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Influence of the Number of Blades on the Mechanical Power Curve of Wind Turbines

M. Predescu[1], A.Bejinariu[2], O.Mitroi[3], A. Nedelcu[4]
ICPE SA-SICE Centre, Bucharest, Splaiul Unirii 313,
Email addresses: [1]predescu@icpe.ro,[2]andrei.bejinariu@icpe.ro,
[3]octavian.mitroi@icpe.ro, [4]adrian.nedelcu@icpe.ro
Tel/fax :+40 21 589 34 70

Abstract. The paper describes the experimental work in a wind tunnel on wind turbine rotors having different number of blades and different twist angle. The aim of the work is to study the influence of the number of blades, the blade tip angles and twist angle of the blades on the power coefficient of the rotor. Also, the experiments evaluate to what extent the power coefficient of the turbine rotor depends on the operating wind speed.

Key words

Wind turbine, blade profile, blade twist angle, power coefficient

1. Introduction

When designing a direct drive wind turbine the interest is to obtain the highest efficiency for the wind speed range of the locations of implementation. If the average wind speed is rather low, the wind turbine should have a better behavior at low wind speeds. The blade of the rotor is the most important component with impact on wind turbine efficiency. According to the previous works, [1] and [6] the generator should be designed for maximum power transfer from turbine rotor to the load, but an appropriate design of the turbine rotor is mandatory for achieving good overall efficiency.

There are several methods of designing the blade profile[2], [3], [5] for selecting the twist of the blades and the blade tip angle for optimum power extraction of wind kinetic energy.

Generally, the design method of main characteristics of turbine rotor is based on simplifying assumptions and optimum design principles theoretically defined and verified in practice[3].

The goal of the work presented in the paper is performing experimental investigation for studying the influence of different parameters, such as number of blades, blade tip angle, twist angle of the tip of the blades on the performances of the rotor of wind turbines. Having the experimental results, the designer could have deeper knowledge of the impact of the characteristics of the rotor turbine on the final performances of the wind turbine and to know how to fit the rotor performances to a specific wind potential.

2. Experimental setup

The experiments were carried out in a closed loop wind tunnel described in previous works, [1] and [6]. The maximum wind speed for tests is actually limited to 13 m/s, due to the technical possibilities of the wind tunnel.

The blades are assembled into a rotor and mounted on a 3,5m mast for positioning the hub on centre on the wind tunnel cross section. The wind tunnel cross section, which is actually 7 m in diameter, could act as a duct and the measurements can give higher efficiency of the turbine than in open air, but the behavior of the rotors is well reproduced. This aspect is now under study.

The airflow on the cross section is uniform within 2% on the area swept by the blades.

For measuring the power curve of the rotor, a 3 phase synchronous generator is used as variable torque break. At the output of the generator is a 3 phase rectifier with a variable power resistor which can be continuously adjusted for setting the desired breaking torque for the rotor.

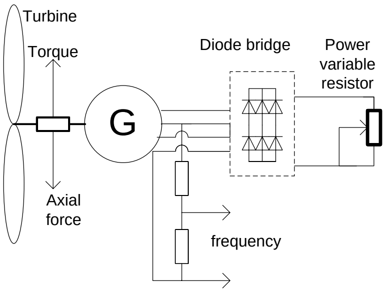

Fig. 1-Electrical layout

The torque is measured by a transducer inserted between rotor and generator. The rotational speed is measured through the frequency of the generator output voltage.

$$n = \frac{f}{p} \quad (1)$$

Where:

n-rotational speed
f-frequency of generator output voltage
p-number of pole pairs of the generator

The generator which is actually designed for 2,5kW wind turbine, is a rare earth permanent magnets synchronous type, with 16 poles for 24 V battery operation. The powerful air gap field and high magnets energy ensure enough breaking torque for fitting the mechanical power curve of the experimented rotors at any given air speeds, up to 11m/s.

The parasitic torque of the measuring chain on the experimental frame is round about 1,3Nm. This torque is produced by generator, about 0,9Nm, and the difference is due to two bearings which is the mechanical fixture of torque transducer. A slight misalignment of generator and torque transducer shafts is also contributing to this parasitic torque. This torque is measured at standstill using a dynamometer.

The air speed is measured by a anemometer, placed 2 m in front of the rotor under measurement, and by a Venturi tub, for comparison.

A data acquisition system acquire data on external trigger, computes the averages on 60 seconds and stores averaged values.

3. Tested components

Two sets o blades were used for experiments, designed for 1 and 2kW wind turbines.

The main data of the blade sets are:

a. Blades for 2kW wind turbine:

Length	1500mm;
Maximum chord	194mm;
Chord at the blade tip	139mm;
Blade twist	22^0

b. Blades for 1kW wind turbine:

Length	1150mm;
Maximum chord	180mm;
Chord at the blade tip	95mm;
Blade twist	17^0

The blade profile is quite similar; it is a modified NACA 449.

The first set of blades, *a*, have been tested in three configurations: 2 ,3 and 6 blades rotors. All the blade tails can be rotated in the hub fixture and set manually to a desired tip angle before measurement. They are identical for both type of blades.

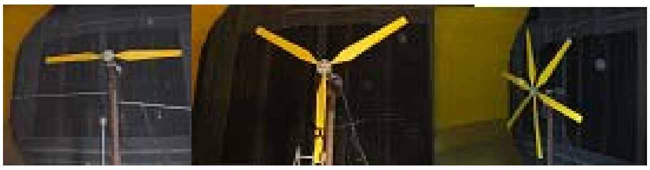

Fig. 2-Experimental rotors with type *a* blades

In Fig 2 is the experimental setup for type *a* blades in 2, 3 and 6 blades rotor assemblies on the measuring mast.

The blades of type *b* are measured only in 3 blade configuration rotor.

4. Measurement method

For a configured rotor and blades the tip angle is set to a selected value and the first experiment is with no load for measuring the cut in wind speed. The wind speed in tunnel is adjusted in steps with enough time lag between steps for allowing the air flow settling along the wind tunnel. In this way, the cut in wind speed is measured. The measurement gives the cut in speed at about 100 turns/min turning speed of the rotor.

The power curve is measured using the variable torque as in Fig. 1. The power resistor is set at the beginning of measurement to the highest value and then the wind speed is also set to the desired value. By lowering the load resistor value, the torque and power generated by synchronous generator is increased until the maximum power is reached. Meanwhile, the data acquisition gathers the data: torque, wind speed and rotational speed of the rotor. The power curves of different configurations are measured for three wind speeds: 6,5m/s, 8,5m/s and 10,5 m/s, which are considered to be reference wind speeds(*Vref)*. The values are the same for all experiments described. Those values are significant for defining power curves of small wind turbines.

The diameters of the rotors are 3,2m when using blades type *a* and 2,6m with the blades type *b*.

5. Measured power curves

A. *Power curves of rotors with type a blades*

The type *a* blades have been tested in 2, 3 and 6 blades rotor configuration.

The blades are designed for 2 kW low wind speed turbine for use in both stand alone battery storage power source and grid-connected wind installation. For these applications, the generators have the same cross section but with different type of windings.

The results of the measurements are the power curves *P(n)* with the parameter wind speed *v*. From those data, the measured power coefficients *Cp* are calculated against tip speed ratio, λ . The power [3] and tip speed ratio are calculated using (2) and (3):

$$Cp = \frac{P}{\pi \frac{\rho}{2} \cdot v^3 \cdot R^2} \quad (2)$$

and

$$\lambda = \frac{2 \cdot \pi \cdot R \cdot n}{v} \quad (3)$$

Where:

P-measured mechanical power
ρ-air density
v-measured airspeed
λ-tip speed ratio
D-rotor diameter
R-rotor radius

During measurements, the wind speed in tunnel cannot be set practically at exact desired values, *Vref,* listed above. The wind speed can vary with 0,5m/s dispersion from the desired values. Therefore, a small correction [3] is applied to the measured power, using (4):

$$P = Pm \cdot \left(\frac{vref}{v} \right)^3 \qquad (4)$$

Where:

vref-reference airspeed, defined above

Pm- measured power

B. *Power coefficients for 2 blades rotor*

The results of the measurements are in Fig.3 to 6. The optimum operation of the rotor with the type *a* blades is at small blade tip angle. Therefore, the power coefficients are measured for 0^0, 2^0, 5^0, 7^0 and 10^0. At higher tip angles, the power coefficient is small enough to be considered for the operation of a wind turbine.

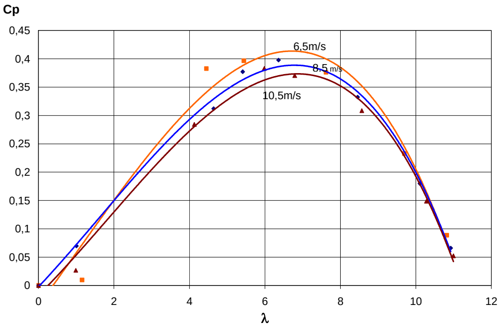

Fig. 3-Cp for 2 blades at 0^0

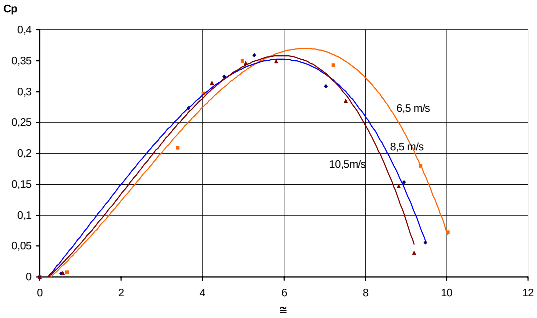

Fig. 4-Cp for 2 blades 2^0

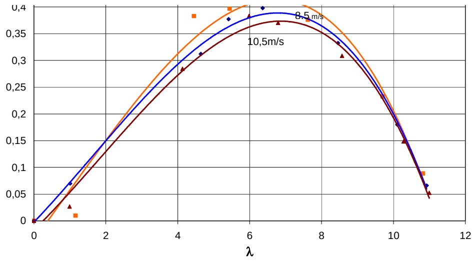

Fig. 5-Cp for 2 blades 5^0

The results of the measurements on 2 blades rotor can lead to several conclusions:

- The power coefficient decreases with the blade tip angle;
- Blade tip speed ratio, λ, at maximum power, decreases with blade tip angle ;
- The power coefficient varies slightly with wind speed: at low wind speed the power coefficient is the higher than at higher wind speed;
- The maximum power conversion efficiency is at small tip angle.

The type *a* blade is actually designed for a wind turbine with good behavior at low wind speeds, specific for wind potential in many places. However, the value of the power coefficient varies within 10% when the wind speed is between 6,5 and 10,5m/s.

Due to high twist angle of type *a* blades, the most favorable blade tip angle for operation of the wind turbine is small, 2^0. The optimum value of blade tip angle should be selected depending on the wind potential at the location of the operation. If the wind potential is high, the blade tip angle should be smaller and the power coefficient is higher. Where the low wind speed is predominant, the tip angle should be increased for having lower cut in wind speed.

C. *Power coefficient for 3 blades rotor*

In the figures 7-9 are the results of the measurements on 3 blade rotor, with the same diameter as 2 blades assembly.

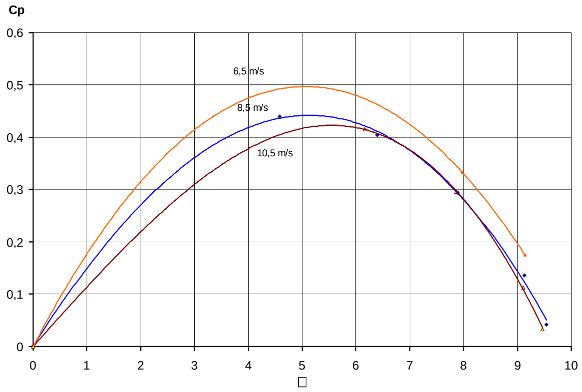

Fig. 7-Cp for 3 blades 0^0

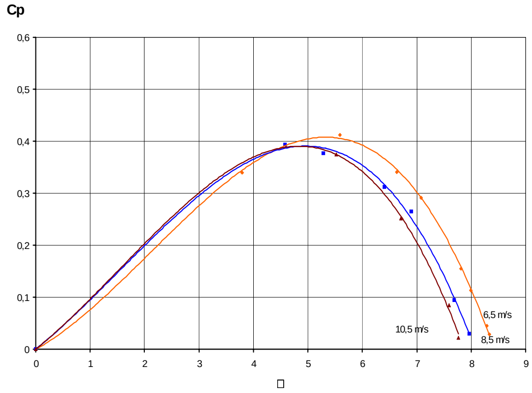

Fig. 8-Cp 3 blades 2^0

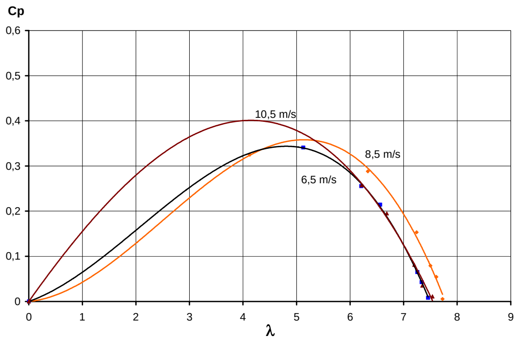

Fig. 9-Cp 3 blades 5^0

For 3 blades, the rotor behaves similar to the 2 blade rotor. But, the power at same blade tip angle is higher than for 2 blades, as it was expected. In the same time, the tip speed ratio, λ, is lower than for 2 blades.

D. Power coefficients for 6 blades rotor

In Fig. 10 -13 are the results of the measurements of 6 blade rotor *a* type.

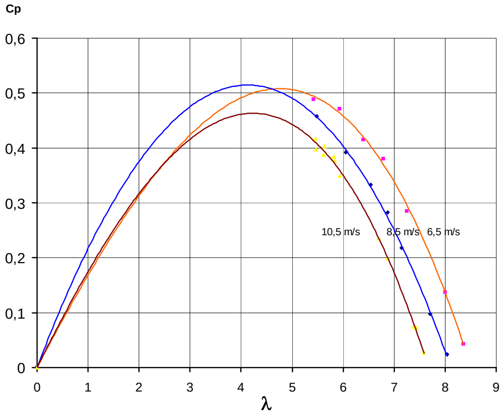

Fig. 10-Cp for 6 blades 0^0

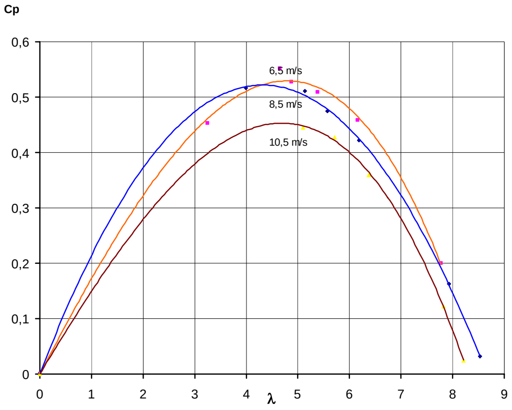

Fig. 11-Cp for 6 blades 2^0

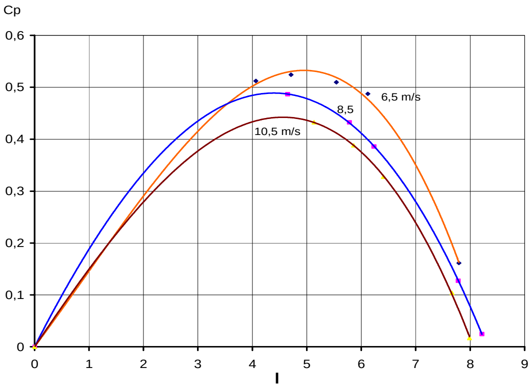

Fig. 12-Cp for 6 blades 5^0

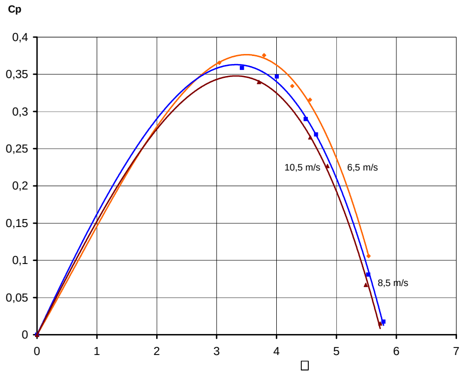

Fig. 13-Cp for 6 blades 10^0

The 6 blades rotor has good power coefficient, and is showing small variation on extended range of blade tip angles, from 0^0 to 5^0. Also, the power coefficient is higher at low wind speed but the variation is within 10% in most measurements.

*E. Summary results on rotor with blades type **a***

For *a* type blade, the most important characteristics, from the designer's point of view are the dependence of power factor, tip speed ratio at maximum *Cp* and cut-in wind speed versus blade tip angle.

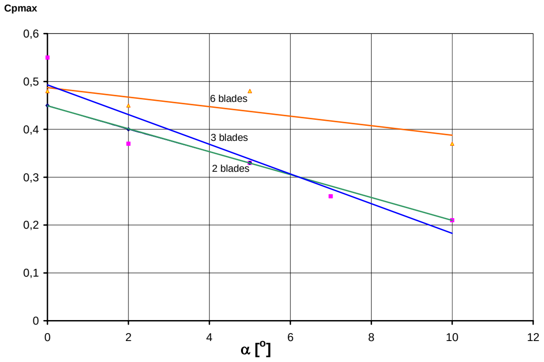

Fig. 14-Power coefficient vs. blade tip angle

In Fig.14 is the variation of power coefficient versus wind tip angle for variable number of blades. The power coefficient is the average for all 3 power coefficients at reference wind speeds.

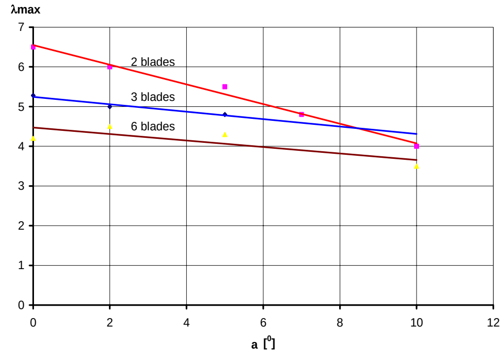

Fig. 15-Tip speed ratio at ***Cpmax*** for *a* type blades

The wind turbine is faster when the number of blades decreases[3]. As can be seen in Fig.15, the tip speed radio, λ, decreases when blade tip angle increases. Furthermore, as α increases, the speed at *Cpmax*, *λmax*, for 2 blades rotor decreases much faster than 3 or 6 blades rotor. For 6 blades, *λmax* decreases much slower. It to notice that at $\alpha=8^0$, 2 blades rotor is as fast as 6 blades one.

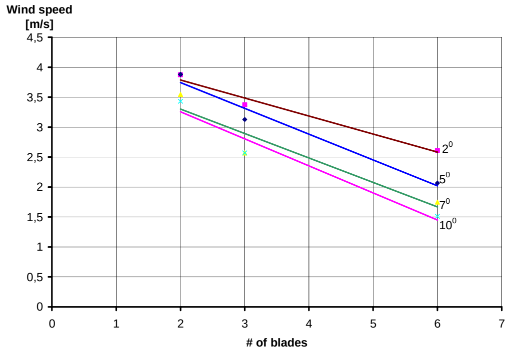

Fig. 16-Cut-in wind speed for *a* type blades

One of the most important characteristic of wind turbines is cut-in wind speed. In Fig. 16 is the variation of cut-in wind speed vs. number of blades, having parameter blade tip angle, α. It is known that as the number of blades increases, the cut-in wind speed decreases. Similarly, the cut-in wind speed decreases as the blade tip angle increases.

The role of wind turbine design process, is the selection of the number of blades, the blade tip angle and cut in wind taking into account the wind potential in which the turbine would operate. The cut in wind speed and power coefficient have the same variation with blade tip angle at a given number of blades: both parameters are decreasing.

F. Power curves of rotor with type b blades

Type *b* blades are actually manufactured for 1kW wind turbine using, to some extent, the optimum design principles[3]. The rotor configuration with type *b* blades has been tested only with 3 blades, considering that the parameters variation with blade number should vary similarly as for type *a* blades.

The role of these measurements is to have an experimental evaluation of the impact of twist blade angle on performances of the wind turbine. The comparison of the power factors of rotors having blades of type *a* and *b* gives a quantitative assessment of the influence of blade twist angle on performances of wind turbines.

The rotor with type *b* blades has maximum power coefficient at 7^0 blade tip angle. The other measurements are for α: 10^0, 12 and 20^0.

The results of the measurements are in Fig. 17 to 19.

The power coefficient of rotor with blades type *b* has the maximum at 7^0 and the value is high. However, the power coefficient decreases as the wind speed decreases.

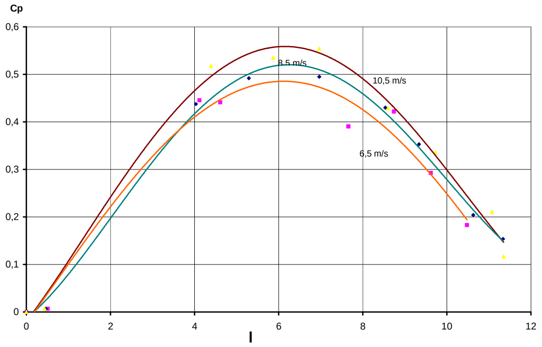

Fig. 17-Cp for rotor type b at $\alpha=7^0$

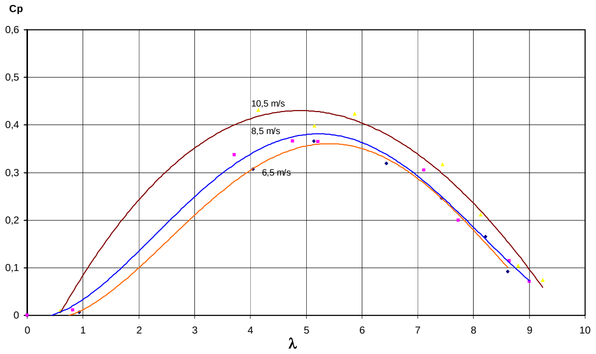

Fig. 18-Cp for rotor type b at $\alpha=10^0$

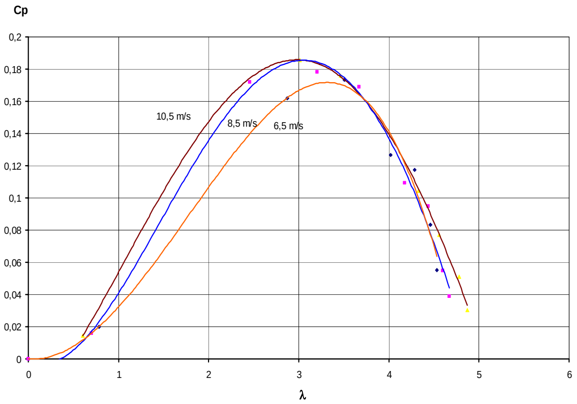

Fig. 19-Cp for rotor type b at $\alpha=20^0$

Therefore, the wind turbines, built with blades of *b* type, are better suited for higher wind speeds.

According to the curve in Fig. 20, the average power coefficient falls rapidly when the blade tip angle increases.

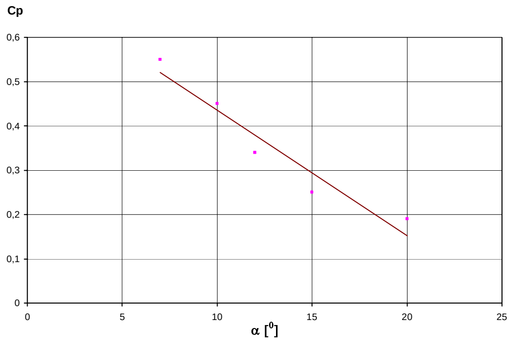

Fig. 20-Cp vs. blade tip angle

In the same way, the tip speed ratio decreases with the increase of blade tip angle, see Fig. 21.

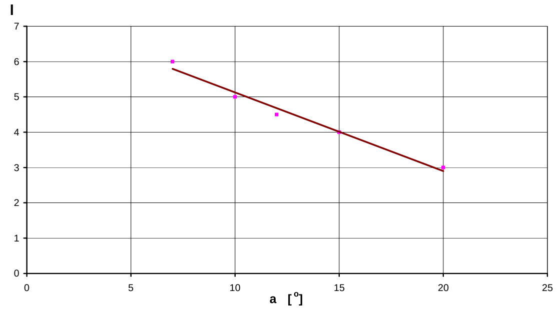

Fig. 21-Tip speed ratio at *Cpmax*

6. Conclusions

The wind tunnel experiments carried out on two different sets of blades revealed the influence of design parameters on the mechanical performances of the rotor of wind turbines.

Two type of blades have been studied, having similar aerodynamic profiles, but different blade twist angle.

The main conclusions are:

a) The blades have roughly the same maximum power coefficient at optimum blade tip angle; if the aerodynamic blade profile is carefully selected the power coefficient is very good;

b) The blades with increased twist should be mounted at small blade tip angles than those with lower twist angle;

c) The rotor with increased blade twist angle has higher power coefficient at lower wind speeds and the blades with optimum selected twist behave oppositely. This can lead to the conclusion that an increased twist should be used for lower wind potential, even though the variation of *Cp* with the wind speed is within 10% on whole normal operating wind speed range.

d) The *Cp* of the rotor with 2 blades is decreasing very fast with the increasing of α; at higher α, the cut in wind speed is lower.

e) The *Cp* of the rotor with 6 blades is decreasing much slower with blade tip angle than the Cp of the rotor with 2 or 3 blades; therefore, the use of increased number of blades gives a larger margin for adjusting the cut in wind speed without affecting too much the power coefficient.

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