© AUG 2019 | IRE Journals | Volume 3 Issue 2 | ISSN: 2456-8880

Design Analysis of 1.5 kW Horizontal Axis Wind Turbine

THIN THIN MAW[1], AYE THAWI THAWI TUN[2], KHIN OHNMAR MYO[3], CHO CHO KHAING[4]
[1]*Department of Mechanical Engineering, Technological University (Loikaw)*
[2]*Department of Mechanical Engineering, Technological University (Magway)*
[3]*Department of Mechanical Engineering, Technological University (Magway)*
[4]*Department of Mechanical Engineering, Technological University (Magway)*

Abstract -- This paper focuses on designing the turbine for an H-rotor type wind turbine (1 kW). It can be used for many purposes including electricity production. Darrieus turbines, the turbine design, which are lift-driven, have a higher power potential than the horizontal, or drag-driven turbines. Power transmission is important for these machines. It is studied base upon the use of the symmetrical NACA0012 turbine blade profile. This research is invented not only to introduce wind power plant but also to analyze wind turbine blade design, i.e chord length, angle of attack. The transmission system is needed to design for the convenience of rotation with appropriate rpm smoothly and no vibrating.

Indexed Terms: Turbine, H-rotor, electricity, power plant, blade

I. INTRODUCTION

Man has always been fascinated by the energy in the wind, perhaps because it is there free, just to be used or so he believes. For centuries, wind energy has been used for many applications such as grinding corn, sailing ships, pumping water and lately for generating electricity. The history of wind mills is lengthy and dates back to about 500 BC when the use of wind mills for pumping water had been documented in a Hindu epic called. Kautilya Arthasastra[4].

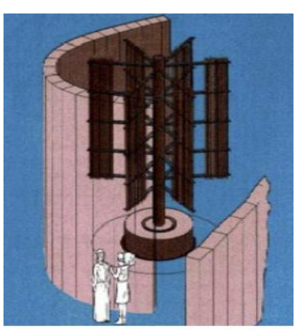


Fig.1. A Simple Vertical Axis Panemone [2]

Around 200 BC Persia developed a simple vertical axis panemone (Fig.1) for grinding grains. Originally, the millstones were placed above the rotor blades. Later on, the design was modified and the millstones were situated under the rotor. Perhaps it was learnt that the wind speed increases with height and the modified design would be more efficient and convenient for the miller as well [4].

There was not much advancement in technology until the late 19th century when the wind turbines were developed for the first time for generation of electricity. In 1891, Paul la Cour developed the first wind turbine for generation of electricity in Denmark shown in (Fig.2) [4].

Fig. 2: Developed Wind Turbines [1]

II. WORKING PRINCIPLE OF WIND TURBINE

The working principle of Darrieus rotor can be simplified as below. First, assume that the retarded wind in front of the rotor still remains straight. When the blades are moving much faster compared to the original undisturbed wind speed i.e. ratio of blade speed to free stream wind speed, TSR > 3. The Figure

3.1 shows the velocity vector of the airfoil blades at different angular position [6].

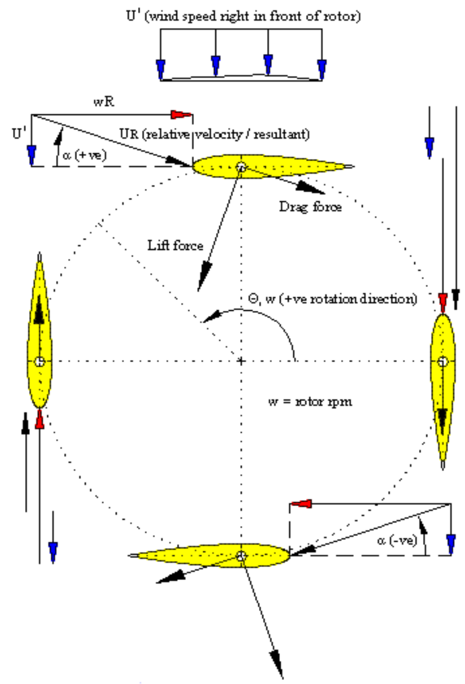


Fig.3. Working system of Vertical Axis Wind Turbine [4]

With such a high TSR, the airfoils will be 'cutting through' the wind with small angle of attack. The resulting lift force always assists the rotor rotation while the drag force always opposes the rotation. As the lift zeroing at the left side (0 degree) and right side (180 degree) where the symmetrical airfoil moves paralleled towind, the torque changes to negative around these position. At the near front (90 degree) and far back (270 degree) position, the lift component is much higher than the drag component, so positive torque is produced. The total torque per revolution will be positive with a good set of airfoils so the rotor will accelerate at the right direction.

During startup, the starting torque depends on the angular position of rotor with respect to the wind direction, so the rotor might rotate at the right direction straight away or wobble a bit before starting. Normally, the rotor will need some form of assistance to reach higher rpm before it begins to rotate by itself as the Darrieus rotor has very low torque at low TSR which can be easily worsened (till negative) by friction in the system [6].

III. THEORETICAL ANALYSIS OF WIND POWER

The power contained in a freely flowing wind stream of cross sectional area A can be expressed as shown in Fig.4.

Fig.4. Wind Stream of Cross Sectional Area

Power = (Volumetric flow rate) x (Kinetic energy per unit volume)

$$P_{wind} = (A\,V) \times \left(\frac{1}{2}\rho V^2\right)$$

$$P_{wind} = \frac{1}{2}\rho A V^3$$

$$= \frac{1}{2} m V^2$$

Where, V = the wind speed (m/s)
ρ = the air density (kg/m^3)
m = the mass flow rate of wind (kg)

Assuming air to be a stable mixture of perfect gases, the air density ρ can be derived from Perfect gas equation as under:

$$PV = m\,R\,T$$

$$\frac{m}{V} = \frac{P}{RT}$$

$$\rho = \frac{P}{RT}$$

Where, P = the absolute pressure in N/m^2
T = the absolute temperature in K and
R = the gas constant for dry air , 287.1 J/kg K

Strictly speaking, R should be gas constant for moist air, which will vary depending upon the moisture content of the air. Since the moisture content present in the air is very small (usually varying between 0.0003 to 0.003 kg/kg of dry air depending upon temperature and pressure), the use of gas constant for dry air introduces negligible error in calculations and is a standard practice for computation of air density [10].

IV. COEFFICIENT OF PERFORMANCE

Coefficient of Performance is defined as the ratio of power extracted by a wind turbine to the total power available in the cross sectional area of the wind stream subtended by the wind turbine. It is generally denoted by C_P and mathematically, and it can be expressed as follows.

$$C_P = P_{turbine} / P_{wind}$$

Therefore, power extracted by a wind turbine can be expressed as

$$P_{turbine} = 0.5\, C_P\, \rho\, A\, V^3$$

Where; A = the swept area of the rotor and
V = the speed of freely flowing wind stream.

Coefficient of Performance is a measure of turbine efficiency and is generally used to compare the performance of various rotors.

Betz limit: Theoretical Value of Cp for Extracting Maximum Power from Wind

Consider a wind rotor to be placed in the path of free flowing wind stream at wind speed V_O as shown in Fig.5. As the wind passes across the rotor, it extracts a fraction of the energy from the wind so that its speed at the exit from the rotor reduces to V_2. The power extracted by the rotor from the wind is given by the following expression:

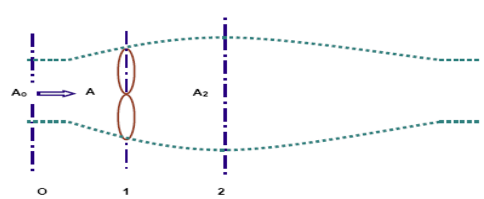


Fig.5. Free Flowing Wind Stream

$$P_{turbine} = 0.5\, m\, V_0^2 - 0.5\, m V_2^2$$
$$= 0.5\, m\, (V_0^2 - V_2^2)$$

Let F be the mean thrust acting on the rotor due to wind. By Newton's second law of motion, it can be written as

F = Rate of change of momentum

$$F = m\,(V_0 - V_2)$$

If V is the wind speed at the rotor, the power extracted by the rotor can also be written as $P_{turbine} = F\,V$

$$V = P_{turbine} / F$$

Substituting $P_{turbine}$ and F from above equation respectively,

$$V = 0.5\,(V_0 + V_2)$$

Also by conservation of mass,

$$m = \rho\, A_0 V_0 = \rho\, A\, V = \rho\, A_2 V_2$$

Therefore, $P_{turbine} = 0.5\, \rho\, A\, V\, (V_0^2 - V_2^2)$

But, $P_{turbine} = 0.25\, \rho\, A\, (V_0 + V_2)\,(V_0^2 - V_2^2)$

$= 0.25\, \rho\, A\, (V_0 + V_2)\,(V_0 + V_2)\,(V_0 - V_2)$

$= 0.25\, \rho\, A\, (V_0 + V_2)^2\,(V_0 - V_2)$

$$P_{turbine} = 0.25\, \rho\, A\, V_0^3 \left(1 + \frac{V_2}{V_0}\right)^2 \left(1 - \frac{V_2}{V_0}\right)$$

Denoting the ratio of exit wind speed to initial wind speed by b i.e, $b = \frac{V_2}{V_o}$,

$$P_{turbine} = 0.25\, \rho\, A\, V_0^3\, (1 + b)^2\, (1 - b)$$

By definition of coefficient of performance,

$$P_{turbine} = 0.5\, C_P \rho\, A\, V_0^3$$

$$C_P = 0.5\,(1 + b)^2\,(1 - b)$$

Determining the velocity ratio b, which will yield the maximum value of C_P.

By using, $\frac{dC_P}{db} = 0$,

$(1 + b)(1 - b) - 0.5\,(1 + b)^2 = 0$

$(1 + b)(1 - b - 0.5 - 0.5b) = 0$

$b = -1$ or $b = 1/3$

$$\frac{d^2 C_P}{db^2} = -2b - 1 - b = -3b - 1$$

$$\left.\frac{d^2C_P}{db^2}\right|_{b=\frac{1}{3}} = -2 < 0$$

Therefore C_P is maximum at b =1/3and the maximum value is given by

$C_{P\,max} = 0.5\,(1 + 0.33)^2\,(1 - 0.33)$

$= 0.593$

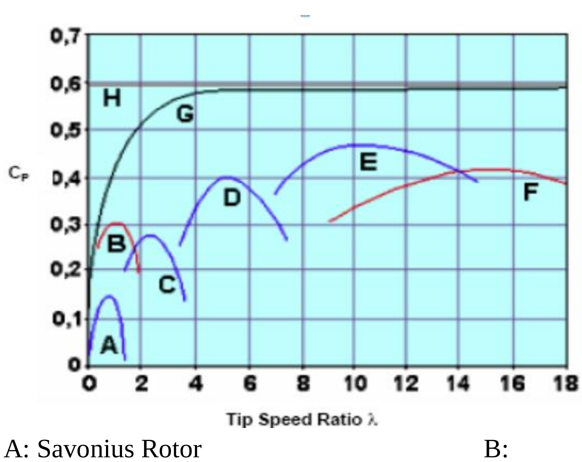
This is known as Betz limit after the name of the person who first derived it. Its significance lies in the fact that it puts a limit on the fraction of the wind energy, which can be extracted by any wind turbine [10].

Tip Speed Ratio

It is defined as the ratio of tangential or peripheral linear speed at the tip of the blade to the free flowing wind speed. It is usually denoted by λ and is mathematically expressed as follow:

$\lambda = \omega r / V$

Where ω is the angular speed of the rotor;r is the radius of rotor and V is the speed of free flowing wind stream.



A: Savonius Rotor B: American Multi Bladed Rotor
C: Dutch Four Arm Rotor D: Darrieus Rotor
E: Modern Two Bladed HAWT F: Single Bladed Rotor
G: Ideal Propeller H: Betz Limit

Fig.6 Variation of Coefficient of Performance

The variation of coefficient of performance, C_P with tip speed ratio λ for various types of typical rotors is shown in Fig.6. By wind tunnel experiments, it has been found that a two bladed HAWT of good aerodynamic design can achieve C_P of 0.48 at tip speed ratio of around 9-11.Likewise a Darrieus rotor has been found to attain a C_P of nearly 0.39 at tip speed ratio of around 5.

$P_{turbine} = 0.5\, C_P \rho\, A\, V^3$

The power extracted by turbine from wind can also be written as product of torque (τ)

$$\tau = \frac{0.5 C_P \rho A r V^2}{\lambda}$$

V. ROTOR SOLIDITY

Rotor solidity, usually denoted by S, is defined as the ratio of the projected area of a rotor to its swept area.

$$S = \frac{\text{Projected area of rotor}}{\text{Swept area of the rotor}}$$

Solidity ratio is always less than 1. A rotor with a high value of solidity ratio has usually high starting torque but low rotational speed. On the other hand, a rotor with low solidity has high operating speeds making it suitable to be coupled with an alternator for generation of electricity.

Turbine Solidity as a Function of TSR:

The operating tip-speed ratio (TSR) for a Darrieus rotor lies between 4 and 6. This design TSR then determines the solidity, gear ratios, generator speeds, and structural design of the rotor.

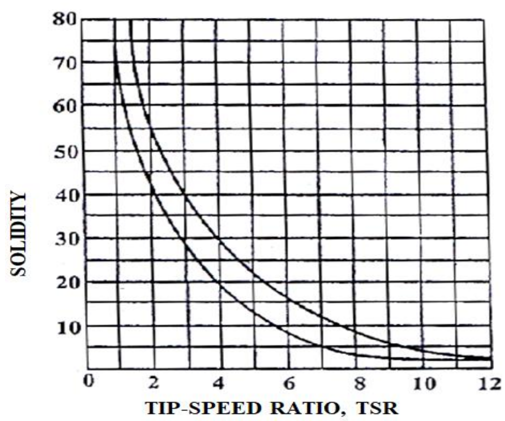


Fig. 7: Rotor Solidity as a Function of TSR

Using this TSR and the graph as show in Fig.7, a value of the solidity is selected. As in the prop-type rotor, the solidity allows for the calculation of blade area.

Solidity times the rotor frontal area gives the total blade area. Dividing the total blade area by the number of blades (usually 2 or 3) gives the individual blade area. The individual blade area divided by the rotor height gives the chord length.

VI. NUMBER OF REVOLUTION (N)

The number of revolution can be defined as

$$\omega = \frac{2\pi n}{60}$$

So, $\lambda = \frac{2\pi n r}{60V}$, $n = \frac{\pi 60V}{2\pi r}$

Rotor Sizing as a Function of Power Required

The rotor diameter required depends upon the power output needed, the wind region in which it must operate, and the tip-speed ratio chosen. Allowance must be made for losses in the generating machine, the transmission system, and all either parts of the drive train. The rotor must therefore develop a good deal more power than the generator outputs [9].

The power of the wind is proportional to air density, area of the segment of wind being considered, and the natural wind speed.

$$P_w = \frac{1}{2} \rho A V^3$$

Where,

P_w = the power of the wind (W)

ρ = The air density (kg/m^3)

A = area of a segment of the wind being considered

V = undisturbed wind speed (m/s)

A turbine cannot extract 100% of the winds energy because some of the winds energy is used in pressure changes occurring across the turbine blades. This pressure change causes decrease in velocity and therefore usable energy.The mechanical power that can be obtained from the wind with an ideal turbine is

$$P_m = \frac{1}{2} \rho A C_p V^3$$

Where,

P_m = Output power of turbine

Cp = coefficient of performance

Air density, ρ, varies with altitude and temperature. For standard atmosphere, the density below (6,096 m) is closely approximated by the relation

$$\rho = \rho_0 \exp(-0.297h/3048)$$

Where,

$\rho_0 = 1.22496\ kg/m^3$ and h is in meter.

The air temperature defined for the standard atmosphere is a linearly decreasing function of altitude given by

$$T = 15-1.983\ (h/304.8)\ °C$$

Design Calculation of Horizontal Axis Wind Turbine

Power Output:

Firstly, the size of the rotor can be calculated by the following equation,

Sizing of the rotor,

$$A = \frac{2\times P_{output}}{\rho\times C_P \times \eta_{m1} \times \eta_g \times \eta_{m2} \times V^3}$$

P = the generated power output (1.5 kW)

ρ = the density of air (1.225 kg/m^3)

V = Wind speed (10 ms^{-1})

η_m = Mechanical efficiency = 0.85

η_g = generator efficiency = 0.75

C_P = power coefficient = 0.3

$$A = \frac{2\times 1500}{1.225\times 0.3\times 0.85\times 0.75\times 0.85\times (10)^3}$$

A = 15.0648 m^2.

A = high × width = 4 m × 4 m (Design Data)

Power of the wind (W) = Input Power to Turbine

$$P_w = \frac{1}{2} \times \rho \times A \times V^3.$$

Then, the power output from Turbine = P_m.

$$P_m = C_p\, P_w$$

$$P_m = \frac{1}{2} \times \rho \times A \times V^3 \times C_P.$$

$$= \frac{1}{2} \times 1.225 \times 4 \times 4 \times (10)^3 \times 0.3$$

$$= 2940 \text{ Watts}$$

Transmission I, the output power = P_{t1}.

$$P_{t1} = \eta_m \times P_m$$

$$= 0.85 \times 2940 = 2493 \text{ Watts}$$

Transmission II, the output power = P_{t2}.

$$P_{t2} = \eta_m \times P_{t1}$$

$$= 0.85 \times 2493 = 2119 \text{ Watts}$$

The output power of generator = $P_e = \eta_g \times P_{t2}$.

$$= 0.75 \times 2119$$

$$\approx 1.5\text{kW}$$

The Choice of Solidity and Number of Blade:

The choice of solidity and the number of blades is important and difficult. The higher the solidity, the higher the power produced and it become higher the torque. Therefore, it may be as high as possible. But rotors with higher solidities run at lower rotational speeds and required more expensive gear boxes. Therefore optimal solidities have been found to be range of 0.1 to 0.2.

Before choosing a final design, it is necessary to determine the number of blades the turbine would have. For a 2- blade turbine, there are times when both blades are in a position such that the wind does not encourage rotation. This is known as the stall position. For a 3-blade turbine, the stall condition is eliminated.

Similarly, two blades involve lower manufacturing cost but three or four blades mean a more uniform torque and easier starting. This is a conceptual reasoning; however, the analysis model is used to test this conceptual reasoning.

Solidity leads to get the blade chord. It can be seen that the main parameter in determining the torque from the turbine is the length of the chord. The torque produced, while in the Darrieus working position, also varied with the chord length of 0.2 and 0.25, which can be seen in Fig.8 and Fig.9.

The final design is chosen the chord length of 0.25 m blades. Thus the solidity range of 0.3 is chosen. This design selection provides an increase Reynolds number for the flow over the blades and subsequently, increases the lift.

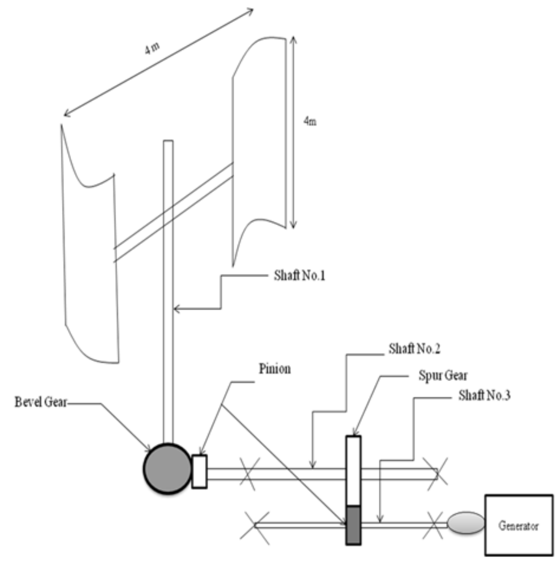


Figure C.1. Sketch of the Support System

Torque Producing Forces F_1 and Centrifugal Forces F_2 of Chord length 0.25 Blade and Results

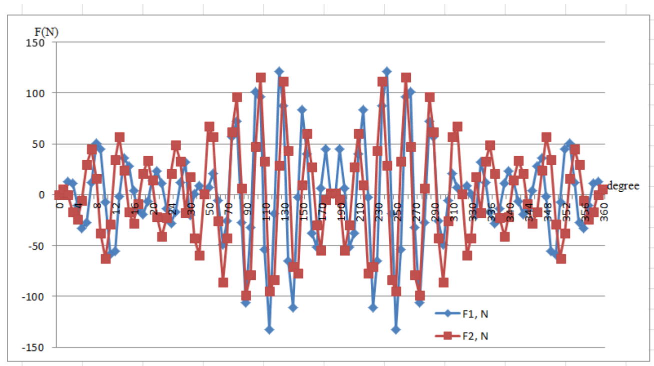


Fig.8. Torque producing Forces for Chord Length 0.2 m and 0.25 m Turbines at TSR = 5

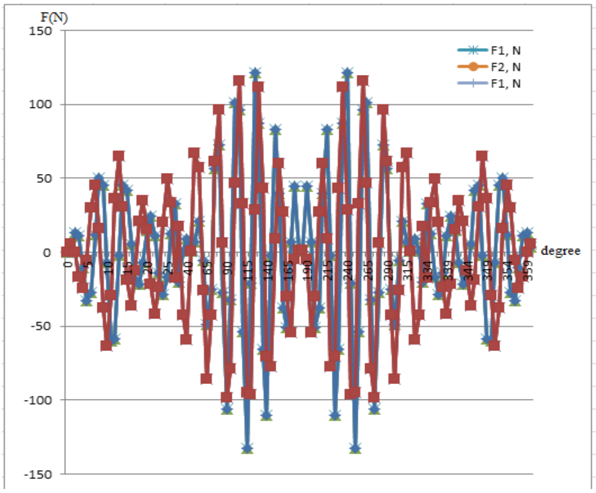


Fig.9. Torque producing Forces for Chord Length 0.2 m and 0.25 m Turbines at TSR = 7.

VII. CONCLUSION

This research papercan be one of the fulfillments of development in wind energy system. As it is mentioned, in this paper wind energy is the one of the best way of clean and cheap energy and most of energy source will based on wind energy in the future. The Vertical Axis Wind Turbine (H-type) is used. All of the materials selected are available from the local market. The major components are rotor blades, generator, gears and electrical equipment. The rotor blade is selected from NACA0012 series.

The selected chord length of the airfoil blade is 0.25 m because the comparison of c = 0.2 and c = 0.25 showed in Fig 8. and 9. Initially, the less torque and the largest centrifugal force are found at the angle of attack approximately 6°.

REFERENCES

[1] J. C. Tannehill, D. A. Anderson, R. H, "Pletcher, Computational Fluid Mechanics and Heat Transfer". Second Edition, January 1997.

[2] John D. Anderson, Jr., "Computational Fluid Dynamics, the Basics with Application". McGraw-Hill Series in Mechanical Engineering, 1995.

[3] Toro EF., "Riemann Solvers and Numerical Methods for Fluid Dynamics: A Practical Introduction". Springer, 1997.

[4] Grant Ingram. "Wind Turbine Blade Analysis using the Blade Element Momentum Method". Version. I, 2005. [1] Martin O. L., Hansen, "Aerodynamics of Wind Turbines". Second Edition, 2008.

[5] Emrah Kulunk, Nadir Yilmaz, "Aerodynamic Design and Performance Analysis of HAWT Blades". FEDSM2009, Colorado, USA, 2009.

[6] Tony Burton, David Sharpe, Nick Jenkins, Ervin Bossanyi, Wind Energy Hand Book.2001.

[7] David A. Spera, "Wind Turbine Technology", 2003.

[8] BUTLER N.D, 2006. Design Optimization of a Wind Turbine Gearbox and Bearings, M. Sc THESIS, Cranfield University.

[9] BTM Consult ApS. International wind energy development - World market update 2007. BTM Consult Aps., I. C. Christensens Allé 1, DK-6950Ringkobing, Denmark, 2008.

[10] Danish Wind Industry Association, www.windpower.org

[11] Eriksson, S.2008. Direct Driven Generators for Vertical Axis Wind Turbines. Digital comprehensive Summaries of Uppsala Dissertation from the Faculty of Science and Technology 547.88 pp. Uppsala. ISBN978-91-554-7264-1. (http://urn.kb.se/resolve?urn=urn:nbn:se:uu:diva-9210)

[12] F. Robelius. 2007, Giant oil fields - the highway to oil. ISBN 978-91-554- 6823-1,Uppsala, Sweden. Ph.D. dissertation, Digital comprehensive summaries of Uppsala dissertations from the faculty of science and technology.