and Renewable Energy Development Authority (SREDA) has targeted generating 5GW of onshore and offshore renewable power sources [3]. Unfortunately, the present renewable energy capacity is less than 4% of the total electricity requirement in 2022. However, the design and optimization of OWTs imposes significant challenges due to the complex interplay of aerodynamic, hydrodynamic, and structural factors. Numerical simulation has emerged as a vital tool for engineers and researchers to analyze and predict the performance of OWTs under various environmental conditions. This paper focuses on the numerical simulation of an offshore wind turbine utilizing QBlade and MATLAB, two powerful tools that facilitate advanced computational modeling and analysis.

The topic of offshore wind energy has gained academic attention in recent years, reflecting its importance in the renewable energy sector. Several studies have employed Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) to understand the performance and structural integrity of offshore wind turbines. Several researchers have explored the aerodynamics of Horizontal Axis Wind Turbines (HAWTs) using CFD simulations to gain insights into performance enhancements through rotor shape optimization [4, 5, 6]. This research underscores the significance of accurate aerodynamic modeling, which is integral to simulating wind turbine performance. QBlade, an open-source software designed for the aerodynamic analysis of wind turbines, has gained popularity among researchers due to its user-friendly interface and powerful algorithms [7]. Several studies have successfully employed QBlade for the design and analysis of both onshore and offshore turbines. For instance, Alaskari et al. [8] demonstrated the efficacy of QBlade in optimized rotor design, providing a benchmark for performance evaluation in various wind conditions. Their findings highlighted the software's capability to facilitate cost-effective and efficient turbine designs. MATLAB also plays a crucial role in the simulation and modeling of offshore wind energy systems. By providing a flexible programming environment, MATLAB enables researchers to implement complex mathematical models and simulations [9]. Moreover, the integration of QBlade and MATLAB presents a unique opportunity for comprehensive analysis. Overall, the numerical simulation of offshore wind turbines using QBlade and MATLAB signifies a vital step towards optimizing design and performance.

2. Methodology

In this study, the QBlade BEM module is used to run the simulations of the model turbine in QBlade. Empirical wind turbine modelling is implemented to run the simulation in MATLAB Simulink. Figure 2 illustrates the flow chart of the adopted methodology for this study.

2.1 Mathematical Modelling

Blade Element Momentum (BEM) Theory

To solve the problem in QBlade BEM theory is applied. BEM theory was developed by Glauert. Blade element theory relies on airfoil aerodynamic characteristics, and momentum theory, treats the blade as multiple independent stream tubes while disregarding spanwise flow Manwell et al., [10]. Equations 1 and 2 describes the momentum theory for each stream tube, predicated on the conservation of momentum in both axial and rotational directions.

$$dT = \rho U^2 4a(1-a)\pi r dr \quad (1)$$

$$dQ = 4a'(1-a)\rho U \pi r^3 \omega dr \quad (2)$$

where dT and dQ are the differential thrust force and torque, r is the radius of the stream tube (or blade element), and ω is the angular velocity of the wind turbine rotor.

Equations 3 and 4 outline the aerodynamic normal force, equivalent to the thrust force in Equation 1, and the torque of the blade element, corresponding to the torque in Equation 2. These equations are based on the known airfoil lift and drag coefficients, C_l and C_d, with an assumed induced relative wind velocity, U_{rel}, to the airfoil.

$$dF_n = 0.5B\rho U_{rel}{}^2(C_l \cos\varphi + C_d \sin\varphi)cdr \quad (3)$$

$$dF_n = 0.5B\rho U_{rel}{}^2(C_l \sin\varphi - C_d \cos\varphi)cdr \quad (4)$$

where B is the blade number, ρ is the air density, φ is the angle of relevant wind.

The integration of the blade element theory and momentum theory yields both axial and angular induction factors, denoted as a and a', respectively. These factors are subsequently employed in computing the induced relative wind velocity, U_{rel}, with respect to the airfoil. The calculated induced wind velocity is then used iteratively in the determination of blade element aerodynamic forces, with the process repeated until the newly computed induction factors, a and a', converge within an acceptable tolerance of their previous values.

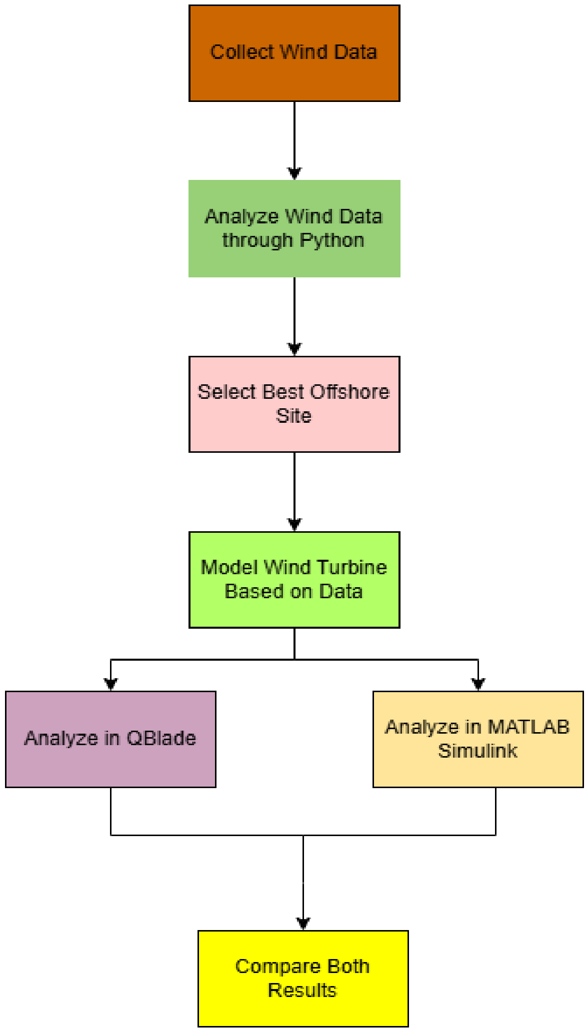


Fig. 2 Illustration of adopted methodology for the study.

Power generation

The formula for calculating the power generation (P) of a wind turbine is:

$$P = 0.5 \times \rho \times A \times C_p \times U^3 \quad (5)$$

P represents the power generated (W) by the wind turbine, ρ (rho) is the air density (kg/m^3) at the location of the wind turbine, A is the swept area (m^2) of the rotor blades, C_p is the power coefficient and U is the wind speed (m/s) at the location of the turbine.

Power Coefficient (C_p)

Power coefficient is one of the main performance indicators of a wind turbine. It is dimensionless and denoted as C_p. C_p is defined as the ratio of actual power output to the theoretical power of the wind.

$$C_p = \frac{P_{Rotor}}{P_{Wind}} = \frac{P_{Rotor}}{0.5\rho A U^3} \quad (6)$$

Thrust Coefficient (C_t)

Thrust Coefficient (C_t) is the ratio of thrust force acting on the rotor and the dynamic force of the wind flowing through the rotor area [10]. C_t can be expressed as-

$$C_t = \frac{T_{Rotor}}{F_{Dynamic}} = \frac{T_{Rotor}}{0.5\rho A U^2} \quad (7)$$

Torque Coefficient (C_m)

Torque Coefficient (C_m) is the ratio of actual rotor torque to the theoretical rotor torque. It is expressed as-

$$C_m = \frac{T_m}{T_{theoretical}} = \frac{T_m}{0.5\rho A U^2 R} \quad (8)$$

Where R is the radius of the wind turbine rotor.

Tip Speed Ratio (TSR)

Tip Speed Ratio (TSR) is the ratio of rotor tip speed to the wind speed. TSR can be represented as-

$$TSR = \lambda = \frac{\omega R}{U} \quad (9)$$

where U is the free stream wind velocity, R is the radius of the wind turbine rotor and ω is the rotational speed of the rotor.

Empirical Formula for Wind Turbine Modelling

Power, p extracted by a wind turbine can be expressed as [11]-

$$P = \frac{1}{2}\rho A C_p(\beta,\lambda)U^3 \quad (10)$$

Here, β is the pitch angle for the blades and λ is the tip speed ratio (TSR).

Power coefficient of a turbine can be determined by using the formula [11]:

$$C_p(\beta,\lambda) = c_1\left(\frac{c_2}{\lambda_I} - c_3\beta - c_4\beta^2 - c_5\right)e^{\frac{-c_6}{\lambda_I}} \quad (11)$$

Here c_1, c_2, c_3, c_4, c_5 and c_6 are turbine coefficients. The values of these coefficients are tabulated in Table 2. λ_I is the intermittent TSR. λ_I is related to λ and β as follows:

$$\frac{1}{\lambda_I} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (12)$$

Table 2 Values of turbine coefficients [11].

Turbine Coefficients	Values
c_1	0.5176
c_2	116
c_3	0.4
c_4	5
c_5	21
c_6	0.0068

3. Results and Discussion

For this study three offshore sites are primarily selected. The selected sites are 30 km, 50 km and 60 km off to the Inani, Cox's Bazar in the offshore region of Bay of Bengal. Wind data at 50 m height from the sea surface is collected for these sites from NASA's power project wind database (NASA Power Project, 2024). Collected data for the years 2012 to 2023 are analyzed using Python programming. The results of the analysis are tabulated in Table 3. Wind speed distribution with time for the selected location in the year 2023 is shown in Figure 3.

Table 3 Summary of wind data analysis using Python for different sites.

Site 1 (m/s)		Site 2 (m/s)		Site 3 (m/s)	
mean	4.726	mean	5.41	mean	5.414
std	1.937	std	2.452	std	2.482
min	0.78	min	0.99	min	0.81
25%	3.29	25%	3.62	25%	3.64
50%	4.44	50%	4.95	50%	4.95
75%	5.845	75%	6.78	75%	6.73
max	18.11	max	20.3	max	20.7

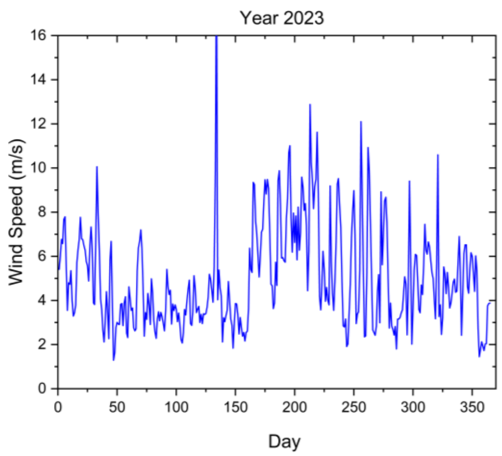


Fig. 3 Wind speed distribution of the selected location in 2023.

From Table 3 it is found that site 1 has relatively low wind speed than the other two sites. Though site 2 and 3 have the same mean wind speed but site 3 is 60 km away from the shore. On the other hand, site 2 is 50 km away from the shore. Besides, for both locations avg. value of 50% wind speed is also same (4.95 m/s). Based on these analysis site 2 is selected as it has relatively higher potential than the other two sites. For the selected site NREL 5 MW baseline wind turbine has been scaled down and modeled in QBlade.

A comparison of the generated model with the NREL 5 MW baseline turbine model is shown in Table 4.

Table 4 Comparison of the model turbine with NREL 5 MW baseline turbine.

Items	NREL 5 MW	Model Turbine
Number of Blades	3	3
Rotor Diameter (m)	126	75
Rotor Speed (rpm)	12.1	16.3
Hub Height (m)	90	50

The generated model turbine and its chord length and twist angle distributions are shown in Figure 4 and Table 5, respectively.

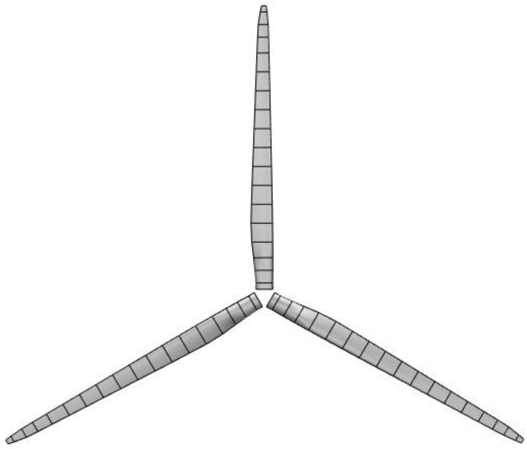


Fig. 4 Illustration of the generated model in QBlade.

Table 5 Chord length and twist angle distribution of the model.

Model Turbine		
Position (m)	**Chord (m)**	**Twist (deg)**
0.893	2.107	0
1.707	2.107	13.308
3.333	2.293	13.308
4.958	2.479	13.308
6.988	2.711	13.308
9.429	2.767	11.48
11.87	2.652	10.165
14.311	2.528	9.013
16.752	2.384	7.797
19.193	2.23	6.546
21.634	2.083	5.362
24.075	1.937	4.189
26.517	1.791	3.126
28.958	1.644	2.319
31.399	1.498	1.526
33.433	1.376	0.863
35.06	1.241	0.37
36.687	0.844	0.106
37.5	0.572	0

Coefficient of Performance (C_p) of a wind turbine measures its ability to convert kinetic energy into power. Figure 5 illustrates the Cp vs TSR graph for the model turbine. From the figure it is seen that for the model at optimum TSR (7.53), C_p is found to be 0.48. It is also observed that C_p is positive for model 1 even after 16 TSR. According to Betz limit the maximum C_p can be 0.593. So, the model turbine shows good performance as it has high value of C_p at optimum TSR.

The thrust coefficient (C_t) is a dimensionless parameter that quantifies the axial force exerted by the turbine relative to the incoming flow momentum. For wind turbines with a high-thrust coefficient, the turbulent wake occurs near the rotor, resulting in improved recovery. C_t essentially measures the efficiency of a wind turbine in converting the kinetic energy of the wind into mechanical energy. A higher Ct indicates a more efficient turbine, as it extracts a larger portion of the wind's energy. Figure 6 depicts comparison of C_t vs TSR for the model turbine. At optimum TSR C_t value is found to be 1.06 and the maximum value of C_t is found as 1.61.

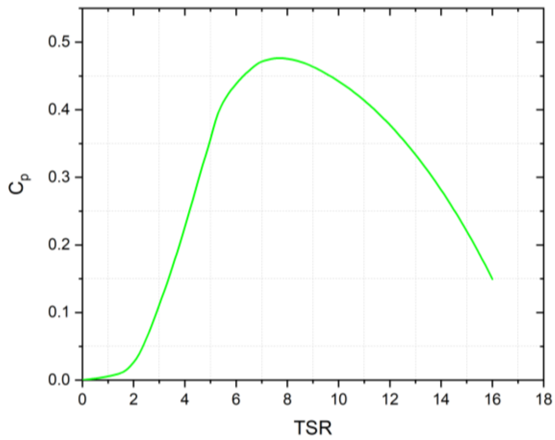


Fig. 5 Cp vs TSR graph for the model turbine.

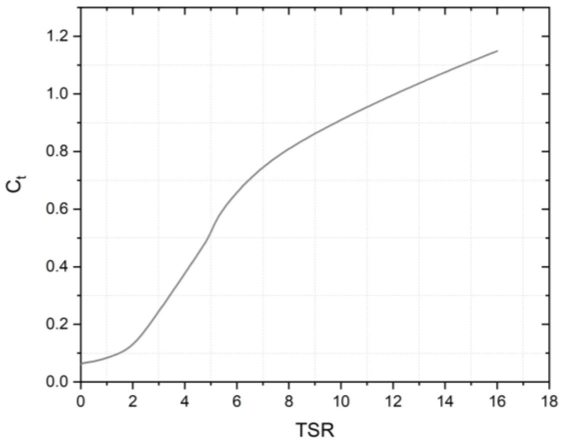


Fig. 6 Ct vs TSR graph for the model turbine.

Figure 7 shows a comparison of power vs TSR for the model turbine. It is seen that, for the model turbine maximum power is achieved at its optimum TSR. The maximum power for the model turbine is found to be 738 kw. Moreover, it is observed that the model turbine produces power even after 14 TSR.

Figure 8 illustrates comparison between C_p vs wind speed. For the model turbine C_p is negative till the wind speed 3.5 m/s. Which suggests that the cut in speed for the modeled turbine is 3.5 m/s. The maximum value of C_p for the model turbine is found to be 0.48 at its rated wind speed of 8.3 m/s.

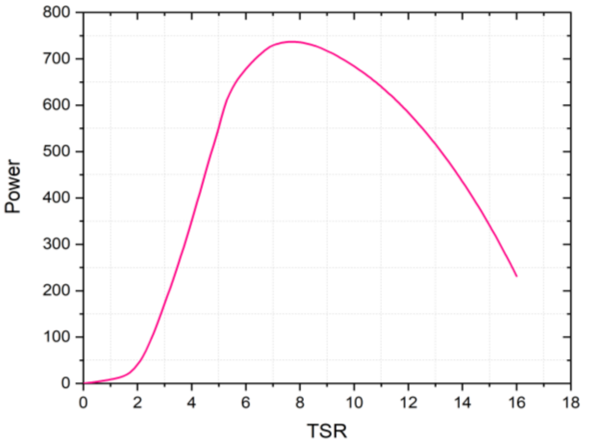


Fig. 7 Comparison of power vs TSR for the model turbine.

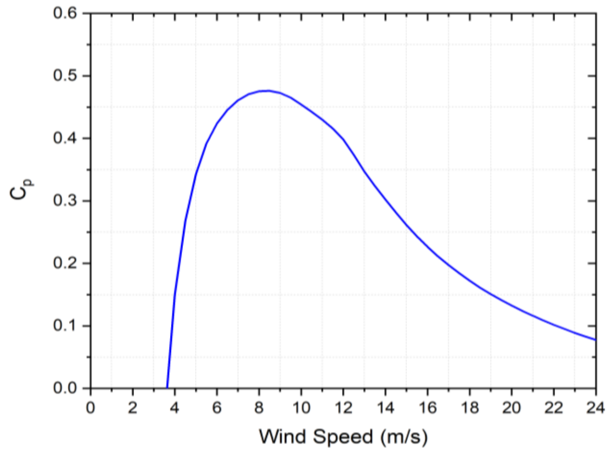
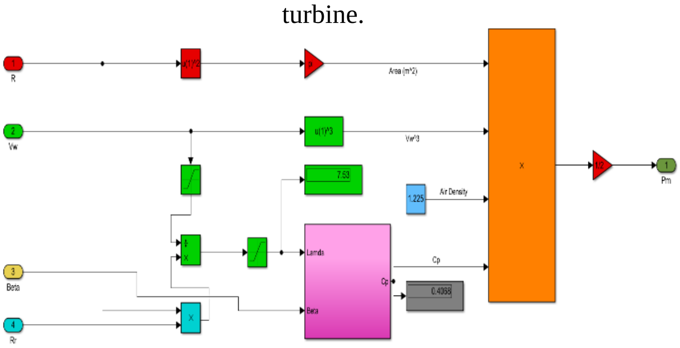
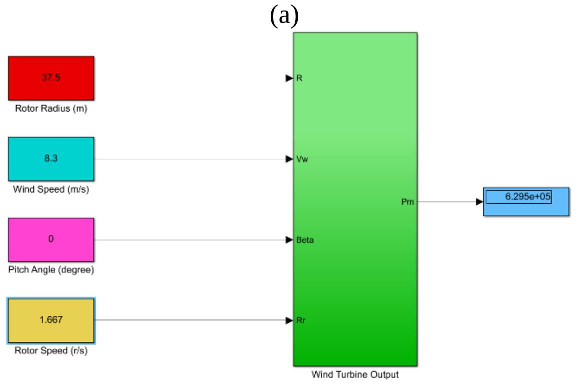


Fig. 8 Comparison of C_p vs wind speed for the model turbine.



(a)



(b)

Fig. 9 Illustration of (a) wind turbine modelling and (b) modeled wind turbine in MATLAB Simulink.

Figure 9 (a) shows the modelling of wind turbine in MATLAB Simulink. This modelling is done using empirical formulas of wind turbine modelling. Equations 10, 11 and 12 have been used to model the turbine in MATLAB Simulink. Figure 9 (b) illustrates the modeled wind turbine. It is seen from Figure 9 (b), that for knowing the value of the output power turbine rotor radius, wind speed, intermittent wind speed and turbine speed is given as input. From the MATLAB Simulink simulation it is found that the designed turbine can produce 629 kw of aerodynamic power having a Cp value of 0.4071. So, it is observed that power simulated from the MATLAB Simulink simulation is almost 14.7% less than power simulated using QBlade.

4. Conclusion

Offshore wind energy can be a potential candidate to accomplish the energy demand of Bangladesh. The development of the offshore wind energy sector is still limited due to the lack of reliable survey data, expertise and unattractive policies. This study analyzes wind speeds of three offshore locations using Python programming and selects a suitable site. BEM modelling and simulation of a model turbine suitable for the selected site has been done using QBlade. Moreover, the model turbine is modeled using empirical formulas and simulated in MATLAB Simulink. At optimum TSR C_t value is found as 1.06 and the maximum value of C_t is found as 1.61. It is found from the QBlade simulation that for selected location the model turbine can generate 738 kw of aerodynamic power having Cp value of 0.48. On the other hand, MATLAB Simulink shows the model turbine can generate 629 kw of aerodynamic power having a Cp value of 0.4071. The results obtained from this study will help to design and optimize small scale wind turbines at offshore locations of Bangladesh.

References

[1]https://www.statista.com/statistics/476327/global-capacity-of-offshore-wind-energy/ (Access 08-12-2024).
[2] BPDB, Annual Report 2021-2022 of Bangladesh Power Development Board (BPDB), *BPDB*, 2021.
[3]https://elibrary.sreda.gov.bd/public/admin/files/books_202104 281990004944.pdf (Access 08-12-2024).
[4] Siddiqui, M. S., Khalid, M. H., Badar, A. W., Saeed, M., & Asim, T., Parametric analysis using cfd to study the impact of geometric and numerical modeling on the performance of a small-scale horizontal axis wind turbine, *Energies*, 15(2), 505, 2022.
[5] Mezaal, N. A., Osintsev, K. V., & Alyukov, S. V., The computational fluid dynamics performance analysis of horizontal axis wind turbine, *Int. J. Power Electron. Drive Syst*, 10, 1072-1080, 2019.
[6] Nigam, P. K., Tenguria, N., & Pradhan, M. K., Analysis of horizontal axis wind turbine blade using CFD, *International Journal of Engineering, Science and Technology*, 9(2), 46-60, 2017.
[7] Marten, D., Wendler, J., Pechlivanoglou, G., Nayeri, C. N., & Paschereit, C. O., QBLADE: an open-source tool for design and simulation of horizontal and vertical axis wind turbines, *International Journal of Emerging Technology and Advanced Engineering*, 3(3), 264-269, 2013.
[8] Alaskari, M., Abdullah, O., & Majeed, M. H., Analysis of wind turbine using QBlade software, In *IOP conference series: materials science and engineering* Vol. 518, No. 3, p. 032020, 2019.

[9] Bhayo, M. A., Yatim, A. H. M., Khokhar, S., Aziz, M. J. A., & Idris, N. R. N. , Modeling of Wind Turbine Simulator for analysis of the wind energy conversion system using MATLAB/Simulink, *IEEE Conference on Energy Conversion (CENCON)* (pp. 122-127), IEEE, 2015.

[10] Manwell, J. F., McGowan, J. G., & Rogers, A. L., *Wind Energy Explained*, John Wiley & Sons, 2010.

[11] Soetedjo, A., Lomi, A., & Mulayanto, W. P., Modeling of wind energy system with MPPT control. *In Proceedings of the 2011 International Conference on Electrical Engineering and Informatics* (pp. 1-6), 2011.