Starting Torque Study of Darrieus Wind Turbine

M. Douak, Z. Aouachria

Abstract—The aim of our study is to project an optimized wind turbine of Darrieus type. This type of wind turbine is characterized by a low starting torque in comparison with the Savonius rotor allowing them to operate for a period greater than wind speed. This led us to reconsider the Darrieus rotor to optimize a design which will increase its starting torque. The study of a system of monitoring and control of the angle of attack of blade profile, which allows an auto start to wind speeds as low as possible is presented for the straight blade of Darrieus turbine. The study continues to extend to other configurations namely those of parabolic type.

Keywords—Darrieus turbine, pitch angle, self-stating, wind energy.

I. INTRODUCTION

THE wind continued to be a major source of energy in world the period just prior to the Industrial Revolution, but began to recede in importance after that time. At the end of 2007, [1] reports that over 94GW were in operation throughout the world, mostly in Germany (22.2 GW), the United States (16.8 GW), and Spain (15.5 GW). Wind continued to be the major source of energy and is one of the most promising and potential alternative of renewable energy. There is over 95GW in operating throughout the world especially in Germany (22.2GW), in the United States (16.8GW) and Spain (15.5GW) [2]. In addition, to growing economic attractiveness of the wind energy, there are more ecological arguments for its use: i. Wind-power plants emit absolutely no CO2, by far the major pollutant when fuels (other than hydrogen or biomass) are burned; ii. As do nuclear plants, the operation of wind turbine leaves behind no dangerous residues; iii. Decommissioning costs of wind turbines are much smaller than those of many other types of power plants, especially compared with those of nuclear generators; iv. Land occupied by wind farms can find other simultaneous uses such as in agriculture. Several wind machine configurations including; i. drag-type turbines, ii. Lift-type turbines (with vertical or horizontal axes), iii. Magnus effect wind plants and, iv Vortex wind plants have been studied by [3]-[5]. Some difficulties appear during the design and simulation of rotational equipment especially when this equipment is in contact with a given fluid. Among these equipments the wind turbine represents a devise which can utilize the wind's kinetic energy to produce the mechanical energy or electrical energy. The vertical axis wind rotor as another important kind wind turbine is a good choice for mean and small scale wind power generation [6]. It has received, more and more attracts for its advantages of simple design, low cost and good maintenance [7]. In addition, in urban areas the wind is very turbulent and unstable with fast changes in direction and velocity. In these environments the vertical axis wind turbines (VAWT) have several advantages over horizontal axis wind turbines (HAWT). However, the starting performance is one of the problems which greatly affect the development of the straight bladed vertical wind turbine [8], [9]. As a result, designers are compelled to supply such wind rotors with additional devices (the electric motor, Savonius rotor, etc.) to spin up the rotor and put it in operating conditions [10]. This approach increases the cost and adds complications to the design. Several solutions have been presented to overcome the Darrieus type VAWT inability to self start: use of a guide-vane using a hybrid configuration of a Savonius VAWT (drag type wind turbine) and a Darrieus VAWT (lift type wind turbine), use of mechanical system to optimize the blade pitch Reference [11], [12] use respectively blades that change their form during operation and [13]-[16] study specific blade profile capable of offering self-start capabilities to the wind turbine without extra components. In this work, we include a new mechanism to make the rotor self-starting and increase the time of its operation.

II. GENERATION PROBLEM

The Darrieus rotor usually suffers from a low starting torque. Variable pitch machines have blades which can be rotated about their long axis, changing the blades' pitch angle. Changing pitch also changes the angle of attack of the relative wind and the amount of torque. Variable pitch provides more control options than does stall control. On the other hand the hub is more complicated, because pitch bearings need to be incorporated. In addition, some form of pitch actuation system must also be included. In some wind turbines, only the outer part of blades may be pitched [17]. This is known as partial span pitch control. In this new design shown in Fig. 1 (a), we overcome this problem by allowing each straight blade about an axis along its pith (span). For any airfoil to generate useful lift, the attack angle must always remain less than the airfoil stalling angle. The angle of attack (α) is the acute angle between the wind and the chord line of the airfoil. The stalling angle of the airfoil is determined from the lift coefficient curve of the airfoil. In the case of a rotating blade, the angle of attack (α) is measured between the relative wind speed and the chord line, as shown on Fig. 1 (b), where V is the wind speed at the rotor and U is the blade speed. The configuration of Fig. 1 (b) represents the operating condition of a Darrieus rotor when the ratio $\lambda =U/V$, which is called the tip speed ratio, is in the range

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(4° – 10°). In this range the attack angle remain smaller than the stalling angle and thus the wind produces a useful lift force. At low rotational speeds the blade speed, U, becomes small. This leads to a low tip speed ration and increases the angle attack to causes the aerodynamic stall of the blade. Stall occurs when the angle of attack exceeds a certain critical value (say 10 to 16 degrees, depending on the Reynolds number and separation of the boundary layer on the upper surface takes place, as it is shown in Figs. 2 (a), (b).
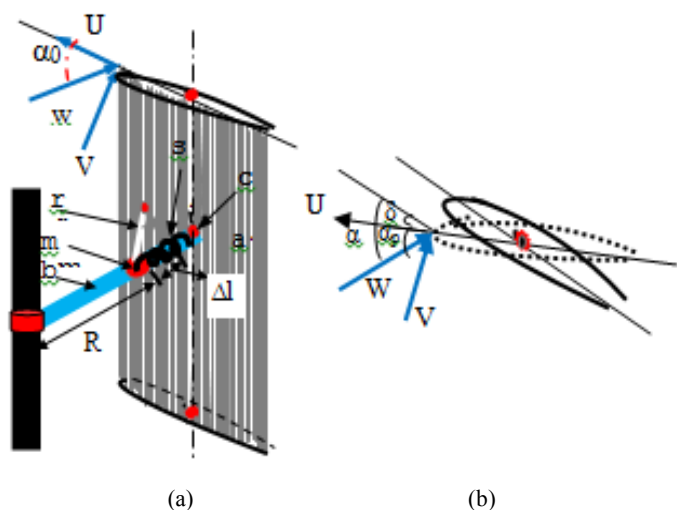

Fig. 1 (a) new design model (b) Pitching the blade at low rotational speed

A rotating turbine blade sees air moving toward it not only from the wind itself, but also from the relative motion of the blade as it rotates. As shown in Fig. 1, the combination of wind and blade motion is like adding two vectors, with the resultant moving across the airfoil at the correct angle to obtain lift that moves the rotor along. As shown in Fig. 1 (b), however, increase the angle of attack too much can results in a phenomenon known as stall [15]. The present approach is described on Fig. 1 (a) where the straight blade, (a), is hinged to its arms, (b), through hinges (c) so that the pitch angle α is changed to the favorable angle of attack, δ, shown in Fig. 1 (b) This control is determined by a mass (m) connected to a spring (s) and a rod (r) which pushes the leading edge of the blade during its low rotation at the hinge. At low rotational speed, the spring pushes the mass which forces the rod to make the leading edge of the blade to the desired pitch angle. As the operating rotational speed builds up, the centrifugal force moves the mass, m, away from the axis of rotation and releases the blade gradually from the piece, r. At the operating rotational speed, the blade will be totally free from the control system and will be tangent to the circular path. The number of blades on each model changed during researches from 2 to 4, the blade profile has been chosen axially symmetric of the type NACA-0015. If blades were fastened on the wind rotor cross-arms rigidly (the classical scheme of Darrieus rotor), than the angle of the profile chord of blade to the tangent to rotation circle was equal to +4∘. The mechanism of blades control provided angular oscillations of blades relative to the

blade axis and during one revolution the angle of blade installation changed from −14 to +25 grades [10].

(a) Angle of attack   (b) Stall case

(c)
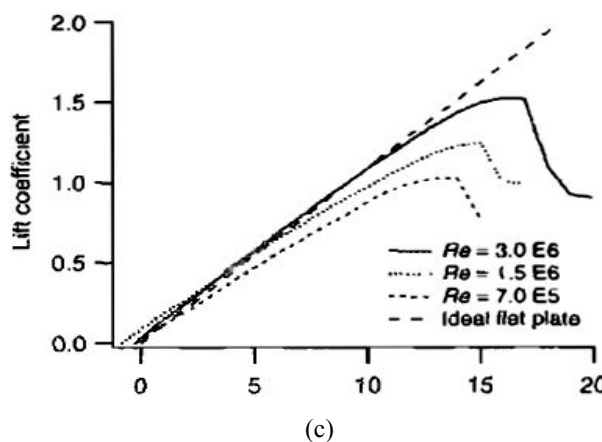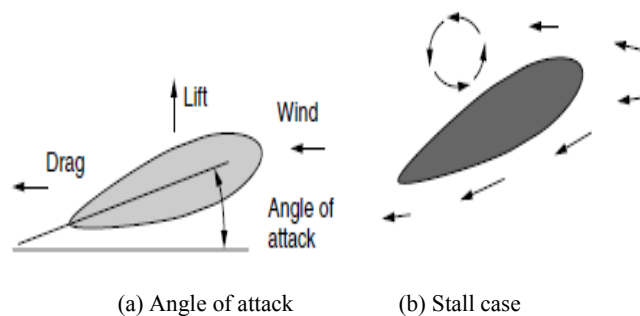
Fig. 2 Lift coefficient versus angle of attack degrees for different Re [17]

III. GENERAL OVERVIEW

Wind turbine power production depends on the interaction between the rotor and the wind. Experience has shown that the major aspects of wind turbine performance (mean power output and mean loads) are determined by the aerodynamic forces generated by the mean wind. A number of authors have derived methods for predicting the steady state performance of wind rotors. The classical analysis of the wind turbine was originally developed by [18] in the 1930's. Subsequently, the theory was expanded and adapted for solution by digital computers [19]-[21]. In all of these methods, momentum theory and blade element theory are combined into a strip theory that enables calculation of the performance characteristics of an annular section of the rotor. The characteristics for the entire rotor are then obtained by integrating, or summing, the values obtained for each of the annular sections. General aerodynamic concepts and the operation of airfoils are then introduced. This information is then used to consider the advantages of using airfoils for power production over other approaches.

IV. MODELING OF THE ROTOR EFFICIENCIES

Symmetric airfoil sections are assumed here since both positive and negative angles of attack are experienced as the

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blades make a circuit. According to the triangle of speeds, the relative velocity, w, is related to the blade velocity, U, and the absolute wind velocity at the rotor speeds, v, by:

$$w = v - u \tag{1}$$

With its components, in the reference reaper, formed by the airfoil chord of the wing and the direction perpendicular to the cord, are respectively:

$$w_c = u + V\cos\theta, \qquad w_n = V\sin\theta, \ u = \omega R \tag{2}$$

where θ is the blade angular position. The speed w is then

$$w = \omega R\sqrt{1 + 2\lambda\cos\theta + \lambda^2} \ , \ \lambda = \frac{\omega R}{V} \tag{3}$$

and the angle of attack for a fixed blade becomes

$$\alpha = \tan^{-1}\frac{\sin\theta}{\lambda + \cos\theta} \tag{4}$$

For a pitched blade, the angle of attack, α, is

$$\alpha = \tan^{-1}\frac{\sin\theta}{\lambda + \cos\theta} - \delta \tag{5}$$

The components of the resulting force F acting on the blade element can be expressed as:

$$F_T = \frac{1}{2}C_T\rho c W^2 \quad \text{and} \quad F_N = \frac{1}{2}C_N\rho c W^2 \tag{6}$$

The tangential force coefficient CT and normal force coefficient CN are given by:

$$C_N = C_L\cos\alpha + C_D\sin\alpha, \quad C_T = C_L\cos\alpha - C_D\sin\alpha \tag{7}$$

If c, is the blade chord and h, is the blade span, then the blade surface is S = c.h

$$T = \frac{0.5\rho S R b}{2\pi}\int_0^{2\pi} C_T w^2 d\theta \tag{8}$$

The power coefficient is defined as a ratio of the produced power to the maximum available power

$$C_p = P / P_{max} \tag{9}$$

with

$$P = T\omega = \frac{0.5\rho S R b \omega}{2\pi}\int_0^{2\pi} C_T w^2 d\theta \tag{10}$$

and

$$P_{max} = \frac{1}{2}\rho A V_1^3 \tag{11}$$

where A = 2Rh, is the area swept by the rotor during a rotation and

$$V_1 = \frac{2V}{1 + a} \tag{12}$$

The rotor is solicited, in the direction of the velocity V, by the force:

$$F = \frac{0.5\rho S R b}{2\pi}\int_0^{2\pi}(C_N\sin\theta - C_T\cos\theta)w^2 d\theta \tag{13}$$

This force is expressed by Betz (1931) as:

$$F = \frac{1}{2}\rho A(V_1^2 - V_2^2) \tag{14}$$

when we write V_1 and V_2 in function of V putting $V_2 = aV_1$, and taking account to (13), and after some calculus, we deduce finally,

$$C_p = \frac{\dfrac{0.5\rho S R b}{2\pi}\int_0^{2\pi} C_T w^2 d\theta}{0.5\rho A V^3\left[1 + \dfrac{Sb}{8\pi A V^2}\int_0^{2\pi}(C_N\sin\theta - C_T\cos\theta)w^2 d\theta\right]^3} \tag{15}$$

V. RESULTS AND DISCUSSION

Results released by this study concern both a conventional and the new self-starting Darrieus rotor. The properties of fluid and geometric parameters of the Darrieus turbine used in the calculation are notified by: NACA-0015, R =1m, H =1m, $\rho = 1.225$kg/m^3. At low speed, conventional Darrieus rotor with the fixed blades is not able to generate energy of with the fact that the angle of tack is higher than the angle chock which results from the force of the weak bearing pressure and with the strong drag that induces a negative torque. The present design changes the angle attack to a favorable value as described early and makes the torque positive for this low range of the tip speed ratios. Figs. 3 and 4 present, respectively, the local angle of attack and the velocity triangle at blade positions. Small tip speed ratios lead to large incidence variations during a revolution. In particular, the angle of attack becomes very large and overtakes the static stall angle of foils, about 12-15°. In Fig. 5, we observe that, at very high tip speed-ratio, the angle of attack will become too small, which results in low values of the torque and power coefficient.
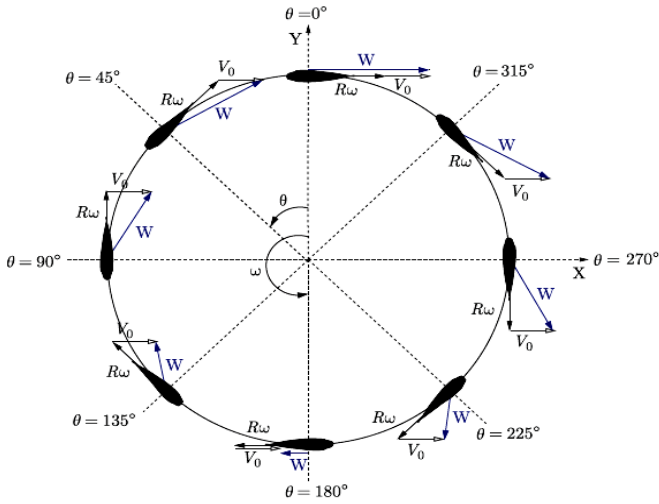
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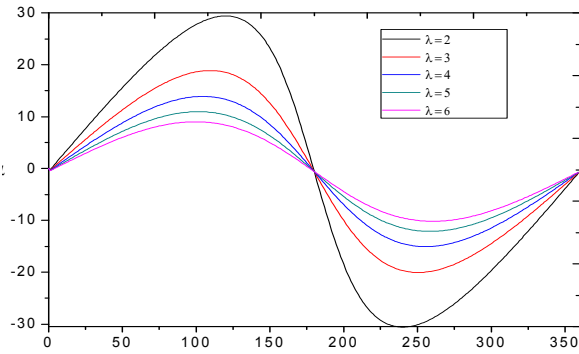
Fig. 3 Velocity triangles at different positions of the blade
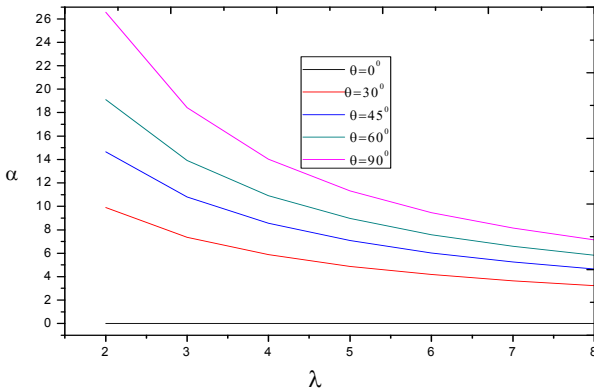

Fig. 4 Angle of attack versus position angle at different 1

Fig. 5 Angle of attack variation vs 1 at different angular positions

Figs. 6, 7 present the normal and the tangential components; Fn and Ft, for le tip speed ratio equal 7, of the hydrodynamic forces respectively. In the upstream semi circle as shown in Fig. 7 (a), corresponding to the case of Inviside flow, with θ increasing from the 0° position, the tangential force becomes positive and reaches a maximum near θ = 90° before decreasing until θ =180°. One can observe the same behaviour in the downstream semi circle between the θ =180° and 360° position. This positive tangential force is responsible for the turbine rotation while that the normal forces at the

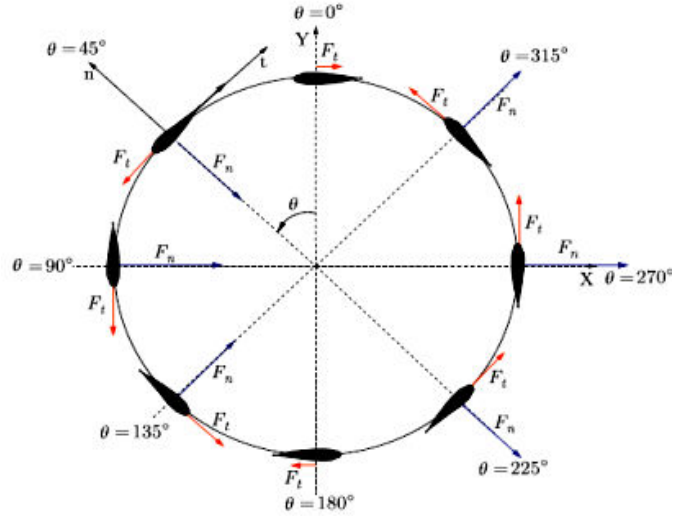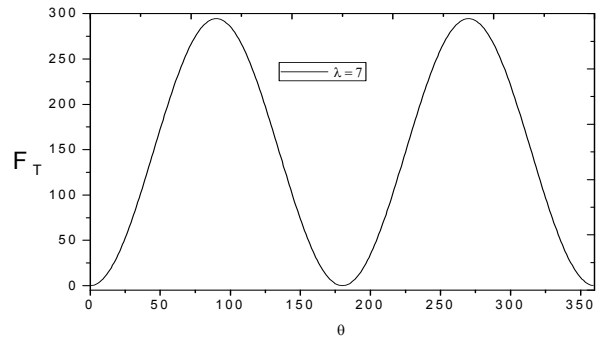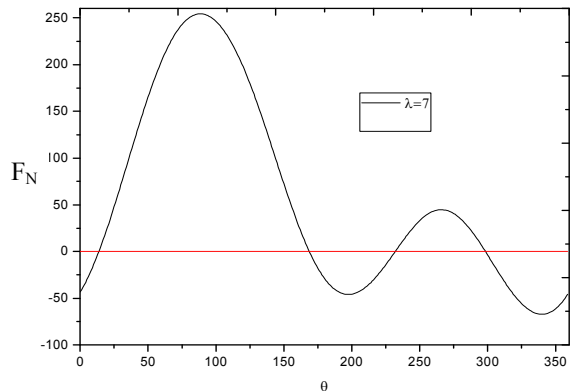downstream side on the blades presented in Fig. 7 (b), are considerably smaller than at the downstream side.

Fig. 6 Normal and tangential forces

(a)

(b)

Fig. 7 Tangential forces diagram for λ = 7

On Fig. 8, the variation of the torque for both fixed and pitched blade rotor of similar geometries is presented. We find that, for variable-pitch blade, the torque created is relatively higher than the correspondent of fixed blade. The variable-pitch blade starts up faster than the conventional rotor. The wind turbine will be thus able to develop the power at low

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speed, as it is shown on Fig. 8. It gives the variation of the power coefficient in function of the tip-peed ratios. In Fig. 9, we have plotted torque variation for various values of the wind speed. This variation is required by an end use device may be plotted in Fig. 8 and the resulting intersections with the curves of the torque available on the shift of the rotor will give the operating points of the combined system. Depending on the speed range of the generator or pump, it may be necessary to use the gearbox. The study of the rotor geometry effect on the efficiencies of the Darrieus shows that the produced is directly proportional to the number of the blades and the blade chord, whereas maximum solidity is defined as:

$$\sigma = \frac{b\,c}{D} \tag{16}$$

where, b is the blade numbers, c is the profile cord and D the rotor diameter. Then, it is possible to study the effect of geometry on rotor performance by considering one parameter only, namely. Fig. 8 shows the effect of the solidity on the power coefficient. We observe that the maximum of power coefficient increases with the solidity parameter. When   is greater than 0.14 the curves are not plotted for clarity. We conclude that the maximum of the pose coefficient occurs at the value equal 0.14.
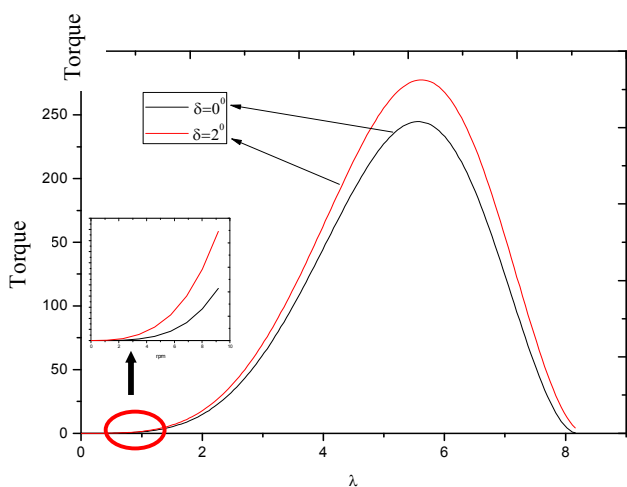

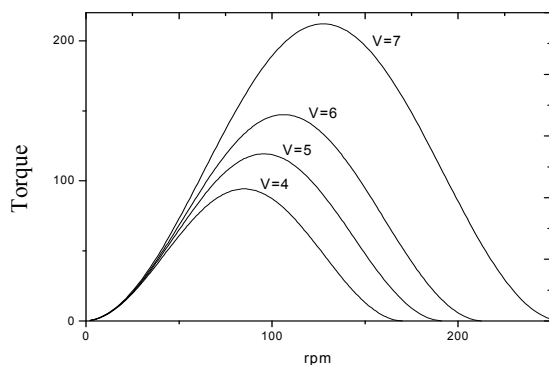Fig. 8 Torque versus l for fixed and pitched blade

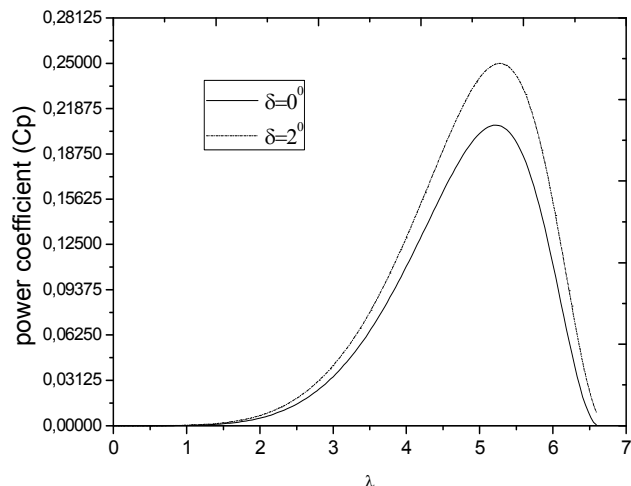Fig. 9 Torque versus RPM for different solidities wind speeds

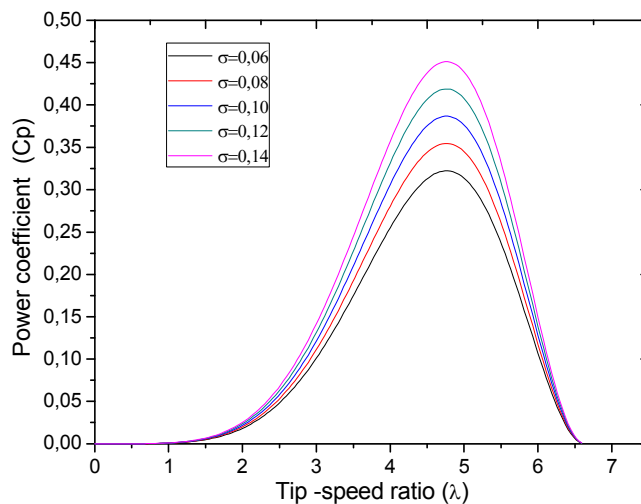Fig. 10 Comparison of the power coefficient for fixed and pitched blade rotor

Fig. 11 Power coefficient versus λ for different values of solidity

VI. Conclusion

The rotor height, h, does not affect the power coefficient because it appears in the expressions of both the produced and maximum available power. However, it does affect the value of the torque and the power. Both of these values increase with the value of h. In the figures, results are given for a height to diameter ratio equal to 1.0. These results are partials and our investigation continues for obtaining an optimal design of the rotor capable to work in hybrid Solar-Wind system.

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