A Comprehensive Review of Developing Horizontal Axis Wind Turbine Rotor Blade for Domestic Applications

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Abstract – *Energy conservation, Pollution prevention, Resource Efficiency, System Integration and life cycle are very important terms for sustainable conservation. Over the span of 12 years a considerable number of airfoils have been developed for horizontal axis wind turbine. For example, 25 specially tailored airfoils for wind turbines (HAWT) originated from the joint work between national renewable laboratory (NREL) and airfoils Inc. (Tangler and Somers, 1995). Wind energy is cheapest cost option for power generating capacity in increasing number of countries and other parts of world putting their step forth to increase eco-friendly nature of power production. The best performing HAWT over VAWT along with micro scale wind turbine could noticeably supply the demand for the electricity in domestic applications. Also, blade design and optimization of the blade as one of the most important part of wind turbine is also addressed in this study. The performance of the wind turbine rotor also depends on the wind characteristic of the site and the aerodynamics shape of the blades. The blade geometry determines the torque and the power generated by the rotor from aerodynamic point of view an economical and efficient blade design is obtained by the maximization of rotor power coefficient which is also addressed in this review paper.*

Key Words: Aerodynamics, Environment, Energy, Renewable Energy, Horizontal axis wind turbine, Rotor Blade, Wind Energy

1.INTRODUCTION

The significance of alternate energy sources like solar, wind, biomass etc. has exponentially increased in recent years due to the ever increasing demand for clean energy. Harvesting of wind energy has also gathered sufficient momentum in recent days. Estimation of technical and economical wind energy in various regions has gathered momentum. [1] Small wind turbines are increasingly contributing to the energy needs of both isolated and grid connected consumers. Wind mills have been used for many centuries for pumping water and milling grain. The discovery of the internal combustion engine and the development of electrical grids caused many windmills to disappear in the early part of the 20th century. However, in the recent years, wind turbines are used again to produce electricity for many purposes. [1-3] While wind turbine technology is going by the way of larger scale and off—shore wind farms. It is also important to develop small wind turbine generators which are sufficiently safe and easy to run on individual homes for self-sufficient and independent power production. Usually, small wind turbines are designed with a high tip speed ratio as compared to large wind turbines, thus their rotational speed becomes very high.

Wind turbines used for generating electricity have existed for more than one hundred years this has been achieved by an annual growth rate in the industry manufacturing wind turbines of more than 20% and in some countries as Denmark the contribution to the total electricity produced from wind turbines in 2009 is closed to 20%. [1]

2. LITERATURE REVIEW

2.1 Classification of Wind Turbine

Classification of wind turbine is done on the basis of its type of wind, capacity, or size according to Renewable 2015 Global Status Report [10].

SCALE	POWER RATING
Micro	50 W to 2 kW
Small	2 kW to 40 kW
Medium	40 kW to 999 kW
Large	More than 1 MW

Table 1: *classification of wind turbine*

The two basic types of wind turbines are:

2.1.1 Horizontal Axis Wind Turbine (HAWT)

These type of wind turbines have main rotor shaft and generator at the top of the tower pointing at wind also tower produces turbulence so most of the wind turbines are of upwind type, have gear box which converts slow rotation of blades into fast rotations which helps to drive electric generator. Generally, the turbines used in farms are of three blades and computer controlled motors. Also have high tip speed high efficiency and good reliability [6].

2.1.2 Vertical Axis Wind Turbine (VAWT)

These types of turbines have vertical rotor shaft and are only useful where wind speed is highly variable, unlike horizontal axis wind turbines the gearbox assembly is places near ground. These wind turbines operate at low drag to lift ratio.

There are several types of VAWT *viz*. Darrius wind turbine, Giromill, Savonius wind turbine, Parallel turbine [6]

2.2 Components of Wind Turbine

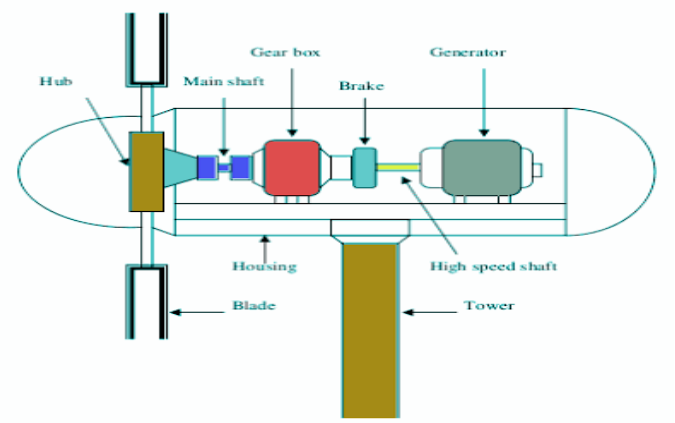

Fig 1: *Major Components of a horizontal axis wind turbine*

Rotor and Rotor Blades- The energy in the wind turns two or three propeller-like blades around a rotor. The rotor is connected to the main shaft, which spins the generator to generate electricity. Most wind turbines have upwind rotors with three blades three blades have advantage that the polar moment of inertia with respect to yawing is constant and independent of the azimuthal position of the rotor [4].

Drive train- The drive train consists of rotating parts of wind turbine. It consists of low speed shaft which in on the rotor side a gear box and a high speed shaft which is on the generator side. Other drive train components support bearings, one or more couplings and a brake, also rotating parts of the generator also parallel shaft and planetary gear boxes are used. Some wind turbine designs use specially designed low speed generators requiring no gear box [4].

Generators- In all wind turbines synchronous or induction generators are common. Induction generators produce electrical power when their shaft is rotated faster than synchronous speed of the equivalent induction motor. Down side of the induction generators need an induction motors to run 1500+ RPM to meet the synchronous so a gearing is almost always needed. Permanent magnet alternators (PMA) are can be very efficient, in the range of 60%-95%. Brushed DC Motors are commonly used for home built wind turbines [4].

Nacelle and yaw system- This consists of the wind turbine housing, machine bedplate and yaw orientation system or main frame. Yaw orientation system is required to keep the rotor shaft properly aligned with the wind and it is connected by bearing to tower. Sometimes the whole mechanism is controlled by yaw control system as this system equipped with direction sensors anemometer mounted on nacelle [15].

Tower and foundation- This category includes tower structure and supporting foundation. For smaller turbines, guyed towers are used. Tower height is typically 1 to 1.5 times the rotor diameter. The height of tower varies with the type of wind turbine and also the site of installation, height of tower should be such that there will be minimum obstacle in the wind flow direction as power is directly proportional to cube root of wind speed. The height of the tower is selected depending upon the location of wind turbine. Tower height is equal to rotor diameter when the field open but when the field is surrounded with trees and buildings then height of wind turbine is two or three times of rotor diameter [16].

Controls- the wind turbine control system includes the following components:

Sensors-speed, position, flow, current, voltage, temperature
Controllers- mechanical mechanisms, electrical circuits, and computers
Power amplifiers-hydraulic pumps and valves switches
Actuators-motors, piston, magnets, solenoids [15].

From the review of literature on micro and small capacity wind turbines it is found that careful design, fabrication and testing of turbine blades is very essential for achieving best performance. Also aerodynamic performance of the turbine blades depends on the air foil section of the blade. Limited work is done on CFD studies of low capacity wind turbine rotor blades.

3. WORKING PRINCIPLE

3.1 Aerodynamics principle of wind turbine

As the classical theory of wind turbine rotor aerodynamics, the BEM method (also known as Strip theory or Glauert /Wilson method) combines the Momentum theory and Blade Element theory. As shown in Fig.2 [7], the blade is divided into several sections and each section sweeps an annular area when the rotor rotates. These annuli are separated and no interaction between each other. In other words, the stream tube is decomposed along different radius positions and each annulus has its own momentum balance. By dividing the wind turbine blades into annular blade elements and applying one-dimensional linear momentum conservation to the annular elements, the forces and power are calculated and integrated based on the sectional airfoil lift and drag coefficients, the chords and twist angles of the blade geometry. The airfoil aerodynamic characteristic data i.e. the lift drag and moment coefficients are often obtained from wind tunnel measurements. [7]

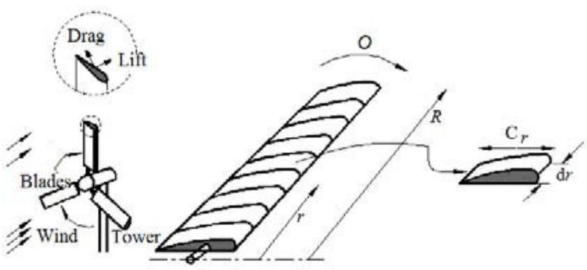

Fig 2: *Blade element model [7]*

The lift and drag forces of a blade element are calculated by the lift and drag coefficients from wind tunnel test, it can be defined as: [7]

$$dF_L = \frac{1}{2} C_l \rho U_{rel}^2 c_r dr \quad (1)$$

$$dF_D = \frac{1}{2} C_d \rho U_{rel}^2 c_r dr \quad (2)$$

Hence the forces in the flow direction FN and perpendicular to the flow direction FT are obtained: [7]

$$dF_N = \frac{1}{2} Z \rho U_{rel}^2 (C_l \cos\varphi + C_d \sin\varphi) c_r dr \quad (3)$$

$$dF_T = \frac{1}{2} Z \rho U_{rel}^2 (C_l \sin\varphi - C_d \cos\varphi) c_r dr \quad (4)$$

This is a great development in the history of the wind turbine aerodynamics, which relates the blade geometry to power and thrust forces using lift and drag coefficients. It gives a principle to design optimal blade geometry. [7]

3.2 Power Curve Modelling Methodology

The function of wind turbine is to convert the kinetic energy associated with wind into electrical energy. The power output is totally depending upon the wind speed. The power output is always fluctuating with wind speed as wind speed is not constant with time. The different techniques available in literature for WTPC (Wind Turbine Power Curve) modelling have been classified into parametric techniques and non-parametric techniques as shown in figure 3. [3]

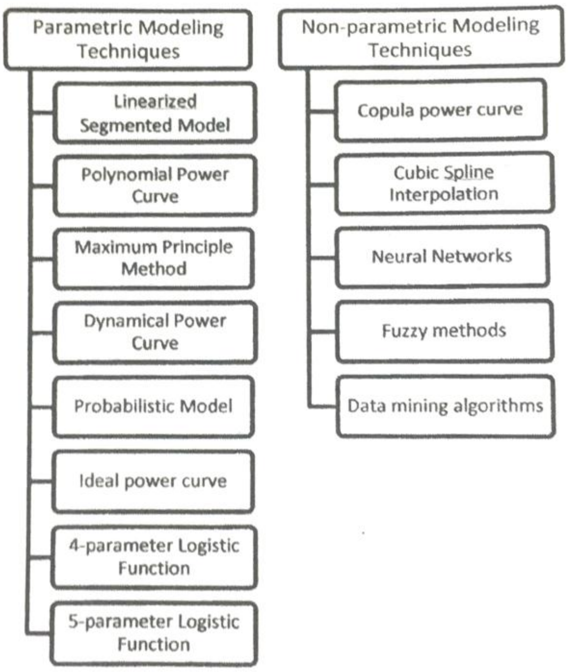

Fig 3: *WTPC Modelling Techniques [3]*

3.2.1 Mathematical Model

Under the constant acceleration, the kinetic energy of an object having mass m and velocity v is equal to the work done W in displacing that object from rest to a distance s under force F.

$$E = W = Fs \quad (3.2.1)$$

According to Newton's law,

$$F = ma \quad (3.2.2)$$

Hence,

$$E = mas \quad (3.2.3)$$

Using the third equation of motion:

$$V^2 = u^2 + 2as \quad (3.2.4)$$

We get:

$$a = (v2 - u^{2)}/2s \quad (3.2.5)$$

Since initial velocity of object is zero, i.e. u = 0, we get:

$$a = v^2/2s \quad (3.2.6)$$

Substitute it in equation (3.2.3) we get:

$$E = ½\ m\ v^2 \quad (3.2.7)$$

Power in wind is given as rate of change of energy:

$$P = DE/dt = ½\ v^2\ dm/dt \quad (3.2.8)$$

We know mass flow rate as:

$$dm/dt = \rho\ A\ dx/dt \quad (3.2.9)$$

As $$dx/dt = v \quad (3.2.10)$$

$$dm/dt = \rho\ A\ v \quad (3.2.11)$$

Hence from equation: (3.2.8)

$$P = ½\ \rho\ A\ v^3 \quad (3.2.12)$$

Power curve of wind turbine shows that; how large the electrical power output will be for the turbine at different wind speeds [8]

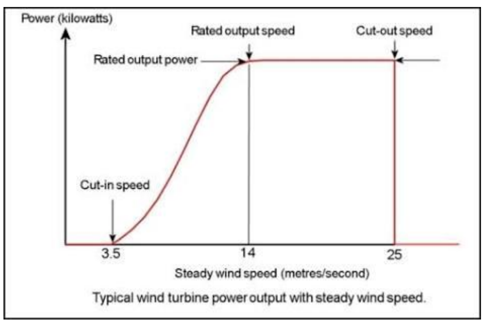

Fig 4: *Power curve for wind turbine [8]*

4. REVIEW ON AERODYNAMICS OF HAWT

4.1 Momentum Theory

4.1.1 Actuator Disc Theory

A simple model was developed by Betz in (1926) [1, 3, 4, 7] based on linear momentum theory. This theory was developed over 100 years ago to study the performance of ship propellers [4]. The actuator disc theory [1, 3, 4, 7] is used to determine the power coefficient.

Following assumptions are made in this analysis [3]-

- Air is incompressible and homogeneous with steady state flow
- Air flow is one dimensional
- Infinite number of blades
- No frictional drag

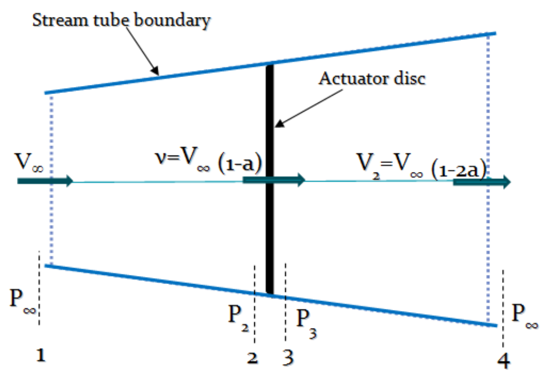

Fig 5: *Actuator Disc Model of Wind Turbine (adapted from Manwell et al. 2002) [4]*

Applying the three conservation equations to the control volume one can find the net force on the content of control volume. That net force is equal and opposite to thrust T, which is the force of the wind on the wind turbine. According to conservation of linear momentum, the thrust is equal and opposite to change in momentum of an air stream.

Output power obtained is written as,

$$P = \frac{1}{2}\,\rho\, A\, V_\infty^3\, 4a(1-a)^2$$

Where:

P: Output Power
A: Swept area of rotor
V: Velocity Gain
a: axial induction factor
ρ: Density of Air

4.1.2 Betz Limit

Wind turbine rotor performance is determined by power coefficient Cp which is the fraction of power in the wind that can be extracted by rotor [3].

$$C_p = \frac{P}{\frac{1}{2}\rho\, A\, V_\infty^3} = \frac{Power\ Output}{Power\ in\ the\ Wind}$$

Maximum Betz limit is:

$$C_{p,max} = 0.593$$

There is no turbine which can produce power more than 59.3% which was defined by Betz and hence limit is called Betz-Joukowsky limit. For this case, flow through the disc in stream tube with upstream cross section area of 2/3 of disc cross sectional area expands to two times the disc area at downstream. This result shows that if the ideal rotor operates at wind speed at rotor disc 2/3 times that of free stream wind speed then it will produce maximum possible power output.

4.1.3 Thrust Coefficient

The axial thrust can be written by considering axial thrust coefficient in equation (3.1.7) of thrust as:

$$T = \frac{1}{2}\,\rho\, A\, V_\infty^2\, 4a(1-a) \quad (4.1.1)$$

The coefficient of thrust can be characterized as similar to the power coefficient

$$C_T = \frac{T}{\frac{1}{2}\rho\, A\, V_\infty^2} = \frac{Thrust\ Force}{Dynamic\ Force} \quad (4.1.2)$$

$$C_T = 4a(1-a) \quad (4.1.3)$$

For maximum power coefficient (for axial induction factor a = 1/3) the value of thrust coefficient can be CT = 8/9 and unity for axial induction factor a = 1/2. The problem arises when the value of 'a' is less than ½ because wake velocity becomes zero or even negative in such a condition the momentum theory as defined no longer applies and an empirical modification has to be made.

4.2 Blade Element Theory

Blade element theory basically involves the division of rotor blade into *N* number of elements and calculating the flow separately for each element. Considering the annular stream discussed in previous section with wake rotation in which the velocity in the direction of stream flow associated with blade element is given by '*v*'. Total tangential velocity experienced by blade elements is given by the sum of tangential velocity of blade element '*Ω*' and tangential velocity of wake '*W*', therefore,

$$V_T^2 = V_\infty^2(1-a)^2 + (\Omega + \Omega a')^2 r^2$$

Where 'V_T' is total velocity experienced by blade element at distance 'r'

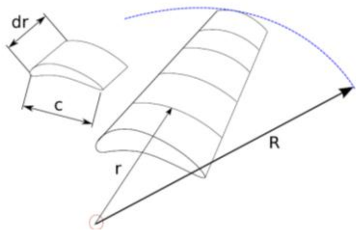

Fig 6: *Blade Element Model*

As the blade is divided into '*N*' number of elements each element will experience different velocity component as each element will be having different local radius '*r*'

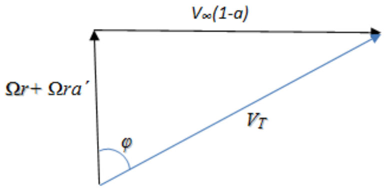

Fig 7: *Velocity triangle for blade element*

Where ∅ is the relative angel between total velocity and plane of rotation.

4.3 Blade Element Momentum Theory

The blade element momentum theory (BEM) is the most used aerodynamic model for wind turbines because it is extremely fast and provided that good input in the form of tabulated airfoil data exists also quite accurate. The HAWT Blade design is based on the BEMT, a combination of the momentum theory and the blade theory. [19]

BEM theory can be used for geometrical and aero dynamical design of small wind turbine rotor blade which gives a set of power coefficient and torque coefficient as a function of tip speed ratio.

5. REVIEW ON DEVELOPMENT OF AIRFOIL BLADES

5.1 Design of airfoil blade

QBLADE [17] is used for wind turbine design and performance calculations. This software is available free of cost under the General Public License. From QBLADE simulation we get CL/CD ratio for various angle of attack. Also, we get maximum power coefficient C_p, thrust coefficient C_t. Optimum Design parameters can be calculated from QBLADE software such as maximum Angle of Attack (AoA) etc.

QBLADE working model includes:
- Airfoil design and analysis
- Extrapolation of Lift and drag polar
- Blade design and optimization
- Turbine definition and simulation
- Cross section of wind turbine blade, have shape of an air foil.

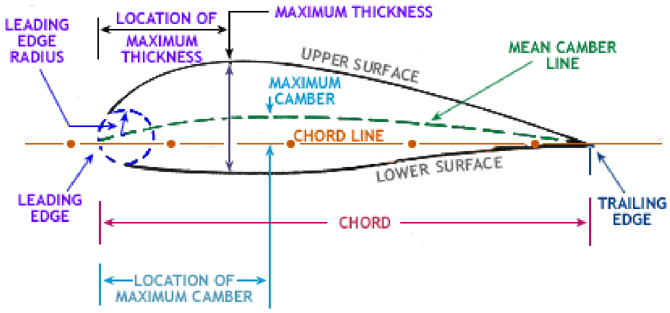

Fig 8: *Nomenclature of airfoil geometry [18]*

From figure 8 following terms can be defined as:
Chord line: straight line drawn from leading edge to trailing edge.
Chord (c): length of chord line.
Mean camber line: curved line drawn from leading edge to trailing edge. It is equidistance from lower as well as upper surface of an airfoil.
Maximum camber: maximum distance between mean camber line and chord line.
Maximum thickness: maximum thickness between upper and lower surface which is normal to chord line of an airfoil.
Angle of attack: angle between chord line and stream flow.

6. REVIEW ON TESTING TECHNIQUES

There are three methods of testing for wind turbine motors; wind tunnel testing, tow testing and field testing. Field testing presents the proper wind environment, but it also brings new challenges in recording and measuring test data simultaneously.

6.1 Field testing

Primary purpose of field testing is to construct an initial picture of test validity and reliability. The test is administered to an adequate number of examinees (this number varies depending on the type of statistical analyses that will be carried out), and the raw data is used in the psychometric analysis.

6.2 Wind tunnel testing

Wind tunnel is the test rig designed for aerodynamic studies. It is used to visualize measure and analyze the effect of fluid passing over solid object.

In this study suction type subsonic educational wind tunnel is used for airfoil testing. This type of wind tunnel is one of the simplest wind tunnels used for studying the effect of flow over solid body. Here solid body is considered as one of the elements of rotor blade having cross section of airfoil.

Subsonic Wind Tunnel

This type of wind tunnel is used for low wind speed with Mach number less than 1 (*M<1*). Suction type of wind tunnel have fan mounting at outlet of the tunnel. Suction type of subsonic wind tunnel is seen in Figure 9.

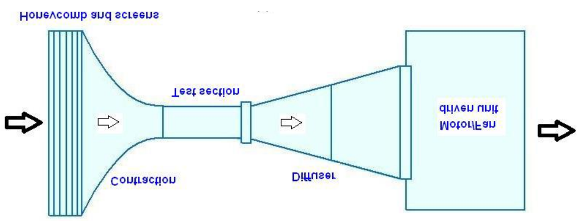

Fig 9: *Suction type subsonic wind tunnel*

3. SUMMARY & CONCLUSION

A lot of work has been done by researchers across the world in development of medium (~41 kW- 999 kW) to large (~1 MW- 6) capacity wind turbines, but limited work has been done in developing micro (~40 W- 2 kW) to small (~2.1 kW- 40 kW) capacity wind turbines. In this work we refer the micro capacity wind turbine and we studied about both category of wind turbines i.e., horizontal axis as well as vertical axis wind turbine. In this review paper the components and the working principal of horizontal axis wind turbine is explained. I have also reviewed the blade element theories in brief. The previous air foils were designed according to the environmental conditions of western countries which are different from India, hence those air foils are inconvenient for Indian environment. Also the air foils designed are for large wind turbine blades which are not suitable in case of small wind turbine blades. For designing purpose, we studied about Q-Blade simulation in which air foils are designed, analyzed and optimization of their blade design can be carried out. At the end we focused on testing techniques for wind turbines.
Major requirement of constructing micro capacity wind turbine is that, these turbines are simple in construction and requires less amount of investment. Since turbines are small in size, so it will harness a limited amount of wind. Therefore, it can be used for low power domestic applications, such as charging of batteries, street lights, on busy road. Large scale wind turbines alter the global climatic conditions and have adverse effect on the atmosphere on other part small scale wind turbines have great scope for producing power which will be sufficient for domestic application without altering any climatic condition.

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BIOGRAPHIES

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