CHAPTER - I

INTRODUCTION

The enormous potential of wind as energy source, mainly because of its renewable nature and decentralised availability, makes it a promising energy option. A wind machine is essentially a device to convert the kinetic energy available in moving air into usable form of work such as pumping water and generation of electricity. Based on the wind data for Indian conditions, it is found that windmills designed to respond to low wind speeds of 12 km/h are likely to be most appropriate for water lifting from shallow wells on small farms (77, 79). Apart from irrigation, the wind power can also be used for grinding, cane crushing, aeration of fish ponds and threshing (70).

There are two basic types of windmills — horizontal axis and vertical axis. The horizontal axis machines are most common of all wind turbines. The windmills with design tip-speed ratio upto 3.0 are known as low speed windmills and those with higher values as high speed windmills. For running irrigation pumps and other stationary devices, low speed windmills are suitable as these have better torque characteristics. Most recent works on wind energy appears to be related to the generation of electrical power and little effort has been directed to water pumping windmills for irrigation (38).

Multibladed windmills have been found to generate high starting torque and operate well even in low winds (70, 84). Review of different designs of multibladed windmills reveals that the blades of some are tapered outward and of some inward. A few designs have constant-chord blades for ease in manufacture. There is a very wide variation in design of low speed multibladed horizontal axis wind turbine (HAWT) rotors, in respect of their blade shape and number of blades. The number of blades in the existing designs of low speed HAWT rotors has been found to vary from 6 to 45 (10). Therefore, different design parameters for a low speed HAWT rotor need to be optimized.

Sails have been found aerodynamically inefficient for wind turbines (74). Owing to low Reynolds numbers encountered by low speed windmills, cambered steel plates have been preferred over airfoils of NACA or Wortman series (14). The cambered steel plates have fairly good lift/drag characteristics and are easy to manufacture (33). In different designs of the wind rotors using cambered steel plates, it is found that the arching or camber, which is the ratio of concavity to the chord length, varies widely from one design to another. In view of the importance of camber on aerodynamic performance of blades, some studies were conducted in the past to generate lift and drag characteristics. But these were limited to angle of attack range of -10° to +20° (14).

Owing to variation in magnitude of wind speed and rotor load, the rotors' operating tip-speed ratios often deviate from the design value resulting in wide variation of angle of attack (24). In a wind rotor, the range of variation of the angle of attack with speed and radius is considerable, far greater than what is normally found over aircraft wings. Therefore, to select an airfoil section, for design of wind rotors or to predict the performance of a rotor made with certain airfoil section, the aerodynamic characteristics (lift and drag) of the airfoil across a wide range of angle of attack is necessary. Except within a narrow range of angle of attack, airfoil characteristics are highly non-linear, and results of wind tunnel tests must be used in practice in place of analytical predictions (37). The information on lift and drag properties of airfoils such as cambered steel plates, which are suitable for low speed multibladed horizontal axis windmills, is very limited (25). Therefore, it is necessary to generate lift and drag characteristics of cambered steel plates across a wide range of angle of attack for optimization of camber and making available the airfoil data for performance prediction.

The design of HAWT rotor for a given diameter involves determination of number of blades, type of airfoil and radial variation of blade chord length and twist (20, 34). The normal procedure for determining blade shape for a HAWT rotor is to optimize independently each radial element by continuously varying chord and twist to obtain maximum energy extraction at design tip-speed ratio. The design tip-speed ratio of a wind turbine is that at which all blade elements operate at optimum angle of attack resulting in minimum drag-to-lift ratio.

Propeller theory development followed two independent approaches. One of these has been called momentum theory and the other, blade element theory. The basis of the momentum theory is to determine forces acting on the blade to produce the motion of the fluid. The theory has been useful in predicting ideal efficiency and flow velocity. It, however, does not give the information on the rotor shape necessary to generate the fluid motion. The approach of blade element theory is opposite to that of the momentum theory in that the concern is with the forces produced by the blades as a result of the motion of fluid. The early theoretical aerodynamic designs of HAWT rotors were based on assumptions that the blades operated without frictional drag and that there were infinite number of blades in the rotor (20). These assumptions facilitated closed form solution for design of rotors with maximum efficiency. For this, the strip theory, which is combination of momentum theory and blade element theory was used. The strip theory also assumes that the flow around a blade element is two-dimensional.

Following the resurgence of wind power in early 1970 s, the efforts were made to arrive at optimum design and to predict the peak performance of HAWT rotors by taking into account the effects of drag and a finite number of blades. Some approaches considered the effect of only drag (23, 47, 76, 89), whereas others (73, 81, 85, 86) took into account the effects of tip-losses through a finite number of blades also. The optimum design and peak performance prediction methods do not yield closed form solutions when the effects of drag and tip-losses are considered. The major complexity in these methods is the number and type of iterative processes required to satisfy the continuity and momentum relationships simultaneously with the flow around blade element, drag and blade tip effects in order to find the axial and angular speed interference factors (75). Therefore, it is necessary to extend the aerodynamic analysis of HAWT rotors to arrive at conditions for maximum power extraction. The additional relationship thus obtained may facilitate closed form solution for optimum design and peak performance prediction for HAWT rotors.

Owing to variation in wind speeds and mis-matching of load, the wind rotors operate quite often at tip-speed ratios lower as well as higher than the design value. Therefore, it is desirable to predict the output power of a HAWT rotor, not only at design value of tip-speed ratio but also at other values.

The effect of finite number of blades on power output from a HAWT rotor is taken through Prandtl tip-loss factor. The factor is unity for infinite number of blades. The tip-loss factor of unity signifies no tip-losses. The effect of number of blades, as incorporated through tip-loss factor, on peak and off-design performance of HAWT rotors obtained through computer simulation reveals that a rotor with large number of blades performs better (35, 85). However, when the number of blades in a rotor is increased for a given solidity ratio (the ratio of area occupied by blades to the rotor swept area), the chord length reduces, reducing the Reynolds number of rotor blades. At low Reynolds numbers, the aerodynamic performance of airfoils deteriorates resulting in reduction of power output from rotor. The peak and off-design performance prediction methods employing computer simulation and using airfoil data, do not take into account the effects of Reynolds number on rotor performance. Thus, by using these methods alone, the number of blades for a HAWT rotor cannot be optimized. In view of this, it is necessary to optimize the number of blades in low speed HAWT rotors through wind tunnel studies on model rotors which are theoretically designed for maximum power extraction.

There is wide variation in flow conditions across a rotor model in wind tunnel and those across the full size rotors operating under actual wind conditions. It is, therefore, desirable to scale-up the optimally designed wind rotor model and test under actual wind conditions for obtaining its power and torque characteristics.

In view of the above, the studies on design and performance aspects of low speed horizontal axis wind turbine rotors were undertaken with the following objectives :

(i) To study the lift and drag characteristics of steel plates with different cambers over a wide range of angle of attack in order to optimize the camber of blade for application to wind energy conversion systems.

(ii) To develop a model through aerodynamic analysis for optimum design, and peak and off-design performance prediction of HAWT rotors.

(iii) To study power and torque characteristics of aerodynamically designed rotor models through wind tunnel testing, for optimization of number of blades in low speed HAWT rotors.

(iv) To develop a scaled-up unit of optimally designed rotor model and test for its power and torque characteristics under actual wind conditions.

In order to achieve the above objectives, seven blades with camber varying from zero to 14 per cent were tested in wind tunnel at Reynolds number of 2.23 x 10^5. From the aerodynamics of HAWT rotors, a relationship among drag-to-lift ratio, tip-loss factor and speed interference factors was established. With the help of this relationship, optimum design, and peak and off-design performance prediction methods for HAWT rotors were developed.

The results from the new optimum design and peak performance prediction method were compared with those from the other established methods. The solidity ratio and blade twist were optimized through optimum design method. The number of blades for low speed HAWT rotors was optimized through wind tunnel testing of rotor models. After optimization of design parameters, a 5 m diameter rotor was developed and tested under actual wind conditions. The test results of the 5 m diameter rotor were compared with those of the corresponding model and also with those obtained through the off-design performance prediction method.