Design and Simulation of Small Wind Turbine Blades in Q-Blade

[1]Veeksha Rao Ponakala, [2]Dr G Anil Kumar
[1]PG Student, [2]Assistant Professor
School of Renewable Energy and Environment, Institute of Science and Technology, JNTUK, Kakinada, India

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Abstract- Electrical energy demand has been continuously increasing. Power generation using wind turbines is becoming viable solution as there is demand for cleaner energy sources. Wind power generators are usually located away from human dwellings for higher power generation. In any other case, turbines placed at lower altitudes, are subjected to low wind speeds and non optimal wind flow conditions. Vertical axis wind turbines (VAWTs) are more efficient than the horizontal axis wind turbines (HAWTs) for low wind speed applications because of their ability to capture wind flowing from any direction. Therefore, VAWT systems are more suitable for residential and urban applications as they are universally adaptable. Major limitation observed in VAWT is high drag and turbulent force produced by the blade. This paper presents the VAWT rotor blade design to overcome the limitations. By considering the parameters required for design of blade geometry, National Advisory Committee of Aeronautics (NACA) series 0016- 64 can be utilised for optimum aerodynamic performance. NACA 0018 airfoil is selected and analysed within the required range of Reynolds numbers and wind speeds in Q-Blade software. With the proper airfoil design optimal for low wind speed conditions, the turbine efficiency can be increased in addition to maximisation of the power produced.

Index Terms- VAWT, Rotor Blades, Airfoil, Lift Force, Drag Force, Q-Blade.

I. INTRODUCTION

With the growing energy requirements and global crisis of climate change, there is dire need for development of sustainable energy technologies. Over the decades, the energy generated from alternative sources has increased with concern regarding depletion of fossil fuels and their harmful effects on environment. According to REN21 Global Status Report 2017 [1], power generated from renewable energy sources has increased tremendously in 2016, with installed capacity of 921GW contributing to 30% of the world's power generation capacity. The increased energy production from renewable energy sources is driven by the reducing prices for renewable energy technologies (majorly, solar PV and wind power) and extensive research to reduce the capital investment for utilising renewable sources. Figure 1 shows global installed renewable energy capacities.

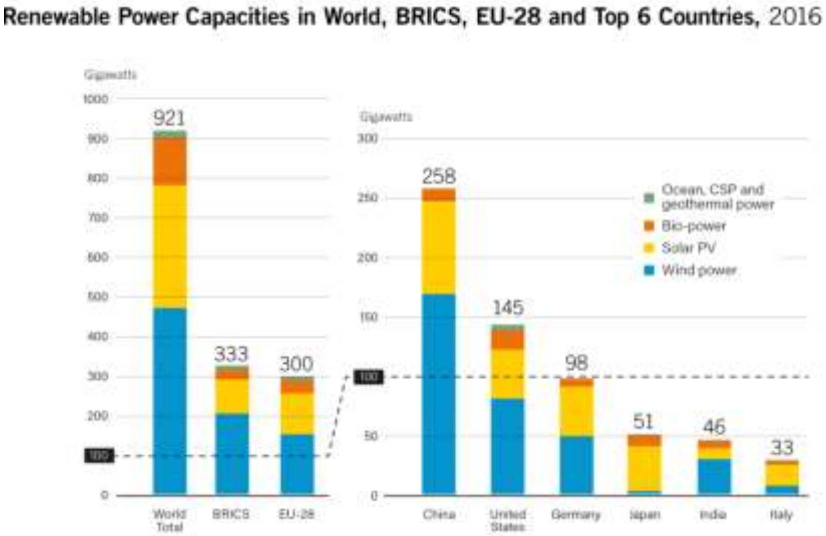


Figure 1: Global Installed Renewable Energy Capacities [Source: REN21 Global Status Report 2017]

With 55 GW of additional wind power generation in 2016, total installed wind power capacity is nearly 487GW, that accounts to approximately 53% of global renewable energy installed capacity. Wind power generation is a growing market that gives us sustainable and environment friendly solution to meet the current energy demands, as shown in Figure 2. Wind power is the most viable resource among the renewable sources because it's abundant, clean and does not have any direct harmful effects on the environment. Wind turbines are majorly used to extract power from the wind [2]. Output power of wind turbines is directly proportional to cube of wind velocity, so small changes in wind velocity result in significant increase in power generation.

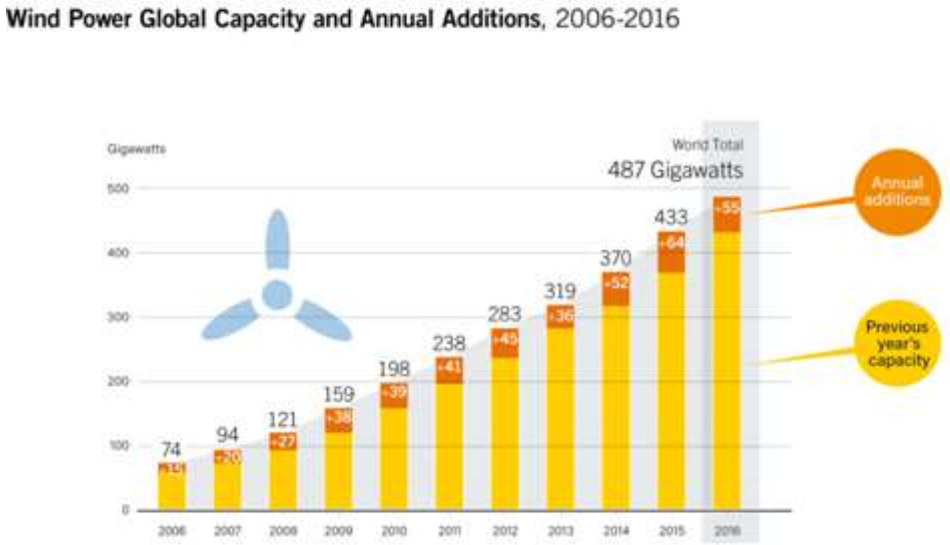


Figure 2: Global Wind Power Capacity, Annual Additions 2006-2016
[Source: REN21 Global Status Report 2017]

The present study is to develop an effective blade design for VAWT system. Parameters affecting the aerodynamic performance of rotor are studied and blade design is developed to extract maximum energy. Rotor blades are modelled using Q-Blade software. The results obtained show a significant improvement of performance of wind turbine at low wind speeds.

II. THEORETICAL BACKGROUND

This section will consider important theoretical aspects of wind turbine rotor design such as aerodynamics and factors affecting performance of wind turbines. Wind is established as a renewable resource which is sustainable and reliable for power generation. The factors governing the performance of small scale wind turbines are explained in detail [3].

A. Wind

Wind is movement of air current over the earth surface. Uneven heating of atmosphere by solar radiation results in differential pressure regions causing wind flow from high pressure region to low pressure region. Uneven heating is due to irregular earth surfaces and rotation of earth [4]. Density of air reduces when it is heated which lowers the pressure. Due to this, warm air rises above relatively cool air and results in pressure differences. The rotation of earth causes further turbulence and causes varying wind patterns with different wind speeds across the earth's surface. This flow of wind (kinetic energy) is captured by wind turbines to produce electricity. The kinetic energy of wind flow is converted to mechanical energy and then to electrical power by a generator. Kinetic energy carried by wind in its unperturbed state is given by,

$$P = \frac{1}{2}\rho A V^3 \qquad (1)$$

Where,

ρ = Air density

A = Rotor swept area
V = Wind velocity

There exists a physical limit to amount of energy that can be extracted from wind which is not dependent on the wind turbine design. The magnitude of energy extracted is dependent on the differential wind speed over the wind turbine. Higher the wind speed differential, higher is the quantity of energy harnessed. Ideally, zero final velocity would imply maximum conversion efficiency. The zero flow criteria cannot be achieved in dynamic conditions, therefore total kinetic energy may not be utilised.
This is mathematically explained by Betz theory and indicates that maximum turbine efficiency is 59.3% (coefficient of power, C_p = 0.593 referred to as Betz limit).

Betz theory is developed by assuming constant linear velocity over the turbine. Therefore, dynamic rotational forces such as turbulence, vortex shedding and wake rotation will further limit the maximum efficiency.
These losses can be minimised by:

- Selection of aerofoils of rotor blades with high lift to drag ratio.
- Avoiding low tip speed ratios (which result in wake rotation).
- Designing specific tip geometries.

B. Aerodynamics

Aerodynamic performance of rotor is a fundamental factor that governs the conversion efficiency [5]. As shown in the Figure 3, when rotor blades rotate, two forces acting on the blades are lift and drag force.

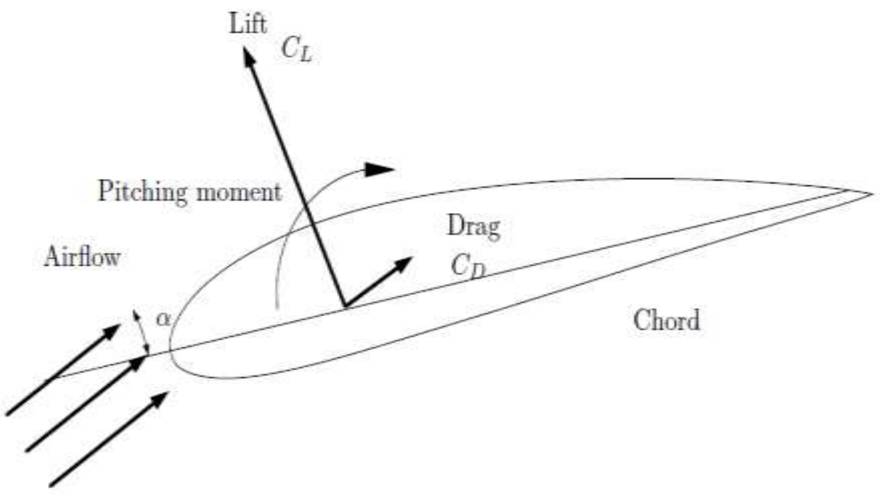


Figure 3: Aerodynamic properties of rotor blade
[Source: Fluid Dynamics Review, 2015]

Force acting perpendicular to direction of the wind as a consequence of differential pressure between upper and lower airfoil sections is defined as lift force (represented in Figure 3 by non-dimensional force coefficient C_l). The drag force acts along the direction of wind flow as the result of viscous friction force at the airfoil surfaces (represented in Figure 3 by non-dimensional force coefficient C_d). Angle of attack [α] of incident wind on the rotor blade increases with the drag force until the point of stall.

Turbine blades are shaped similar to airplane wing as same principles are utilised to convert wind flow to mechanical energy. Lift force is created as the wind takes longer to travel on the upper side of the rotor blade (due to the blade design) and hence travels faster to reach the end of the blade. As a result, a low pressure zone on the upper side of the blade is formed and blade is pulled in the downward direction creating movement which is known as lift. Airfoils of rotor blades are designed to utilize the advantages of this phenomenon.

Angle of attack, as shown in Figure 3, is the incident angle of the wind on the rotor blade or angle made by vector representing wind flow direction and chord line of the blade. When the angle of attack increases (beyond critical angle of attack around 15°), there is momentary reduction in the lift, which is defined as stall. Critical angle depends upon design of airfoil and Reynolds number.

Due to stalling, air rotates around the turbine blades in an irregular vortex causing turbulence as shown in Figure 4. This regime is characterized by constant and chaotic changes in the wind flow pattern. To avoid losses due to stalling, this phenomenon should be studied and taken into consideration while designing the wind turbine blades.

Major factors to be considered for development of aerofoil profiles are sensitivity of blades to soiling, thickness of cross sections and dynamic conditions such as stall. Modern materials can be used to design airfoils with thin cross sections and higher lift to drag ratios at the tip, thus increasing the efficiency. Further, higher lift coefficients in thin airfoil sections will reduce the chord lengths which in turn reduce the material usage.

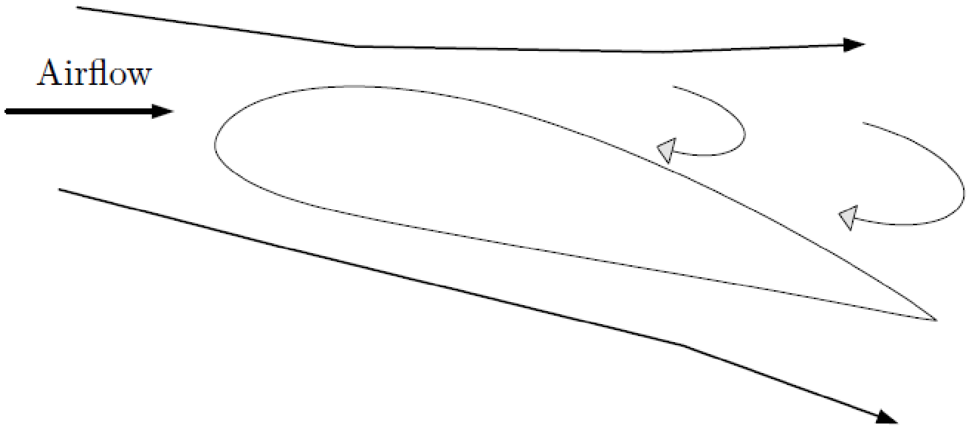


Figure 4: Concept of stall in aerodynamics
[Source: Fluid Dynamics Review, 2015]

C. Tip Speed Ratio

Tip Speed Ratio is defined as the relation between rotor blade angular velocity and relative wind velocity. This parameter is the most important factor while designing the rotor for maximum efficiency (other parameters are selected based on tip speed ratio).

$$\lambda = \frac{\omega R}{V} \tag{2}$$

Where;
λ = Tip Speed Ratio;

ω = Rotational velocity (rad.s^{-1});

R = Radius;
V = Wind speed.

Theoretically, for selecting optimum tip speed ratio aspects such as efficiency, torque, mechanical stress, aerodynamics and noise should be taken into consideration [6]. Turbine efficiency can be increased with selectively higher tip speed ratios (however, as the tip speeds increase, noise, aerodynamic and centrifugal stress increases). Table 1 give brief description of effect of tip speed ratio on performance parameters and design considerations.

Table 1: Tip Speed Ratio Design Considerations

Parameter	**Low Tip Speed Ratio**	**High Tip Speed Ratio**
Value	$1 < \lambda < 2$	$\lambda > 10$
Application	Conventional wind mills and water pumps	Single or two bladed prototypes
Torque	High	Low
Efficiency	Decreases significantly below 5 due to rotational wake created by high torque	Insignificant increase above 8
Aerodynamics	Simple	Complex
Aerodynamic Stress	Decreases	Increases in proportion with rotational velocity
Blade Profile	Large	Narrow
Area of Solidity	Increases, multiple blades required	Decreases significantly
Centrifugal Stress	Decreases	Increases with square of angular velocity

Higher tip speeds indicate reduced chord widths in turn leading to narrow blade profiles. This reduces the material usage and production costs. However, for high tip speeds centrifugal and aerodynamic stress increases. With increased forces the structural strength of the turbine reduces and results in failure of operation. Blades which are designed to operate at high tip speeds develop less torque at lower wind speeds and this result in higher cut in speeds and difficulties with self starting. Also, noise increases proportionately with sixth power.

For optimum design of energy conversion system, tip speed ratio of 9-10 for two bladed turbines and 6-8 for three bladed turbines are selected.

D. Airfoil Selection

With technological advancement, numerous types of airfoil shapes are available for development of blades for both conventional aviation and wind turbine technology. For wind energy systems, dedicated airfoils are designed. Shape of airfoils in small wind turbines is not as critical as in large wind turbines. However, airfoils used in small wind turbines should be operable even at low angle of attack where drag coefficient should be much lower than lift coefficient.

NACA series airfoils are used to design the blade geometry. NACA airfoil selected for designing the rotor blades of mini whirlwind turbine should have the following characteristics:

- High lift coefficient and low profile drag coefficient;
- Controlled stall characteristics;
- Optimum airfoil thickness;
- Negligible pitching moment coefficient;
- Ability to function at low Reynolds number wind condition;
- Stiffness at blade root section.

By considering the parameters required for design of blade geometry, NACA series 0016- 64 can be utilised for optimum aerodynamic performance [7]. This series of airfoils are practically tested within the required range of Reynolds numbers and surface conditions.

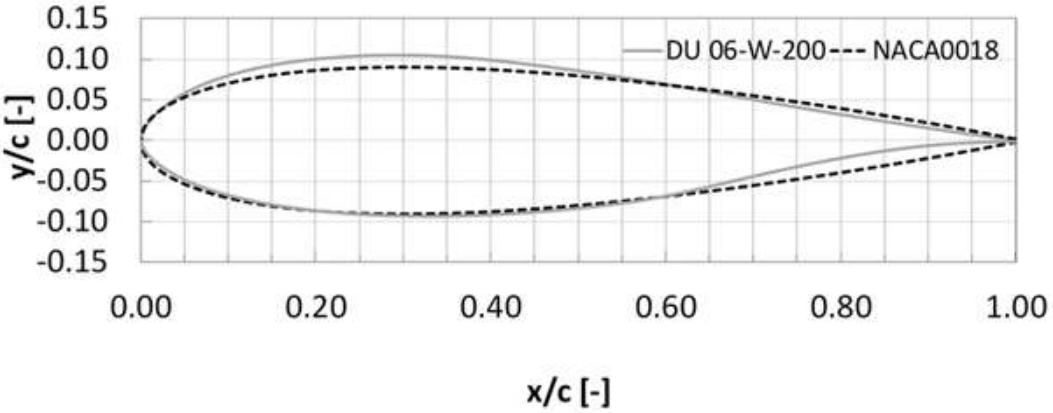


Figure 5: Coordinates and Shape of NACA 0018 Airfoil
[Source: NACA Airfoil Data]

From a test conducted at Pennsylvania State University low-speed and high-turbulence wind turbine model has maximum lift coefficient for the design Reynolds number of $0.4*10^6$, estimated to be 1.10 [8]. Further in this study, Q-Blade software is used to study the selected airfoil in the potential flow conditions.

E. Angle of Twist

The lift generated by an airfoil is a function of the angle of attack to the inflowing wind. The incoming angle of the air stream is dependent on the rotational speed and wind velocity at a specified rotor radius. The angle of twist required is dependent upon tip speed ratio and desired airfoil angle of attack. Generally the airfoil section at the hub is angled into the wind due to the high ratio of wind speed to blade radial velocity. The total angle of twist in a blade maybe reduced simplifying the blade shape to cut manufacturing costs. However, this may force aerofoils to operate at less than optimum angles of attack where lift to drag ratio is reduced.

III. ROTOR BLADE DESIGN IN Q-BLADE

A. Q-Blade Software

Q-Blade is open source wind turbine rotor blade calculation and design software. Q-Blade software allows us to define an air foil, compute its polar performance and directly integrates with the wind turbine rotor design and simulation [9].

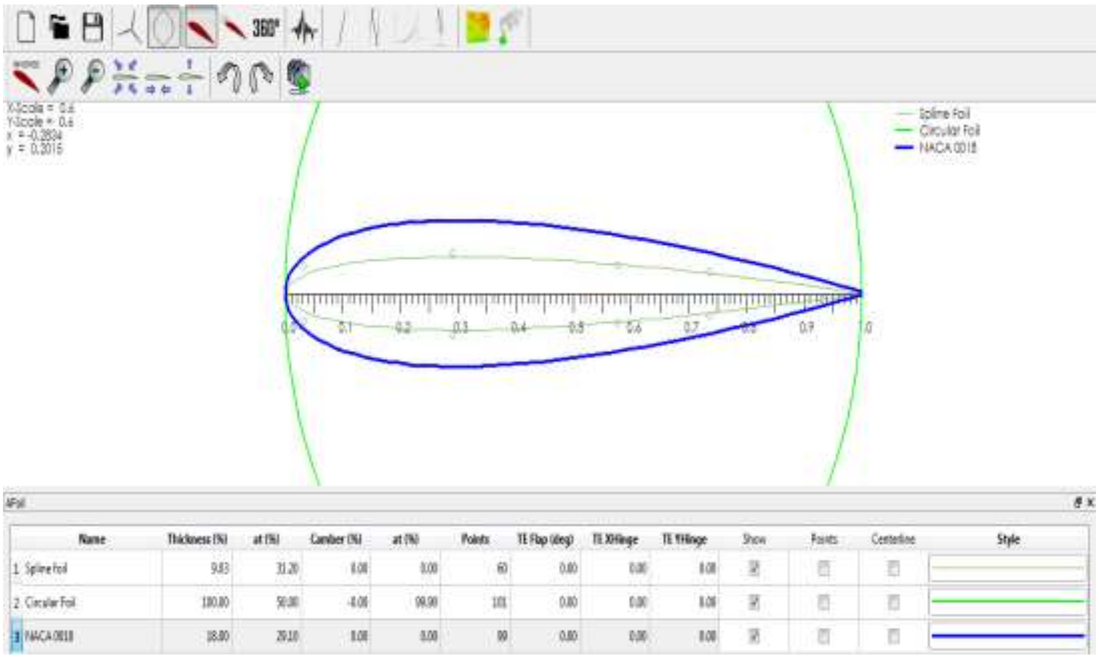
Q-Blade also gives deep insights into all the relevant rotor and blade variables with its post processing functionality. Software is very flexible and has user friendly interface for wind turbine rotor blade design.

Basic Functionality:

- Airfoil generator;
- Blade design and optimization;
- Defining BEM(Blade Element Momentum);
- Multi parameter rotor simulation;
- Visualization of rotor blades;
- Blade geometry export functionality;
- Testing of aero elastic code.

B. Airfoil Design in Q-Blade

- For the design, NACA 0018 airfoil is selected due to its surface pressure distribution characteristics [10].
- Airfoils are created using splines.
- Desired NACA airfoil can be imported using import function in Q-Blade.
- NACA airfoils geometries are inbuilt in the Q-blade software and additional airfoil data can be integrated by importing airfoil data file in '.dat' format.
- The scale and chamber of the airfoils can also be adjusted.
- NACA 0018 with less thickness is selected for the tip selection of the blade. Circular foils are also used at the tip of the blade so that the blade can be fixed in the hub.



Name	Thickness (%)	at (%)	Camber (%)	at (%)	Points	TE Flap (deg)	TE XHinge	TE YHinge	Show	Points	Centerline	Style
1 Spline Foil	9.83	31.20	0.00	0.00	60	0.00	0.00	0.00	☑	☐	☐	
2 Circular Foil	100.00	50.00	-0.00	99.90	101	0.00	0.00	0.00	☑	☐	☐	
3 NACA 0018	18.00	29.10	0.00	0.00	99	0.00	0.00	0.00	☑	☐	☐	

Figure 6: Airfoil Generation in Q-Blade

X-Foil analysis is performed on the airfoils and C_l and α graphs are obtained. This can be done by using XFOIL Direct Design button (second red button). Analysis can be defined for variable Reynolds number, angle of attack of the blade with the increment.

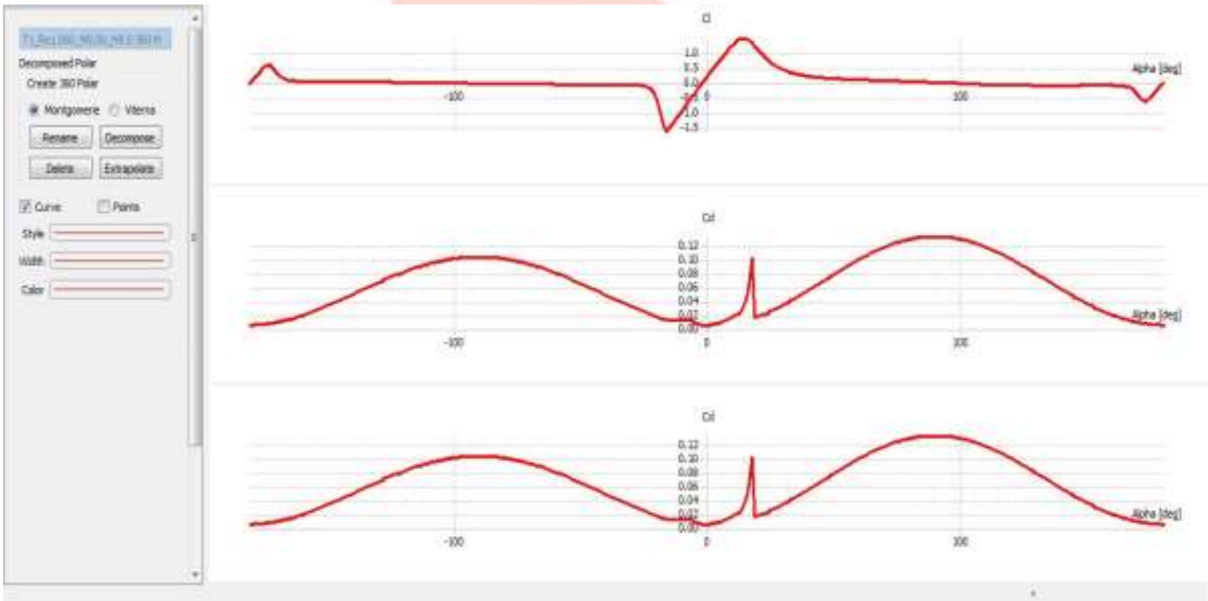


Figure 7: 360 Extrapolation Graph

The different airfoils are used to generate various lifts at given twist. To generate the maximum power they are placed at different positions and chords, as described in Table 2. The airfoils at the tip have less twist when compared to the airfoils from the root since they have to generate more lift. It is considered by the analysis in C_l and α graph. When the air flows on the airfoil, this twist is sufficient to lift the blade.

Table 2: Blade Specification Table

	Pos (m)	**Chord (m)**	**Twist**	**Foil**
1	0	0.2	24.74	Circular Foil
2	0.07	0.2	24.74	Circular Foil

3	0.125	0.53	24.74	NACA 0018
4	0.25	0.44	9	NACA 0018
5	0.5	0.32	5	NACA 0018
6	0.75	0.26	2	NACA 0018
7	1	0.15	0.6	NACA 0018

C. BEM Simulation in Q-Blade

Three rotor blades have same design and 3D rotor can be created from the single blade design. Further, power simulation is carried out on the rotor blades. Rotor BEM simulation is used with simulation parameters tip speed and Reynolds number. A rotor simulation can only be defined when any rotor blade is present in the runtime database. When defining a rotor simulation, the user has to select the desired corrections to the DMS algorithm and the simulation parameters [11]. Once a simulation is defined, the user can select a range of tip speed ratios and the incremental step for the simulation. Analysis is performed based on the obtained simulation graphs and blade design is varied for further modelling.

IV. RESULTS AND DISCUSSION

The obtained rotor model is simulated in Q-blade by multi-parameter BEM theory. Simulation is further carried out and the results obtained for power coefficient (C_p) and Power (P) are plotted as follows:

A. Power coefficient [C_p] Vs Tip Speed Ratio [λ]

Currently available commercial small wind turbines have coefficient of power in the range of 0.2 – 0.3. Significantly less than coefficient of power measured in large scale wind turbines which have high power generation capacity. Value of coefficient of power in wind turbines is mainly dependent on the rotor blade profile. NACA 0018 airfoil is used for rotor blade design. Blade profile can be further optimised to increase the power coefficient. Power coefficient is maximised to value 0.45 for tip speed ratios 4 to 7, as shown in Figure 8.

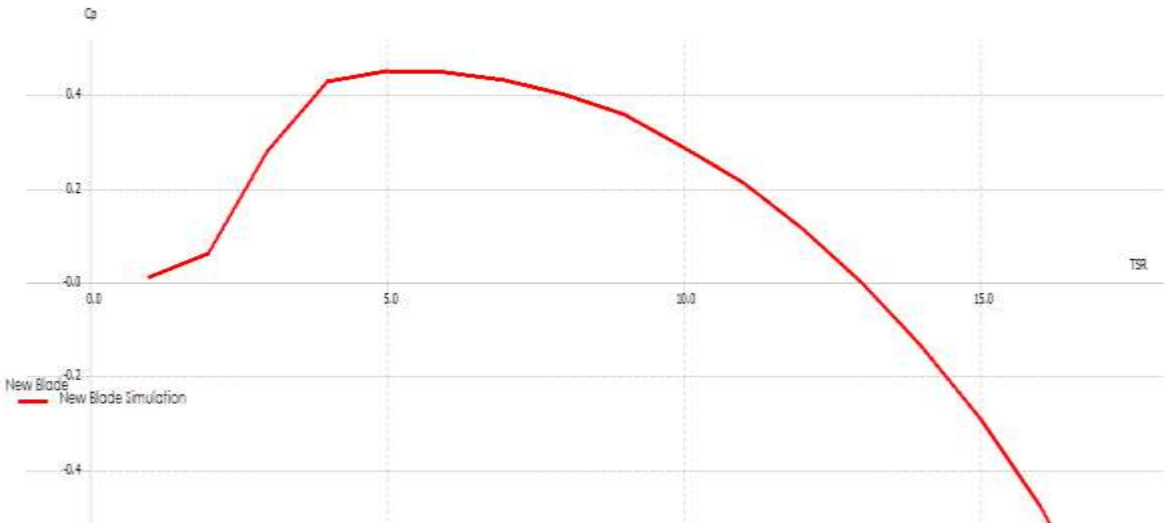


Figure 8: Power coefficient [C_p] Vs Tip Speed Ratio [λ]

B. Power [P] Vs Tip Speed Ratio [λ]

Rotor blades have optimal tip speed ratio designed, at which they will produce maximum power. Power generated by a wind turbine is proportional to the air mass lifted/ raised by the rotor blades in given time. An increase in tip speed ratio results in decrease in the mass being lifted and affects the power output. The power curve in the Figure 9 shows the correlation between power output and TSR and power output reaches its maximum values for tip speed ratios of 4 to 7. It is intended that wind turbine be operated in that range of tip speed ratios for maintaining high power output.

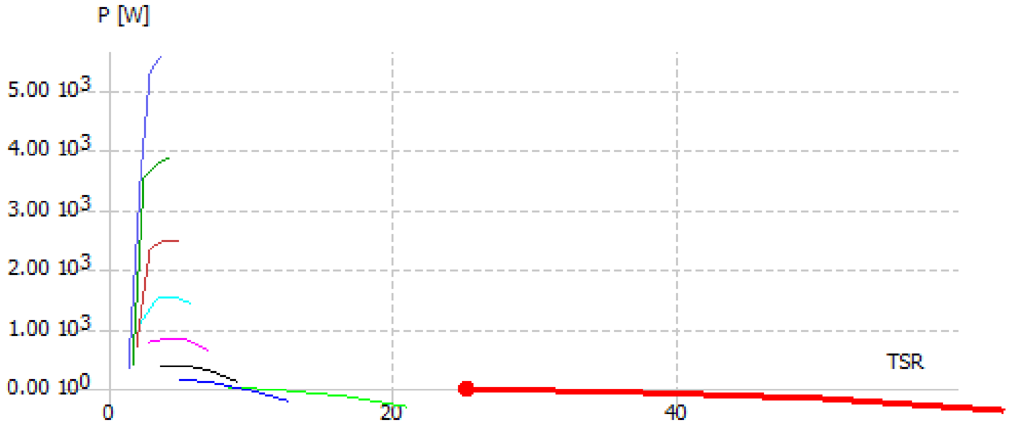


Figure 9: Power [P] Vs Tip Speed Ratio [λ]

C. Lift and Drag Coefficients

C_l is the property of airfoils defining the lift force. For VAWT, high value of C_l is required. Figure 10, shows the variation of C_l with angle of attack [α] and drag coefficient C_d.

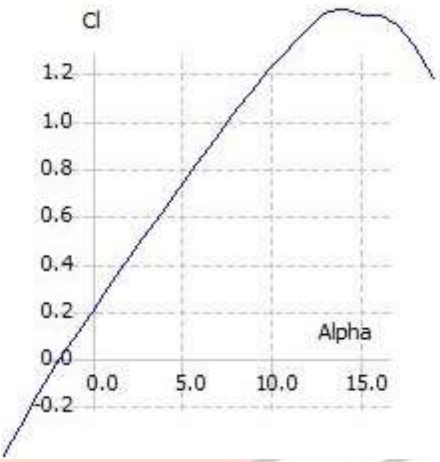


Figure 10 (a): C_l Vs Angle of Attack [α]

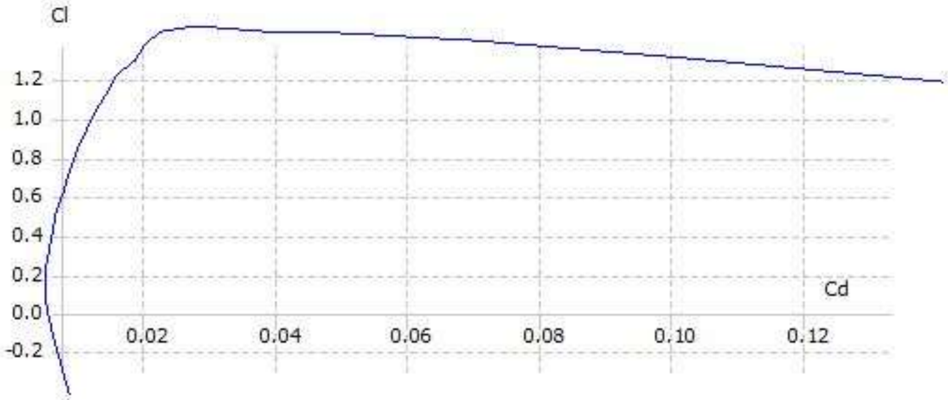


Figure 10 (b): C_l Vs C_d

C_l/C_d is an important parameter in airfoil design considerations to minimize drag force and stay elevated. In wind turbines, it is important to maintain high lift coefficient. Figure 11, shows the variation of C_l/C_d with angle of attack [α].

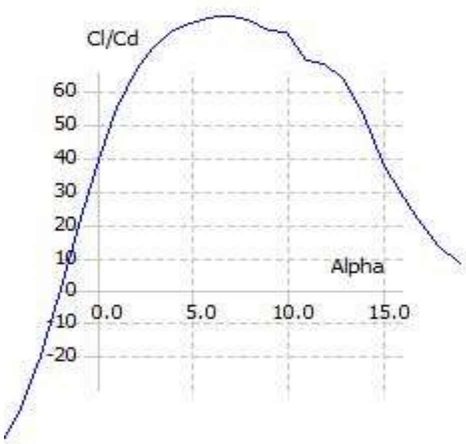


Figure 11: C_l/C_d Vs Angle of Attack [α]

V. CONCLUSION

Rotor blades of wind turbine were designed to improve the performance and utility of small wind turbine systems. The design proposed in this paper incorporates NACA 0018 airfoils due to its surface pressure distribution characteristics. This enhances the performance of wind turbines at lower speeds. Rotor blade geometry is studied and design is developed in Q-Blade software. Based on the design and simulations performed, following conclusions are obtained:

- The torque of the rotor for different wind speeds are investigated by varying blade quantity. It is observed that turbines with higher the number of blades result in better torque in low wind speed conditions. Torque is important for the turbine to be self-starting and to operate as standalone system. The drawback of high number of blades is heavy drag force generated. The limitation of self-starting ability in case of wind turbine can be overcome by incorporating hybrid drag type rotor blade design.
- The number of blades affects the TSR and C_p produced by the wind turbine. Three blades are optimal to achieve stable power coefficient.
- Properly designed rotor blade with optimized dimensions can be used to increase the lift coefficient.
- For the blade design presented in this paper, C_l/C_d ratio is maximised for angle of attack [α] of 5° to 10°.
- As the power generated by a wind turbine is proportional to the air mass lifted/ raised by the rotor blades in given time, with increase in lift coefficient, power generation increases.
- Blade profile is optimised to increase the power coefficient. Power coefficient is maximised to value 0.45 for tip speed ratios 4 to 7.

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