Chapter 2

Literature Survey

Wind turbine is the most potent alternative which can convert wind energy into electric power. This source is found to be economical and effective means to cut down electrical cost. In olden days wind turbines were not developed for power generation, they were used to produce repetitive mechanical task for pumping water or to grind grain. These were called as wind mills. Charles F Brush developed the first power producing wind turbine in 1888 in United States. Eventually wind turbines became popular due to development in steel. [1]


Rotor diameter of the turbine was 18 meter diameter having three-bladed rotor and a rated output of 100 kW. Horizontal Axis Wind Turbines are efficient in converting wind energy into electric energy at large scale. Due to this reason they have been more dominant commercially. Horizontal Axis Wind Turbine are
huge, they require large space, high installation cost, high maintenance cost, which makes them unaffordable for generation of power for domestic purpose.

Vertical Axis Wind Turbines have the capability of operating in turbulent wind because of which they can be installed at lower heights. As the gear box mechanism is located at ground level, their maintenance is not cumbersome. No pitch and yaw mechanism is required for vertical axis wind turbine. Due to these advantages of VAWT, makes it best suited for generating power for domestic purpose. In 1927 the first aerodynamic vertical axis wind turbine was developed by Darrius in France. The turbine was based on the principle that its blade speed was multiple of wind speed. The apparent wind throughout the whole revolution coming in as head wind with only limited variation in angle. In 1975, P J Musgroves put endeavors in straightening the Darrius blades which led to straight blade vertical axis wind turbine known as H-rotor vertical axis wind turbine. In 1986 Sir Robert Mc Alpine and Northern Engineering developed an arrow head blade of 25 m large and 130 KW rated capacity located in Carmarthen bay in South Wales. In 1922 Finnish Engineer S J Savonius developed Savonius turbine which was simple structure with two cups or half drums fixed to the rotating shaft in opposite directions. Each cup or half drum intercepts the wind and rotates the shaft, which brings the opposite part of the drum or cup in the wind flow. The cup or drum repeats the process so as the shaft rotates and completes the rotation. In between 1970-80 lot of research has been carried out on Darrius vertical axis wind turbine. Few researchers used symmetrical airfoil blade profile. The principle behind using symmetrical airfoil was that it would generate lift force from both the side for 360° path of the blades rotation. Researchers from
Italy developed Ropatec type of turbines which are Hybrid Darrius and Savonius wind turbines. To reduce the noise level in Darrius turbine, researchers from New Zealand developed Vertical Axis wind turbine, Solwind model. These turbines are quite operated turbines, by virtue of their design, the blades do not make the conning noise which occurs in conventional horizontal axis wind turbine when the blade passes close through the mast. The blades of this turbine are always at the equidistant from turbine mast. The Wind Side Wind Turbine of Finland has developed a vertical axis wind turbine working on sailing engineering principle. This turbine is rotated in two spiral formed vanes. This turbine is known as Helical wind turbines [3] [4] [5].

Study of vertical axis wind turbine requires a literature review of several different areas. The literature in these areas can be classified mainly into the following:

1) Analytical and preliminary design estimation

2) Experimental analysis

3) Detailed fluid flow Numerical analysis

4) Notable innovative designs.

These areas are discussed in following sections.

2.1 Analytical and Preliminary Design Estimation

Most of the analytical philosophies applicable for horizontal axis wind turbine such as blade element theory, power calculation, etc. are also applicable for VAWT.
Initial analytical work includes power calculations, blade element momentum theory, power generation and structural analysis has been focused on improving the performance of turbine by improving the aerodynamics of blades. Gundtoft [6] book elaborates about the energy obtained from the wind in an idealized wind turbine (Proof of Betz law) and the design process for the rotor. Further, this book elaborates optimal design guidelines for rotor pitch angle and chord length and other characteristic of the rotor blades viz. coefficients of lift and drag. This book also covers the the step wise procedure for calculation of the power of a given rotor using the BEM theory and efficiency of a wind turbine.

A book by Muyeen [7] gave detailed analysis of a Wind Power Generation System using various analytical expressions. Power generation analysis also includes various turbine system components viz. synchronous generator with permanent magnets, active rectifier and voltage source inverter. Further, he has explained various other topics speed control of generator, turbine modelling along with induction machine, etc. It gives useful information regarding Converters and inverters. Study has been conducted on Control Strategies for Variable-speed Fixed-pitch Wind Turbines, Variability and Predictability of Large-Scale Wind Energy, Operation.

Dimitris in his book [8] provides a great deal of material on structural analysis using FEA. It presents effect of material damping of composite structures. Further part of the book is extended to developing novel shear beam finite element. The model is fortified due to its inclusiveness to geometrical non linear parameters.
2.2 Detailed Fluid Flow Numerical Analysis

With advancement in computational speed, Computational Fluid Dynamics (CFD) is becoming useful in detailed analysis of new models of wind turbines for its performance improvement. Aerodynamic performance of HAWT has been done by using iterative methods. Major work has been done on developing time dependent models for two dimensional and three dimensional flow, flow field condition, Wake dynamics, etc.

Optimal twist of windmill blade was examined on the axis of blade element momentum theory. The drag and lift forces were estimated using CFD analysis for various angle of attack [9]. Further, CFD models were developed for the performance estimation and the evolution of wake geometry estimation study of a Savonius wind turbine under flow field conditions [10]. CFD simulations were done to explore the possibility of increasing the efficiency of the blades at higher wind speeds while maintaining efficiency at the lower wind speeds, flow fields analysis for different turbulence model [11, 12].

Deglaire et al. [13] developed a model for two dimensional flow around a moving profile. The model was suitable for fast aerodynamic and aeroelastic coupling calculation. This developed methodology which was used to represent any profile, pitching motion and blade attachment position. The method was based on conformal mapping technique and Laurents series decomposition and is faster and more accurate than standard panel methods.

Zanon [14] developed a 2D vortex panel model with a viscous boundary layer formulation for simulating VAWT including the effects of dynamic stall. Tescione et al. [15] investigated development of the near wake of VAWT using stereoscopic
particle image velocimetry. The experiments demonstrated the evolution of the vorticity shed by the blade and it organizes in large scale vertical structures at the edges of the wake resulting into asymmetric induction field in the wake. Nini et al.\cite{16} carried out three-dimensional simulations around three blade straight VAWT which demonstrated strong interactions between the blade and the blade wake. The three dimensional model could capture the blade and the tip vortices and the aerodynamic disturbances from the turbine shaft and the support arm. Castelli et al.\cite{17} presented a model for the evaluation of aerodynamic and internal contributions to VAWT. This was achieved by specially designed coupling code, which helps in estimating both tangential forces and centrifugal forces.

McNaughton et al.\cite{18} presented detailed flow analysis of VAWT, which includes the evolution of the skin-friction coefficient over the blade throughout a cycle. The analysis enabled a better understanding of the flow structure and the dynamic stall effects as well as blade-vortex interaction. Siddiqui et al.\cite{19} studied the effect of variation in geometric design of VAWT using CFD. The geometric variations considered were flow performance related to tip effects, spanwise flow effects, effect of supporting arm and central hub. Islam et al. \cite{20} compiled the main aerodynamic models that have been used for performance prediction and design of straight bladed Darrieus-type VAWT. These models include double-multiple stream tube model, vortex model and the cascade model. Rolland et.al.\cite{21} compared the CFD estimated performance of novel design VAWT with wind tunnel test data and demonstrated that the simple turbulence modeling techniques were sufficient to obtain performance parameters with reasonable accuracy. Wakes et.al. \cite{46} presented numerical method to investigate the influence of
operating conditions on VAWT through unsteady wind environment. The results indicated that for fluctuating free-stream wind conditions for thicker airfoil were desirable. CFD analysis was also utilized to get the detailed insight of flow around the VAWT. Shi et al. [22] used two-dimensional vortex type aerodynamics model for VAWT, which combines a source-vorticity panel formulation for the blades and a vortex blob. Curvature effects are also taken care of by the model. Goude et al. conducted a numerical study on performance of turbine in free flow and in channel. Comments are made on time taken for convergence of the solution and the performance of the turbine [23].

Coxa and Echtermeyer [24] used Finite Element Analysis (FEA) approach for wind turbine blade made of hybrid composite material yielding low weight and high strength. Lavassa et al. [25] performed analysis for gravity, seismic and wind loadings of tubular tower of 44075 m high made of steel S355J2G3 is done by using two different finite element models. Hameed and Kamran [26] studied the performance of blade at extreme wind conditions. The maximum stress and deflection values were estimated. Chou and Tu [27] study provides significant insights into post-disaster inspection of tower failure during typhoon. Krishna et al. [28] documented the standard which provided the guidance for calculating basic design loads to be assumed in the design of the buildings.

### 2.3 Experimental Analysis

In experimental analysis attempt has been made by researchers to maintain control over all the factors that may affect the result of an experiment. The major focus of experimentation was performance enhancement, to study the effect of design...
parameters on the performance and optimization of the wind turbine. Greenblatt et al. [30] assessed turbine performance enhancement resulting from the control of dynamic flow separation and project the validity of upscaling the turbine. They have used plasma actuator at the tip of the blade to impart smooth separation of the dynamic flow. It was found that overall performance improvement up to 30% may be possible. The testing on a small wind turbine was carried in low speed wind tunnel. Samanoudy et al. [29] worked on the effect of design parameters on the performance of the Giromill vertical axis wind turbine. The turbine performance was investigated by varying the design parameter such as pitch angle, number of blades, aerofoil type, turbine radius and its cord length. Further the results were used to compare the performance achieved by changing the design parameter. It was found that pitch angle, turbine radius and chord length has a significant effect on turbine power co-efficient. Vertical axis wind turbine (VAWT) performance improvement studies include modifications in blade design, orientations of blades and attachments to change wind pattern.

Daegyoun and Morteza [31] experimentally investigated the effect of upstream flap deflector for improving power performance. Significant improvement in power output was demonstrated with installation of counter-rotating turbines outside the near-wake region. Bedon et. al. [32] proposed design based on advanced chord distribution for Darrieus wind turbines. Optimization was performed for improving power coefficient with chord as design variable which resulted in 6 % improvement in power performance. Similar VAWT optimization efforts include optimized site-specific VAWT design by Saeidi et al. [33] and Optimization of Darrieus VAWT using evolutionary algorithm.
Recently, Ismail and Vijayaraghavan [34] studied the effects of airfoil profile modifications of VAWT performance, which include combination of inward semi-circular dimple and Gurney flap at the lower surface of the NACA-0015 aerofoil. A response surface approximation based optimization approach is utilized to enhance the torque produced by turbine blades. Li et al. [35] worked on the problem of VAWT in cold climate, icing, and snow. Due to above climatic condition the performance of the VAWT is affected. They simulated the condition of rime type icing on the leading edge of the blade surface by clay. The effects on the rotation and power performance of VAWT were measured in wind tunnel. Bhuyan and Biswas [36] compared the self-starting characteristics of H-rotor and Hybrid H-Savonious rotor VAWT and found that hybrid design fully exhibits self-starting capability at all azimuthal positions, signified by the positive static torque coefficients values. Attempts were made to improve the self-starting speed of Darrius hydrokinetic wind turbine by studying the forces acting on the straight blades and varying the pitch angle [37]. Novel vertical axis sail rotor was used and force analysis for one complete rotation was made for enhancement of self-starting speed [38]. Effect of cambered airfoil on self-starting speed of vertical axis wind turbine was studied. Cambered aerofoil improves the self-starting speed with low power coefficient as compared to that of symmetrical blades [39]. Evaluation of different wind turbine configurations of VAWT has been done from the most important aspects including coefficient of power, tip speed ratio, blade design, aerofoils [40].

In wind tunnel experimentation, when the turbine model is placed in the test section, the confined space for wind to flow gets blocked by the model. Due to this
the wind velocity in the proximity of the model is more. As the size of the model increases the blockage also increases. For conduction of experimentation in wind tunnel the velocity in test section has to be corrected by multiplying with blockage factor. The literature available on blockage factor revolves around estimation of blockage factor and corrected velocity.

Biswas et.al. reviewed the wind tunnel testing on three bladed Savonius designs. Relevance to the overall study, Biswas calculated Power Coefficients with and without Wind Tunnel Blockage Correction Factors for tunnel interference, adopting the Pope correction. It was that the tunnel blockage effect was an deciding parameter for wind tunnel performance analysis of VAWTs, whose effect was much more severe in low speed wind tunnel applications. Biswas results corroborates the fact by stating that the rotor blockage effect increases the local free stream velocity in the test section, of which the effect has been quantified using a velocity increment (Pope Correction). This study assessed the performance of the rotor evaluated from variation of Power Coefficient with TSR. Allowing for the Blockage correction, the maximum Power Coefficient on average reduced 5%, a significant reduction when dealing with a Power Coefficient of 28%, this reduction is used as a source of comparison to later application of the Pope Correction to the current wind tunnel results. Ross and Aaron have investigated the wake and solid blockage effects of vertical axis wind turbine in closed test section wind tunnel. These researchers have extensively investigated blockage effects produced by vertical axis wind turbine in wind tunnel. It was found that the flow filed surrounding this wind turbine is symmetric, periodic, unsteady, separated and highly
turbulent. They examined the wake characteristics and VAWTs performance produced by vertical axis wind turbine. During the comparative studies of numerical and experimental results, wind tunnel blockage plays an important role.

CFD simulations of VAWT were also compared with wind tunnel test results during design and validation process. Howell et.al.\cite{45} carried out numerical analysis and wind tunnel test on small vertical axis wind turbine. He found that surface finish of rotor plays a vital role in performance of wind turbines. Solidity effect on performance was also studied. Rolland et al.\cite{21} carried out experimental investigation under controlled conditions useful for validation of CFD model of novel VAWT. They compared the CFD estimated performance of novel design VAWT with wind tunnel test data and demonstrated that the simple turbulence modeling techniques were sufficient to obtain performance parameters with reasonable accuracy.

Wekes et al.\cite{46} presented numerical method to investigate the influence of operating conditions on VAWT through unsteady wind environment. Recently, Ahmadi-Baloutaki \cite{47} studied the effect of external free-stream turbulence on the aerodynamics of VAWT using controlled level of wind turbulence in wind tunnel testing. The study demonstrated that the turbulence generated downstream of the current grid was quasi-isotropic. Abraham et.al. \cite{48} \cite{49} \cite{50} \cite{51} Novel vertical axis wind turbine was developed to reduce the negative drag and thrust loading by using venting apertures and capping on the turbine flaps. Venting provides only marginal improvement, capping greatly increases power generation. Experimentally and numerically the effects of wind speed, turbulence intensity, airfoil shape, and strut mechanism with and without variable-pitch on the performance of the
turbine are carefully assessed [52]. Optimum shape of the Darrieus-type wind turbine was found by examining aerodynamic characteristics and the separated flow occurring in the vicinity of the blade [53].

2.4 Notable Inovative Designs

Many researchers had put their endeavours in developing innovative vertical axis wind turbines which are capable in confronting the problems encountered by the existing wind turbines. They have developed turbines which are site specific, reduction in noise and weight.

Newman and Ngabo [54] used sails for their wind turbine. Two types of sail a double sail and jib sail was tested. The performance of sail type wind turbine is almost 50% of the turbine with solid blades. This could be overlooked by the ease in manufacturing the turbine. Pope et al. [55] had performed energy analysis on four different wind power systems, including both horizontal and vertical axis wind turbines. They took two aerofoil (NACA 63(2)-215 and FX 63-137) commonly used in HAWTs and VAWTs (Savonius and Zephr).

Biswa et al. [56] developed a new aerodynamic model for obtaining the performance characteristics of a vertical axis wind turbine to estimate aerodynamic loading, which was subsequently used for dynamic analysis of VAWTs. The model incorporates gyroscopic generation through an induction or synchronous type generator. Kumbermuss et al. [57] introduced a novel magnetic levitated bearing suitable for VAWTs. The bearing system generates a magnetic force, which can support the weight of the wind turbine rotor. They had done simulation of the bearing by using finite element method which reveals that how low
the torque of this bearing is. Small scale model of novel magnetic levitated bearing system has been fabricated and tested. Chong et.al. [58] developed a novel power-augmentation-guide-vane (PAGV) to improve the wind rotor performance. Greenblatt et.al. [59] deployed inboard and outboard plasma actuations on the blade to counter the positive and negative angle of attack that produces dynamic stall.

In the process of improvement of VAWT, self-starting wind speed was also considered important performance parameter. Chong et.al. [60] developed a novel omni-direction-guide-vane for improvement of self-starting behavior of VAWT where the cut-in speed was reduced. Due to low self-starting wind speed requirement, working hours of the turbine has been increased. Subsequently the power output of the turbine is increased. Bedon et.al. enhanced the aerodynamic performance of a Darrieus wind turbine operating with the rotation axis tilted (10° and 20°) with respect to the free-stream wind speed is achieved [61]. Burlando et.al. achieved 10% of performance gain by adoption of stator vanes around a multi-stage vertical-axis wind turbine [62].

Sargolzae and Kianifar [63] had used Artificial Neural Network (ANNS) for predicting power factor and torque of wind turbines. In this research the rotor with different configuration was located in the wind tunnel and test was repeated 4-6 times in order to reduce errors. Simulation of rotors power factor and torque for different tip speed ratio and different blade angles was carried out. The simulated results show a strong capability for providing reasonable prediction and estimations of the maximum power of rotor and maximizing efficiency of Savonious turbines. According to artificial neural network simulations and the experimental
data they concluded that increasing tip speed ratio leads to higher power and torque.

Merits and demerits of various configurations of VAWT were reviewed by Bhutta et. al.\cite{64}. Abraham et al.\cite{65} studied the historical performance of Savonius vertical axis wind turbine and its optimization was done to enhance the performance. Tjui et.al. had done a comprehensive assessment of all the configurations of Darrius turbines is articulated\cite{66}.

2.5 Summary

Making an exhaustive study of literature on VAWTs it is seen that considerable work has been done in fluid structure interaction domain. Many researchers have made an attempt for studying the effects of flow, dynamic flow separation at the tip of the blade. Research work has also been carried out in understanding the formation of wake near the blade, static stall and dynamic stall numerically. To analyze the performance of wind turbine many researchers have carried experiments in wind tunnel. They found the solid blockage effect affects the performance of wind turbine model compared to the real time wind turbine. Thus considerable work has also been done in analyzing the solid blockage effect numerically. It is understood that most of the research in vertical axis wind is obtained on estimating power and torque coefficients either experimentally or numerically by using CFD as numerical tool. It is seen that very few researchers have done analytical estimation of power and torque coefficients. It is also found that very few researchers have worked on structural analysis of VAWT. The motivation for the current research stems from an investigation of the factors that influence the
performance of VAWT. Thus an attempt would be made to develop innovative
turbine to give better performance compared with available VAWTs.