INTERNATIONAL JOURNAL of RENEWABLE ENERGY RESEARCH
Prasad S.S. et al., Vol.2, No.4, 2012

Optimized Design of Rotor Blade for a Wind Pump

Prasad S.S.*‡, Virupaxi Auradi**

*Digital Operations Supervisor, Technicolor India Pvt., Ltd.

prasadss@gmail.com, venkataramu_ps@yahoo.com

‡ Corresponding Author; Prasad S.S., Digital Operations Supervisor, Technicolor India Pvt., Ltd., +91 9972610716, prasadss@gmail.com

Received: 06.09.2012 Accepted: 03.10.2012

Abstract- Design of a rotor of a wind mill is very crucial to harness wind energy. The aerodynamic design of rotor involves optimizing the rotor and its components to produce maximum power co-efficient which is the ratio of actual rotor output to the wind energy available for a given rotor area. The design of a wind mill although looks simple but involves complex and detailed design of its components like rotor, transmission, load matching, yawing mechanism etc. In addition it also involves study of wind and estimation of its power carrying capacity. In this paper, a rotor for wind mill at Bagur of Hosadurga district (Karnataka) is designed to achieve maximum power coefficient by optimizing various parameters like no. and shape of blades, chord width, tip speed ratio etc.

Keywords- Wind energy, wind mill, rotor, blade, design, power coefficient.

1. Introduction

Water pumping is one of the most basic and widespread energy needs in rural areas of the world. It has been estimated that half the world's rural population does not have access to clean water supplies. [1]. Water supplies such as wells and dugouts can often be used for agricultural fields. However, the availability of power supplies is often limited, so some alternate form of energy is required to convey water from the source to a point of consumption. Wind energy is an abundant source of renewable energy that can be exploited for pumping water in remote locations. A wind pump is a windmill used for pumping water, either as a source of fresh water from wells. It is one of the oldest methods of harnessing the energy of the wind to pump water.

Wind power technology dates back many centuries. Wind machines which harness the power of the wind date back to the time of the ancient Egyptians. Hero of Alexandria used a simple windmill to power an organ whilst the Babylonian emperor, Hammurabi, used windmills for an ambitious irrigation project as early as the 17th century BC. The Persians built windmills in the 7th century AD for milling and irrigation and rustic mills similar to these early vertical axis designs can still be found in the region today. In Europe the first windmills were seen much later, probably having been introduced by the English on their return from the crusades in the middle east or possibly transferred to Southern Europe by the Muslims after their conquest of the Iberian Peninsula. It was in Europe that much of the subsequent technical development took place. By the late part of the 13th century the typical 'European windmill' had been developed and this became the norm until further developments were introduced during the 18th century. By the end of the 19th century there were more than 30,000 windmills in Europe, used primarily for the milling of grain and water pumping. The first half of the 20th saw further development, particularly a move toward propeller type wind machines for electricity production.

The major advances in the design of the wind pump, however, took place in the USA. The technology was taken up and developed by the early pioneers or settlers who needed a method of lifting ground water for irrigation, for watering of livestock and later for providing water for steam locomotives which began to spread across the country. There were several significant technical developments to the commercial machines during this time; the ability of the machine to turn into the prevailing wind automatically; the development of a self governing mechanism which automatically turned the machine out of the wind when the wind velocity became high enough to cause damage; various improvements in rotor design and general durability and the introduction of gearing mechanisms. The technology was soon taken up worldwide, especially in the newly settled arid regions, such as South Africa, Australia and Argentina, where previously a lack of water had always prevented settlement and economic development in remote areas.

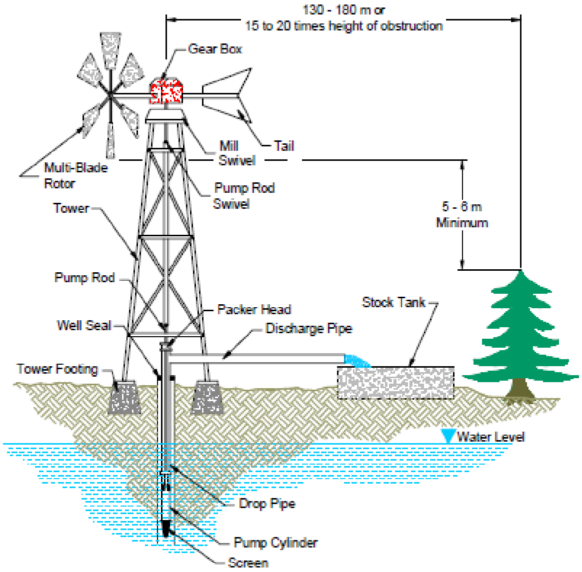

Fig.1. A typical windmill water pump

With the advent of cheap fossil fuels in the 1950's and 1960's and the development of pumping technology the wind pump became almost obsolete. In the recent years with regular fuel crises and rising prices there has been a revival of interest in wind power and wind pump. Wind pumps are very popular for rural areas of especially the developing world like Africa, Asia and Latin America for one of the following end uses:

- village water supplies
- irrigation
- livestock water supplies

In this paper an effort is made to design the rotor of a wind pump for a small scale agricultural irrigation application. The site at Bagur of Hosadurga district (Karnataka) was selected based on study of wind velocity pattern, where the wind velocity is good enough to sustain wind energy based irrigation solution for agricultural purposes. The blade geometry of rotor of a wind pump is optimized its best performance. The design procedure is adopted from the methodology used by National Aerospace laboratories, Bangalore for their wind machine installations. Since this design process involves a lot of mathematical calculations and computations, an effort is made to automate the process by using computer simulation using the design steps.

2. Design Procedure

The steps for design procedure of a rotor of wind mill for rural application is summarized in fig 2.

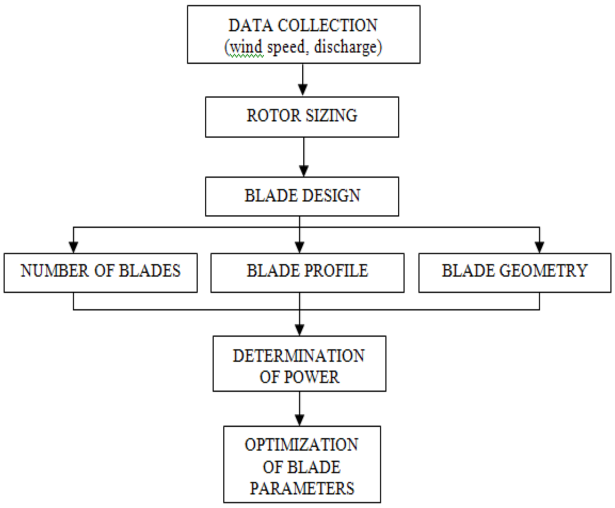

Fig. 2. Design procedure of a rotor of wind mill for rural application

2.1. Assumptions

The following assumptions are taken for designing the rotor of a windpump:

a. The wind is flowing at a constant speed of 6 m/s

b. The coefficient of wind power C_p is 0.3.

c. The transmission efficiency of gear box and other combinations is $\eta_t = 0.95$.

d. The efficiency of pump η_p is 0.35.

e. The rated discharge and rated head for the pump is 3.15 litres/sec and 7m.

f. The water for a small-scale irrigation is pumped at the rate of 90,000 litres/day.

g. The pump runs for 8 hours per day.

Based on the above assumptions the size of the rotor is selected. The blade profile is then optimized. Some of the other design parameters are listed below in table 1.

Table 1. Design Parameters for rotor of a wind pump

S No.	Design Parameters	Value
1.	Chord width at the tip	0.25 m
2.	Chord width at the root	0.5m
3.	Design tip speed ratio, λ	3
4.	Number of blades, B	3
5.	Angle of attack, α	4^o

a. Sizing of Rotor

The power carried by the wind is estimated by the equation

$$P = \tfrac{1}{2} \rho A V^3 \text{ Watts} \tag{1}$$

Assuming C_p (coefficient of power) to be 0.3 the power available at the output shaft of the rotor Pout is given by

$$P_{out} = 0.5\, C_p\, \rho A V^3 \text{ Watts} \tag{2}$$

Assuming the 95% transmission efficiency of gear box and other combinations, the power available at the input shaft of the pump is given by

$P_{in} = 0.5\ \eta T\ C_p\ \rho\ AV^3$ Watts (3)

The hydraulic power required to pump discharge (q) and head (H) is given by

$P_{hyd} = g\ H\ q$ (4)

The power required to run the pump is given by

$P = P_{hyd} / \eta_p$ (5)

Using the above data a proper rotor size is selected from design data book [3]

2.2. *Aerodynamic Design of Blade: Calculation of Blade Setting Angle β*

The blade is divided into 8 equal segments or elements. Now, consider in a unit element the local tip speed ratio is given by:

$\lambda r = \lambda_d\ r / R$ (6)

where,

r = radius of each element from the center of the rotor.

c = chords at radius r.

Φ = local angle between relative wind direction and rotor plane.

R = radius of the rotor

Then, we know that

$\Phi = 2/3 \arctan(1/\lambda_r)$ (7)

The local solidity, σ is given by

$\sigma = (B \times C)/(2\pi r)$ (8)

where, B = number of blades

We know that

$\Phi = \alpha + \beta$ (9)

where,

β= blade setting angle

α = angle of attack

2.3. *Calculation of Axial and Tangential Induction Factors (a & a')*

If the blades are manufactured assuming the linear twist for a constant angle Φ, we will not get the appropriate lift coefficient (C_1), drag coefficient (C_d) and the torque (T) as calculated theoretically. Hence to get realistic values close to the theoretical values of the power that the rotor can generate, it is essential to calculate the new value of FI using axial induction factor 'a' and tangential inductor factor a' using the following equations

$\Phi = \arctan((1-a)(1+a')) * (1/\lambda)$ (10)

where, a=G/(4+G)

a' = H/(4-H) (11)

where, G = σ(local)*C1*cos(Φ)/sin2Φ (12)

H = (σ1 * C1)/cos Φ (13)

For the values of FI calculated above, the values of a and a' are determined using the above formulae. The value of a and a' are calculated based on the new value of FI taking the previous values of a and a' from stage 1. This iteration is continued as shown below

a(from stage 1) - a(new) = 0 and

a'(from stage 1) - a'(new) = 0

2.4. *Calculation of Torque Coefficient*

Combining momentum theory and blade element theory, the torque that the individual blade element can develop can be calculated using formula

$$dC_q = (1-a)^2 \sigma C_1 \left(\frac{1-C_d}{C_1} * \frac{1}{tan\emptyset}\right) * \frac{2*r^2*dr}{R^3} \quad (14)$$

where dr = width of the element

r = distance between the centroid of the individual element to the center of the rotor.

As values of a, a' and C_d/C_1 are not known the above equations cannot be solved. Therefore first we will apply boundary conditions at 2,4,6 and 8 elements at which the aerodynamic properties are known. The torque contribution from individual elements can then be calculated using the above equations. The cumulative power coefficient can be calculated by using the equation:

$C_P = C_q * \lambda_{design}$ (15)

2.5. *Optimization of Blade Parameters*

For a given diameter of rotor the optimized values of blade parameters is calculated for maximum power coefficient. The blade parameters to be optimized are chord, number of blades and blade setting angles. A computer program in Turbo C is used for determining the CP of the machine for different blade parameters.

2.6. *Linearization of Blade Setting Angle*

The values of β varies from root to tip of the blade and is not linear. Fabrication such a blade with varying twist at each element is difficult and expensive. Hence, as per standard codes we have to keep the value of α between 2 - 8°.

3. Results and Discussion

The characteristic of a rotor is represented by C_P Vs λ graph, which is also known as the rotor performance curve as shown in fig 3. It can be seen from the graph that the value of CP is maximum for a tip speed ratio of 3. Hence a tip speed ratio of 3 is considered for further optimization.

Increasing the chord width or the number of blades may not necessarily result in higher CP on the other hand; a good combination of the blade parameters with lower chord width and fewer numbers of blades can result in higher CP.

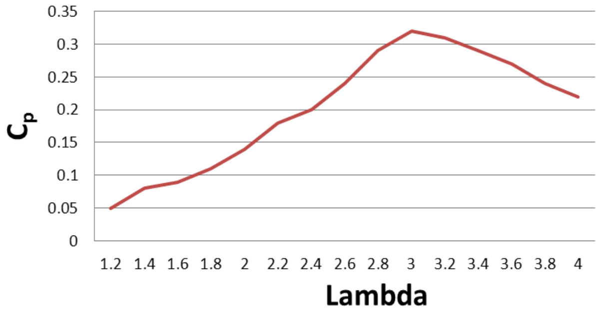

Fig. 3. Performance of rotor

In the present case, a blade with 30mm chord at the tip and 500 mm chord at the root with 4 blades and with twist varying from 8 degree at the tip to 32 degree at the root gives a CP of 0.43, which is the best for the rated wind speed and the diameter of the rotor.

4. Conclusion

The electrical connectivity of rural India is not very good and also that transmission and distribution losses are significant. An effort has been made in this paper to optimize the rotor of wind pump for achieving maximum efficiency. This work can be scaled up renewable energy applications rather than adding up to grid capacity. While there is no doubt that wind energy has great potential to add up to the gird capacity of our country it also presents a great potential for direct conversion to usable energy. So it is imperative upon us the engineering community that we innovate new ways to convert renewable energy to usable form and find ways to benefit the end user directly with energy available locally in their community.

Scope for Future Work

There is a lot of scope for refining the results with various combinations of number of blades, chord length and blade setting angle. The best design can then be considered for POC and pilot fabrication of the machine. Also there is scope for using different materials for the fabrication of blade which have better stability, efficiency and cost effective.

CFD is one of the powerful tool for analysis of blades of wind machines. CFD analysis of wind turbines is at the edge of what commercial CFD packages can offer and this creates the opportunity for research into CFD methods that will allow engineers to simulate complete turbines at realistic conditions. The key problems in CFD analysis are the difficulty in simulating the rotating blades, taking into account the effect of the tower supporting the turbine and the adequately modelling the structural response of blades of very large diameter. Other important effects include flow transition on the blades, modeling dynamic stall and 3D aerodynamic effects.

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