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Research Article

Design of Windmill for lifting Water

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Abstract

In our analytical design, we used 24 blades of a horizontal axis windmill. Each blade has a radius of 1.5 m gives a solidity of 1.018. The torque output of the windmill is 74.24 Nm and this is enough to withstand the desired flow rate of (2.31 X 10-4) m3 per second with a maximum head of 28m.

Keywords: *VAWT, HAWT, Solidity, Betz theorem, thrust coefficient.*

1. Introduction

The primary source of energy has been coal, oil, natural gas, nuclear energy, and wood. However, all these sources are limited in existence and these are cause of pollution and this has led to development and more focus on sustainable energy supply with minimum pollution effects. Hence research and development has shown that wind energy, solar energy and biomass are the important solutions to the above problems because they are eco-friendly and easily available in nature.

The main aim of this project was to design and development of a windmill and therefore our scope is limited to a windmill for water lifting.

Windmills are classified into two main types based on the axis about which they rotate. Horizontal axis have the main rotor shaft running horizontally and if the rotor must be oriented in the direction of the wind, a wind vane is coupled with a servomotor. Vertical axis have the main rotor shaft running vertically. The rotor assembly can have two or more blades depending on the desired solidity.

2. Objective

The primary focus of the project is to design of a windmill. Key parameters are given below.

1) Improving torque on the existing designs.
2) Improving efficiency based on the current designs.
3) The design must be a low-cost model.

3. Problem define

Wind is a natural and renewable resource that is freely available all over the world. Using this generated power for lifting water would save a lot on power costs that are continuously on the rise. Also, wind power is available in remote regions where power grid not exist. A windmill provides the best way of using wind energy and using it lift water that is below the surface or delivering the water to elevated storage tank.

4. Design Scope

The design of a windmill is a very wide subject and therefore this design is based on analysis of various components of windmill and their actual drawings. This includes the rotor assembly i.e. the blade and the hub, transmission shafts (both vertical and horizontal) the gear box which houses the gears, actuating pulley and the piston actuating mechanism.

The design does not contain pump selection. the design process started off with analysis of the existing Windmill designs and their respective operating condition. In order to obtain the optimum design parameter such as Torque and power produced by the windmill, various calculations and structural analysis to be done.

5. Theory

5.1 Power Coefficient Cp

The power coefficient is defined as the ratio of the actual power output (Hw) to the theoretical power in the wind (Ht).

Power = Force * Velocity
Force= Rate of change of momentum

But,

Momentum= Mass * Velocity

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For a fluid of density (ρ), flows through a cross-sectional area of A,

The mass flow rate is given by

$\dot{m} = \rho . A . V$

Average force= ½ ρ.A.V^2

H_t=1/2 ρ.A.V^3

$C_p=H_w/Ht = \frac{H_W}{0.125\rho\pi D^2\, V^3}$

5.2 Swept Area, A_s

This is the section of air that encloses the wind turbin in its movement and interaction with the rotors to produce the rotary motion. For a Horizontal Axis Wind Turbine , the swept area is circular in shape. For a Vertical Axis Wind Turbine with straight blade, the swept area is rectangular in shape.

The swept area for the HAWT is calculated by:

A_S= ¼ π.D^2

Where: As – Swept area (m2)
D – Rotor Diameter (m)

NOTE: The rotor radius is the distance from the tip of one blade to the center.

5.3 Tip Speed Ratio

Tip Speed ratio is ratio of the speed of the windmill rotor tip, at radius R when rotating at radians per second rps to the speed of the wind V m/s. It is numerically represented as:

$\lambda = \omega . R / U_O$

When the windmill is stationery, the tip speed ratio is zero. This implies that rotor has stalled. This is experienced when the torque produced by the wind is below the level needed to overcome the resistance of the load. With a tip-speed ratio of 1, it implies that the blade tips are moving at the same speed as the wind At a tip speed ratio of 2, the tips are moving at twice the speed of the wind and so on.

From empirical results, the optimal tip speed ratio maximum power extraction is achieved for a windmill with N blades is:

$\lambda = 4\pi/N$

5.4 Specific Speed of the Windmill

This is the angular velocity in revolutions per minute at which a turbine will operate if scaled down in geometrical proportion to such a size that it will develop unit power under unit head.

5.4.1 Cut in Speed

This is the speed at which the turbine starts to produce any useful power. It is the lowest speed at which power output of the turbine Hw is greater than zero.

5.4.2 Cut out Speed

This is the wind speed at which the turbine stops to produce any useful power. This is the highest speed at which power developed by the wind turbine is just zero.

5.4.3 Rated Wind Speed

Wind speed at which the rated power is produced, this value defines the shape of the power curve.

5.5 Torque Coefficient, Ct

The torque coefficient is the non-dimensional measure of the torque produced by a given size of rotor in a given wind speed. This is given as the ratio of the actual torque produced to the torque due to the force of the wind on the rotors. It is represented mathematically by:

$C_t = \frac{T}{0.5\ \rho . A_S\ U_O}$

Where: T – The actual torque produced (Nm)
Uo – Wind speed (m/s)
As – Swept Area (m2)
R – Radius (m)

5.6 Rotor Solidity

Solidity of a windmill loosely refers to the proportion of a windmill rotors' swept area that is filled with solid blades. This is the ratio of the sum of the width or 'chords' of all the blades to the circumference of the rotor. This is represented mathematically by:

Solidity = $\frac{N . A_B}{A_S}$

Where:
N – Number of Blades
A_B – Area of one blade (m2)
As – Swept Area (m2)

At maximum efficiency, the tip-speed ratio is very low 1.25. The efficiency of the high solidity windmills is slightly lower than that of the faster types of rotors. These multi-bladed rotors have a much higher torque coefficient at zero tip-speed ratio (i.e. between 0.5 and 0.6) than any other types.

On the other hand, the low solidity rotors have a higher efficiency with the highest values of Cp. They have very high tip speed ratio. To achieve these optimum operating conditions, the rotors have to be set at a slight angle to the plane of rotation. The starting torque is very low implying that they can only start against the loads that require little torque to start them such as centrifugal pumps and electricity generators.

5.7 Thrust Coefficient C_T

This is non-dimensional measure of the force that falls on the windmill. It define as the ratio of the actual thrust force on the windmill to the average force from the wind.

It is represented mathematically as:

Force of wind= 0.5 $\rho . A_s \, U_o{}^2$

Thrust Force on the windmill, FT;

=0.5 $C_T \rho . A_s \, U_o{}^2$

6. Wind Power Derivation

6.1 Wind Power

Wind Power (P_w) or Kinetic energy per unit time = 0.5 $\dot{m}V^2$

Where:($\dot{m}$)=$\rho . A . V$

Thus Power (Pw) = ½ $\rho . A . V^3$,Watt

Where: A=swept area of blade (m^2)

=

Where: R =Radius of blade (m)

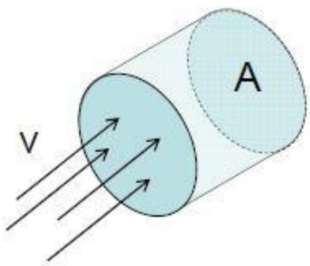


Fig 6.1: Illustration of area and velocity.

6.2 Efficiency in Wind Power Extraction

The efficiency in wind Power extraction is a function of Power Coefficient Cp, where Cp is the ratio of power Extracted by the Windmill to the total contained in the wind resource.

$Cp = P_T / P_W$

Windmill Power Extracted PT = $P_W \times Cp$ (Watts)

The Betz Limit is the maximum possible value for Cp which is equal to 16/27 but the optimum possible for a multi-blade windmill is 30%.

6.3 Torque Extracted

In the windmill, Torque output is given by the ratio power extracted to rotor speed.

$T = P_T/w$

Rotor Speed $w = \lambda . v/R$

Where: λ = Tip speed ratio

v= wind speed (m/s)

R = Length of blade (m)

But $P_T = ½ \, \rho . \pi . R^2 \, V^3 . C_p$ Watts

Therefore:

$T = \frac{\rho . \pi . R^3 . v^2 . C_p}{2 . \lambda}$ (Nm)

7. Power and Torque Characteristics

7.1 Power – Speed Characteristics

In order for the wind pump to work as desired, the pumping requirements must be matched with the wind speed as well as the rotor shaft power available. The sample figure below indicates how one would match a wind speed of 5 m/s with required pump power requirement.

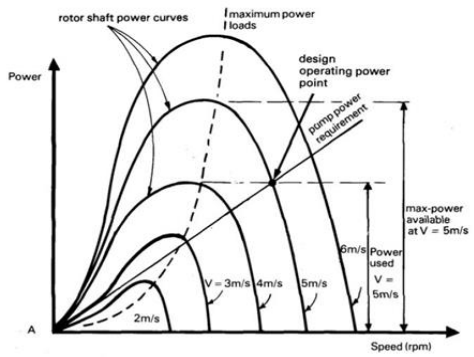


Fig 7.1: Power of a windmill as a function of rotational speed for various wind speeds. Source S.B Kedare (2003)

7.2 Torque-Speed Characteristics

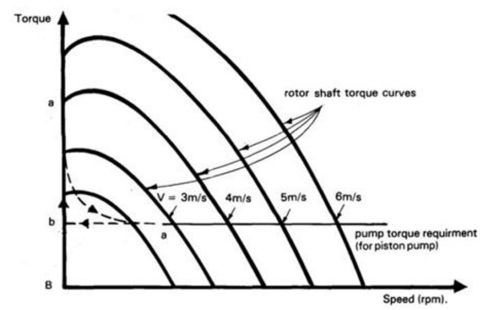


Fig7.2: Torque of a windmill rotor as a function of the rotational speed for the various wind speeds. Source S. B. Kedare (2003)

In pump selection, the rotor shaft torque has to be matched to the pump torque requirements as well. The pump in this case is the piston pump. The figure below shows how one would match a pump depending on the torque requirements.

8. Design of blade

8.1 Blade Design Consideration

Betz' Theorem

Power is extracted from the wind by decelerating it. There's however a limit as to how much power can be extracted from the wind. According to Betz' Theorem, this deceleration is as much as a third of the upstream velocity. This translates to 59.3%. Any further deceleration of the wind will divert the wind away from the rotor.

According to Newton's third law of motion; for every action, there is equal and opposite reaction. Therefore, the decelerating force on the wind is equal to the thrust force which the wind applies to the rotor. In designing the rotor, the main goal is to make sure that the thrust produced is able to produce Betz' optimum deceleration.

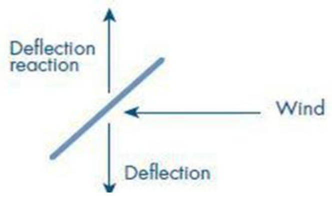


Fig 8.1: Illustration of the reaction force that causes thrust

The other source of the thrust that enables the rotors rotate is the Bernoulli Effect. According to the Bernoulli Effect theorem, faster moving air has lower pressure. The blades of the windmill are shaped such that the air molecules moving around the blade travel faster downwind side of the blade than those moving across the upwind side of the blade.

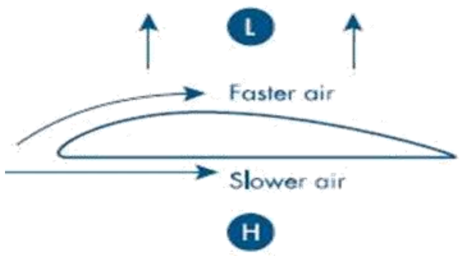


Fig 8.2: Illustration of the Bernoulli Effect causing lift (blade cross-section)

This shape is known as an aerofoil. The curve in the downwind side of the blade is much larger whereas the one on the upwind side is relatively flat. Given that the air moves at a faster velocity on the curved downwind side of the blade, the pressure on this side of the blade is less. This difference in pressure on the opposite sides of the blade causes the blade to get a 'lift' towards the curve of the aerofoil.

Torque and Speed

The two main components in mechanical power are force and speed. Torque is a twisting or turning force and pumping requires a lot of torque particularly when starting off from an idle state. Generators used for power production on the other hand require a lot of speed. The power might be the same but the pump and generator will utilize this power differently. The power from the rotor is a function of both torque and rotations per minute (angular velocity of the rotors).

Tip Speed ratio	No .of Blade	Functions
1	6-20	Slow pumps
2	4-12	Faster pumps
3	3-6	Dutch 4-bladed
4	2-4	Slow generators
5-8	2-3	Generators
8-15	1-2	Fastest Possible

The following table shows the typical choices for the tip speed ratio and blade number for the case of pump (windmill) and generators (wind turbine).

8.2 The Aerofoil

In the design of the cross-section (aerofoil) of the blades, there are some key considerations and specifications that should also be taken into account to ensure maximum thrust and lift. The following figure shows these important specifications.

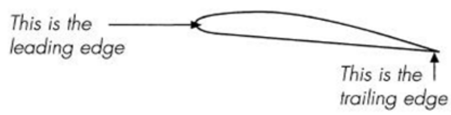


Fig 8.3: Illustration of the leading and trailing edges

The other important specification is the Angle of attack (α). This is the angle between the chord line and the relative air (or wind) movement. It is illustrated in the figure below.

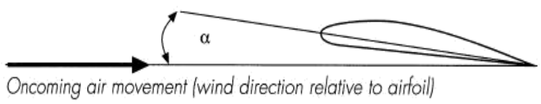


Fig 8.4: Illustration of the angle of attack

The angle of attack has a direct impact on the lift experienced and thus the lift coefficient as well. Wind tunnel studies have proved that the drag to lift ratio is not a constant factor. The best ratio is usually at an angle of attack of around 400.The Lift Coefficient (CL) is approximately equal to radians. The typical range of the Lift Coefficient is 0.8 to 1.25.The following table shows data for the different shapes.

Table 8.1: Data for some common blade cross-sections

Section	Sketch	Drag/Lift Ratio	Optimum angle of attack	Lift Coefficient (C_L)
Flat plate		0.1	5^0	0.8
Curved Plate (10% curvature)		0.02	40^0	1.25
Curved plate with tube on concave side		0.003	4^0	1.1
Curved plate with tube on convex side		0.2	14^0	1.25
Aerofoil		0.01	4^0	0.8

8.3 Calculation of the Rotor Radius

Power required to pump water is normally determined by the flow rate and the total head generated. This is shown below;

Water Horsepower $=\rho . g . Q . H$ Watts

Where: ρ - Density of water (kg/m3)
g- Acceleration due to gravity (m/s)
Q- Flow rate (m3/s)
H- Total Pumping head in meters of water

9. Proposed design requirements

Proposed head = 28 m
Proposed Volume Flow rate= 20m3 per day =2.31 × 10-4 m3 per second
Taking the daily mean wind speed in Pune.
Highest daily mean = 5 m/s
Lowest daily mean = 4 m/s
Given the average wind speeds, the lowest average mean wind speed was selected i.e. 4.5 m/s.
Power required to pump the water is given by:
Hydraulic Power, Ph= ρ.g.Q.H W
Substituting for g=9.81 m2/s;
Q = 2.31 × 10-4 m3/s; H = 28 m
= 1000 × 9.81 × 2.31 × 10-4× 28
= 63.58w

In order to the power required from the wind, various losses have to be considered. The table below shows various losses (wind energy handbook)

Table 9.1: Power losses in a windmill

Factor	Typical efficiency
Rotor to shaft	92-97%
Shaft to gear box	93-96%
Gear box	99 %
Pump	60-75%

Hence before losses occur, the input power to the system is given by:

Input = output/(efficiency)

- Before pump loss

Average Efficiency of pump is 70%
P = 63.58/70*100 = 90.82 W
This is the power that is transmitted from the shaft to the pump.

- Before shaft losses

Average efficiency of the shaft from the gearbox to the pump is 95 %.

P = 90.82/95*100 = 95.6 W
This is the power that is transmitted from the gearbox to the vertical shaft

- Before gearbox losses

Average efficiency of the gear box is given as 99% which is the actual efficiency of the gears
P = 95.6/99*100 = 96.56 W
This is the total power transmitted from the horizontal shaft to the gearbox.

- Before shaft losses

The efficiency of the horizontal shaft is given by 95%
P = 96.56/95*100 = 101.64 W

This is the amount of power required from the wind.
However, according to the Betz limit, the efficiency in wind power extraction is a function Power Coefficient Cp, where Cp is the ratio of power Extracted by the Windmill to the total contained in the wind resource.
Cp= PT/P

Where: Windmill Power Extracted PT = P × CP

PT = ½ ρ.A.V^(3)*C_P

The Betz Limit is the maximum possible value for Cpwhich is equal to and therefore making the maximum efficiency being 59%. However the maximum practical value of Cp is 0.3 (wind power handbook).

Hence the power intercepted by the wind is given by:
Pwind = 101.64/0.3 = 338.8 W

This is the power in the wind.

The power can also be calculated by the formula:

Pw = ½ ρ.A.V^(3)

Where: A- Area covered by the blades
ρ= Density of air at ambient condition

V=Mean wind speed = 4.5 m/s

Pw =
1/2 * 1.205.A.(4.5)^(3)

A_s= 6.14 m^2

Area of rotor $A_S = \pi . R^2$

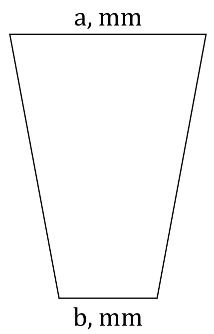
Radius of rotor R= 1.47m= 1.5m

Diameter of rotor= 3m.

Solidity = $\frac{N \times A_B}{A_S}$

Where,
N–Number of Blades
A_B–Area of one blade (m2)
As–Swept Area (m2)

Here we used N=24



here, in this design a= 390mm, b=150mm and height h=1200mm
so area of trapezium shape = ½ ×[1.2(0.35+0.15)]
$A_{B} = 0.3\, m^2$

Solidity = $\frac{22 \times 0.3}{7.0688}$ = 1.01

Torque developed

Torque is given by the ratio power extracted to rotor speed.

T =P_T/w

Rotor Speed w=$\lambda . v/R$

Where: λ = Tip speed ratio
v= wind speed (m/s)
R = Length of blade (m)

But P_T= ½ $\rho . \pi . R^2 \, V^3 . C_p$ Watts

Therefore:

$$T = \frac{\rho . \pi . R^3 . v^2 . C_p}{2 . \lambda} \quad \text{(Nm)}$$

$$= \frac{1.207 \times \pi \times 1.5^3 \times 24 \times 4.5^2 \times 0.3}{2 \times 4\pi}$$

= 74.24Nm.

Conclusion

From the design, it can be concluded that

- The total torque output of the windmill is 74.24 Nm and this is sufficient to sustain the desired flow rate of (2.316 X 10-4) m3 per second with a maximum head of 28m, and also to overcome other barriers to motion e.g. friction.
- The number of blades used is 24 & this gives a solidity of 0.8, the minimum (optimum) value of solidity for a windmill and therefore ensures conformity with the standard specifications.

Recommendations

The next phase of the project should be the fabrication and testing of the windmill. The focus should then shift to the effectiveness of the windmill by improving the efficiency and reducing losses that might be in the present design.

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