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Principle of Rotor Design for Horizontal Axis Wind Turbines

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Abstract: To increase the efficiency of wind turbines, rotor planning principles are very important for wind turbines with horizontal axis. It is not possible to expect the maximum efficiency from a wind turbine that is installed without doing the optimization processes. At this point, rotor blades aerodynamic features are very important. It is necessary to put forward the power value that can be obtained from rotor blades. It is possible to conduct power tests indoors or under natural conditions. But in both methods, real rotor blades have to be produced. And this means cost. For this reason, first miniature blades can be produced and the tests can be conducted on these miniature rotor blades. This, along with theoretic studies, will help us to have a good opinion.

Key words: Wind turbine, rotor design, aerodynamic, HAWT

INTRODUCTION

Humans used the fire as the first energy sort, except the food. Humans lived only with the food until use of the fire. In addition, humans separated with use of the fire from the other alive. Afterwards one used the wood for the fire to burn and it not extinguishes. They had to division of labour with the social living. Therefore humans used a new energy sort. The new energy sort was another humans. Because of nomadic life had to move from a place to other. The result of nomadic life was used the animals for transport. Another energy sort used by humans is water power. This had been used with end Nomadic life by humans. And humans have used the wind for sailing boats and in 12th Century (D.C.) with windmill. After 16. Century increased particularly the energy consumption because of the coal production. Petroleum was used in 19 Century. Ages of the industry began with petroleum and large humans' municipality affected. Afterwards humans discovered the nuclear energy (Inan, 1995).

End of the 20th Century began it problems with environment. And that us led to clean and renewable energies. This clean and renewable energies are sun, geothermal, biomass, water power, wind etc. (Inan, 1995).

All of the energy that earth's surface needs come from the Sun. Approximately 1-2% of that energy is transformed into wind energy (Vindmolleindustrien, 2006). Thus, we can say wind energy is solar energy that is transformed into velocity energy (kinetic energy) (Karadeli, 1999). Wind is defined as the movement of air in the atmosphere to balance the heat imbalance that is caused by uneven heating of air by the main energy source, the Sun (Ozdamar and Colak, 2000).

The main forces in atmosphere that produce wind and effect its speed is; pressure grading force, diverting force, centrifugal force and friction force (Yavuzcan, 1974). Pressure gradient force acts to move the air from high pressure to low pressure. Diverting force affects the air from two ways: one is as diverting force of earth's rotation for movements that are created along latitude circles and the second one is as diverting force of earth's rotation for movements from the equator to poles or in the opposite direction. Winds, in general, are under the effect of a force that wants to divert them from their centre because they curl around a centre. This force is called centrifugal force. Friction force tries to decrease the speed of wind. The effect of this force is the greatest when near to earth's surface (Yavuzcan, 1994).

IMPORTANCE OF ROTOR

Rotor is the organ that transforms the kinetic energy of wind to mechanic energy. For this reason it is very important for wind turbines. It is very important for rotor and rotor blades to have optimum features, because these have a direct effect on the efficiency of wind turbines.

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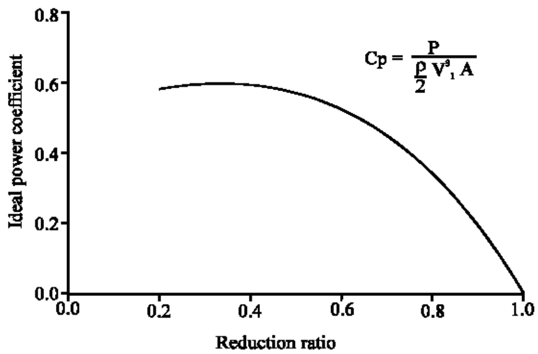

Fig. 1: Power coefficient (Cp) according to Betz (1926)

A flow mass has a kinetic energy because of its speed (Klug, 2001).

$$E = \frac{m}{2} \cdot V^2 \quad (1)$$

The achievement derives from the energy per time. Computes of the mass flow:

$$m = \rho \cdot V \cdot A \quad (2)$$

Into these conditions we can compute the power with the following equation (Klug, 2001);

$$P = \frac{\rho}{2} \cdot A \cdot V^3 \quad (3)$$

Power equity gives the theoretic power that can be obtained from the kinetic energy that is stored in wind as Watt. This theoretic power has to be transformed into useful power by the help of turbine rotor. At this point a constant, which is effected by wind speed, turbine shaft speed and blade choice has to be taken into consideration. This constant is called ideal power constant (Cp). Blade type, blade form, inclination angle and speed of blade's tip are effective factors in here. In Fig. 1 the diagram of the ideals power coefficient. Theoretically ideal power constant cannot exceed 0.59. This constant is called Betz constant. In practice, this value is even smaller (Becenen and Eker, 2001). Because mechanical losses (η) come into effect in practice. But mechanic efficiency value can be neglected in calculations, because it is close to 1. Our equation with this knowledge is below:

$$P = \frac{\rho}{2} \cdot A \cdot V^3 \cdot Cp \cdot \eta \quad (4)$$

One thing that must not be forgotten in here is that air density is 1.225 kgm^{-3} under standard meteorological conditions (temperature: 15°C and air pressure: 1013.3 hPa) (Klug, 2001). The changes in air temperature and air pressure will change air density.

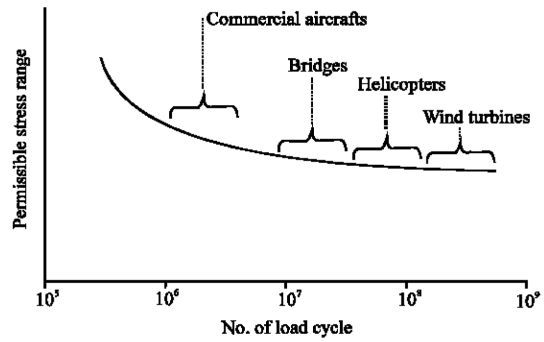

Fig. 2: Number of cycles of different structures during lifetime (Klug, 2001)

THE WIND TURBINE ROTOR AND THE OTHER CONSTRUCTIONS

In Fig. 2 number of cycles of different structures during lifetime.

Commercial airplanes have more stress than the bridges and the helicopters. Opposite this is lower the number of revolutions than the bridges and the helicopters. In this sequence, the bridges come after from the commercial airplanes. The helicopters have more stress than after the bridges. And the wind turbines come at the last sequence. This knowledge shows us the wind turbines not very much stress, although has higher numbers of revolutions works.

INTENTION THAT ROTOR DESIGN

- To low wind velocity high power supply.
- Supply the high power to low hub height.
- Supply the high power in small rotor diameters.
- The power coefficients of the rotor increase.
- Optimal the tip speed ratio of the rotor produce.

ROTOR DESIGN PRINCIPLES

Obtaining maximum energy production from a wind turbine depends on various factors. These are factor like the height of wind turbine; wind turbine blade's sweep area and aerodynamic structure, air density and wind speed. The most important ones of these factors are the height of wind turbine and aerodynamic structure of wind turbine blade. The height of wind turbine is important because wind speed increases as we go away from earth's surface (Yavuzcan, 1994; Klug, 2001). Aerodynamic structure of wind turbine blade is important, because it can transform maximum 59% of the kinetic energy that wind has to useful energy (Klug, 2001).

Rotor aerodynamic of wind turbine: In transformation of wind energy, which is formed by heating of different

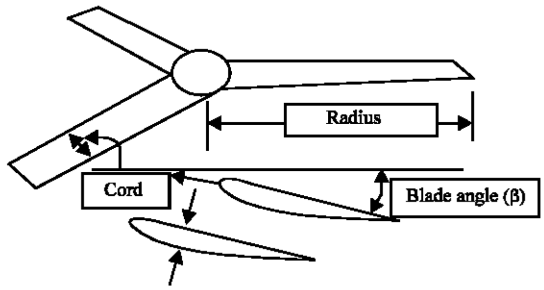

Fig. 3: Adjustment the angles β (Piggott, 2006)

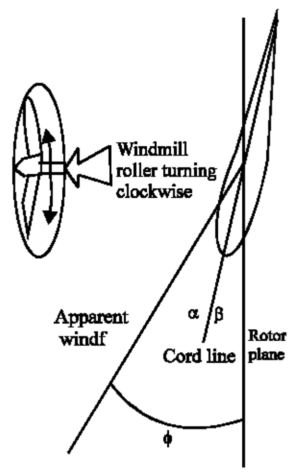

Fig. 4: Some angles of sheet profiles (Piggott, 2006)

points of the atmosphere by the main energy source sun, to electric energy; wind rotor, which is the first ring in transformation chain, can be designed according to Betz or Glaubert-Schmitz for the purpose of transferring the existing wind power with minimum loss (Ozdamar and Kavas, 1999).

Computes rotational speed of a blade element of rotor, which lies with distance r of the rotor center, like down (Ozdamar and Kavas, 1999):

$$V_r = \omega r = \frac{\pi n r}{30} \quad (5)$$

And the tip speed ratio of rotor can compute with the following equation (Ozdamar and Kavas, 1999).

$$\lambda = \frac{V_r}{V} = \frac{\pi \cdot n \cdot r}{30 \cdot V} \quad (6)$$

In a blade design must adjust the angles beta (Fig. 3), in order to use the cord at the blade (Piggott, 2006).

Wind blowing from opposite direction, gathers up the real wind in order to give the visible wind that provides lifting and dragging forces (Piggott, 2006).

If a wind turbine rotor is wanted to be designed, then the assault angle is dependent on the visible wind's Φ

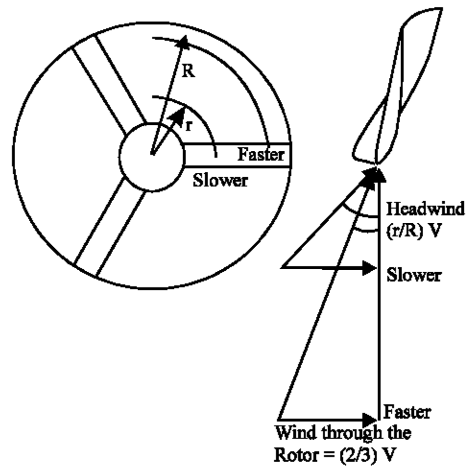

Fig. 5: That wind volume that the blade elements works (Piggott, 2006)

angle and blade angle (Fig. 4). Blade angle controls assault angle, thus it controls the lifting and dragging amount in the blade (Piggott, 2006).

In practice, most profiles produce the best lifting/dragging curve when the assault angle is 5 degrees. As a general principle, when detailed data cannot be obtained, giving this assault angle means exposing blade angle (Piggott, 2006).

$$\beta = \Phi - 5 \quad (7)$$

When blade angle is being prepared, cord width has to be prepared also. Here is the reason for this; every blade element is under the effect of a certain wind as a string in order to work. A string with radius "r" is small near the centre and it gets greater as it gets far from the centre and wind amount in the string is kept low. The most important part of the thing is blade's far most part from the centre (Fig. 5). The part that is closest to centre is less important, but inevitably it is in a different form (Piggott, 2006).

According to Betz, wind decelerates its speed in a ratio of 1/3 in every part of rotor's sweeping area and this deceleration is realized by pushing force that is closely related with lifting force. From this regulation the following equation comes (Piggott, 2006).

$$C = \frac{16 \cdot \pi \cdot R \cdot (\frac{R}{r})}{9 \cdot \lambda^2 \cdot B} \quad (8)$$

Compute for the blade number can use the following equation (Piggott, 2006):

$$B = 80 / \lambda^2 \quad (9)$$

The cord in the outside part of the blade can compute with the following equation (Piggott, 2006):

$$C = \frac{4D}{\lambda^2 B} \tag{10}$$

Blade's outer part is more important for rotor's movement. But blade's inner part has to be designed wider in order to help the rotation power at the start (Piggott, 2006).

Wind turbine rotor height: As wind speed gets away from earth's surface, it frees itself from the friction effect caused by the roughness of earth's surface. Thus it moves more freely. As it gets away from obstacles that decelerate its speed, its speed increases. It is assumed that winds that are 1000 m above the earth's surface, namely geostrophic winds are not affected by the roughness of earth's surface and friction losses. At the light of these thoughts, we can say that there is a relation between wind speed and wind height. This is the reason why wind turbines are built as high as possible (Becenen and Eker, 2001).

The wind speed values with the rotor axis height can compute with the following equation (Klug, 2001).

$$V(h) = \frac{u^*}{k} \ln \frac{h}{z_0} \tag{11}$$

The roughness coefficient of values into this equation comes from the observation, the assumption and the experience (Klug, 2001).

Wind turbine rotor diameter: Besides determining turbine height, the diameter of the wind that rotor blade sweeps has to be determined. The diameter of the wind that rotor blade sweeps has a direct effect on the power that will be obtained from turbine. Our rotor's diameter will determine the area of wind section that rotor sweeps (Klug, 2001).

$$P = \frac{\rho}{2} \cdot \frac{\pi \cdot D^2}{4} \cdot V_3 \cdot Cp \cdot \eta \tag{12}$$

The wind potential in where the wind turbine rotor will operate: Wind potential in where the wind turbine will be installed is very important. For this reason it is one of the parameters that have to be considered in rotor design. Wind speed potential in where the wind turbine will be installed has to be observed at least for 6 months. Wind potential is directly effective on the efficiency of the wind turbine rotor.

Wind speed is the most important factor about the energy of the wind. The power that will be obtained from wind is directly proportional to wind speed's third power.

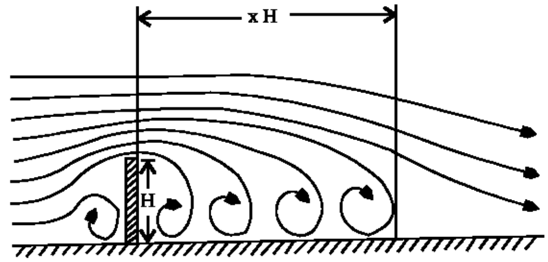

Fig. 6: Holding back the wind against that obstacle (Klug, 2001)

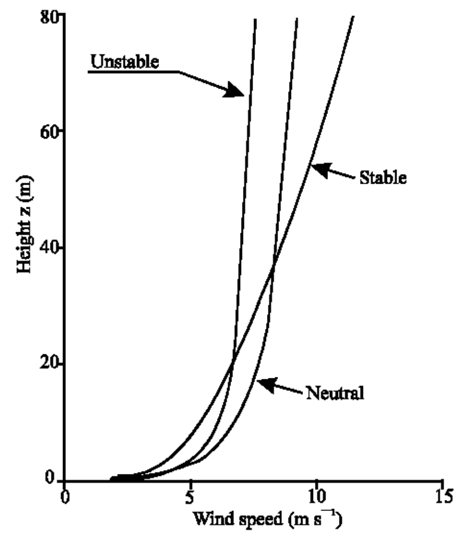

Fig. 7: Vertical wind profile

For example, roughly speaking, if wind speed is 1 m sec^{-1}, then the power that will be obtained is $1^3 = 1$ W and when the speed increases to 2 m/sec, then the power that will be obtained will be $2^3 = 8$ W, when the speed increases to 2 m sec^{-1}, then the power that will be obtained will be $3^3 = 27$ W and so on (Vindmolleindustrien, 2006).

When wind speed has this much effect on the power that will be obtained from the wind turbine, the wind potential in where the turbine will be built is very important. The main objective is to find the point where the wind speed is maximum and install the turbine there.

Land structure of the place where the wind turbine rotor will operate: There is a relation between wind speed and wind height. This relation is dependent on some conditions. These conditions originate from land shapes. Same conditions do not apply in a flat land surface and a surface with obstacles. In a flat land surface as height increases, speed also increases in a direct ratio, but this will not be true in a land surface with obstacles. In a surface with obstacles, wind will have to climb over obstacles to resume its course and this will cause a pause in wind's speed.

If the most important criteria for obtaining energy from wind are wind speed, then it is very important to find the areas where wind speed is high and install wind turbine rotor there. But we don't have to make a false assumption that when we increase the height we will always catch winds that contain more energy (Fig. 6).

The factors that wind speed is affected depending on height are; Von Karman constant, surface friction speed and roughness length.

Von Karman constant is taken in various values between 0 and 4; roughness length is taken between 0 and 5. A graphic regarding these values are given below (Fig. 7).

The performance demanded from wind turbine rotor: Before choosing a wind turbine for an enterprise, first we have to determine how much electric power our enterprise needs. This way, power of the wind turbine that will be installed can be determined. The performance demanded from the rotor has to be determined according to the enterprise's installed power. At this point power amount that the enterprise will need in the future has to be considered also (Yavuzcan, 1978).

Total power of the central (Yavuzcan, 1978):

$$N_T = N_{max} + N_R + N_N \tag{13}$$

For the maximum consume used power is here (Yavuzcan, 1978);

$$N_{max} = N_L + N_F + N_{PL} \tag{14}$$

The power of light of the enterprise is (Yavuzcan, 1978);

$$L_P = (b \cdot a)/1000 \tag{15}$$

PRINCIPLES OF DESIGNED ROTORS

Calculations about designed test blades: Determining specific gravity of air: The air temperature values in the wind tunnel while working the experiment blades are to be measured. And it can compute with the following equation. So, this worth will determine the atmospheric density (Vardar, 2002).

$$\rho = 1.293 \cdot \frac{273}{273 + t} \tag{16}$$

Determining area of rotor cross-section: The plane of section the rotor is a steady worth and it dependent to diameter of the rotor. At the computation of the plane of section the rotor uses the following equation.

$$A = \frac{\pi \cdot D^2}{4} \tag{17}$$

Calculating the theory power of wind that goes to rotor: The wind has a kinetic energy because of its speed. Because of the kinetic energy, here gives a power. And this power is the maximum power from the wind comes and is usable. This the maximum power can compute with the following equation (Klug, 2001).

$$P_{max} = 0.5\ \rho\ A\ V^3 \tag{18}$$

Determining electrical power value on electric motor: Because of the wind speed the rotor will turn. And therefore into the electrical engine current and voltage will come out. The worth of this current and voltage can measure with the circuit analyzers. And this two worth writes into the following equation, in here gets the electrical power (Erna, 1977).

$$N = U\ .\ I \tag{19}$$

Determining blade's tip speed ratio: Tip speed ratio is relationship with the rotational speed (Of point on distance of the r (radius) from the centre of the rotor is the rotational speed) and the wind speed. This rotational speed can determine with the following equation (Ozdamar and Kavas, 1999).

$$V_r = \frac{\pi . d . n}{30} \tag{20}$$

And the tip speed ratio can compute with the following equation (Ozdamar and Kavas, 1999).

$$\lambda = \frac{V_r}{V} \tag{21}$$

Calculating power coefficient: The entire theoretical power of the wind cannot transform into the practical power (Betz, 1926). During the transformation give some power losses. At this condition must compute relationship of transform from the theoretical wind power to axle power. In the computations can use the following equation (Ozdamar and Kavas, 1999).

$$C_P = C_{PSchmitz}\ .\ \eta_p\ .\ \eta_t \tag{22}$$

In the Table 1 the worth of vortex loss.

Table 1: Values of $C_{Pschmitz}$ according to λ (Ozdamar and Kavas, 1990)

λ	5	6	7	8	9	10
$C_{pschmitz}$	0.55	0.555	0.559	0.563	0.566	0.568

The profile loss can compute with the following equation (Ozdamar and Kavas, 1999).

$$\eta_p = 1 - \frac{\lambda}{\varepsilon} \quad (23)$$

The slide number can compute with the following equation (Ozdamar and Kavas, 1999).

$$\varepsilon = \frac{C_L}{C_D} \quad (24)$$

The worth of this ε hanges dependently with the blade profile.

The speed values obtained with the experiments write into the following equation (Piggott, 2006).

$$Re = 68500.C.V \quad (25)$$

If the computed Re values and the used profile observes, can obtain the optimum CK/CD worth and α (attack angle) (with the help of the software Snack 2.0).

The tip loss can compute with the following equation (Ozdamar and Kavas, 1999).

$$\eta_t = 1 - \frac{1{,}84}{B\lambda} \quad (26)$$

Determining shaft power: With the Eq. 18 and 22 can determine the theoretical wind power and the power coefficient. This two worth writes into the following equation, can put the practical axle power of the blade profiles (Ozdamar and Kavas, 1999).

$$P_s = P_{max}.C_P \quad (27)$$

Calculations about real blades: Taking the results of tests into consideration, the power value that can be obtained from rotor shaft that will be installed on wind turbine can be calculated by the following method.

Determining area of rotor cross-section: Also the plane of section the rotor of the real blade can compute with the equation 17 (Birnie, 1999). The values of the rotor diameter must be same for compare the rotors after the computations.

Determining shaft power of rotor: The worth of Cp, which is used at the rotor axle power, was computed the worth with the Eq. 22. The values of the atmospheric density and the wind speed must be steady for compare the rotors after the computations. The rotor axle power of the real blades can compute with the following equation (Klug, 2001).

$$P_s = 0.5\ \rho\ A\ V^3\ C_P \quad (28)$$

Adapting real blades to region's wind presence: Wind speed values that are used in here are values that were measured and observed for at least 6 months. Wind speed values that are used in here are values measured 10 m above ground. The power coefficient value that is used in here is important. To compare the rotors at the end of calculations, specific gravity of air value has to be taken as a constant value.

Calculating area of rotor's cross-section: The plane of section the rotor at the real blades adaptations into the region, can compute with the help of the Eq. 17 (Birnie, 1999).

Determining wind speed on the height of rotor axis: The wind speed in the rotor hub height can compute with the help of the following equation (Klug, 2001).

$$V(h) = (u^*/k)\ \ln(h/z_0) \quad (29)$$

Calculating rotor's shaft power: The power in the axle can compute with the help of the Eq. 25 (Klug, 2001).

CONCLUSIONS

To increase the efficiency of wind turbines, rotor planning principles are very important for wind turbines with horizontal axis. It is not possible to expect the maximum efficiency from a wind turbine that is installed without doing the optimization processes.

Like in every topic, to be successful when making use of wind energy, basic values must be based on scientific data. When the topic is considered from this point of view, rotor design parameters have to be put forward in wind turbines. Starting from here, the most suitable systems can be developed by taking source data as a basis.

The basic strategy is to put into practice high performance systems that can compete.

Nomenclature

E : Kinetic energy (Nm)
ρ : Atmospheric density (kgm^{-3})
Cp : Ideal power coefficient (%)
V_r : Rototional speed ($m\ s^{-1}$)

R : Radius (m)
n : Revolution number (rpm)
β : Blade angle (Grad)
t : Air temperature (°C)
$C_{PSchmitz}$: Vortex loss (%)
η_t : Tip loss (%)
C_L : Lift coefficient of blade profile
P_s : Power of rotor shaft (W, kW)
h : Measuring height of wind speed (m)
a : Population
N_L : Maximum power of light (W)
N_{PL} : Power loss of that Net (W)
N_R : Reserve power (W)
z_0 : Rough height (m)
α : Angle of attack (Grad)
Φ : Angle of the apparent wind (Grad)
C_D : Drag coefficient of blade profile
N_T : Total power of the central (W)
N : Electrical power of the electrical motor (mW)
r : Distance, a point the rotor, of the rotor center (m)
m : Flow masse (kg)
P : Power (W)
η : Mechanical output
ω : Angular velocity (grad)
D : Diameter (m)
λ : Tip speed ratio
B : Number of blades
P_{max} : Theoretical power of wind (W)
η_p : Blade profile loss (%)
ϵ : Slide number
Re : Reynold number
K : Von karman coefficient (0,4)
L_P : Power of light (kW)
b : Power of light each person (W)
N_F : Maximum force power (W)
N_{max} : Maximum consumer power (W)
N_n : Inside necessarily power (W)
V : Wind speed (m s^{-1})
A : Cross-section area (m^2)
u* : Friction velocity of wind
C : The cord in the tip that blade profile (m)
U : Electrical voltage of the electrical motor (V)
I : The electric current of the electrical motor (mA)

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