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Abstract— **Renewable energy sources play an important role due to the increasing economic, social, and environmental issues caused by the use of fossil fuels. In this work, wind power can be considered as an effective renewable energy resource. The main objective of this research is to design a micro-scale Horizontal Axis Wind Turbine (HAWT) that may be mounted on rooftops or moving vehicles. The proposed wind turbine model was designed using Q blade software. The five-blade wind turbine was used for the design due to the increased efficiency, especially under low wind speed conditions. Then the wind turbine was validated under varied wind speed conditions. The derived optimum parameters for the five-blade wind turbine were 0.39 m blade length, 0.04 m hub radius, and 6 tip-speed ratio. The wind turbine has a 65W power output, with 0.45 of power coefficient at 6 m/s, wind speed.**

Keywords- Five Bladed; HAWT; Renewable Energy; wind energy

I. INTRODUCTION

Renewable energy sources include solar energy, wind energy, falling energy, geothermal energy, ocean currents, biomass energy, Etc. Among them wind energy is one of the best achievable energy sources. Overall, using wind to produce energy has fewer effects on the environment than many other energy sources. Wind turbines do not release emissions that can pollute the air or water and do not require water for cooling. In the other side, wind power is cost effective, land-based utility scaled lowest priced energy source available today[1]. Many countries around the world have already invested a lot of money into large wind farms in the countryside, at sea, in the mountains, or at the beach.

Since wind speed and direction are stable, it is easy to predict how much energy wind farms will produce. But in cities having skyscrapers, apartment complexes, can easily push the wind in different directions or change it. So, micro wind turbines are used to solve these problems [2]. Micro wind turbines can also be used as alternative sources of energy in locomotives, small moving vehicles or can be mounted on any flat surfaces to capture wind energy.

In order to obtain the maximum energy from wind turbine, its efficiency has to be improved. During the last few years, many methods and techniques were developed by researchers to enhance the efficiency (performance), based on the accurate analysis and optimization of the design parameters of the wind turbine blades [3].

Blade Element Momentum theory (BEM) is one of the important methods is used to simulate the wind turbine blade and improve its performance [4]. In order to optimize blade number and selection of tip speed ratio corresponding to the solidity, a small wind turbine blade was designed and optimized [5]. BEM simulation was done using multiple parameters in Q Blade software. Finally the Power Coefficient (C_P) graphs were plotted against tip speed ratio to test the whole range of wind speeds and select the most suitable condition.

II. LITERATURE REVIEW

A. Number of blades of wind turbine

The power that wind turbine gets from the wind is directly related to the area of the blades that are swept by the wind. This means that the blades have a direct effect on how much power is made. The more blades a wind turbine has, the more torque (the force that makes it turn) [7], [8] and the slower it turns because it has to work harder against the wind flow [6]. That is why, most of the time, turbines that make electricity have to run at high speeds and do not need much torque. So, a smaller number of blades leads to more power being made [9]. Most wind turbines with a horizontal axis have three blades. The decision to make turbines with three blades was a middle ground. A design with one blade is the most efficient because it has the least amount of drag. But a single blade throws off the balance and is not useful [10]. And also, two-blade wind turbines have an unbalanced torsional force acting at the center (and supporting pole) of the blade.

B. Different analysis on wind turbine blade

Ahmad Sedaghat et al. [11] found that the flow of wind is different in different places. This paper looks at the aerodynamic performance of a wind turbine blade when the speed is constantly changing. A compact BEM analysis was used to find the best design for horizontal axis wind turbine blades with speeds that change continuously. They also figured out the values of the power coefficient for the best blade geometry at different ratios of tip speed to lift and drag to lift at different speeds. The paper also concluded the power performance of a wind turbine with variable speed is better than that of a wind turbine with a constant speed.

Sabbah Ataye et al. [12] say that a wind turbine blade is composed of various parts, such as the leading edge, the trailing edge, the spar, and so on. With the help of a real model, this paper looks at the overall damage to the edge of a wind turbine blade. The paper study is based entirely on visual scanning of the trailing edges of 81 blades with 100 KW and 18 blades with 300 KW.

C.P. Chen et al. [13] say that the speed of the wind is an important factor that helps turbines work better. But sometimes a wind speed that is faster than what is needed causes failure. In this paper, a theoretical and experimental approach is used to study the behavior of small composite sandwich turbine blades when they are subjected to very high wind loads. The study will look at the strength of two types of composite sandwich wind blades that are 1 m and 2.5 m long.

C. Different types of wind turbine system

Previous studies have been done on how the design of different types of wind turbine systems affects the budget. One of these types of research is a case study that looks at the business analysis of an already installed system [14]. For a home in Ireland, the system has a rated capacity of 10 kW and a maximum rated output capacity of 12 kW. It has 3 blades. Three-phase power is used to power the house. The generator is a three-phase, three-pole, synchronous generator with a permanent magnet. It is expected that the technical performances will be. The study was done using the expected value for the wind turbine performance, which is between 900 and 2,100 kWh per month. In the study, the estimated wind speed is given as 11 m/s. The wind speed cut-in was 2.2 m/s and the wind speed cut-out was 30 m/s. The rotor of the turbine is 3m in diameter. The speed range of the rotor is from 0 to 260 rpm. The information needed for this research conclusions was gathered over the course of 3 years. The way the above research was done was by going to the sites to get the numbers from the electrical equipment and then getting the utility bills. The initial cost, the output power, the output energy, and the financial investment review are used to measure the performance.

Also, research based on mathematical modeling has been done on the outdoor performance of micro-scale type wind turbine systems. The study used a small module wind turbine that was already in use [15]. The wind turbine was controlled by data loggers and a controller. The above research, which includes an experiment to test the model, is looking at how well the existing stand-alone wind turbine works in terms of electricity. The data from the manufacturer was then compared to the results of the experiment. The study was based on the idea that the system would either be connected to an existing building that is already connected with grid to meet the energy needs, or it would generate and send power to an existing grid. In this study, the wind turbine has a horizontal axis and 3 blades. At the time that the study was done, the rated wind speed for the turbine was 12.5m/s. In this study, a high-performance 12V battery with a rate of 100A for 20 hours was used. The study found that consumers and designers of micro-wind turbines cannot use the manufacturer's data to get the expected amount of power.

Also, studies have been done to come up with a way of use the Blade Element momentum theory to model a small-scale wind turbine system easily [16]. In the study, an algorithmic program has been shown that changes the well-known blade element momentum theory. The study has also thought about how the wind turbine blades could be made using a technique called "additive manufacturing". The cost of making microscale wind turbine systems might go down if the additive manufacturing method is used. The BEM-based algorithm has been used to make an optimization strategy, which is then used to make the modeling process easier. The results show that the algorithm works well, but more testing and validations are needed before optimization techniques can be used to design small wind turbines.

Another study looks at the pros and cons of small-scale wind turbines from a business and legal point of view, while this research focuses on the technical aspects. Researchers have already done studies on how to improve wind capture in places with low wind speeds and how to make a micro-scale wind generator for use in homes. One example of this kind of study was done by two UK universities and a company. It looked at how to do an aerodynamics-based study on a smaller scale wind turbine system by using a wind tunnel for a physical test and the CFD approach for validation. The proposed wind turbine system has a new scoop section built into it. The results of this study shows that a wind turbine with a scoop can make more power than one without a scoop [17].

III. METHODOLOGY

A. Determine the number of blades for maximum efficiency

The number of blades on a turbine is a crucial factor that impacts its overall performance, including its speed and efficiency.

Compared to three-blade wind turbines, five-blade wind turbines have a much better annual performance in places where the average wind speed is 5 m/s and there is not much wind. The annual output of a five-blade wind turbine can be more than 60% higher than that of a traditional three-blade turbine. The speed of a five-blade turbine blades is 60% of that of a three-blade turbine. Wind turbines with five blades are much less likely to break down at high speeds. Five-blade wind turbines make it much less likely that the over-speed control will fail. This makes sure that things will work well in the long run. The five-blade wind turbine has slower blades than the three-blade wind turbine, which makes it quieter.

In the end, having fewer blades makes the flow go faster, while having more blades makes the torque go up. Designs in the middle of these two extremes make the most power. For optimizing the number of blades, it not important to look at how well the wind turbine works, how much it costs depending on how many blades it has, how heavy the blades are, and how physical, geometric, and aerodynamic the blade design can be. It is also important to have the right number of blades to make sure that performance curve of the turbine is the best it can be for overall performance and efficiency [9].

B. Determine the best shape and airfoils selection

Multiple airfoils were utilized to alter the thickness of the blade and improve the performance of the design. SG 6040, SG 6042, and SG 6043 were considered when designing with Q Blade. Flat back airfoils (SG 6040) are utilized in the inboard region while thick airfoils (SG 6042) are used in the mid span region for greater bending stiffness and strength than sharp trailing edge (TE) airfoils (SG 6043). For more efficient utilization of materials against external bending loads, spar cap thickness is stepped transversely [18].

C. Determine the blade length

The length of wind turbine blades is mainly determined by the wind conditions in the wind turbine installation area. The blade length will depend on the size of the wind turbine, wind speed in the installation area, and other factors such as local regulations or restrictions. Longer blades can absorb more wind energy and produce power more quickly in windy environments. However, higher wind speeds will make the blades spin more quickly, which puts more strain on the shaft and bearings. This is why in some cases, it is important to design a thicker blade with a relatively high drag to prevent the blades from spinning too fast. In low wind areas, longer blades are not very common because less wind is available to generate electricity and are therefore less likely to be worth the investment [19]. This is why this blade design is too short.

D. Determine the parameter values related to the mathematical model

The four parameters considered were hub radius, angle of twist, position, and chord. For the consistency of the assembly, the twist of the blades was considered rather than the pitch [20]. As any changes in the parameter were made, the values were interpolated as shown in figure 1.

At first, blades with low twist angles were considered for this project because blades with lower twists suggested higher power coefficient values in Q Blade [20]. However, when

Blade Data

Blade 9

5 blades and 0.04 m hub radius ☑ Blade Root Coordinates

	Pos (m)	Chord (m)	Twist	Foil	Polar
1	0	0.025	41.855	Circular Foil	CD = 1.2 360 Polar
2	0.03	0.042	21.1081	SG6040	T1_Re1.000_M0.00_N...
3	0.07	0.033	15.5434	SG6042	T1_Re1.000_M0.00_N...
4	0.11	0.027	10.9355	SG6042	T1_Re1.000_M0.00_N...
5	0.15	0.023	8.18033	SG6043	T1_Re1.000_M0.00_N...
6	0.19	0.02	6.35533	SG6043	T1_Re1.000_M0.00_N...
7	0.23	0.018	5.05989	SG6043	T1_Re1.000_M0.00_N...
8	0.27	0.016	4.09364	SG6043	T1_Re1.000_M0.00_N...
9	0.31	0.014	3.34563	SG6043	T1_Re1.000_M0.00_N...
10	0.35	0.013	2.74962	SG6043	T1_Re1.000_M0.00_N...
11	0.39	0.012	2.26364	SG6043	T1_Re1.000_M0.00_N...

Figure 1: Q blade parameters

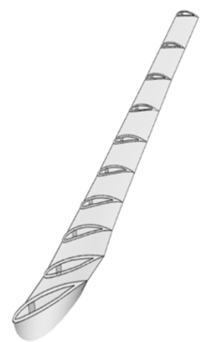

Figure 2: structural blade analysis

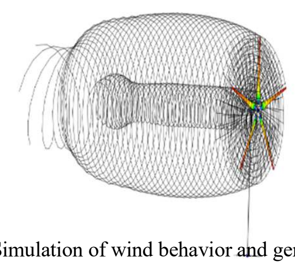

Figure 3: Simulation of wind behavior and generating power

tests were done with blades that had less twist, the rotor did not move. This can be explained by the shape of the blades: if there is not enough twist at the base of the blades, the rotor would not turn because there is not enough torque. As a result of that, the blades with a higher angle of twist were considered.

E. Blade structural analysis

This analysis is based on validation the strength of the blade and select the internal structure for the propeller blades [21]. Most suitable spar thickness and shell thickness was determined by using previous studies. (Figure 2)

F. Simulation on wind flow behavior

Non-linear lifting line simulation was done as shown in figure 3. It simulate the behavior of the wind mesh through the wind turbine. The wind is rotating regularly that can be prove the safety and success of the wind blade. The wind turbine will generate 65 W power even though it is in low wind speeds (6m/s).

IV. RESULTS AND DISCUSSION

The final design of the blade, which has different cross-sections from the root to the tip, was based on the BEM theory. Also, the BEM theory was used to combine three suitable airfoils into one to create the new airfoil perform better. Figure 4 shows the components of the SG 6040, SG 6042, and SG 6043 circular airfoils that are used in the final blade design.

The rotor BEM simulation was utilized to determine the wind turbine output power by varying the wind speed of the Tip Speed Ratio (TSR) from 3m/s to 7m/s. The findings of Figure 5 indicate the maximum TSR value at a wind speed of 6 m/s and the determinant factors for TSR, such as wind speed and rotor rotation. As the turbine rotation increases, the resulting TSR also increases, as illustrated in Figure 5. Based on the wind speed tests, the maximum TSR value with a five-bladed turbine at a wind speed of 6 m/s is equivalent to TSR 6, with an output power value of 65 W. It can be seen that the overall value of the maximum power coefficient on the selected blade is 0.45.

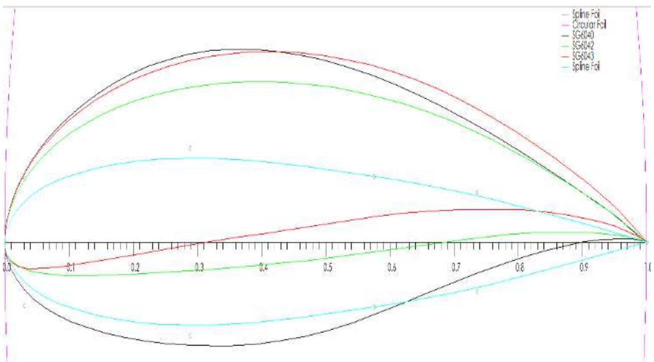

Figure 4: The sections of the airfoils circular foil, SG 6040, SG 6042 and, SG 6043

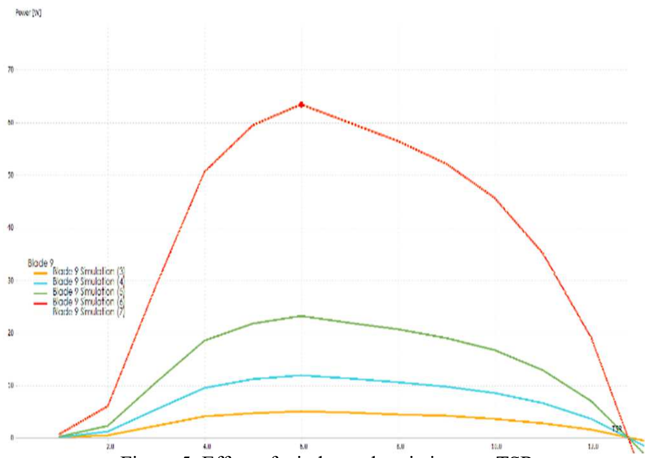

Figure 5: Effect of wind speed variations on TSR

The force that moves a wind turbine is called "lift force." The lift force will be perpendicular to the apparent velocity, and it will usually increase with the angle of attack (AoA). Along with the lift force, an undesirable drag force also increases. This drag force can never be completely removed, so it must be kept to a minimum. The best performance a wind turbine can give is at an angle called the optimum attack angle.

At this angle, the lift to drag ratio is at its highest. In this work, the used airfoils were looked at to find the CL/CD versus the Angle of Attack using Q blade software. It was noticed that the interpolated airfoil had a higher CL/CD at different Reynolds numbers with the range of Angle of Attack.

With an angle of attack of less than 4.2 degrees and a Reynolds number of 100,000, the interpolated airfoil had a higher CL/CD ratio than SG 6040, SG 6042 and SG 6043. Also, when the Reynolds number is set to 75,000, the interpolated airfoil had a higher CL/CD ratio for all angles of attack. When the wind speed is low and the highest possible Reynolds number is chosen, the CL/CD ratio is higher. So, the Reynolds number was set to 100,000 during the simulation, and it was found that an interpolated blade between the profiles SG 6040, SG 6042 and SG 6043 meets all the criteria in terms of a high CL/CD ratio at low Reynolds numbers and gives relatively high performance given the limitations.

In order to get the most power out of the turbine, the blade length was set to 0.39 m during the optimization process. This was done because 0.39 m was the maximum length allowed in the proposed study. The values of these parameters will be used to make the blade using the Q blade. The Q blade was used to make the blade even smoother where it changed from one airfoil to another, as shown in Figure 6.

This blade is thought to be the final design. After improving the design of the final blade using the Q blade and the BEM simulation, the CP of the blade went up to almost 0.45, which is pretty high considering the size and speed of the wind.

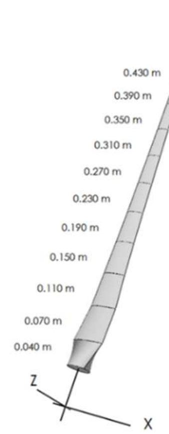

Figure 6: Resultant blade with Airfoil sections along the length of the blade

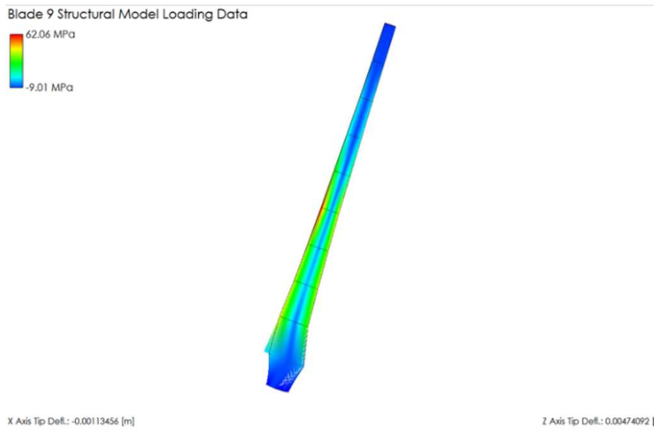

Figure 7: Stress analysis of the blade

At the same tip speed ratio (λ), increasing the rotor diameter (D) has a small effect on the CP value. On the other hand, if the length of the rotor blade is longer than 0.39 m, increasing the tip speed ratio will lead to an increase in CP for the same rotor diameter. The results showed that CP goes up in the same way that rotor diameter goes up. Since the design was based on an ideal average wind speed of 6 m/s, this is where the maximum CP of 0.45 was found. When the speed of the wind is different from what was planned, the CP usually goes down.

The mass of the blade depends on how thick the spar cap is, which can be made as thin as possible at different cross-sections to fulfill the level of strain that is allowed. Also, the choice of material for the shell and the material inside of the blade has a big effect on how heavy the blade is. The thickness of the shell layer and the inner layer was 9% of the local chord length of the blade section.

In order to find out how well the designed blade works, a stress-analysis simulation could be run using Q Blade to show the stresses on the blade that are caused by the loads that the wind puts on it when the wind turbine is running. It was important to know the internal structure of the blade, as well as the material of the shell and the material inside. The software was used to figure 7 out how much the blade weighed. The results of the stress analysis are depicted in figure 7.

Validation of modeling and simulation of the blade using the Q blade program. When developing wind turbine blades, important elements such as blade twist angle, blade chord, aerodynamic qualities, and power and load curves were taken into account.

The mathematical formulations utilized were based on the Blade Element Momentum technique (BEM). As the number of blades grows, the slipstream impact also increases. To improve the total performance and efficiency of a turbine, it is crucial to match the generator performance curve with the optimum number of blades. The behavior of the rotating blades was examined from a different perspective, focusing on the stress and vibration assessments of the rotating blades under different working situations.

CONCLUSION

The purpose of this work is to develop a horizontal-axis wind turbine blade profile to achieve higher power coefficient with relatively lower Reynolds' number. The design of the blade was achieved using BEM theory, and optimization was done using the Q Blade software. The results indicate that the selections of blade profiles should be based on the interpolated airfoils that are produced from the SG6040, SG6042 and SG6043 airfoils. The resultant turbine parameters were found to be having five blades, with 0.39 m blade length, 0.04 m hub radius, and 6.0 tip-speed ratio. The turbine can produce approximately 65 watts of power with a power coefficient of 0.45 when the wind is blowing at 6m/s.

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